A SYSTEMS APPROACH TO MANAGING R&D IN THE ROAD INFRASTRUCTURE SECTOR IN SOUTH AFRICA

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A thesis submitted to the Faculty of Engineering, University of the Witwatersrand, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 2009

DECLARATION

I hereby declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Signed: ………………………………..

Date: …………………………………

ABSTRACT

The importance of science and technology in South Africa in the next decade has been emphasised in the National R&D strategy, and a target expenditure of one per cent of GDP on R&D has been set. Research programmes in transport in the 1990s did not yield the expected outcomes and impact due to severe fragmentation of the programmes and subsequent diminished funding and output. Road authorities and the private sector expressed a need for the improvement of the associated management processes. International work in technology management has focused mainly on linear models of managing the development of hard products for the consumer market. These models are not suitable for the road building industry where the majority of the R&D programmes are aimed at the development of new knowledge, engineering methodology and associated engineering solutions. In addition, the R&D process is complex with many elements and interactions, and thus a simple linear management model is unlikely to yield the desired results. This thesis is aimed at the development of a systems-based R&D management model and tools for road engineering and shows that their implementation has a significant impact on R&D outputs.

This study evaluated international best practice as well as the success and failure factors of six local R&D programmes. A developmental research approach was used to identify the problem, develop a solution and test the solution in a number of R&D programmes. The model is based on a systems approach, taking aspects of cybernetics and complexity theory into consideration and is radically different from the linear approaches usually followed in the management of the development of consumer products. A set of analysis tools supporting the strategic model was developed. These include a strategic needs determination process, the technology tree tool and a research effectiveness measurement system. The new conceptual model and the associated analysis tools were implemented in four significant research programmes in the public sector, private sector and research organisations. The emphasis was on managing the synergy between the programmes in a holistic approach, thus enhancing the outcome and impact of the programmes. It is shown that the implementation of the models and tools had a significant effect on the R&D output from these research programmes. Finally, two protocols for the use of the model and tools were developed and their use in the Labour-Intensive Construction field demonstrated.

DEDICATION

This work is dedicated to my wife, Urszula, for the many long hours of discussion and for providing support through the long period of time needed to complete this work, as well as to my parents, Martien and Hettie, for providing me with a sound education.

ACKNOWLEDGEMENTS

The author would like to express his gratitude to the following people and authorities:

Thanks to Professor Rob McCutcheon of the University of the Witwatersrand for acting as supervisor of the work, and for providing inputs into the work programme and information analysis. Mr Wim van Steenderen of the University of the Witwatersrand is thanked for his assistance with the analysis of the Witwatersrand Research Centre for Employment Creation. Thanks to Professor Younis Ballim for his advice once the work had been completed. A special word of thanks goes to Professor Steve Emery for his assistance as co-supervisor of this work and his excellent advice and inputs which are greatly appreciated. Professor Alta van der Merwe is thanked for her advice on, and inputs into, the work as well as the presentation of the results.

The Council for Scientific and Industrial Research (CSIR) of South Africa, particularly the former Division for Roads and Transport Technology and the Built Environment Unit, their directors, management and colleagues are thanked for their support and for affording the opportunity to conduct this research. In particular, Dr JH Maree and Mr Phil Hendricks are thanked for creating the supportive environment in which the work was conducted.

The South African Bitumen Association (Sabita) is gratefully acknowledged for their co-operation in the development of the initial models and their implementation. Particular appreciation is expressed to Mr Rob Vos of Sabita who acted as a sounding board for many of the early concepts developed.

A number of colleagues in the CSIR are thanked for their many hours of hard work in implementing the systems, particularly Mr Benoit Verhaeghe. All the many colleagues in the public and private sector are thanked for their support in the implementation of the model and tools.

I would like to thank my wife, Urszula, for many hours of discussion and advice. Thanks to Linton Davies for language editing and Jenny Tweehuijsen for proofreading of the text.

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LIST OF ABBREVIATIONS AND SYMBOLS

AAPT	Association of Asphalt Pavement Technologists
AASHO	American Association of State Highway Officials
ADHI	Accelerated Development High Impact project
ALF	Accelerated Loading Facility
ANC	African National Congress
APT	Accelerated Pavement Testing
AREST	Asphalt Research Strategic Taskforce
ARP	Asphalt Research Programme
ARRB	Australian Road Research Board
AsgiSA	Accelerated and Shared Growth Initiative for South Africa
ATC	Annual Transport Convention
BBRU	Bituminous Binders Research Unit
BE	Built Environment Unit (CSIR)
BMLC	Bituminous Materials Liaison Committee
Boutek	CSIR Division of Building Technology
CalAPT	California Accelerated Pavement Testing programme
Caltrans	California Department of Transportation
CAPSA	Conference on Asphalt Pavements in Southern Africa
CM	Composite Macadam
CoD	Centre of Development
CoE	Centre of Excellence
COLTO	Committee of Land Transport Officials
CoPS	Complex Product Systems
CPM	Critical Path Method
CRREL	Cold Regions Research and Engineering Laboratory
CSIR	Council for Scientific and Industrial Research, South Africa
CSRA	Committee of State Road Authorities
CUTA	Committee of Urban Transport Authorities
DACST	Department of Arts, Culture, Science and Technology
DoT	Department of Transport (national)
DRTT	Division of Roads and Transport Technology (Transportek, CSIR)
DST	Department of Science and Technology

DTI	Department of Trade and Industry
E80	Equivalent standard 80 kN axles
EIC	Employment-Intensive Construction
EIEC	Employment-Intensive Engineering Consultants
ETB	Emulsion-treated base
FHWA	Federal Highway Association
FRD	Foundation for Research Development
Gautrans	Gauteng Department of Public Transport, Roads and Works
GEAR	Growth, Employment and Redistribution strategy
GEMS	Granular Emulsion Mixes
HMA	Hot-Mix Asphalt
HMC	Highway Materials Committee
HVS	Heavy Vehicle Simulator
ICAP	International Conference on Asphalt Pavements
ICT	Information and Communication Technologies
IMTK	Innovation Management Tool Kit
IT	Information Technology
ITS	Intelligent Transport Systems
KPI	Key Performance Indicator
LAMBS	Large Aggregate Mixes for Bases
LIC	Labour-Intensive Construction
LITE	Labour-Intensive Training and Engineering
LTPP	Long-Term Pavement Performance
MESALs	Million Equivalent Standard Axle Loads
MIPD	Management of Investments in Product Development
MIT	Massachusetts Institute of Technology
MLS	Mobile Load Simulator
Navplan	Research Management Consortium for the Department of Transport
NCHRP	National Cooperative Highway Research Programme
NEPAD	New Partnership for Africa’s Development
NPWP	National Public Works Programme
NTC	National Transport Commission
NIRR	National Institute of Road Research (CSIR)
NITRR	National Institute for Transport and Road Research (CSIR)

NSI	National System for Innovation
NDPW	National Department of Public Works
OECD	Organisation for Economic Cooperation and Development
PERT	Programme Evaluation and Review Technique
PG	Parliamentary Grant
PMG	Project Management Group
PMS	Pavement Management Systems
PPGS	Product Performance Guarantee System
R&D	Research and Development
RAP	Research Advisory Panel
RDAC	Research and Development Advisory Committee
RDP	Reconstruction and Development Programme
RIFSA	Road Infrastructure Framework for South Africa
RMC	Road Materials Committee
RTMC	Road Traffic Management Corporation
RPF	Road Pavements Forum
RRAC	Road Research Advisory Committee
S&T	Science and Technology
Sabita	South African Bitumen Association
SADC	Southern African Development Community
SAMDM	South African Mechanistic Design Method
SANRAL	South African National Roads Agency Ltd
SARB	South African Roads Board
SAT	Society for Asphalt Technology
SET	Science, Engineering and Technology
SIM	Stress-in-Motion system
SMA	Stone Mastic Asphalt
SMMEs	Small, Medium and Micro Enterprises
STEEP	Sociological, Technological, Economic, Environmental and Political
STEP	Strategic Positioning funding
SWOT	Strengths, Weaknesses, Opportunities, Threats
TAI	Technology Achievement Index
TDL	Traffic Data Logger
TDWG	Technology Development Working Group

TFA	Technical Focus Area
TNO	Organisation for Applied Scientific Research (Netherlands)
TSI	Total Systems Intervention
TPA	Transvaal Provincial Administration
TQM	Total Quality Management
Transportek	CSIR Division of Roads and Transport Technology
TRB	Transportation Research Board
TRH	Technical Recommendations for Highways (manual)
TRL	Transport Research Laboratory (United Kingdom)
TSI	Total Systems Intervention
UCB	University of California at Berkeley
USACE	United States Army Corps of Engineers
UW	University of Washington (Seattle)
VTI	Swedish National Road and Transport Research Institute
WES	Waterways Experiment Station
WM	Waterbound Macadam
WSDOT	Washington State Department of Transport

1 INTRODUCTION, SCOPE AND OBJECTIVES

1.1 Background

> *"Infrastructure is one of the pillars of this strategy* [growth and development strategy] - *it provides the link between economic growth and meeting basic needs. Let us invest in the future of this country, in the human resources that are the heart of the economy, in the technological development and innovations that are at the cutting edge of competitiveness." – Thabo Mbeki.*

It is recognised that innovation and Science, Engineering and Technology (SET) have a major impact on the economic growth of a country[1, 2]. This is also of strategic importance to South Africa, not only as a key enabler of economic growth, but also as a platform for the development of human resources as described in the South African National Research and Development Strategy[3]. This strategy highlights a number of key focus areas for SET development and innovation to address the future challenges that face South Africa. These include biotechnology, information technology, manufacturing technology, technologies to add value to natural resources, and technologies that will alleviate poverty. The strategy furthermore places specific emphasis on innovation and the management of these technologies in a coherent and integrative manner.

Transport and transport infrastructure play a major role in both economic development and poverty alleviation and therefore SET, which support these sectors, are deemed to be of major importance.[4,5] Transport is also of particular importance to South Africa[6,7] . The challenges being faced are that the layout of cities is ineffective due to the apartheid policies of the past, roads are the main carriers of freight and the cost of logistics is high[8].

This chapter first highlights the importance of SET in the development of a country, specifically South Africa. Second, the importance of the transport sector in the socio-economic development of countries is discussed. The need for Research & Development (R&D) is highlighted by the fact that both these aspects are important to South Africa, coupled with the relatively poor state of infrastructure in South Africa. An effective R&D programme in transport infrastructure will ensure the development of optimal solutions and new technologies in this field, thus maximising benefit of government expenditure on infrastructure.

SET in the transport field covers a wide range of topics from design methods and prediction models to materials and hard products. The field is therefore multidisciplinary in nature and the management thereof is relatively more complex than, for example, the management of the development of consumer products.[9] This study also showed that the R&D management models and processes used in the South African transport sector since 1988 have been less than effective, thus pointing to the need for a different approach. The contribution of this thesis is the development of a non-linear, systems-based R&D management model and decision-support tools, the assessment of the impact of the implementation of this model in the road engineering sector in South Africa, the development of an implementation protocol for the model and tools and the assessment of these protocols by applying them to the Labour-Intensive Construction (LIC) field.

Secondly, this chapter summarises the problem definition and the research method followed to develop a new R&D management model. The specific contribution made by this work and the associated publications are also discussed. Finally, an outline of the thesis is provided.

To be able to argue the case for an emphasis on transport technology, infrastructure technology as well as on the optimum management of research and development (R&D) programmes relating to these areas, a number of aspects need to be considered. These are discussed in more detail in Sections 1.1.1 to 1.1.6 and include the following:

- the definitions of science, engineering and technology (SET), research and development (R&D) and innovation;
- the importance of SET, R&D and innovation and how they impact on society;
- the special context and importance of SET, R&D and innovation in South Africa;

- the importance of transport and infrastructure with specific emphasis on road infrastructure;
- the nature of the problem of R&D and innovation in transport; and
- the status of R&D and innovation in the field of transport.

1.1.1 Definitions

Basic definitions of science, engineering, technology, basic research, applied research, experimental development and innovation are given in Appendix A in the companion document to this thesis.

Innovation is defined by Roberts[10] as follows:
"Innovation is composed of two parts: (1) the generation of an idea or invention, and (2) the conversion of that invention into a business or other useful application. Or in simple terms:

Innovation = Invention + Exploitation"

Invention is the process of *idea generation* and making ideas work. Essential to this process is the element of *creativity*. The exploitation process includes the stages of commercialisation and technology transfer. R&D can thus be seen as an element which occurs early in the process of innovation. Pistorius[11] highlighted the fact that innovation can occur in many spheres of life, including:

- financial, e.g. life insurance and banking;
- administrative procedures, e.g. democracy;
- services, e.g. self-service shopping, and
- technological.

This thesis focuses on R&D management for the process of technological innovation in road engineering.

Discussion of definitions

In addition to the definition above, Burgelman *et al.*[12] state that:
"*Technology refers to the theoretical and practical knowledge, skills, and artefacts that can be used to develop products and services as well as their production and delivery systems.*"

The process of innovation often consists of incremental advances leading to major technological change over time. Roberts[10] defines technological innovation as a multi-stage process with several feedback loops.

Creation of scientific knowledge, basic R&D and applied R&D are the processes usually associated with the invention part of the innovation cycle. Engineering usually follows R&D in the innovation cycle and leads to the development of new technology. The last part (exploitation) of the innovation cycle also includes elements such as commercialisation and marketing. This thesis focuses on the management of the research, development, engineering and technology development phases of the innovation cycle, and not on the exploitation (product commercialisation) phase. Some aspects of technology transfer are addressed as they pertain to the R&D management process.

These definitions elucidate the discussion that follows on the importance of SET, both generally and specifically in the South African context, the importance of the transport sector as well as the status of and shortcomings in the current management of R&D in the transport sector.

Of significance is the understanding that the management of R&D in the civil engineering field, and in particular in road engineering, embraces a relatively broad spectrum of activities. R&D in road engineering includes the development of new design methods, algorithms, materials, software solutions and some hard products mainly related to testing equipment and road building materials. This focus is substantially different from classical technology management which focuses mainly on hard product development for the manufacturing industry and the Information and Communication Technology (ICT) industry (see analysis in Section 2.11).

1.1.2 The importance of SET, R&D and innovation

SET (Science, Engineering and Technology) has a broad impact on society, including the stimulation of economic growth[13], socio-economic impact[14], changes in the commercial sector[15], enhanced performance of the manufacturing sector[16], organisations and management,[17,18] politics[19], intellectual property rights[20], philosophical thinking[21] and even the psyche of mankind[22]. In addition, SET has had marked positive and negative impacts on the environment[23]. Kuittinen *et al.*[24] showed that R&D intensity has a significant impact on the financial performance of companies. The role of technology in the development of a country was also highlighted by Roux *et al.*[25], who indicated the relationship between the UN Technology Achievement Index (TAI), GDP per capita and the Human Development Index (see Figure 1.1 below). The TAI is a composite index that captures technological achievement in a country in four focus areas: creating new technology; diffusing recent innovations; diffusing existing technologies; and building a human skills base for technological creation and adoption[26]. These data indicate that technology development (and therefore R&D to generate these new technologies) has a significant impact on both economic development and social development.

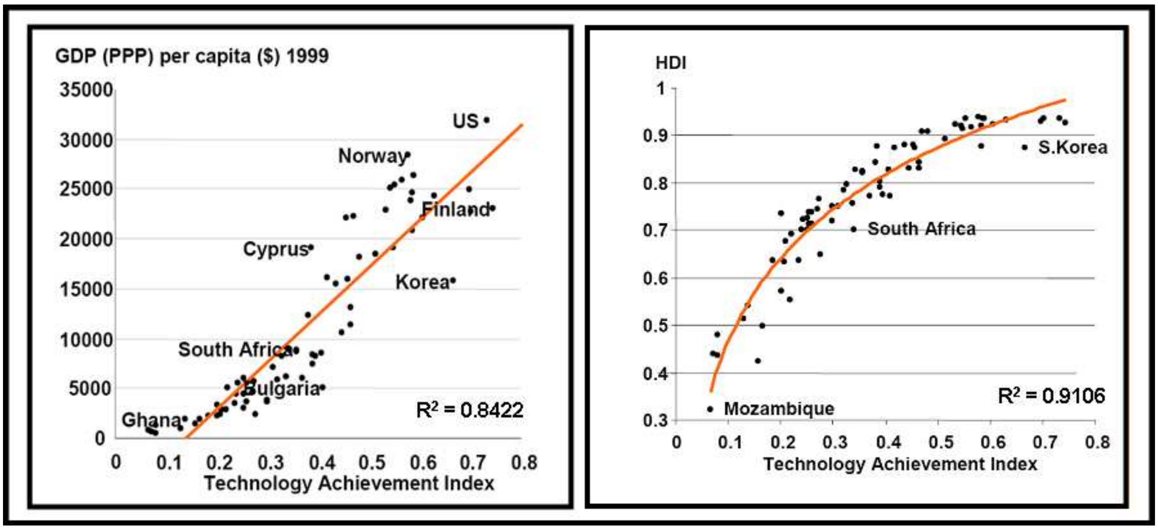

Figure 1.1: The dependence of wealth and living standards on technology (after United Nations reported in: Roux *et al.*[25])

Cetindamar *et al.*[27] stress the specific importance of effective technology management in developing countries to ensure economic growth. Luggen and Tschirky[28] stress the importance of effective technology management in smaller companies, so-called new technology-based firms (NTBFs), to allow sufficient flexibility and speed of response for the smaller firms to compete with larger firms.

1.1.3 The importance of SET in South Africa

Between 1990 and 1994, the South African government neglected R&D to the extent that the national expenditure on R&D dropped from 1.1% of GDP to only 0.7% of GDP in 1994[3]. It then increased to 0.95% in 2007[36], which still compares unfavourably with international standards such as those in the OECD where the average is 2.15% over the public and private sector. Walwyn[29] indicated that Business Expenditure on R&D (BERD) is particularly low and that an increase of 85% above reported figures for 2004 is required to maintain South Africa's investment in R&D at 0.9% of GDP.

The National R&D Strategy of 2002 recognises the key role of SET in the economy[3]. This strategy specifically states that it is critical to increase the rate and quality of innovation in South Africa. In addition, it has a specific focus on the balance between national competitiveness and improved quality of life, both of which depend significantly on a quality SET programme. Furthermore, it cites countries such as South Korea, Chile, Australia, Malaysia and Finland, which have all benefited from the correct and appropriate SET strategy and which have facilitated these countries' rapid progress towards prosperity. It states that R&D investment is a significant contributor to human resource development. In addition to the negative economic impact, the decrease in R&D expenditure has therefore also contributed to the current critical shortage of highly skilled manpower, especially civil engineers[30], and the associated required capability in science, engineering and technology. In a study of Japan (a successful developed country), Korea (a successful newly industrialised country) and South Africa (a successful developing country), Lingela and Buys[31] found that Korea has nine times more researchers per capita than South Africa. This is indicative of the low levels of investment in R&D in South Africa. In addition, Grobbelaar and Buys[32] found that South Africa's capability to deliver R&D outputs is under threat due to a high student-to-lecturer ratio, coupled with a lack of investment in the South African research core.

De Wet[33] highlighted the importance of a national strategy for R&D, particularly in developing countries where 'technology colonies' exist, as well as the importance of bridging the gap between local research capability and the implementation of first world technologies. A country that fails to achieve this will be unable to cross the innovation chasm, causing it to remain dependant on foreign technologies and not receive the full benefit of technological development. This aspect was also emphasised by Nolte and Pretorius[34]. Buys[35] found that South African industry in general is operating as a Stage III technology colony that focuses on local improvement of products and processes using foreign technology, and as such is very dependent on international partnerships.

The importance of correcting the funding situation is emphasised in the National R&D Strategy through the setting of a target to double government spending on R&D over a three-year period between 2004 and 2007. However, in reality R&D expenditure in South Africa reached only 0.95% by 2007[36]. Of equal concern is the low level of R&D investment in construction-related R&D. The South African National R&D survey found that R&D expenditure in construction-related fields (including transport infrastructure) was only 0.2% of industry turnover in 2006[37].

The Council for Scientific and Industrial Research (CSIR) of South Africa, a parastatal organisation, is the largest research organisation on the African continent. Through a number of international peer reviews and stakeholder discussions in 2002 and 2003, the CSIR realised that it had, similarly to the rest of South Africa, lost some of its science and technology base[38]. A strategic process (the Beyond 60 strategy)[38] was then launched to provide for a renewal of the science and technology base and the transformation of the scientific and technical manpower of the CSIR.

1.1.4 Importance and status of the transport industry in South Africa

Transport and transport infrastructure impact on South Africa in a number of ways. Firstly, the provision of adequate transport facilities, including road infrastructure and access streets is essential for providing the basic needs of people. Secondly, the road building industry provides an ideal opportunity for job creation, the development of human resources through skills and technical training and the development of small entrepreneurs and contractors. Finally, a quality primary and secondary road network is associated with economic growth which in turn ensures sustainable employment opportunities. This association is emphasised by the relationship between Gross Fixed Capital Formation (GFCF) as a percentage of GDP and growth in GDP[39] – see Figure 1.2 below. The 2007 figure of percentage GFCF vs. growth indicated in Figure 1.2 was reported by SAFCEC[40].

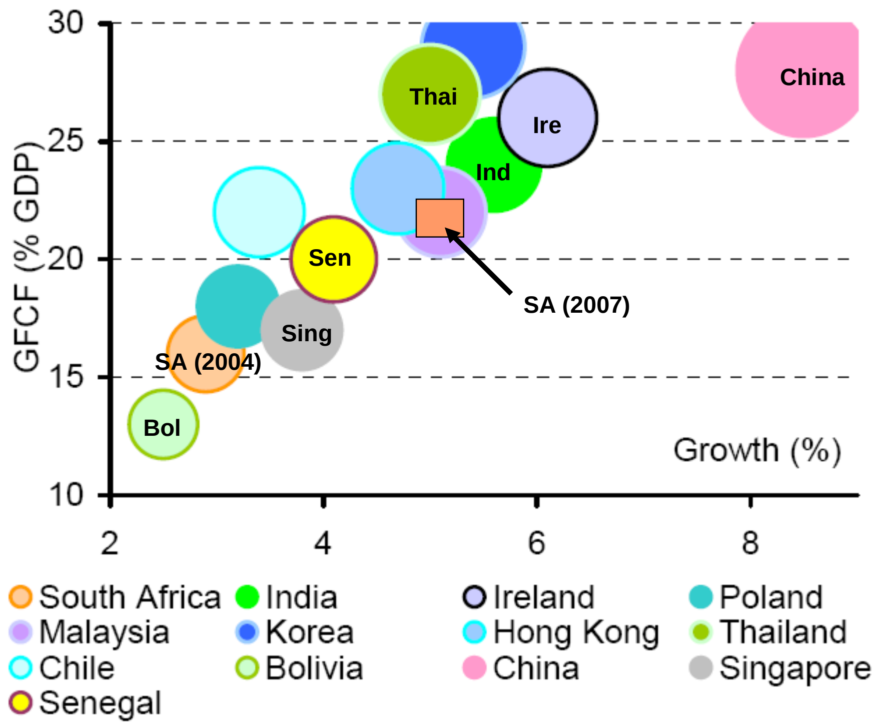

Figure 1.2: The relationship between GFCF and GDP in a number of countries[39]

The importance of infrastructure investment (including significant transport infrastructure investment) is also highlighted in the Accelerated and Shared Growth Initiative for South Africa (AsgiSA)[41]. AsgiSA has set a target of 25% of GDP for investment in infrastructure (9% and 16% public and private sector respectively) to achieve an economic growth rate of 6%. This is in line with the relationship in Figure 1.2.

However, the South African Institution of Civil Engineering (SAICE) reported in a recent study that the condition of South African infrastructure is not acceptable (for example national roads were rated as being in a fair condition but all other roads were in a poor to very poor condition)[42]. In addition, SAICE found that whereas Western Europe, North America, India and China have one engineer per 130 to 450 people, only one of every 3 200 South Africans is an engineer, a ten to twenty-fold disadvantage. The Road Infrastructure Framework for South

Africa (RIFSA)[43] highlights the need for investment in road infrastructure and gives an action plan for road infrastructure development in South Africa.

In response to the growing understanding of the need for investment in infrastructure, the South African government announced a plan in 2005 to invest R320 billion in infrastructure over a five-year period from 2005[44]. The importance of infrastructure is also evident from the emphasis placed by government on the Extended Public Works Programme[45], and regionally, infrastructure is a major factor in the New Partnership for Africa's Development (NEPAD)[46] strategy. Flagship projects such as the Gautrain project[47], which will provide rapid transit between Johannesburg, Pretoria and O R Tambo International Airport, will require major innovation and capacity development in the transport sector, mostly supported by government. Koh[48] emphasised the importance of technological progress and its role in the economic progress in Singapore. He also discusses the important role of government in creating and supporting the institutions and infrastructure to manage the transition to an innovation-based economy. This focus on infrastructure investment further emphasises the importance of R&D, which will yield the solutions and technologies to maximise the benefit from government expenditure on infrastructure (including roads).

1.1.5 The complex nature of the R&D process

Complexity theory, which is associated with complex systems, has been the subject of research over the past 30 years and has found applications in a number of fields including management science, astronomy, chemistry, evolutionary biology, geology and meteorology[49]. Complexity of systems should not be confused with complicatedness (difficult to understand). Cilliers[50] states: "*There is no denying that the world we live in is complex, and that we have to confront this complexity if we are to survive, and, perhaps, even prosper*". The traditional way of dealing with complex issues is to engage them from what is perceived to be a scientifically determined, secure (and usually fixed) point of reference. Not only does Cilliers call this approach an avoidance of complexity, but solutions that are based on this premise will also of necessity be linear, and therefore not responsive to changes in needs and constraints. Such solutions are thus unlikely to be useful when phenomena such as human capital development and management processes need to be addressed.

Cilliers[50] also analysed the nature of organisations and showed that they are inherently complex systems. An analysis was done in this study to show that the research process exhibits many of the characteristics of a complex system (see Chapter 2, Table 2.1). This is confirmed by Wagner-Luptacik *et al.*[51] who state that the innovation process in a company is a truly dynamic and complex system and that simplistic linear models fail to predict the behaviour of the system accurately. However, in a survey of 68 companies and in five in-depth case studies, Dekkers[52] found that industrial practices in innovation management still rely on incremental innovation, depend on hierarchical managerial practices and have an inward departmental orientation, and therefore do not take cognisance of the complexity of the process.

1.1.6 R&D in the transport sector in South Africa

In the manufacturing sector, particularly in consumer product development, the management process is often very linear – progressing from idea generation and R&D, to engineering, product manufacturing and marketing (see Chapters 2 and 3). However, new knowledge generation in the transport sector is multidisciplinary in nature, covering fields such as transport policy and planning, traffic engineering, materials science, road structural design, intelligent transport systems, etc. The outputs and outcomes of research and development activities are mainly new engineering methodology, decision-support systems, prediction models and some new hard products. The R&D and innovation processes in road engineering are therefore not linear ***but rather an iterative, systemic process of knowledge generation and learning*** (see Chapter 3). The management of this process should therefore take cognisance of the inherently complex, systemic nature of the process.

1.2 Brief problem statement

From Section 1.1, the following are key aspects to be considered in R&D management in the road engineering field:

- SET and R&D in the transport sector (including road engineering) are important in a developing country such as South Africa.
- Historically, transport R&D programmes have declined for a number of reasons which include the use of simplistic linear management models (see detail in Chapter 3), tendering processes that lead to fragmentation of the programme, and a reduction in funding levels to 50 times less than the target set in the National R&D strategy.
- The R&D process is a complex system in itself and includes a number of organisations that are themselves complex systems and therefore a simplistic linear management model is unlikely to yield the desired results.

Furthermore, the analyses done in this thesis which are discussed in Chapters 2 and 3 indicate that:

- Traditional R&D and innovation management models were developed for hard product development and are linear in nature, following the steps of idea, research, development, engineering, manufacturing and marketing.
- More than 72% of case studies in a typical technology management handbook and series of journal articles deal with hard product development and most of the remainder with software development – none dealt with R&D in infrastructure or transport.
- Traditional R&D management models do not take cognisance of the complexity of the process of developing new knowledge, engineering methodology, know-how, expertise and capacity building such as that needed in the transport sector.

The analyses in Chapters 2 and 3 indicate the need for a systems-based management model and tools for R&D in the transport and road engineering sector that take cognisance of the complexity of the R&D process. This is discussed in detail in Chapter 4.

1.3 Research questions and thesis statement

Based on the above argument the following research questions are defined (see Chapter 4 for detailed discussion):

- To what extent are currently used technology management practices and models applicable to the management of R&D in the road engineering field?
- What are the critical success factors for an effective R&D management model in the road engineering field?
- What are the critical principles and required elements of a systems approach to such a model?
- What are the appropriate decision-support tools required for managing complex, multi-disciplinary research programmes in the road engineering field?
- If a new approach and a new management model are implemented, what effect will they have on the research output of the road engineering research programme?

Based on the previous discussion and the research questions, the following thesis statement is defined as follows:

> ***The development and implementation of a systems-based conceptual management model and decision-support tools in a road engineering research programme will lead to an increase in research effectiveness in terms of number of outputs and long-term growth in the R&D programme.***

1.4 Scope, context and limitations of the study

As indicated in the preceding sections, a new approach to the effective management of R&D in the transport industry and road engineering is essential to address the significant challenges that face South Africa. The magnitude and complexity of the challenge demands a national, co-ordinated approach, including national, provincial and local government structures, educational institutions, research councils and the private sector, to effectively address the process of managing the development of relevant knowledge and technologies to solve current as well as future problems in the industry. Furthermore, R&D activity in the road infrastructure sector is multidisciplinary in nature and is complex.

This thesis therefore focuses on the following aspects:

- the definition of the problem through:
  - a review of classic R&D management and innovation management processes and models as described in the literature;
  - a review of the history and performance of a selection of R&D programmes and projects in the transport industry in South Africa and a quantitative analysis of the associated data;
- the definition of the problem and the formulation of required research methodology to solve the problem;
- the identification of important characteristics of an R&D management model;
- a survey aimed at R&D managers locally and internationally to verify the validity of the use of these management model characteristics;
- the development of a new model for managing R&D for the road infrastructure industry in South Africa (including a strategic-level conceptual model, decision-support tools and a system for evaluating research effectiveness);
- the evaluation of the model through an analysis of the implementation of the proposed model in a number of research programmes and the lessons learnt in this process;
- the development of an implementation protocol for R&D management in road engineering; and
- an assessment of the protocols by applying them to the Labour-Intensive Construction field.

Limitations

This thesis is limited to R&D management in the road engineering industry and does not cover aspects related to marketing and business development that are part of the broader innovation process. The models and tools developed here have been tested mainly in the road engineering field and their applicability in other fields has not been shown extensively.

1.5 Summary of research method

The approach followed in this thesis is a mixed research model employing both the qualitative as well as the quantitative analysis of information and data. More specifically, a developmental research approach as described by Thomas[53] was followed. According to Thomas, developmental research comprises three phases:

- analysis of the problem;
- development of the solution; and
- evaluation of the implementation of the solution.

In this thesis therefore, firstly the management of the complex process of R&D in the transport sector and road engineering field is analysed. Secondly, a new conceptual model and supporting decision tools are developed that are tailor-made for the development of new engineering methodology as opposed to hard product development. Thirdly, the implementation of these models in two local research programmes and a large research project is evaluated and the effect thereof determined. Lastly, implementation protocols for the management of R&D are developed and their applicability in the LIC field is assessed.

The quantitative and qualitative analyses of the literature, existing innovation management models and case studies were used to develop a set of ***tenets*** for the development of a conceptual R&D management model and supporting decision tools. The table of tenets is used to summarise the learning in a specific chapter and to facilitate the link to the next chapters. The model and tools were developed interactively through discussions and trials in research programmes in the public as well as private sector.

Data collection

The data and information contained in this thesis were compiled from personal interviews and workshops as well as from analyses of six historical research programmes and three significant long-term research projects using a case study approach.[54] In addition, a survey was done to assess the degree to which research managers use specific elements of R&D management processes and how important they consider these characteristics to be.

The data were collated from literature reviews and case studies and then analysed and reduced to twelve tenets for the development of the conceptual model and tools. The quantitative data were generated from the analysis of the financial records of the CSIR as well as from the records of the Navplan[i] organisation. Information on the number of research outputs from the road engineering programme was compiled from CSIR records and from the website of the Southern African Bitumen Association.

1.6 Significance and contribution of the work

The work conducted for this thesis contributed the following:

- a paradigm shift away from simplistic linear models of managing R&D in the road engineering sector to a systems-based approach that takes cognisance of complexity, cybernetics and systems theory;
- a new non-linear, systems-based conceptual model for managing R&D;
- the technology tree tool for managing a portfolio of projects in the engineering methodology field;
- a tool for carrying out facilitated needs determination in a multi-disciplinary research field;
- a tool for assessing the effectiveness of the research programme;
- insights and lessons learnt from implementing a new R&D management paradigm;
- the development of an implementation protocol for R&D management as well as a protocol for the implementation of the technology tree tool; and
- recommendations for the use of the two protocols in the Labour-Intensive Construction (LIC) field.

1.7 Publications from this study

The following publications have thus far been generated from this study:

- Rust FC and RM Vos. "A proposed holistic approach to the management of technology development in the transportation industry". Transportation

[i] Navplan was a consortium of organisations appointed by the Department of Transport to manage the transport R&D programme in the mid-1990s.

Research Record No. 1637, Transportation Research Board, Washington DC, USA, pp 18-23, 1998.

- Rust FC, RT McCutcheon and L Coetzee. "Transport research: Quo Vadis?" Proceedings of the Annual Southern African Transport Conference, 2008.
- Rust FC, L van Wyk, H Ittmann and K Kistan. "The role of R&D in transport infrastructure in South Africa." Proceedings of the Annual Southern African Transport Conference, 2008.

1.8 Outline of the thesis

A thesis map is shown in Figure 1.2.

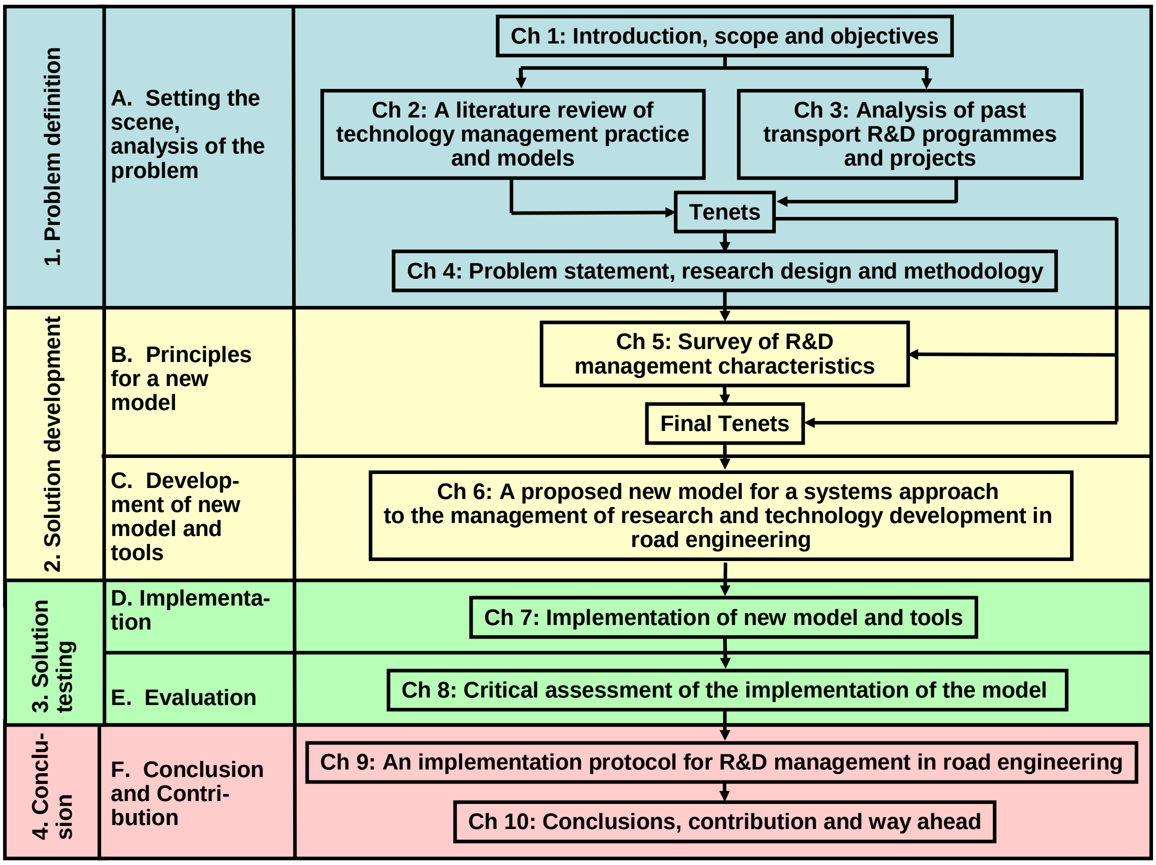

Figure 1.2: Thesis map

In line with the developmental research approach, the thesis is divided into four main parts:

- The analysis of the problem – Chapters 1 to 3, followed by a formal problem statement and research methodology section in Chapter 4.
- The development of a new solution.
- An analysis of the implementation of the new model and tools and the success thereof.
- The development and demonstration of an implementation protocol for R&D management in road engineering.

It should be noted that the analysis in Chapters 2 and 3 was used not only to define the problem, but also in parallel to compile the qualitative data required to determine the desired characteristics of a new approach to R&D management.

The thesis is organised into the following chapters:

Chapter 1: Introduction, scope and objectives

The chapter sets out the background to the work done, the need for a new approach to R&D management in road engineering and the scope of the work.

Chapter 2: A literature review of technology management practice and models

The chapter focuses on a literature review of general technology management practices and their characteristics as well as the general aspects of systems theory. It also discusses the results of a literature study to assess existing technology management models in terms of their applicability in the road engineering field. A set of principles or tenets is defined that informed the development of the new management model.

Chapter 3: R&D management in the South African transport industry – an analysis of past research programmes and projects

This chapter deals with the analysis of South African transport research programmes since 1980. The work focuses on the analysis of programme objectives, management structures and processes, research procurement processes, trends in project size over time and trends in total research funding over time, and also focuses on the advantages and disadvantages of different approaches in the past. The final part of the chapter defines criteria for the assessment of R&D programmes and management models. These criteria were used to evaluate the models discussed in Chapter 2 and the R&D programmes and projects discussed in Chapter 3 in terms of their applicability to R&D management in road engineering. The analysis was also used to enhance the tenets defined in Chapter 2.

Chapter 4: Problem statement, research questions, research design and methodology

The chapter summarises the problem as defined in the first three chapters and then defines a set of research questions and the thesis statement. The research methodology to address the research questions is discussed.

Chapter 5: A survey to determine the importance of selected characteristics to a new R&D management model

The work conducted in the previous chapters was used to define selected characteristics and tools that could be important to the development of a new R&D management model in the road engineering sector. The survey questionnaire was distributed to 126 local and international R&D managers. The degree to which these characteristics and tools are used by them as well as their importance is analysed.

Chapter 6: A prototype model for a systems approach to the management of R&D in the road infrastructure industry

This chapter focuses on the development of a new model and decision-support tools for the holistic management of R&D in the road building industry, based on the tenets developed.

Chapter 7: Implementation of new model and tools

The implementation of the above model in a number of research programmes is described and the lessons learnt from its implementation are summarised.

Chapter 8: Critical assessment of the success of the implementation of the model

The impact of the implementation of the model on the output of selected road engineering R&D programmes in South Africa is assessed.

Chapter 9: Implementation protocol for managing R&D in road engineering

Protocols for the implementation of the conceptual model and technology tree tool are developed. The implementation of these protocols in the Labour-Intensive Construction field is discussed.

Chapter 10: Conclusions, contribution and way ahead

The contribution of the work and the potential way ahead are reflected upon.

1.9 Conclusion

In this chapter the background of and motivation for the thesis are given. The specific characteristics of R&D in the transport sector are discussed. The difference between hard product development and R&D for the development of new engineering methodology requires an innovative approach. The thesis statement places emphasis on the development and implementation of R&D models and decision-support tools that are systems-based and thus take cognisance of complexity theory and systems approaches. The work in this study was undertaken mainly utilising a developmental research approach, surveys and case studies.

2 A LITERATURE REVIEW OF TECHNOLOGY MANAGEMENT PRACTICE AND MODELS

2.1 Introduction

The background and issues related to the management of R&D in the road infrastructure sector are addressed in this chapter through a discussion of the general aspects of the broader technology management discipline under the following headings:

- the history and nature of the technology management discipline;
- the systems paradigm;
- strategic planning considerations;
- process issues related to technology management; and
- organisational issues relating to technology management.

Next, the technology management models and R&D management models available in the literature are discussed. The applicability of the models to R&D management in the road engineering sector is evaluated in Section 2.10.

As indicated in Chapter 1, the thesis does not cover the commercial and marketing aspects of technology and innovation management. The purpose of the chapter is to define the technology management landscape and the relevant issues pertaining to technology management to assist with the definition of the problem of managing R&D in the road infrastructure sector. Important aspects that should be considered in the development of a new model for the management of R&D are summarised in a table of tenets at the end of the chapter (Table 2.6).

2.2 History and definition of technology management and innovation

2.2.1 History of technology management

Technology began with the dawn of mankind. In its earliest form it consisted of basic weapons and tools and the ability to make fire, and later the wheel was developed. Technology can be defined as the products, tools, methods, processes and services that are used by mankind. According to the online Encarta encyclopaedia[55], the term is derived from the Greek words *tekhnè*, which refers to an art or craft, and *logia*, which means an area of study. Thus technology literally means ‘the study of crafting’ and therefore in the scientific world it is an essential process which follows the research phase in the innovation chain. Technology management addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructure) needed to achieve and maintain (and grow) a market position and business performance in accordance with the company’s objectives[56].

As indicated in Chapter 1, SET (Science, Engineering and Technology) has a broad impact on society, ranging from the stimulation of economic growth[13] and socio-economic deveopment[14] to positive and negative impacts on the environment[23] and even the human psyche.[22] Thus technology not only influences everyday life but can also significantly enhance a country's competitiveness through innovation and by providing essential developments for local and export markets. It was also shown in Chapter 1 that technology development plays a major role in job creation and the development of human and organisational capacity and is therefore essential for a healthy economy.[3] The rapid world-wide changes in social development, with the accompanying changes in needs, place new demands on technological development and indeed accelerates the rate of development of new technologies (Freeman)[57].

> *“Whether like the sociologist, Marcuse, or the novelist, Simone de Beauvoir, we see technology primarily as a means of human enslavement and destruction, or whether, like Adam Smith, we see it as a liberating Promethean force, we are all involved in its advance. However much we might wish to, we cannot escape its impact on our daily lives, nor the moral, social and economic dilemmas with which it confronts us. We may curse it or bless it, but we cannot ignore it.”* - Freeman

In a climate of rapidly increasing technological development and the increasing impact of technology on industry and society, amidst an increasing scarcity of resources (human, financial and raw materials), it has become imperative that technological development and innovation be managed effectively[58]. The discipline of technology management dates far back. Early work by academics focused mainly on two themes (Roberts[10]): historical romanticism about the lives and activities of great 'creative inventors' like Edison and Bell, and psychological research into the 'creativity process'.

> *"While those writings made interesting reading, in my judgment, neither track contributed much useable knowledge for managers of technical organisations... researchers who were focusing at that early time upon issues of R&D management, were not paying much attention to organisational variables or to innovation as a multi-stage, multi-person, complex process."* - Roberts

According to Roberts, industry in the USA in the early 1960s was not overly enthusiastic about the attempts of social science to probe the reasons for successful research. In the 1980s, however, there was broad acceptance of the results of studies of the process of research development and engineering. Technology management today forms an integral part of strategic management in major corporations.

The evolution of strategic management can be roughly divided into three phases: the 1960s when multi-year budget projections were used, the 1970s when market growth/share matrices and market attractiveness considerations were developed, and the 1980s during which technology as a strategic factor became important and was indeed included in strategic planning. In 1962 the MIT's (Massachusetts Institute of Technology) Sloan School of Management initiated a research programme on the Management of Science and Technology, and in 1988 the University of Miami initiated the first in a series of international conferences on the Management of Technology[59]. Current developments in technology management are also published in a variety of journals such as the Harvard Business Review, the Sloan Management Review, the International Journal of Innovation Management and Research Technology Management. Courses dealing with technology management are presented at many universities, including the Sloan School of Management of the MIT, the University of Lausanne in Switzerland, Cambridge University, and in South Africa at the Universities of Stellenbosch and Pretoria.

2.2.2 *Definition of innovation and the process of technology management*

In view of the renewed emphasis on science and technology in South Africa discussed in Chapter 1 and the renewed focus on research in organisations such as the CSIR, it is important to define these terms and their inter-relationship more clearly. As shown in Chapter 1, Roberts[10] sees the development of technology as the process of invention and innovation. He gives a definition of the two terms as follows:

> *"Innovation is composed of two parts: (1) the generation of an idea or invention, and (2) the conversion of that invention into a business or other useful application. Or in simple terms:*
>
> *Innovation = Invention + Exploitation"*

Invention is the process of idea generation and making ideas work and often contains a significant element of research and development, as well as scientific discovery. The exploitation process includes the stages of commercialisation and technology transfer.

Burgelman *et al.*[12] show the relationship among key concepts concerning technological innovation (see Figure 2.1). They list the following key activities:

- 'tinkering' or experimenting;
- research activities;
- development activities;
- product/process development activities; and
- market development activities.

Adams *et al*[60]*.* defined seven dimensions of the innovation process:

- input management, focusing on providing resources for innovation activities (e.g. funding, human resources, equipment, facilities and new idea generation processes);
- knowledge management, the absorption of knowledge and an organisation's ability to identify, acquire and utilise external knowledge critical to its success;
- innovation strategy, a plan (consistent with the organisation's overall strategy) that continuously informs decisions on resource allocation to

innovation projects and activities that are designed to fulfil the organisation's objectives;

- organisational culture and structure concerning the way staff are grouped and the organisational culture within which they work;
- portfolio management, focusing on a process for making strategic, technological and resource choices that govern project selection and the future shape of the organisation;
- project management, the activity of managing the complex innovation process to turn the inputs into a marketable innovation; and
- commercialisation, which is concerned with making the new process or product a commercial success, and includes aspects such as marketing, sales, distribution and joint ventures.

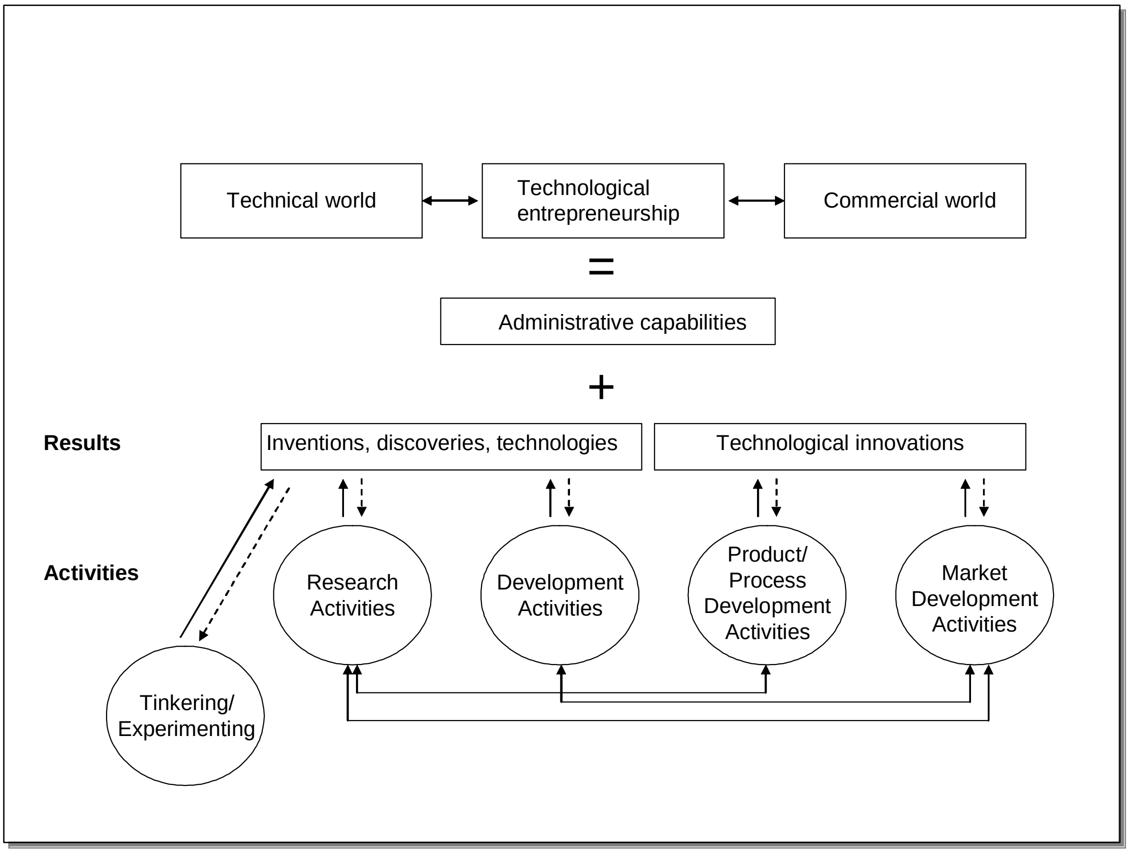

Figure 2.1: The relationship among key concepts concerning technological innovation (after Burgelman *et al.*12)

Henderson and Clark[61] defined types of innovation as follows:

- *Radical innovation*: establishes a new dominant design and new set of core design concepts embodied in components that are linked together in a new architecture.
- *Incremental innovation:* refines and extends existing design; underlying core concepts and linkages remain the same.
- *Modular innovation:* changes components in the design but not the linkages between them.
- *Architectural innovation:* core components and concepts remain the same, but with a change in the architecture of the product, thus linking together existing components in a new way.

Note: R&D in the road infrastructure sector often follows the route of architectural innovation, integrating capabilities to deliver new results.

Roberts defines the management of technological innovation as the process of applying resources to:

- create new knowledge (research);
- generate technical ideas aimed at new and enhanced products, manufacturing processes and services (applied research);
- develop new ideas into working prototypes; and
- transfer them into manufacturing, distribution and use.

Technological innovation can be depicted as a multi-stage process with several feedback loops. This is shown in a simplified version in Figure 2.2 (after Roberts[10]). Roberts' process includes the following stages:

Stage 1: Recognition of opportunity

Stage 1 focuses on developing a motivating idea and defining one or more technical and/or market goals. The managerial issue at this stage is how to stimulate idea generation through the appropriate staffing, structure and strategy. According to Roberts, it is critical at this stage to have small amounts of R&D financing available free from complex and discouraging evaluative procedures. To set up stringent, formal approval processes at this stage is a major mistake.

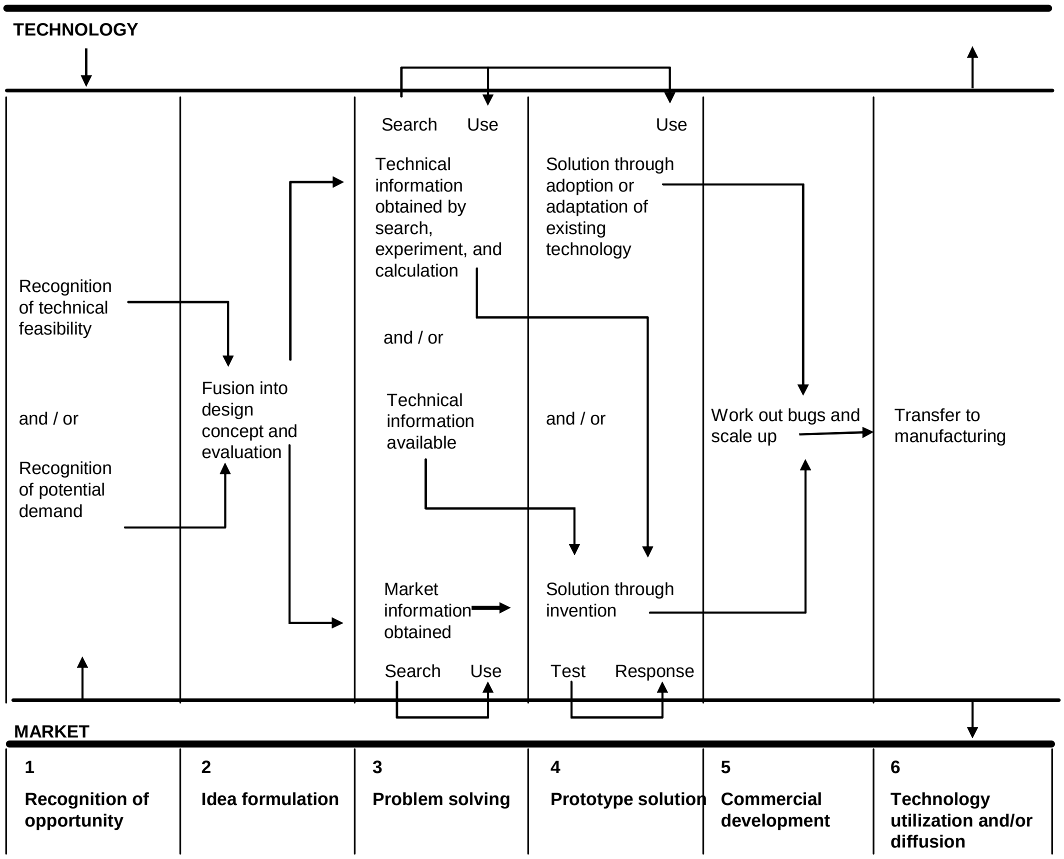

Figure 2.2: The multi-stage process of innovation (after Roberts[10])

Stage 2: Idea formulation

This stage focuses on the development of design concepts and evaluating them.

Stage 3: Problem solving

During this phase detailed market and technical information is accumulated through research and experimentation.

Stage 4: Prototype solution

The prototype solution can be developed through a new invention or through the adaptation of existing technologies.

Stage 5: Commercial development

In this stage detailed specifications are formulated and manufacturing engineering of ideas is done. The managerial issues involve co-ordination of staff of various disciplines, achievement of goals within time and on budget and delivering of a specific output. This stage involves tight control and a focus on financial criteria. This stage often takes more time and resources than the other stages put together.

Stage 6: Technology utilisation and/or diffusion

This involves the transfer of the technology to large-scale manufacturing and implementation.

Although not shown in Figure 2.2 for simplicity's sake, the process usually involves multiple feedback loops which are essential to successful innovation. According to Roberts, three of the main dimensions for technological innovation are staffing, structure and strategy. These will be discussed below.

Wolfe[62] stated that "*There can be no one theory of innovation, as the more we learn, the more we realize that 'the whole' remains beyond our grasp*", and that "*Several theories of innovation exist, but each applies under different conditions*". This emphasises the importance of developing a fit-for-purpose R&D management process for the road engineering field that will by definition differ from that for hard product development.

2.3 The systems paradigm

> *"I must create a system or be enslav'd by another man's" - William Blake, poet.*

Peter Senge[63] states:

> *"From a very early age, we are taught to break apart problems, to fragment the world. This apparently makes complex tasks and subjects more manageable, but we pay a hidden, enormous price. We can no longer see the consequences of our actions; we lose our intrinsic sense of connection to a larger whole. We then try to see 'the big picture', we try to assemble the fragments in our minds, to list and organise all the pieces. But as physicist David Bohm says, the task is futile - similar to trying to*

reassemble the fragments of a broken mirror to see a true reflection. Thus, after a while we give up trying to see the whole altogether."

According to De Rosnay[64], analytic approaches and systems approaches are somewhat more complementary. Analytic approaches aim to reduce a problem to its elementary elements in order to study in detail and understand the types of interaction that exist between elements of the problem. Usually one variable at a time is changed to observe the result and then general laws are inferred that will enable the prediction of future results. To this end, the laws of the additivity of elementary properties are used. This is particularly the case in homogeneous systems, those composed of similar elements and having weak interactions among them where the laws of statistics readily apply. However, these laws do not apply in highly complex systems composed of a large diversity of elements with strongly linked interaction between them. In complex problems and systems, the new methods pertaining to the systems approach are more useful.

The importance of systems thinking in technology management was shown by Gaynor[65] (p 3.4). However, systems approaches have, to date, focused on a cycle of awareness, acquisition, adaptation and abandonment of technologies of hard products and not on engineering methodology and knowledge. In view of the objective of developing an R&D management model that takes cognisance of the complexity of the process in the road infrastructure sector, it is important to highlight some of the main aspects of systems thinking and the related topics of cybernetics and complexity theory.

2.3.1 Cybernetics

Cybernetics was first conceived in 1948 by Norbert Wiener and is defined by the Encyclopaedia Britannica online[66] as: *"The science of regulation and control in animals (including humans), organizations, and machines when they are viewed as self-governing whole entities consisting of parts and their organization."* Cybernetics differs from the physical sciences in that it does not focus on material form but rather on the organisation, pattern and communication in entities[66].

Paul Pangero[67] states that: *"The cybernetic approach is centrally concerned with this unavoidable limitation of what we can know: our own subjectivity. In this way cybernetics is aptly called 'applied epistemology'".*

Heylighen *et al*.[68] state in an article on the Principia Cybernetica Web[ii] that cybernetics and systems science are interlinked and together they form a domain that is related to the recently developing 'sciences of complexity', including artificial intelligence, neural networks, dynamic systems, chaos and complex adaptive systems. The interrelationship between systems thinking and cybernetics is illustrated by Heylighen[68]: *"Although the systems approach in principle considers all types of systems, it in practice focuses on the more complex, adaptive, self-regulating systems which we might call 'cybernetic'".*

The use of cybernetics in operational research and management approaches was pioneered by Stafford Beer as early as 1959[69]. Beer gives three basic characteristics of a cybernetic system[70]:

- it is very complex and the detail of the interconnectivity is difficult to define;
- it is very probabilistic and every trajectory within its activities is equally probable; and
- it is self-organising in that its fundamental organisation is generated from within.

Heylighen also discusses the advent of second-order cybernetics. First-order cybernetics in the post-Second World War era focused mainly on the (then) new control and computer technologies and therefore on the engineering approach, where it is the system designer who determines what the system will do. However, in the 1970s, cyberneticists felt the need to clearly distinguish themselves from the mechanistic approaches by emphasising autonomy, self-organisation, cognition and the role of the observer in modelling a system. In second-order cybernetics the observer forms part of the system.

[ii] The Principia Cybernetica Project (PCP) is an international organisation that aims to develop a complete philosophy or 'world view' based on the principles of evolutionary cybernetics.

Ghosal[71] discussed the use of cybernetics and systems approaches in the Council for Scientific and Industrial Research in India to conduct strategic planning for the development of India as well as their use in forecasting and simulation studies.

The use of cybernetic principles in the management of academic institutions is discussed by Birnbaum[72]. He describes the use of 'thermostats' or sensors (monitoring mechanisms in an organisation that collect information pertaining to its function and performance) and feedback loops that allow managers to take action based on positive as well as negative feedback.

Geyer[73] discussed the use of both first-order and second-order cybernetics in sociological thinking. Important aspects of a system based on first-order cybernetics that should be considered are:

- the boundaries of the system are drawn to describe the system and its interaction with its environment outside the system;
- systems and subsystems can form a hierarchically nested set of systems that interact with each other;
- the principle of circular causality holds true in a cybernetic system, therefore the system can impact on itself in a non-linear interaction;
- a cybernetic system contains both positive and negative feedback loops that inform the activity in the system and its performance; and
- cybernetic systems can be used to simulate situations to study phenomena of emergence.

Second-order or modern cybernetics differs from its predecessor in that it specifically includes the observer in the system. Although this paradigm was used mainly to explain living systems such as the human brain, some aspects are also of importance in addressing management problems. Second-order cybernetics specifically focuses on:

- positive feedback loops more than on negative feedback;
- self-organisation of the system allowing self-correction based on stimuli;
- self-reference, which entails a process where the system collects information about its own functioning that will, in turn, influence that functioning; and

- self-steering of the system indicating that a complex system in many ways determines its own future.

From the above it can be noted that cybernetics is closely related to systems thinking. The main emphasis in cybernetic systems is on feedback loops that allow control and correction as well as inherent self-organisation.

2.3.2 Systems thinking

According to Flood and Jackson[74], systems thinking emerged in the 1940s as a response to the failure of mechanistic thinking to explain biological phenomena. In particular, it is necessary to view organisms as whole entities or systems whose identity and integrity have to be respected. Organisms were seen as having 'emergent' properties unique to themselves and which could not be derived from their parts. They were also seen as 'open' rather than 'closed' to their environment. Thus a system comprises ***elements*** which are linked to one another through a series of ***relationships****.* If a group of elements are richly interactive a ***boundary*** can be drawn around them separating them from their ***environment***. A system also has ***inputs*** and ***outputs*** with ***feedback loops*** that influence the operation of the system, and therefore the whole is usually more than the sum of the parts.

Pretorius and de Wet[75] indicate that a system usually also contains a hierarchy, certain fundamental survival functions and a life cycle. They define a basic framework by considering an enterprise as a manufacturing system. They also discuss the importance of the integration of different technologies to optimise productivity.

From the above it can be suggested that effective solving of complex problems requires a holistic approach involving systems thinking. This forms the basis of Senge's 'learning organisation'[63] - an organisation where people continually enhance their capabilities through new thinking patterns and by learning together in teams. Senge[63] furthermore states that innovative learning organisations often focus on five disciplines for success:

- personal mastery - the discipline of continually clarifying and deepening our personal vision and of seeing reality objectively;

- mental models - deeply ingrained assumptions that influence how we understand the world and how we take action;
- building shared vision - the capability to hold a shared picture of the future;
- team learning - the discipline of thinking together through proper dialogue; and
- systems thinking - the fifth discipline which ties all the others together.

Organisational learning can also be effective across industries as shown in a case study on the differences between housing and car production in Japan[76].

Senge[63] states that the key to seeing problems in a systemic way is to view them as circles of influence rather than as one-dimensional straight lines. A simple example is given in Figure 2.3.

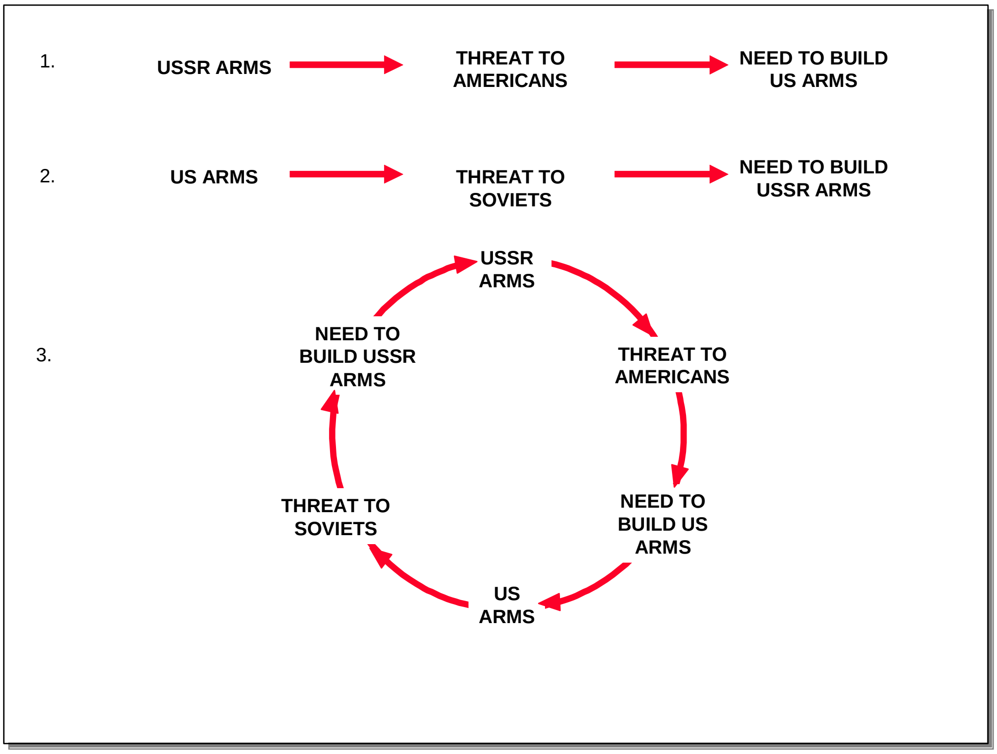

Figure 2.3: Simple diagram to depict a systems approach rather than a linear approach (after Senge[63])

The existence of USSR arms results in a threat to the US which leads to the need to build US arms. This is a one-dimensional linear view of the situation. However, from the USSR's point of view, the existence of US arms results in a threat to the USSR which leads to the need to build USSR arms. The systems way of viewing the situation is to see it as one circle rather than two linear problems and it then becomes a vicious circle.

Senge defines the following systems archetypes:

The reinforcing circle (see Figure 2.4)

The reinforcing circle contains a feedback process which causes actions to snowball.

The balancing process with delay (see Figure 2.4)

This is described as an action towards a goal with an adjustment due to delayed feedback. Being unaware of the delay may lead to over-correction.

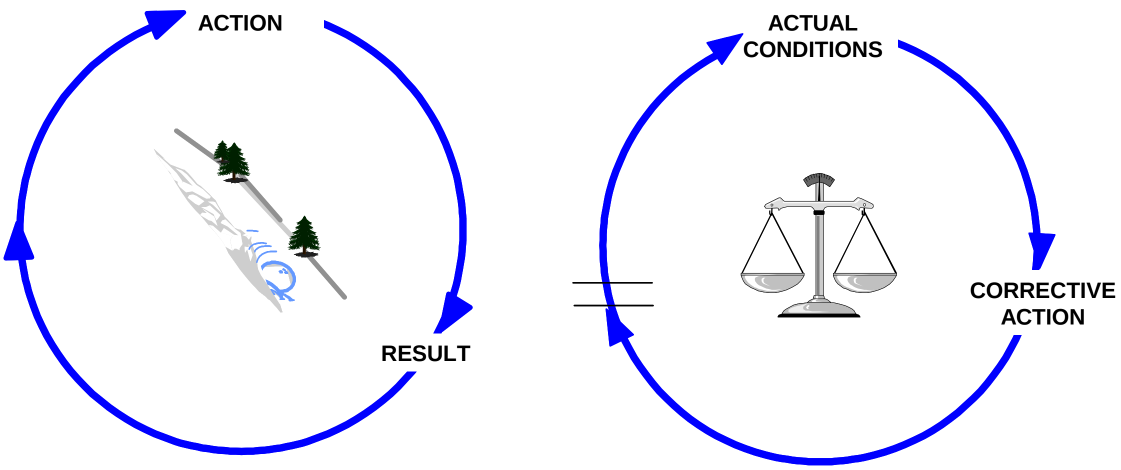

Figure 2.4: The reinforcing circle and the balancing process with delay (after Senge[63])

Limits to growth (see Figure 2.5)

This is described as a process that feeds on itself to produce a period of accelerating growth or expansion. Then the growth begins to slow (often inexplicably to the participants in the system) and eventually comes to a halt, and may even reverse into an accelerating collapse. The slowing process is caused by the limiting condition shown in Figure 2.5 and can be caused by a resource limitation or an external or internal response to the growth.

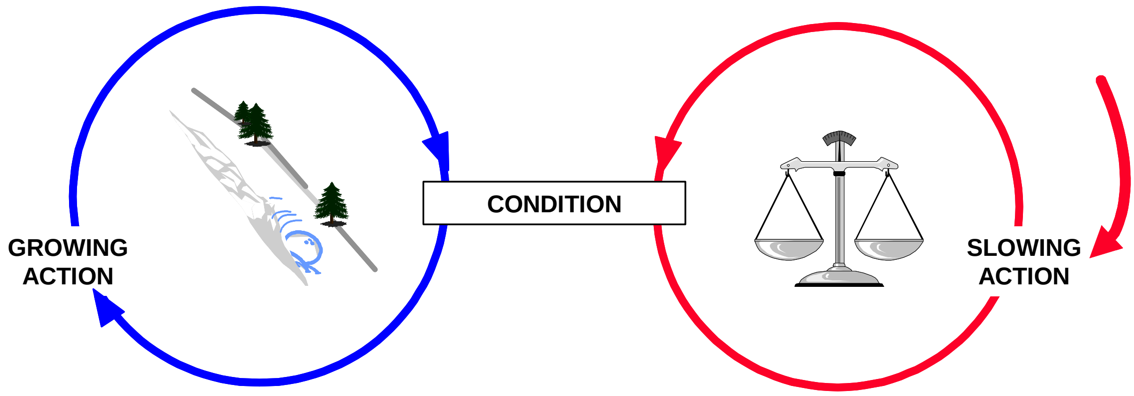

Figure 2.5: Limits to growth (after Senge[63])

Shifting the burden (see Figure 2.6)
If a short-term ‘solution’ is applied to solve a problem it has an apparent positive, immediate result. Increased use of the short-term solution results in less use of fundamental solutions over time with the result that the ability to apply fundamental solutions is lost.

Note: As discussed in Chapter 3, a short-term thinking paradigm caused the demise of the South African national transport research programme - mainly due to the fragmentation of the programme into small short-term projects.

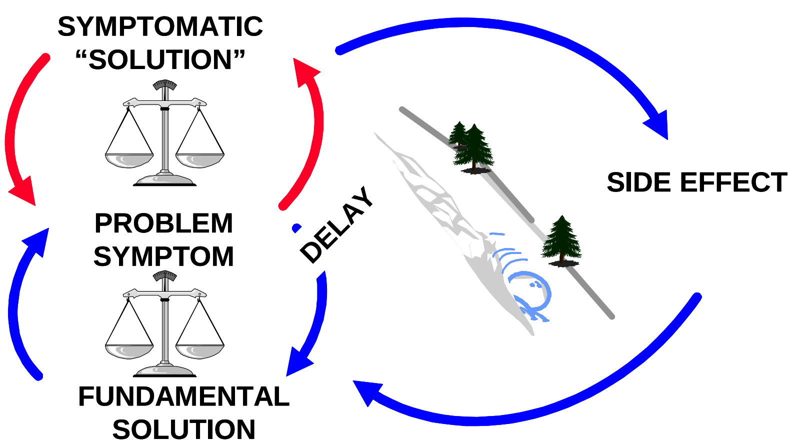

Figure 2.6: Shifting the burden (after Senge[63])

Special case: shifting the burden to the intervener (see Figure 2.7)

A very common and destructive case of shifting the burden is when external interveners attempt to help solve problems, thus addressing immediate symptoms. However, if it is successful, the people within the system never learn how to deal with the problem by themselves.

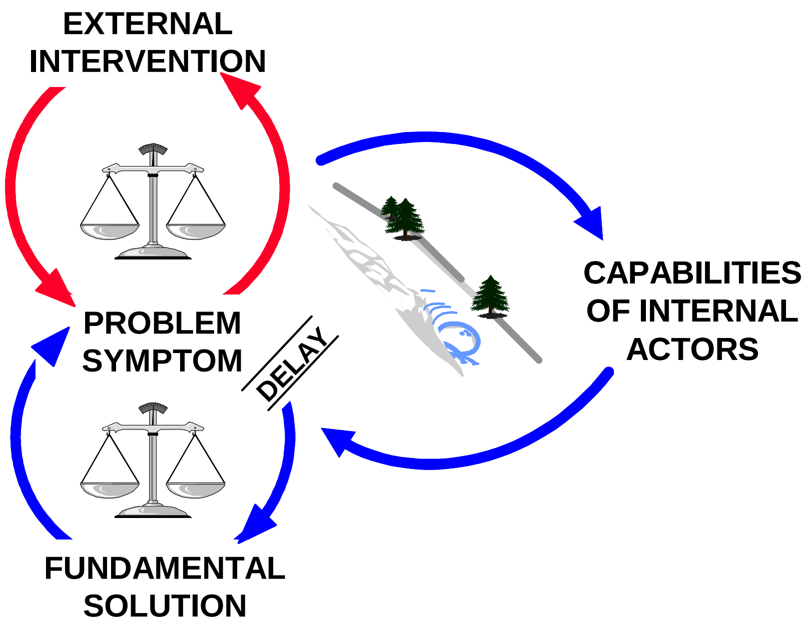

Figure 2.7: Special case: shifting the burden to the intervener (after Senge[63])

Eroding goals (see Figure 2.8)

This is a shifting-the-burden type of system in which the short-term solution involves the decline of a long-term fundamental goal.

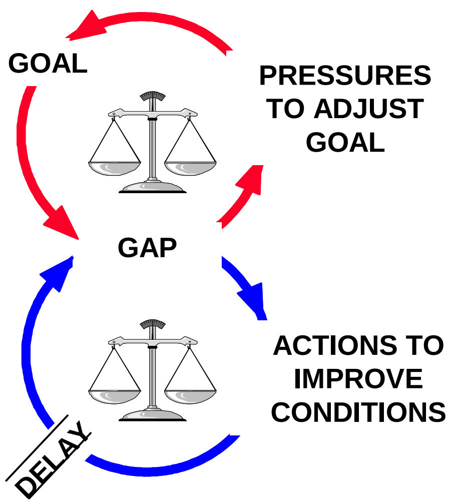

Figure 2.8: Eroding goals (after Senge[63])

Escalation (see Figure 2.9)

Competition between two organisations leads to aggressive behaviour by each which is often seen as a defensive action, thus escalating the process.

Note: Chapter 3 shows that the change in the research procurement process to an open tendering system in the early 1990s introduced destructive competitive behaviour.

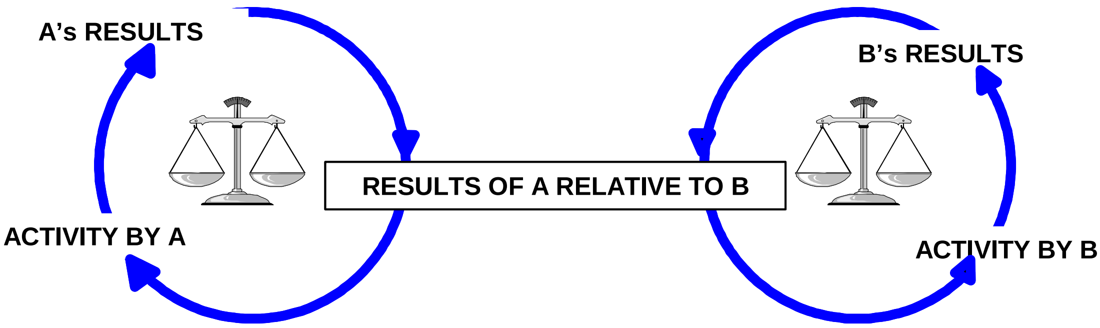

Figure 2.9: Escalation (after Senge[63])

Success to the successful (see Figure 2.10)

When two activities compete for limited support or resources the successful one receives more resources, thereby starving the other.

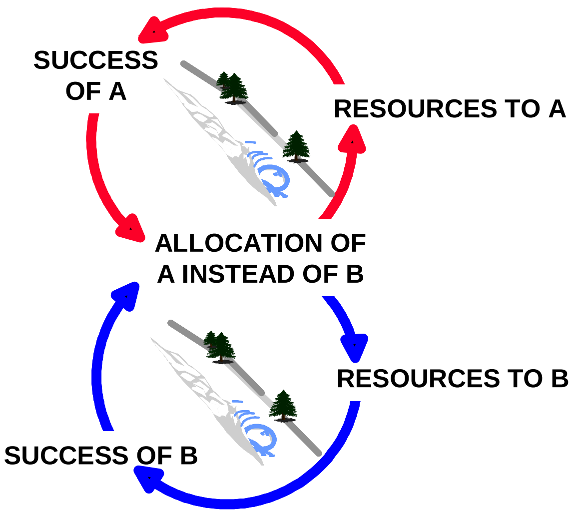

Figure 2.10: Success to the successful (after Senge[63])

Tragedy of the commons (see Figure 2.11)

If individual activities use a common resource based solely on individual needs they may intensify their efforts as they receive diminishing returns, with the result that the resource becomes totally overloaded or depleted.

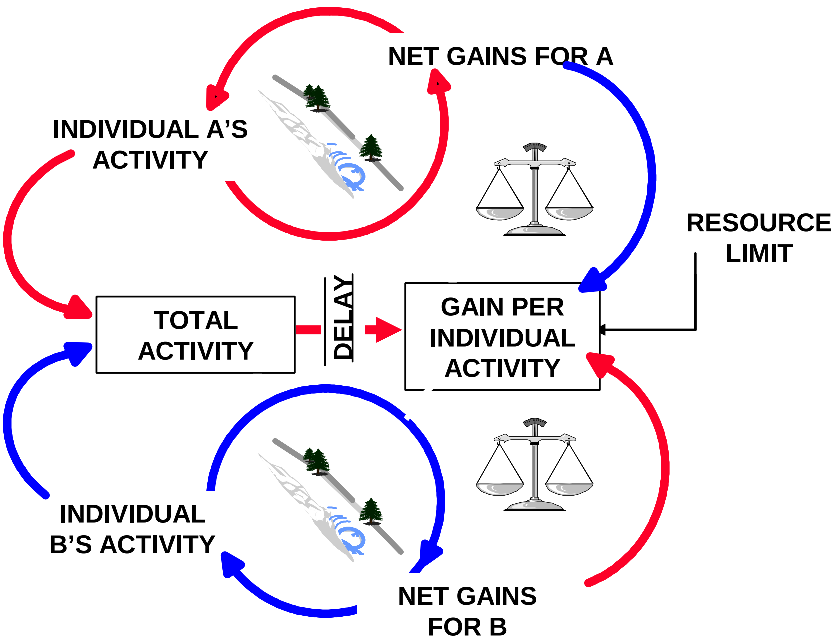

Figure 2.11: Tragedy of the commons (after Senge[63])

Fixes that fail (see Figure 2.12)

A fix, which is effective only in the short term, has unforeseen long-term consequences which results in an increased need for the short-term fix.

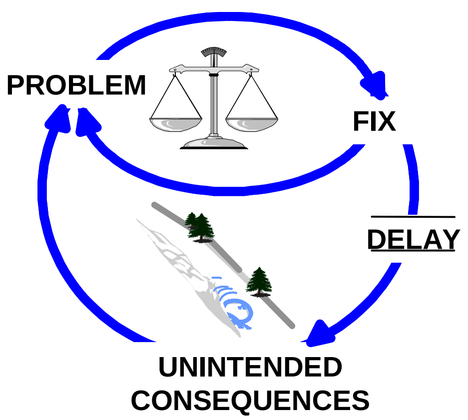

Figure 2.12: Fixes that fail (after Senge[63])

Growth and underinvestment (see Figure 2.13)

Limits to growth can be eliminated or pushed into the future by acquiring and investing in additional 'capacity'. However, if the additional capacity is not of the right quality, takes time to become effective, or if the investment is not aggressive and rapid, it will forestall growth and can lead to a lowering in performance standards to justify underinvestment, causing lowered expectations and decreased performance.

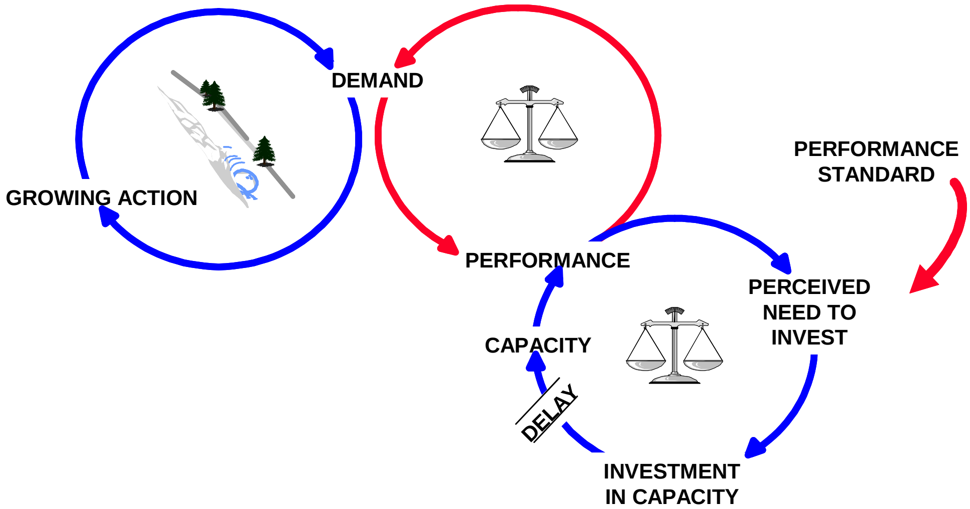

Figure 2.13: Growth and underinvestment (after Senge[63])

Senge[63] concludes that success stems from developing a learning organisation utilising modelling to enhance the learning process and taking a systems approach to analyse and correct problems.

Flood and Jackson[74] describe the use of available systems methodologies in a Total Systems Intervention (TSI) approach to develop creative solutions to complex problems. The TSI approach involves creative thinking about and definition of the main difficulties in a complex problem leading the manager to the most appropriate systems methodology (or combination of methodologies) to address the problem. They discuss the following methodologies:

- system dynamics;
- viable system diagnosis;
- strategic assumption surfacing and testing;
- interactive planning;
- soft systems methodology; and

- critical systems heuristics.

The interactive planning approach seems to be the most relevant for developing a framework for R&D management in the transport industry. The process is based on three principles:

- planning should be participative, indicating that the process of planning is as important as the final outcome;
- the principle of continuity indicates that plans should constantly be revised in order to address changes; and
- the holistic principle indicates that planning should take place at the 'big picture' level as well as at the detail level.

The interactive planning approach involves the following five phases:

Phase I: Formulating the 'mess''

This phase involves the assessment of threats and opportunities facing the organisation and a projection of the future of the organisation should no change be made. This is done by analysing the organisation, its structure, how it works and its interaction with its environment. In addition, obstruction analysis is also conducted before future performance scenarios are predicted.

Phase II: Ends planning

This phase concerns the specification of the envisaged outcome of the process in terms of objectives and goals.

Phase III: Means planning

This involves detailed planning of how the goals and objectives can be met.

Phase IV: Resource planning

During this phase detailed planning around inputs, facilities and equipment, staffing and budgets is conducted.

Phase V: Design of implementation and control

Detailed plans for implementation of strategies and their control are formulated. The process is continuously monitored and the outcomes fed back.

In the spirit of the Total Systems Intervention process, there are, however, also a number of important aspects from the other approaches that can be used. These include the following[74]:

- the principle of self-learning that implies that the process should be designed to learn and improve from its own operation;
- the principle of non-linearity, indicating that a true systems approach is non-linear with a number of feedback loops (the importance of effective feedback loops, especially in R&D, was also emphasised by Reinertsen and Shaeffer[77]);
- the principle of recursion which indicates that the system should be replicated in its parts in order to allow the formation of viable sub-systems, and
- the culture and environment of the system should be taken into account in order to allow for human nature, social constraints, etc.

The use of the above to design a framework for managing R&D is discussed in Chapter 6.

2.3.3 Complexity theory

Complexity theory, which is associated with complex systems, has been the subject of research over the past 30 years and has found applications in a number of fields including management science, astronomy, chemistry, evolutionary biology, geology and meteorology[49]. Cilliers[50] states: "*There is no denying that the world we live in is complex, and that we have to confront this complexity if we are to survive, and, perhaps, even prosper*". Cilliers indicates that the traditional way of dealing with complexity is to engage with it from what is perceived to be a scientifically determined, secure (and usually fixed) point of reference. This approach is seen by Cilliers as an avoidance of complexity. Solutions that are premised on this point of view will also of necessity be linear, and therefore not responsive to changes in needs and constraints. Such solutions are therefore not likely to be very helpful when complex, inherently social phenomena such as human capital development and management processes need to be addressed. Cilliers defines the characteristics of complex systems as follows:

- they comprise a large number of elements that may be simple in their own nature;
- elements interact in a dynamic way by exchanging energy or information – such interactions are rich and are non-linear;
- the system contains many direct and indirect feedback loops;
- complex systems are open systems – they exchange energy or information with their immediate environment and they operate at conditions far from equilibrium;
- complex systems have memory and therefore have a history which is of vital importance to the behaviour of the systems;
- the behaviour of the system is determined by the nature of the interactions and not by that of the components, therefore behaviour cannot be predicted from an inspection of its components - thus the system has ‘emergent’ properties; and
- complex systems are adaptive and can organise and reorganise their internal structure without external intervention.

Cilliers also analysed the nature of large organisations as complex systems and noted the following:

- the behaviour and nature of a complex organisation is determined by the interaction between its members and therefore relationships between parties are critical;
- complex organisations are open systems and therefore large quantities of information flow through them, meaning that a stable state is not desirable;
- the boundaries in an organisation are not clearly defined and there is usually some overlap or co-operation between departments;
- organisations have to interact with their environment and other organisations;
- the context and the history of an organisation determine its nature, and the history is distributed through the elements and interactions;
- unpredictable behaviour and characteristics may emerge from an organisation - they may not be desirable, but are not by definition an indication of malfunctioning;

- due to the nonlinearity of interactions between elements, small causes can have large effects – thus the magnitude of the effect is not only determined by the size of the cause, but also the context and by the history of the system;
- organisations can self-organise in response to external events, especially events that are critical to the system's survival;
- complex organisations cannot thrive when there is too much central control - this certainly does not imply that there should be no control, but rather that control should be distributed throughout the system; and
- complex organisations work best with shallow structures that are not strictly hierarchical.

The above characteristics of a complex system can also be seen in the research process. Table 2.1 below provides comment from the analysis conducted here regarding the complex nature of the research process. This analysis indicates that some of the players in the research process are organisations that, according to Cillers[50], are complex systems. In addition, the research system itself displays many characteristics of a complex system. Cilliers furthermore emphasises that complex systems cannot be managed effectively with too simplistic a model. It therefore follows that a new model for managing the research process should take into account the characteristics of a complex system.

Wagner-Luptacik *et al.*[51] state that the innovation process in a company is a truly dynamic and complex system and that simplistic linear models fail to predict the behaviour of the system accurately. Furthermore, concepts from complexity theory and social systems theory such as self-organisation and emergence provide new insights into product innovation. They conclude that an integrated framework based on complexity theory and systems theory provides a much improved understanding of knowledge production and innovation, especially in the early stages of the innovation process. These early stages are based on R&D and thus this finding is a strong motivation for considering a systems approach to an R&D management model, particularly in the road building sector where R&D is mainly focused on new knowledge generation as opposed to hard product development.

Table 2.1: Characteristics of complex organisations and similarity with the research process

Organisation (after Cilliers[50])	Author's comments on the R&D process
The behaviour and nature of a complex organisation are determined by the interaction between its members and therefore relationships between parties are critical.	A number of players interact continuously at the individual level, namely researchers, practitioners, stakeholders and funders, as well as at the organisational level, namely research organisations, universities, funding bodies, professional institutions, government departments, private sector companies, etc.
Complex organisations are open systems and therefore large quantities of information flow through them, meaning that a stable state is not desirable.	The R&D process needs to assimilate information from outside and continuously transfer knowledge and technology back to users and stakeholders.
The boundaries in an organisation are not clearly defined and there is usually some overlap or co-operation between departments.	The boundary around the R&D process can vary depending on the number of participants. Often there are strategic partnerships and often similar research takes place in more than one organisation.
Organisations have to interact with their environment and other organisations.	The R&D process incorporates a number of organisations that interact with each other and with users and stakeholders in a national system of innovation.
The context and the history of an organisation determine its nature and this history is distributed through the elements and interactions.	The history of transport research is discussed in Chapter 3 of this thesis, and it shown that historic trends had a significant impact on the performance of the programme.
Unpredictable behaviour and characteristics may emerge from an organisation - they may not be desirable, but are not by definition an indication of malfunctioning (emergent properties).	R&D is inherently unpredictable in terms of outcome, and in terms of the operational process in the historic transport research programme (see Chapter 3), the fragmentation of the programme was an unwanted emerging property.

Organisation (after Cilliers[50])	Author's comments on the R&D process
Due to the non-linearity of interactions between elements, small causes can have large effects – thus the magnitude of the effect is not only determined by the size of the cause, but also the context and history of the system.	In the analysis of the set of R&D programmes in Chapter 3, it is shown that the implementation of a tendering process (small change) had a very large detrimental effect (fragmentation and ultimate collapse of the programme).
Organisations can self-organise in response to external events, especially events that are critical to the system's survival.	Some self-organisation took place in the transport R&D programmes, particularly in terms of finding alternative local and international funding sources.
Complex organisations cannot thrive when there is too much central control - this certainly does not imply that there should be no control, but rather that control should be distributed throughout the system.	The strong central control and administration of the RDAC R&D programme (see Chapter 3) with its consequent negative results are examples of this in the transport research arena.
Complex organisations work best with shallow structures that are not strictly hierarchical.	In the R&D process this implies more autonomy to research leaders in decision-making regarding the direction of the research.

However, in a survey of 68 companies and in five in-depth case studies, Dekkers[52] found that industrial practices in innovation management still rely on incremental innovation, depend on hierarchical managerial practices and have an inward departmental orientation.

The models in the work described here are based on the functioning of complex systems as described by Cilliers[50]. Engaging with the management of R&D from a complexity perspective will give rise to a new paradigm based on insights such as:

- R&D and the management thereof are unambiguously situated within a systemic process and therefore the resultant models always remain open to the environment.
- The flow of information through the system is critical to protect it from a state of equilibrium – which to a complex system would spell stagnation and eventually death.
- Networks, rather than hierarchies, define how the various elements in the model interact with each other.
- The interaction of the elements is critical to the understanding and management of the process.
- Management is viewed as an organic process in which feedback loops and the history of the system are important determinants of future actions.
- It is difficult to model the system as the model would have to be as complex as the system itself, and therefore some degree of informed reduction is required.
- The value of scientific knowledge is determined by the participants in the process based on their shifting needs and constraints.
- Therefore diversity (of skills, products and people) and dissent (among various needs and opinions) are inevitable and desired components of the system to ensure that the system can self-organise to produce the optimum possible benefit to the most people.

Clayton and Radcliffe[78] emphasise that complexity is one of the most difficult problems for contemporary science. They also state that, however tempting it might appear, reverting back to a linear way of managing R&D will not make the complexity disappear.

Cilliers[79] furthermore states that: "*Not only are we doomed to face up to complexity, but doing so does not provide us with a means to predict the exact effects of our actions*". This does not, however, absolve us from making decisions and from acting. In the words of Cilliers on modelling and calculation: *"Calculation would never be sufficient. The last thing this could mean is that calculation is unnecessary. On the contrary, we have to do all the calculation we possibly can. That is the first part of our responsibility as scientists and managers".*

The discussion above provides evidence that a balance needs to be struck between considering the complexity of the problem of managing R&D and easily understood management models that can facilitate the process.

2.4 Strategic planning considerations

2.4.1 Linking technology management to strategy

Porter[80] states that:

> *"Operational effectiveness is the means to performing similar activities better than rivals perform them. Strategic positioning means performing different activities from rivals' or performing similar activities in different ways".*

From the viewpoint of technology management, strategic planning should be considered at two levels, i.e. the general business strategy and the specific technology strategy that supports the broad business objectives of the organisation. Roberts[10] indicates that strategic management of technology includes both strategic planning and implementation processes at the overall company level as well as in a more focused manner at the level of the technology development department. He lists the following as important technology-related factors to be considered when conducting strategic planning:

- the size of the organisation - some studies have shown that early initial innovation tends to come from small, entrepreneurial companies with larger organisations becoming more involved as technology development matures;

- technology forecasting - the use of technology scanning and technology forecasting techniques have been of major benefit to some companies;
- the stage of the technology's life cycle - early in a technology's life cycle there tend to be frequent, major innovations as opposed to more incremental innovations in the mature stage;
- the business environment in which the company operates; and
- techniques such as competitive product profiling.

Burgelman *et al.*[12] (p 658) discuss two types of strategic processes linked to innovation:

- induced strategic action in line with the firm's strategy, which usually follows incremental innovation or architectural innovation; and
- autonomous strategic action outside the scope of current corporate strategy, which usually entails radical innovation with the associated disruptions.

It is important to strike the optimum balance between these two processes to ensure both strategic focus as well as room for creativity.

Roussel[81] states that in the face of the increasing rate of technology development many companies find it difficult to invest sufficient R&D funding to meet the challenges that they face. The answer is not necessarily to spend more but rather to utilise available R&D funding more effectively by improved linking of R&D investment to strategy. This implies that the issue of R&D for general management is that it is far too important to be left to technical management alone. Roussel furthermore indicates that a holistic approach, involving all the stages of development of a product (i.e. research, development, engineering design and manufacturing), rather than a sequential approach should be followed. 'Third generation R&D' is defined by Roussel[81] as a process "*seeking to create across business units, across divisions, and across the corporation a strategically balanced portfolio of R&D formulated jointly in a spirit of partnership between general managers and R&D managers.*" This process also includes an assessment of risk and benefits within the portfolio of R&D projects.

It is recognised that technology will play an increasingly more important role in the competitiveness of companies. The effective management of technology development is, however, a complex process. The US National Research Council[82] listed eight challenges in achieving industrial competitiveness:

- the integration of technology strategy into the overall objectives of the company;
- how to enter into and exit from new technologies rapidly and efficiently;
- the effective assessment and evaluation of technology;
- effective technology transfer;
- reduction of new product development time;
- the management of large, complex, interdisciplinary projects or systems;
- the management of an organisation's internal use of technology; and
- how to leverage the effectiveness of professionals.

Roberts[83] conducted an extensive survey of the manner in which some of the largest R&D-performing companies in the US, Western Europe and Japan addressed strategic management of technology. Fewer than 250 companies in these regions collectively spend more than 80% of the funds dedicated to R&D. Roberts found that:

- Japanese and European companies have linked their technology strategies to corporate strategies more thoroughly than US companies and that the degree of this linkage related strongly to enhanced R&D performance.
- The success of a technology strategy depends on commitment and participation from top management, including the Chief Executive Officer.
- In many Japanese companies the Chief Financial Officer is actively involved in integrating technology strategy with overall corporate strategy - indicating the longer-term commitment to technology development in Japanese companies.
- Many US companies are currently decentralising R&D in reaction to pressure to improve product and process development in the short term, but in doing so they are sacrificing support for longer-term development.

- Japanese companies are moving precisely in the opposite direction, linking R&D more strongly to corporate strategy, thus allowing improved strategic control of their R&D efforts.
- There is concern in US companies that their R&D portfolios are inadequate in process support as opposed to product development and, in addition, that there is an imbalance in their portfolios with regard to time orientation (too much emphasis on the short term) and risk orientation (not enough new technology).

Japanese companies, which showed significant technology advances were, at the executive level, more committed to R&D, considered R&D a long-term investment and were linking their technology strategies to overall company strategy by centralising their R&D efforts more than their US counterparts.

Note: As discussed in Chapter 3, South Africa recently followed a US-like approach, resulting in the associated negative outcome. This approach needs to be reviewed to be brought more in line with the strategic approach followed by the Japanese.

From the above analysis it is evident that effective management of R&D must be linked to and founded in the general business strategy of an organisation.

2.4.2 Technology strategy

Burgelman *et al.*[12] (p 142) discuss the three basic elements of technology strategy:

- technological competencies and capabilities;
- the theoretical dimensions in which technology strategy can be expressed; and
- internal and external forces that shape the evolution of a firm's technology strategy.

They give a simple framework for the development of a technology strategy for a firm, comprising technology evolution, industry context, strategic action and organisational context.

Burgelman *et al.*[12] (p 683) also indicated the importance of balancing technology push and market pull in technology strategies of firms. In 'technology push' scientists look for new technological breakthroughs, whereas market pull refers to the obtaining of direction from marketing staff for new product opportunities. They indicate that successful managers are synthesisers, able to put together and link ongoing technical streams with existing corporate commitments and directions and then to relate these to market needs – the so-called concept of double linking, i.e. linking needs to technologies. An imbalance in these two factors can lead to an innovation trap that leads to either too rigid an approach (not sufficient room for invention) or too flexible an approach (too much freedom to researchers). Montoya *et al.*[84] and Arasti and Packniat[85] confirm that a sound technological strategy in a firm does affect productivity positively – even in the case where R&D for smaller projects is outsourced. Thus an organisation's technology strategy should form a cornerstone of and support the objectives of the general business strategy.

2.4.3 Strategic technology management tools

Technology strategy is usually supported by decision-support systems or tools for managing technology portfolios. Brady *et al.*[86] categorised tools and techniques for technology management as being either in the positioning, diagnostic or intervention categories. However, many of these tools are aimed at technology development related to product development for consumer markets. Brady states that increasingly analysts realise that less tangible forms of technology (such as knowledge, skills and competencies) are even more important than hard product technologies in a company's long-term success and survival.

The main aim of the Third Generation R&D[81] approach is to ensure a balanced portfolio of R&D projects with maximum benefits for the investment. The 'balance' in the portfolio relates to a number of factors such as:

- the type of R&D, which is either incremental (small r & large D), radical (large R & and large D) or fundamental (only R);
- the maturity of the technology, namely the embryonic, growth, mature or ageing phases; and

- the likely competitive impact, namely pacing technology, key technology or base technology.

Roussel[81] suggests the use of a number of matrices as a management framework in order to ensure a balanced portfolio of projects. Figure 2.14 shows a plot of a portfolio of projects relating to the maturity of the technology on the one hand and the competitive position of the technology on the other hand. Similarly Figure 2.15 shows a plot of the expected rewards against the probability of success. A further matrix suggested by Roussel plots the projects in terms of the knowledge of the technology in the company versus the knowledge of the market it is intended for (see Figure 2.16). Plotting a portfolio of projects on the above matrices assists in ensuring a balanced approach in terms of high-risk versus low-risk projects as well as balance in both the short-term and long-term nature of the projects in the portfolio.

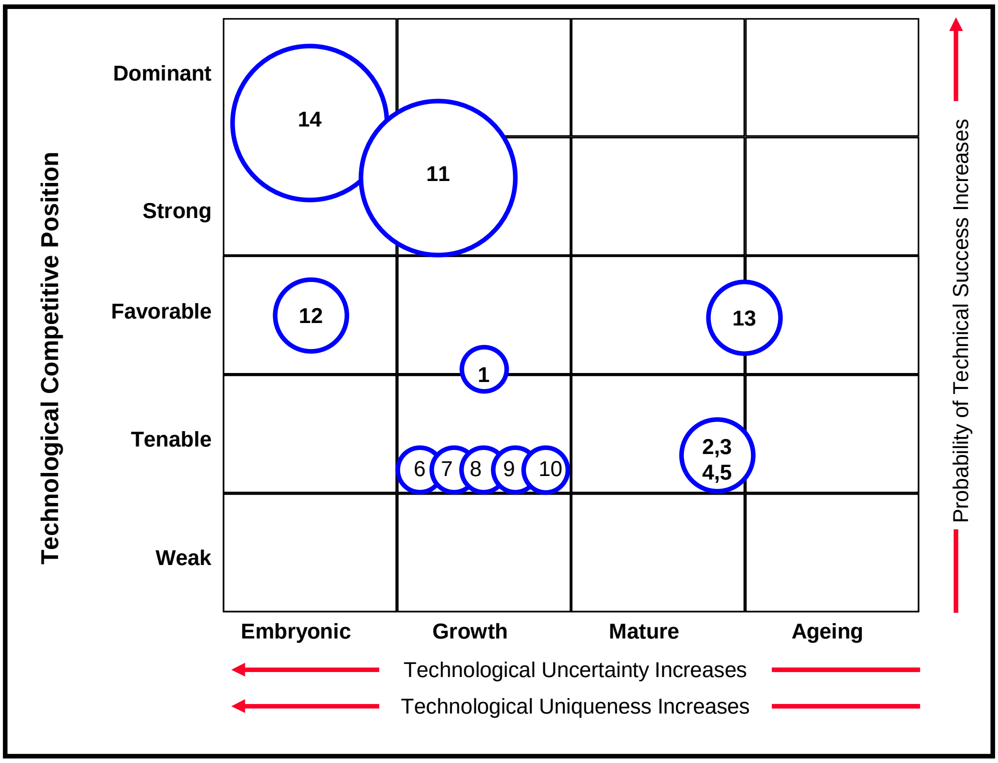

Figure 2.14: Technology maturity vs. competitive position (after Roussel[81])

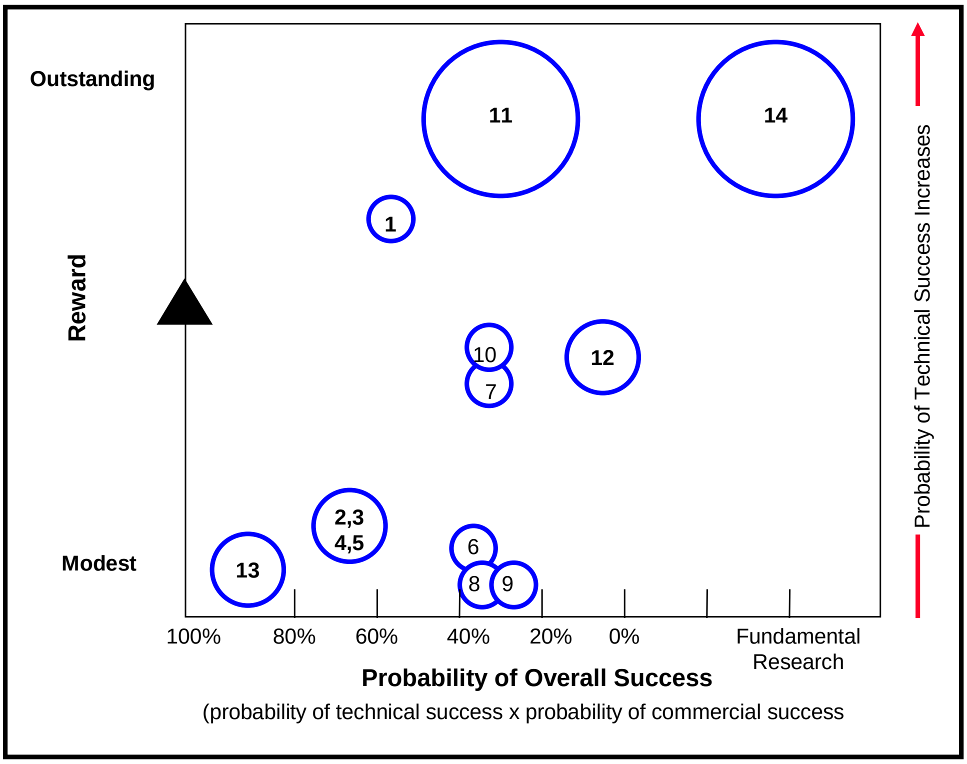

Figure 2.15: Probability of success vs. rewards (after Roussel[81])

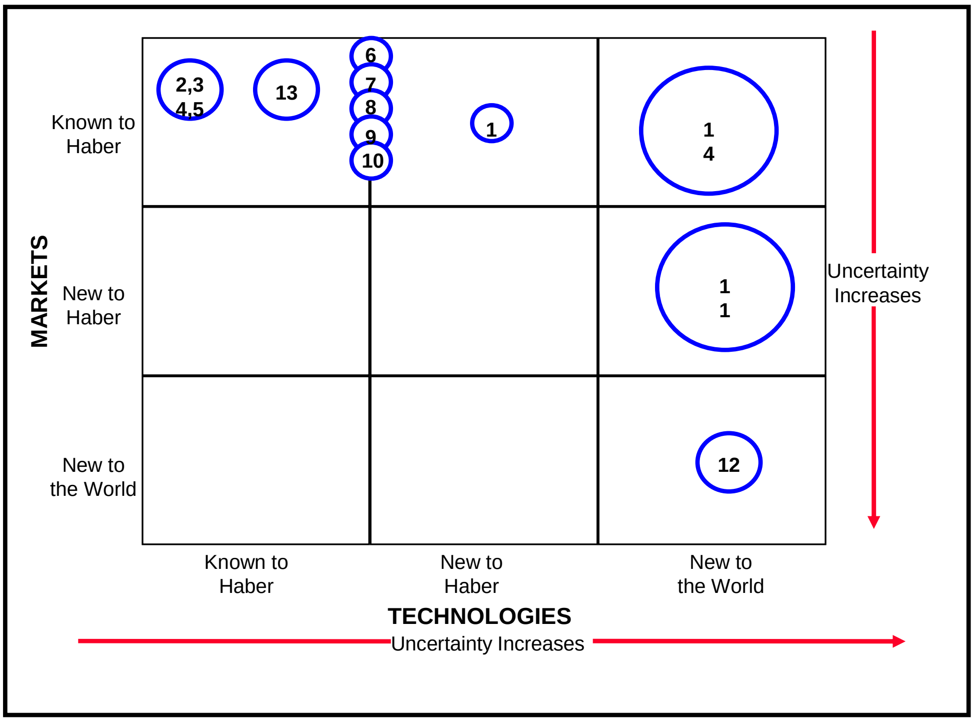

Figure 2.16: Company knowledge of technology vs. market knowledge (after Roussel[81])

The TRIZ concept and system was originally developed by Soviet engineer and researcher Genrich Altshuller and his colleagues in the late 1940s and has been evolving ever since[87]. TRIZ is the Russian acronym for 'theory of inventive problem solving'. The system includes a number of tools that assist engineers to optimise investment in product development and taps into a database of more than two million patents. The tools are structured into a framework consisting of five fields, namely: 'current state', 'resources', 'goals', 'intended state' and 'transformation'. According to Moehrle[87], problem solving using the TRIZ system centres around four stages:

- analysis of a specific problem in detail;
- the matching of this specific problem to an abstract problem;
- on an abstract level searching for an abstract solution; and
- transformation of the abstract solution into a specific solution for the specific problem.

However, the system is mainly intended for hard product development, although there has been some application recently in the solving of management problems[88]. Often companies use some of the concepts to direct their product development projects without using the full system[89].

As discussed in Chapter 1, *innovation* only takes place once *exploitation* of the new technology in the market place has occurred. Hobday and Rush[90] discuss the use of a simple tool, the User Needs Analysis tool (UNA), to involve industry in research programmes. The procedure consists of a series of interviews and questionnaires to obtain information on the industry or company concerned and gain their trust. The main benefits of the approach are:

- building up understanding, agreement and trust with industrial partners;
- assisting with the explanation of the nature and purpose of the research and obtaining feedback from industry;
- researchers can show that they are willing to treat needs seriously and to collaborate with industry;
- researchers are forced to meet deadlines agreed with industry; and
- assisting researchers to understand company structures, strategies, processes and culture.

These tools are used to manage the R&D activities related to the development of hard products for the consumer market. Some of these tools (e.g. the portfolio balance tools) may be applicable to R&D management in the road infrastructure sector. However, the complex nature of this process and the fact that it focuses mainly on the development of the engineering methodology as opposed to hard products, may require tools of a different nature.

2.5 Process issues related to technology management

2.5.1 Managing innovation and creativeness

The success of a technology-based organisation depends, to a significant extent, on its ability to be innovative and creative. Von Hippel[91] indicates that the sources of innovation vary greatly and do not simply stem from product manufacturers. He classifies sources of innovation according to the functional relationship that the source has with the innovation. These could, for example, be users, manufacturers or suppliers. Von Hippel states that the sources of innovation can be related to the potential innovator's expectation of innovation-related profits. It therefore follows that the source of innovation can be predicted and that, by the distribution of profit expectations, the likely sources of innovation may be shifted. This can then, in turn, be used to manage a distributed innovation process. Von Hippel found, with statistical significance, that innovation often takes place at the user interface, for example users were found to be the actual developers of 82% of all commercialised scientific instruments studied and 63% of all semiconductor and electronic subassembly manufacturing equipment innovations studied.

Urban and Von Hippel[92] found that analysis of the needs and solutions coming from 'lead users' can significantly improve the productivity of new product development. 'Lead users' are defined as having the following two characteristics:

- they have needs that **foreshadow** the general demand, i.e. they face them months or years before the bulk of the market; and
- they can obtain **high benefit** from solutions to those needs.

Figure 2.17 indicates that lead users adopt and use new technologies in the early stages of development.

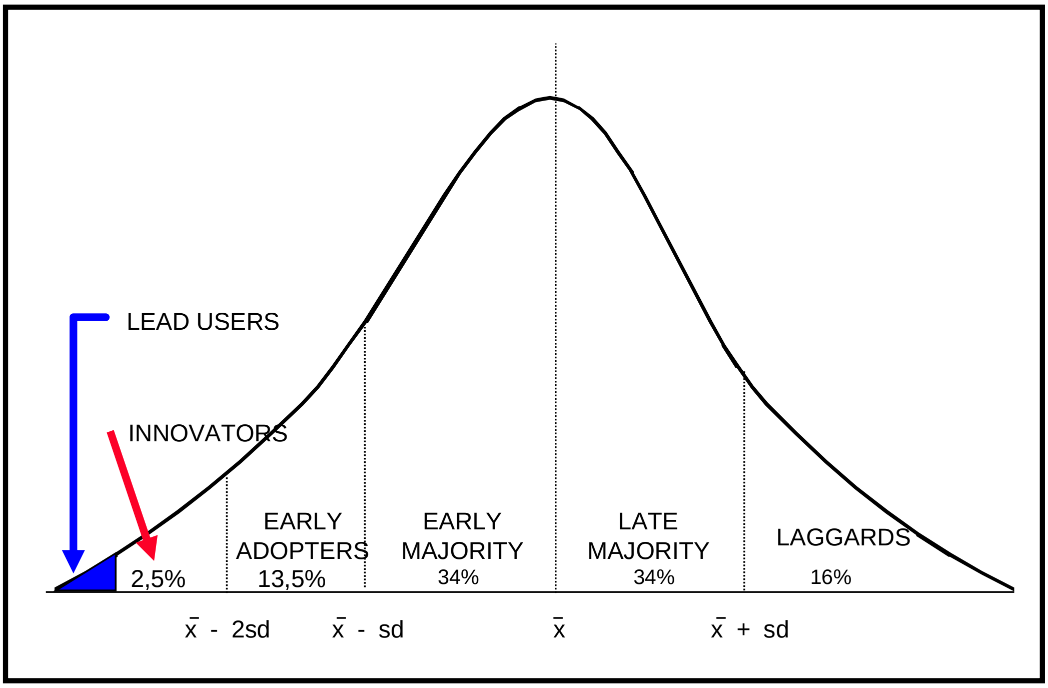

Figure 2.17: Adopter characterisation on the basis of innovativeness (after Urban and Von Hippel[91])

Urban and Von Hippel give the following as steps in using lead users in the innovation process:

Step 1: Specify lead user indicators

This step involves firstly, the determination of technology trends and their related measures, and secondly, the definition of measures of potential benefit.

Step 2: Identify the lead user group

The subgroup at the leading edge of the trend needs to be defined.

Step 3: Generate a concept with the lead users

This may involve group sessions with lead users to evaluate modifications to existing products or new products developed to address their needs.

Step 4: Test lead user concept

The acceptance of the concept by typical users in the market is assessed.

Urban and Von Hippel furthermore reported that the results of an empirical application of the lead user methodology in the area of computer-aided design systems appeared very encouraging and they indeed found it to be a practical method.

Piller and Walscher[93] describe the use of an Internet-based Toolkit for Idea Competitions (TIC) which is based on a company gleaning ideas from its users (often lead users) through a competition on suggestions for new products or improvements. A prize is offered in exchange for the right granted to the company to exploit the idea commercially. They found that the system helps the company increase its level of innovation.

Gann[9] stresses that innovation in longer-term capital investment projects such as transport infrastructure is different in nature from that of the manufacturing sector. Capital projects are usually demand driven and consist of project-based activities rather than batch production or mass manufacturing systems producing goods for the consumer market. Firms in engineering and construction compete in dynamic environments where they need to manage technological innovation and uncertainty across organisational boundaries with networks of interdependent suppliers, customers and regulatory bodies. The knowledge of providing capital infrastructure is distributed throughout these networks and therefore innovation can only take place in an environment where effective communication can take place. In the modern environment this communication can only take place efficiently if new Information and Communication Technologies (ICT) are used effectively. Advantages of using ICT include:

- the integration of information flows;
- automation of routine information processing and communication activities;
- generation of new information on processes and systems integration;
- improved transparency about processes; and
- increased capabilities for knowledge acquisition, feedback and learning.

Such systems can enhance participation in decision-making and can be used to involve clients during the design and construction processes. Similar importance of ICT was also demonstrated in case studies by Brady[94] and Nightingale[95].

Hansen and Rush[96] discuss issues related to innovation in Complex Product Systems (CoPS). CoPs can be defined as high-cost, engineering and information-technology-intensive, customised products with large numbers of tailored subsystems and components. According to Hansen and Rush, examples include aircraft, flight simulators, telecommunications networks, high-speed trains, etc. Studies at the CoPS Innovation Centre at the universities of Brighton and Sussex showed that CoPS typically do not follow the life-cycle patterns of mass-produced goods intended for the consumer market. The process of innovation, and therefore the management of innovation, is also significantly different from that for mass produced products[97].

The following were the main issues related to innovation in developing CoPS products as determined by Hansen and Rush in a study of a number of projects in a selection of organisations:

- definition of client requirements and determination of a clear statement of needs;
- the lack of availability of senior staff for detailed discussions with clients (mainly due to other commitments because of turbulent times in business);
- problems related to the co-ordination of information regarding organisational structure deficiencies and a lack of clear definition of roles of project team members and information transfer mechanisms between parties;
- issues related to technology management, particularly the co-ordination of information and knowledge between new product developments and previous generations of technology;
- the unavailability of key experts who are too thinly spread across organisations and the concomitant overloading of key technical experts;
- inadequate reporting and control mechanisms;
- problems experienced with the use of matrix management systems which lead to programme managers having ‘too much responsibility with too little power’; and
- issues related to organisational culture such as the lack of procedures to make new employees aware of organisational culture and management style.

The development of the software component of CoPS proved to be problematical and Hobday and Brady[98] describe a fast method for analysing software systems in companies and improving them.

2.5.2 Developing core competencies and technology platforms

Organisational growth is one of the main factors ensuring long-term viability in companies. Prahalad and Hamel[99] stress the fact that the successful corporation will have to rethink its business strategy in order to structure itself around core competencies rather than businesses for growth. In a comparative case study of General Telephone and Electronics (GTE) and NEC (a multi-national information technologies company with headquarters Japan), they found that GTE had lost its international position as a leader in telecommunication systems, while NEC had emerged as a world leader in semi-conductors and as a first-tier player in telecommunications products and computers. The main difference between the two companies was the manner in which they structured themselves. GTE structured themselves as a portfolio of businesses while NEC structured themselves as a portfolio of competencies. According to Prahalad and Hamel, the source of NEC's advantage was its ability to consolidate corporate-wide technologies and production skills into competencies that empower individual businesses to adapt quickly to changing opportunities. They see a diversified corporation as a large tree. The major trunks are core products, the branches are business units and the fruits are end products. The root system that provides nourishment, sustenance and stability is the core competency. This is depicted in Figure 2.18.

Prahalad and Hamel[99] define a core competency as the collective learning in the organisation, especially relating to how to co-ordinate diverse production skills and integrate multiple streams of technologies across organisational boundaries. They mention as an example Casio's ability to manufacture miniature radios the size of a business card. In order to achieve this Casio must harmonise know-how in miniaturisation, micro-processor design, materials science and ultra-thin precision casing. Core competencies are therefore not only about harmonising technology streams, but also about the organisation of work and the delivery of value. They give three criteria for a core competency:

- it provides potential access to a wide variety of markets;
- it makes a significant contribution to the perceived customer benefits of the end product; and
- it is difficult for competitors to imitate.

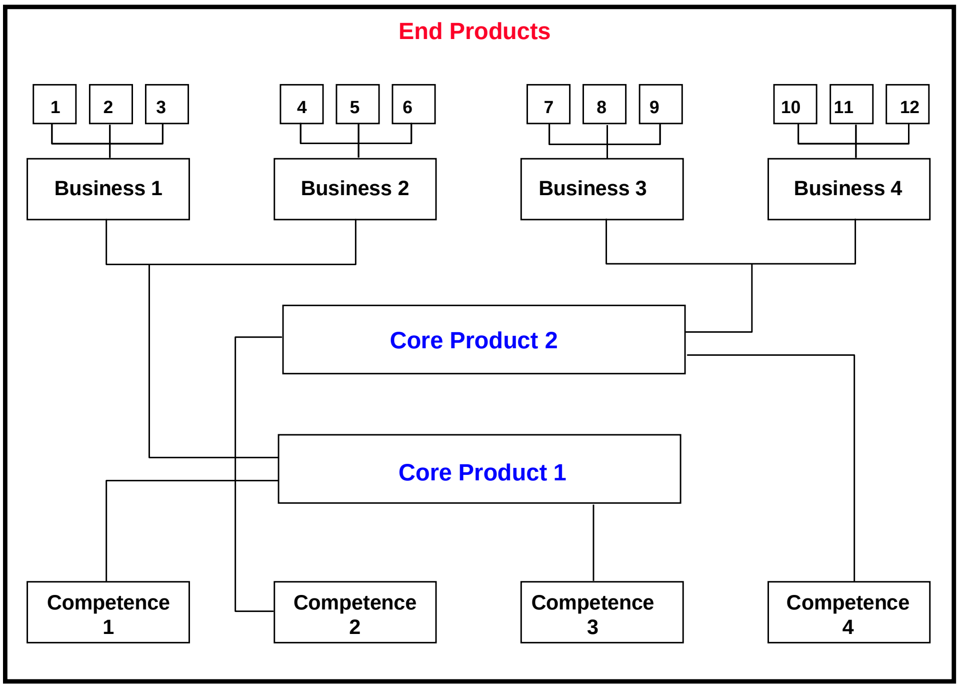

Figure 2.18: Competencies as the root of competitiveness (after Prahalad and Hamel[99])

Core products provide the vital link between core competencies and end products. Examples of core products are Honda's engines, Canon's motors for desk-top laser printers and Matsushita's compressors.

Stalk *et al.*[100] distinguish core competency from a firm's strategic capabilities: *"Whereas core competency emphasises technological and production expertise at specific points on the value chain, capabilities are more broadly based, encompassing the entire value chain".* They define a capability as a set of business processes which are strategically understood. Rush *et al.*[101] stressed the importance of technological capability in successful firms and developed a framework for the measurement of technological capability. The framework is based on a number of elements, including:

- awareness of technology changes in the market;
- building of core competencies relating to a new technology;

- development of technology strategy;
- exploration and assessment of the range of technology options available;
- acquisition of new technologies;
- implementation, absorption and operation of new technologies; and
- exploiting external linkages.

However, the framework does not address the development of capabilities to develop in-house technology, but rather technology acquisition from outside sources.

Meyer and Utterback[102] discuss a similar approach in describing the use of product families and core capabilities. A product family is defined as a set of products arising from a common product platform but each with specific features and functionality required by different sets of customers. A product family typically addresses a market segment, while specific products or product groups address niches within that segment. The product platform is the result of the application of a company's core capabilities. According to Jolly and Nasiriyar[103] a technology platform has a distinctive, inherent set of technologies that provide competitive advantage. Shapiro[104] also discusses the concept of a platform to understand the level of innovation and renewal in a company. Viewing platforms as a foundation on which to build new products (such as those used by the company 3M) and calculating company revenue derived from new platforms is important for understanding the level of product renewal in a company.

As an example of the power of developing product families based on platforms, Meyer and Utterback quote the case of Black and Decker's power tool business. In 1970 Black and Decker had hundreds of products in the market using more than 30 different motors, sixty different motor housings, and dozens of different operating controls. Each product also had a unique armature. B&D's management realised that, in order to remain competitive, it would have to decrease its cost of goods by a third. They then embarked on a $20 million development programme to design product families based on a shared platform. The platform consisted of a standard motor that could serve all their power tool needs, standard motor housings and controls and a standardised adhesive bonded armature. Subsequently, each product family was re-engineered (drills, jigsaws, sanders, etc.). The results were dramatic: a reduction of 50% in product costs, a market share increase from 20% to a dominant share and a reduction in the number of competitors from more than 20 to three.

Meyer and Utterback describe a process of mapping the development of product families chronologically in order to assess the dynamics of a company's core capabilities. This is depicted in Figure 2.19. In this figure the product family is represented in four hierarchical levels:

- the product family itself;
- product platforms within the product family (rectangles);
- product extensions (ovals); and
- specific products.

'Skunk works' projects with no direct commercial output can be the first iteration of a product platform and can provide important technological and market knowledge for subsequent platform extensions.

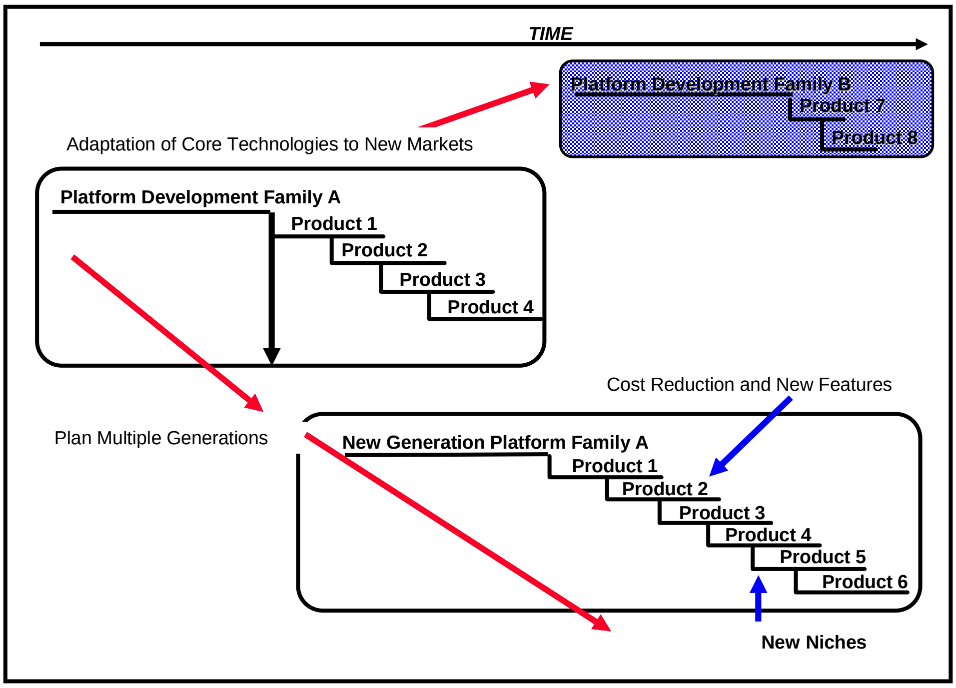

Figure 2.19: The product family approach to new product development (after Meyer and Utterback[102])

Product family maps can be used to assess the core capability of a company by superimposing the history of performance against various factors on the map. Figure 2.20 shows an example of such an assessment where the performance history of the core capabilities most important to the specific product family, i.e. product technology capability, customer needs understanding capability, distribution capability and manufacturing capability were mapped. The ratings were determined by a team representing the management of the company and ranged from worst-in-class to best-in-class on a five-point scale. The method allows flexibility in selecting the most important core capabilities for the specific product family as well as for the weighting of the importance of these capabilities in order to determine a total rating. Similarly, the financial performance of new product families can be mapped and compared with the rating achieved in each core capability, thus allowing strategic insights into the return on investment in the product families.

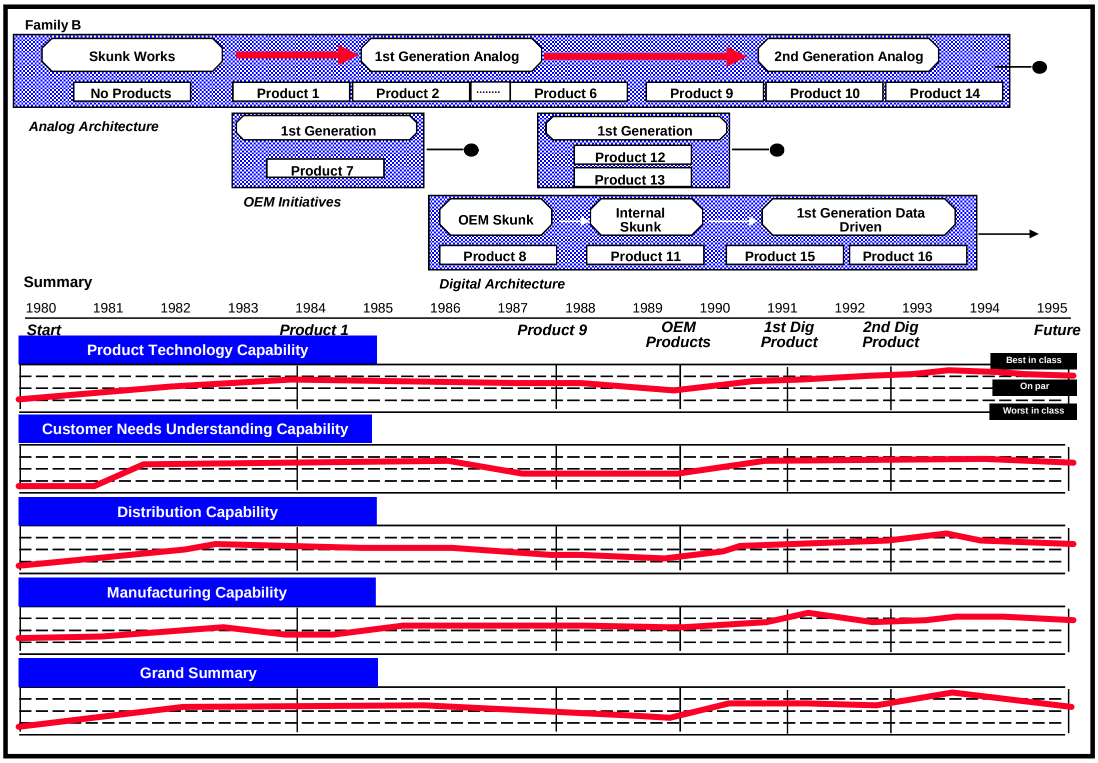

Figure 2.20: Summary core capability assessment for family B (after Meyer and Utterback[102])

Meyer and Utterback conclude that core capabilities are dynamic and warn that they can easily be lost through ill-considered managerial policies or approaches.

In a number of case studies they identified four main factors that could cause the deterioration or loss of a core capability. These are:

- *lack of patience* - unrealistic, short-term horizons;
- *failure to adopt innovations* - technological discontinuities can make a company's products obsolete;
- *coasting on success* - a company can be trapped in its own success and not foresee discontinuities (to be countered through strategic focus and aggressive re-investment); and
- *breaking up design teams* - the maintenance of key individuals is essential to developing and maintaining core capability.

The above can be guarded against by thinking in terms of developing and maintaining core capabilities through development and planned renewal of product platforms as well as planning product families rather than individual products. This requires strategic focus and aggressive reinvestment. In addition, a company should plan according to longer-term horizons including longer-term financial commitments, and should keep core teams together for longer periods of time - perhaps for the life cycle of a product family.

2.5.3 Technology road mapping

Technology road mapping was developed by Motorola and Corning in the late 1970s[105]. Phaal *et al*.[106, 107] state that in essence a technology road map is a simple graphical or tabular diagram capturing a company's technology development strategy. One form of such a technology roadmap is depicted in Figure 2.21, showing a multi-layered time-based chart, which indicates how various functional strategies align. The top part of the roadmap is concerned with the markets for the new products envisaged. The middle layer of the roadmap is concerned with the products, services and operations that will be developed to address the market need. The bottom layer of the roadmap shows the technologies and resources that must be marshalled and integrated to develop the products.

The University of Cambridge Centre for Technology Management has been undertaking research in the area of roadmapping since 1997. Their focus has been on the rapid and efficient initiation of the approach, working in collaboration with industry, and this has led to the publication of the 'T-Plan' guide in 2001[108]. In addition, their efforts have focused on the "*generalization and customization of the method for general strategic appraisal and planning*". The main use of technology road maps is aimed at integrating a commercial company's technology strategy with the general business strategy. Therefore, the concept is mainly a strategic planning tool and often used to communicate such plans effectively. Phaal states: "*Roadmapping is seen as a discrete step in the strategic planning process, used to capture and communicate the outputs from the strategic planning process, as a key step towards implementation."* The major advantage of technology roadmapping is the use of a time-based structured and graphical framework to develop, represent and communicate strategic plans relating to the development of technology, products and markets. In this regard, the method is also similar to other graphical planning approaches such as PERT and Gantt charts.

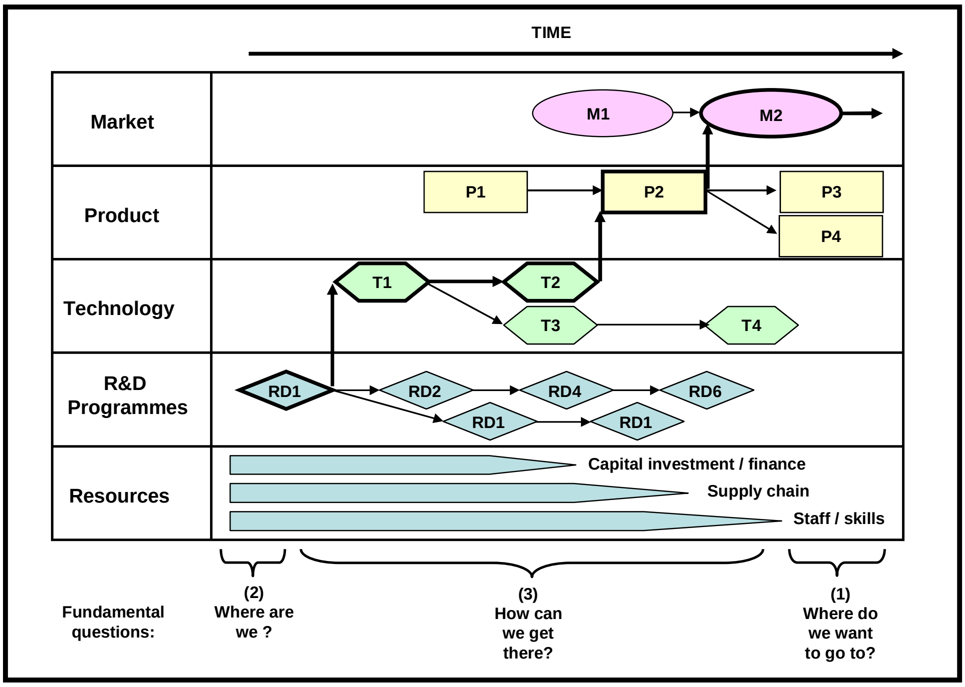

Figure 2.21: Multi-layered roadmap for integration and alignment of strategic plans (after Phaal *et al.*[107])

Road mapping can be used in conjunction with other strategic management tools such as Porter's five forces[109], the well-known SWOT analysis and STEEP analysis. However, developing quality roadmaps depends on the quality of the information recorded in the roadmap. Although roadmaps look simple, the process is often complex and iterative.

Phaal *et al.* [110] listed the following general characteristics of technology roadmaps:

- Roadmaps should be expressed in a graphical form, which is the most effective means of communication. However, the graphical representation is a highly synthesised and condensed form, and the roadmap should be supported by appropriate documentation.
- Roadmaps should be multi-layered, reflecting the integration of technology, product and commercial perspectives in the firm. The roadmapping process provides a very effective means for supporting communication across functional boundaries in the organisation.
- Roadmaps should explicitly show the time dimension, which is important for ensuring that technological, product, service, business and market developments are synchronised effectively. Roadmaps provide a means of charting a migration path between the current state of the business (for each layer), and the long-term vision, together with the linkages between the layers.
- The structure that is adopted for defining the layers and sub-layers of the roadmap is important, and reflects fundamental aspects of the business and issues being considered. Typically these layers relate to key knowledge-related dimensions in the business, such as 'know-why', 'know-what', 'know-how', 'know-when', 'know-who' and 'know-where'.
- The generic roadmapping approach has great potential for supporting business strategy and planning beyond its product and technology planning origins. It should be recognised that it is not a 'black box' methodology, that each application is a learning experience, and that a flexible approach, adapted to the particular circumstances, is considered.

2.5.4 Managing quality in technology development

The topic of quality management has been studied extensively and has been widely reported on. In a survey of 382 companies, Kaynak and Hartley[111] found that companies that implement quality management are more successful than those that do not. Lager[112] found that the implementation of Quality Function Deployment in companies had a significant direct impact on customer satisfaction, although it did not lead to shorter development times for new products. The role of quality in the technology development environment in transport has been reported by Verhaeghe[113].

Examples of the definition of quality are:

- *the conformance to requirements* - Crosby[114];
- *fitness for use or customer satisfaction* - Juran Institute[115];
- *the totality of features and characteristics of a product that bear upon its ability to satisfy stated or implied needs* - ISO 8042[116];
- *the total composite product and service characteristics of marketing, engineering, production and maintenance through which the product or service in use will meet the expectation of the customer* – Feigenbaum[117].

The Total Quality Management (TQM) approach has been lauded by several authors as the answer to quality problems in organisations. Verhaeghe defined Total Quality (after Perigord[118]) as: "*a set of principles and methods organised as a comprehensive strategy with the goal of mobilising the entire company in order to achieve the greatest client satisfaction at the lowest cost".* In simple terms it is defined as: "*delighting the customer by consistently meeting and improving on his requirements"*[119]*.* Pieterse and Pretorius[120] describe a technology strategy assessment framework based on TQM principles.

The process of quality management should be integrated into a holistic framework for R&D management, particularly since it requires a top-down commitment from top management as well as a co-ordinated team approach. In addition, the TQM approach pays for itself and will have a significant positive impact on R&D management.

2.5.5 Measurement of the effectiveness of R&D

General

Innovation outcomes and results are intricately linked to the quality of the R&D management activities that form a part of the innovation chain. The measurement of R&D outcomes and results is complex and the work conducted to date, such as that reported in the OSLO manual[121], focuses on innovation related to the development of hard products in the private business sector.

Often it is very difficult to predict the usefulness of R&D outcomes. Rosenberg[122] gives five dimensions of uncertainty that constrain the ability to predict the value of new technology:

- The usefulness of radical innovations is difficult to appreciate immediately.
- The impact of a radical innovation often depends on complementary discoveries (e.g. the use of lasers in telecommunications depended on the availability of fibre optics).
- Major innovations often constitute new technological systems.
- Major innovations often had their origins in an attempt to solve a specific problem.
- The ultimate impact of technological innovations depends on the ability to effectively link them to specific categories of human needs.

The measurement of research performance is complex and indicators can vary depending on the type of organisation conducting the research, the source of funding or the sector in which the research organisation operates. In a discussion of the RAE, Garret-Jones and Aylward[123] list the corporate performance indicators for research councils in the UK. These include:

- analysis of published research;
- number, type and value of European Union and other international collaborations/partnerships (international standing);
- PhD submission and MSc success rates (trained personnel);
- income from the UK private and public sectors (user perception);
- numbers and value of Collaborative Awards in Science and Engineering (CASE) and other industrial studentships (e.g. Teaching Company Scheme) planned and taken up (industry-focused training);
- impact on work programmes of Council response to Foresight priorities (response to opportunities identified by Foresight); and
- mechanisms for capturing and responding to input from the user community (user and non-academic influence on policies and decisions).

They also state that research councils are expected to use a broader range of indicators than universities evaluated through the RAE.

Bremser and Barsky[124] list the most frequently used R&D metrics as:

- R&D spending as a percentage of sales;
- new products approved/released;
- number of approved projects ongoing;
- total active projects supported;
- total patents filed/pending/awarded;
- current percentage of sales of new products;
- percentage of budget resources dedicated to R&D;
- change in R&D head count;
- percentage of resources dedicated to sustaining existing products; and
- average development cost per product.

Cooper and Kleinschmidt[125] found that a New Product Development (NPD) company's performance depends on a number of factors and defined 10 measures of NPD success:

- success rate of projects;
- percentage of sales coming from new products;
- profitability relative to spending;
- technical success rating;
- impact on the company's total sales;
- impact on the total profit of the company;
- success in meeting sales objectives;
- success in meeting profit objectives;
- profitability relative to competitors; and
- overall success of NPD programme relative to competitors.

Although one or two of these factors may be relevant, the majority of the measures are aimed at financial measures in a private sector company and may therefore not be suitable for the development of measures of engineering know-how and methodology for the public sector.

In a later publication, Cooper and Kleinschmidt[126] listed the three most important key success factors for companies involved in product development:

- product advantage (unique features);

- proficiency of pre-development activities such as screening and market assessment; and
- a clear definition of target market, customer needs and customer preferences.

These are more generic and may be a little more suitable for R&D management in the road building sector.

Germeraad[127] also described some of the typical metrics and indicators used to value R&D activity, mainly in the manufacturing sector (hard products). However, most of the metrics are aimed at return on investment, cost avoidance and product quality. Sohn *et al.*[128] stress the importance of internal management processes, external review and the quality of the analysis of the R&D programme information in companies conducting R&D to enhance the performance of the R&D programme. Once again, these measures are suitable for a product manufacturing company with an internal R&D department. However, they do not address the development of new knowledge and engineering know-how in a government-sponsored research organisation.

Understanding and measuring the effectiveness and impact of research and development (R&D) programmes are becoming more important world wide as researchers increasingly compete for funding and therefore need to justify research expenditure. Recently there has also been increasing pressure to examine the contribution of R&D to the realisation of the mission of funding organisations as well as to addressing broader societal needs and imperatives. The issue of assessing impact derived from R&D investment is complex and often the impact materialises many years after completion of the R&D programme.

Definition of research effectiveness and impact

The Committee on Metrics for Global Change Research[129] defines process, output, outcome and impact as these terms relate to scientific activity (for example the discovery of the Antarctic ozone hole) as follows:

Process — a course of action taken to achieve a goal. For example, process metrics include existence of a project champion and length of time between starting the research and delivering an assessment on stratospheric ozone depletion to policy makers.

Input — tangible quantities put into a process to achieve a goal. An example of input metrics is expenditures for (a) theoretical and laboratory studies on ozone production and destruction, (b) development and deployment of sensors to sample the stratosphere, (c) modelling and analysis of data, and (d) meetings and publications.

Output — products and services delivered. Examples of output metrics include the number of models that take into account new findings on chlorofluorocarbon chemistry or the number of publications and news reports on the cause of stratospheric ozone depletion and its possible consequences.

Outcome — results that stem from the use of the outputs. Unlike output measures, outcome refers to an event or condition that is external to the programme and is of direct importance to the intended beneficiaries (e.g. scientists, agency managers, policy makers, other stakeholders). Examples of outcome metrics are the number of alternative refrigerants introduced into society to reduce the loss of stratospheric ozone and the number of scientific outputs integrated into a new understanding of the causes of the Antarctic ozone hole.

Impact — the effect that an outcome has on something else. Impact metrics are outcomes that focus on long-term societal, economic or environmental consequences. Examples of impact metrics include the recovery of stratospheric ozone resulting from implementation of the Montreal Protocol and related policies and the increase in public understanding of the causes and consequences of ozone loss.

Note: For the purposes of assessing R&D Effectiveness in this study, the inputs (resources), outputs (useful, transferable results), outcomes (effects on funders, recipients of outputs, and directly involved stakeholders) as well as impacts (permanent short and long-term result of the outcomes that can be assessed at the global, national, sectoral or company level) will be addressed in a system to evaluate overall effectiveness. Therefore Research Effectiveness is defined as the combination of all the aspects above.

Dissel *et al.*[130] found that a combination of methods should be used to evaluate technologies for future investment and that a combination of quantitative and qualitative methods is necessary to cover the full required spectrum. One such tool is a score card that incorporates the strategic measures relating to the organisation's strategy.

Kostoff[131] gives three classes of techniques to assess research impact:

- retrospective methods;
- qualitative methods; and
- quantitative methods.

These are briefly discussed below.

Retrospective methods

Retrospective methods do not make use of mathematical tools but rely on case studies of documented results. These are usually conducted to provide some evidence of the benefits flowing from research to inform stakeholders and to motivate the expenditure. There are two major approaches in retrospective studies. The first is to study successful new technologies and then work backwards to identify the underlying research activities that made the technology possible. The second approach is to start with the research activities and then try to work forwards to predict the potential outcome. The back-tracking approach is favoured by many because the data are easier to obtain and research funders may not be interested in understanding potential impact, especially if the research activity does not lead to any successes.

Qualitative methods (peer review)

Peer review involves the evaluation of a research programme by experts in the field who are asked to serve on a panel to conduct the review. It is currently the most commonly used approach to assess the impact of research. The three most important aspects of a good-quality peer review process are:

- the motivation of the peer review leader to conduct a credible process;

- the competence of the individuals as well as the balance in the competency in the group; and
- the independence of the organisation conducting the review.

Some of the problems experienced with peer review include:

- the partiality of peers to influence the outcome for non-technical reasons;
- protection of the research field by an ‘old boys’ network’;
- a halo effect that leads to an enhanced evaluation of scientists and departments with high visibility;
- difference of opinion amongst reviewers about the criteria for evaluation and interpretation of information;
- the peer review process assumes that there is agreement about the definition of good research; and
- the cost of a peer review process can be high.

Quantitative methods

Bibliometrics

The bibliometrics approach focuses on the counting of publications, patents, citations and other items to develop science and technology performance indicators. A significant study[132] of 4 000 researchers in Australia highlighted the following as important factors to measure:

- publication of peer-reviewed journal articles;
- publication of peer-reviewed books and book chapters;
- keynote addresses – including other important presentations at major conferences;
- conference proceedings – publication of papers in peer-reviewed conferences;
- citations of peer reviewed publications; and
- competitive grants – ability to attract competitive research funding.

Patent counts are often used as an indicator of R&D performance, however many companies are now using defensive publishing as an alternative to prevent opposition companies from patenting[133]. This is of particular interest where the value of the invention is too low to justify the high cost of patenting.

Narin[134] emphasises the importance of measuring activity (e.g. number of publications) and impact (e.g. number of citations per publication) as well as linkages (i.e. the intellectual linkages between organisations derived from citations of publications and patents).

Narin[134] also categorises the use of bibliometrics to evaluate performance at the following four levels:

- policy – evaluation of national or regional technical performance;
- strategy – evaluation of the scientific performance of universities or the technological performance of companies;
- tactics – tracing and tracking R&D activity in specific S&T areas; and
- conventional – identifying specific activities and people involved in R&D.

Problems with bibliometrics include:

- Publication counts:
    - indicative of quantity not quality;
    - non-journal methods of publication ignored; and
    - undesirable behaviour (more co-authors than necessary, shorter but more publications are preferred).
- Citations:
    - an intellectual link between citing source and reference article may not always exist;
    - incorrect work may be highly cited;
    - methodological papers are cited the most;
    - self-citation raises the citation count artificially;
    - citations can be lost due to incorrect spelling and inconsistencies;
    - Science Citation Index (SCI) changes over time;
    - SCI biased in favour of English language journals; and
    - same problems as with publication counts.

An analysis of 53 research laboratories[135] indicated that:

- bibliometric indicators and scientific publications are not the only outputs that should be measured, but the other types of outputs that should be measured differ from laboratory to laboratory;

- bibliometric indicators are not equally valid across different types of laboratories; and
- bibliometric indicators are less useful for the evaluation of research laboratories involved in closed-publication markets.

However, bibliometrics alone are not enough to measure the effectiveness of the research activity as emphasised by Butler[136].

Co-occurrence phenomena

This method focuses on the macro-scale impact of research exploits. It assumes that phenomena that frequently occur together in the same domain are related, and the strength of the relationship is assumed to be related to the frequency of the occurrence. The method utilises the analysis of bibliometrics and the subsequent mapping of scientific fields and the occurrence of phenomena to understand the relevant interrelationships[137]. Van Raan[138], however, cautions that ranking of research institutions using bibliometrics alone is improper.

Cost-benefit and economic analysis

Economic measures to calculate the return on investment of research activity have often been used. However, results of a comprehensive survey[139] indicated that although econometric methods have been useful in tracking R&D in the private sector, they fail to produce useful and consistent results when tracking public-funded research programmes. Cost-benefit analyses are difficult to use in public-funded research due to large uncertainties associated with research as well as the difficulty of defining point of origin in time for the analysis. Such analyses can be used indicatively to show the potential pay-off of the research investment through benefits.

Production-function approaches relate outputs to inputs in an estimate model. According to Kostoff[131] much work still needs to be done in the utilisation of these models to estimate the value derived from R&D.

Network modelling for direct and indirect impacts

Network-based modelling approaches focus on the impact that basic research has on its own field, on related research fields, on technologies developed from the research, etc. The nodes in the network represent areas of research and the value of the links between the nodes represents the degree of impact of the first area on the second. Integration of all of the links allows the assessment of the overall impact of a research area. Expert system approaches have also been used to develop so-called expert networks.

In conclusion, Kostoff[131] remarks that:

- bibliometrics are useful to assess the outputs from research, but have a limitation in assessing the quality of the outputs;
- bibliometrics are good as supplementary tools to other methods such as peer review;
- economic indicators are limited due to the uncertainty of the data, although their value becomes more pronounced as the research becomes more applied and potential income streams can be estimated more accurately; and
- data-intensive quantitative analysis will be used increasingly as computing power increases.

The Balanced Score Card approach

A number of authors discuss the use of R&D metrics and indicators that are varied in nature to assess the performance of an R&D programme. The most well-known of these is the Balanced Score Card approach.

Bremser and Barsky[124] and Kaplan and Norton[140] highlighted the benefits of using the Balanced Score Card as a strategic management tool. A Balanced Score Card is a performance measurement system for implementing strategy and basically consists of a set of performance measures (broader than mere financial measures) that are cascaded down from the corporate level to the business unit level and finally the employee level. The benefits of using this approach include the following:

- The BSC utilises causal sets of performance measures to monitor results. Variance analysis of metrics provides insight into deviation from objectives.
- The primary purpose of the BSC is to highlight strategy and its impact on operating decisions. Utilising the BSC over multiple periods provides the

basis for feedback (strategic learning loop and management control loop) and planning.

- The BSC provides a common framework and reference point for employees across levels and functions. The cascading process provides for alignment.
- Most BSC organisations link objectives to personal rewards to guide employee decision-making.
- The requirement to use causal linkages throughout the BSC forces employees to analyse performance deviations and to identify, assess and manage drivers of outcomes and results.
- BSC objectives guide employee decision-making and provide a common framework with which to evaluate decision alternatives.
- The BSC requires frequent monitoring and routine feedback of operating measures to employees across organisation levels. Target setting and budget goals are intended to provide motivation for employee actions.

The Balanced Score Card approach is also used extensively in the CSIR and manifests as a set of Key Performance Indicators that are managed at corporate, operating unit and personal level, thus allowing the cascading of metrics from the top level to the employee level.

Bremser and Barsky[124] conclude that technology is very important, but its impact is not easily measured by traditional financial metrics. This is also confirmed by Coombs and Bierly.[141] The Balanced Score Card approach can be very useful in linking financial and non-financial measures to strategy. Bremser and Barsky also state that the integration of metrics that combine several types of quantitative and qualitative measures is usually the best approach.

Brenner and Tao[142] describe a simple rating tool to assess the value derived from research projects conducted external to Air Products and Chemical Inc. They use a simple rating system to evaluate aspects such as the novelty of the product, the amount of time saved by the research, savings on internal R&D costs, the level of IP generation and the commercial impact of the research. They have found significant benefit in understanding the savings on internal R&D

costs deriving from external R&D projects. In essence this is similar to the Balanced Score Card approach.

Coccia[143] lists the elements of an ideal system for R&D measurement (based on work by Brown and Svenson[144]) as follows:

- it is focused on external vs. internal measurement;
- it is focused on outcomes not behaviour;
- it measures outputs by three dimensions: cost, quantity and quality;
- it is simple; and
- it is objective, not subjective.

Coccia also lists a number of indices used in Italy for measuring R&D performance:

- a measure of self-financing which is the degree to which an organisation generates income from technology transfer activities such as licensing of patents and commercialisation of new innovations;
- an index for measuring personnel in training – percentage of staff in training;
- an index for teaching activity – the number of courses presented per researcher;
- an index for number of publications per researcher; and
- a technometric index that records the number of patents from a research organisation.

Chiesa and Frattini[145] list the following as important objectives for an R&D performance measurement system:

- supporting decision-making;
- enhancing R&D performance;
- motivating personnel;
- supporting the incentive scheme;
- fostering organisational learning;
- enhancing communication and coordination, and
- reducing R&D risks.

In a survey of eight Italian manufacturing firms, Chiesa and Frattini found that the measurement of development projects' performance was mainly focused on efficiency (i.e. costs) and time, while in research activities effectiveness and contribution to value became the critical performance dimensions. In addition, quantitative objective metrics were far more diffused in development than in research measures, whereas qualitative subjective ones were typical of research activities. It is also very important to involve people (researchers and managers) in the development of the measurement criteria as well as in the process of measurement.

Godener and Söderquist[146] also listed important areas to consider in R&D performance measurement:

- financial performance – return on R&D investment;
- customer satisfaction measurements – focusing on market expectation and the success of products in the market;
- process management measures – product quality, lead time and relationship to goals;
- innovation measurements – transformation of research into product, e.g. patents;
- strategic measurements – satisfaction of firm strategic goals;
- technology management measurements – the efficient management of product technology for generating a continuous stream of new competitive products; and
- knowledge management measures – knowledge creation, knowledge transfer, and knowledge exploitation.

Guglielmi *et al.*[147] describe the 'first bounce, last bounce' framework for evaluating R&D outcomes. Essentially the framework focuses on two main stages in the innovation chain, the R&D phase and the commercialisation phase. The result of the evaluation of the R&D phase provides input into the commercialisation stage. However, the framework is essentially geared towards hard product development (in the aerospace industry) through a very linear management process.

Lin and Chen[148] analysed 78 high-technology companies and found that the usual R&D metrics such as number of patents, patent citations and company asset intensity are not well correlated with the success of companies. They conclude that *"R&D performance is a complex construct and should be investigated from multiple dimensional perspectives*." They emphasise the importance of the use of technology strategy and portfolio management tools in conjunction with R&D performance measurement to ensure that companies optimise their results. The pitfalls of using only patent citations to measure R&D outcomes were also highlighted by Marco[149]. Werner and Souder also highlighted the fact that R&D performance is best measured though integrated metrics - a combination of quantitative and qualitative measures[150].

The above analysis of articles in the literature indicates that most processes focus on bibliometrics as the main indicator of the value derived from R&D activity. However, in view of the complex nature of the R&D process in the road infrastructure field and the fact that most R&D in this field is conducted with public funds, there is a need to measure the performance of more aspects. These include, for example, the impact of R&D on government (such as savings in road construction) as well as the impact on communities and the environment.

2.5.6 Technology transfer and diffusion

Technology transfer is an important part of the innovation chain. There are a number of models and theories on technology transfer and diffusion. The well-known S-curve is often used to describe the state of performance of a technology (Betz[151]) and also the rate of diffusion of a technology in the market place. Nieto *et al.*[152] examine the theoretical foundation of the S-curve model and discuss problems experienced with its implementation, particularly the measurement of the performance indicator. Twiss[153] describes the use of S-curves to conduct technology forecasting. He states that in an ever-changing business environment, technology forecasts are essential for companies to remain competitive. Technology forecasting is defined as:

> *"The description or prediction of a foreseeable technological innovation, specific scientific refinement, or likely scientific discovery, that promises to serve some useful function with some indication of the most probable time of occurrence".*

Allen *et al.*[154] discuss the importance of social networks in a company in the development, exchange and dissemination of knowledge within the R&D function in a company. A formal analysis of such networks allows management to foster the network, thus improving its performance. It also assists in recognising critical personnel who contribute to the effective operation of the network, including technology gatekeepers and boundary-spanning individuals. Barbolla and Corredera[155] found that satisfactory technology transfer is a combination of factors, including real interest in the receiving organisation in both project development and in its final result, as well as high motivation and good command of the necessary knowledge to undertake the project.

2.6 Organisational issues related to technology management

2.6.1 Staffing considerations

The staffing of an R&D activity involves two main issues: selecting the right people for the team and creating and managing an environment in which they can achieve optimum productivity and innovation (Katz[158]). According to Katz, the selection of staff for a team should take cognisance of the following important roles:

Idea generators

The role of these members is to develop ideas from ‘market pull’ or ‘technology push’ activities, to initiate projects and to contribute to problem solving. Market pull involves technology development stemming from a perceived customer need or demand in the market, while technology push relates to technology development stemming from internally generated ideas and technologies subsequently introduced into the market.

Product champions or entrepreneurs

Product champions advocate change and innovation. They look for support and adoption of ideas (their own and those of others). The presence of a product champion is essential to the success of innovation. The importance of entrepreneurs was also emphasised by Battisti and Ganotakis[156].

Note: In the development of new engineering methodology or products, champions in industry external to the R&D organisation are essential to ensure the successful implementation of the new technology. This has been demonstrated in several research programmes as discussed in Chapter 3.

Vojak *et al.*[157] found that personality characteristics play as an important a role as technical skill in the success of researchers. In particular, the following characteristics frequently appeared in successful innovators:

- energy and enthusiasm;
- persuasiveness;
- confidence and boldness without being arrogant;
- persistence and perseverance; and
- passion about projects.

Programme managers or leaders

The role of the programme manager (sometimes referred to as the 'business innovator') is to provide the support functions of planning, scheduling, monitoring and control, technical work supervision and business and financial coordination related to the project.

Gatekeepers

The gatekeeper is a special communicator who links teams internally and relays messages from the external environment.

Sponsors or coaches

This role is usually performed by a senior person in the organisation who is not directly involved in the project. The role is one of providing encouragement and support and making resources available.

These critical roles are essential for successful innovation. The organisation should therefore recognise these roles and should implement appropriate staff management processes including recruitment, job assignment, personnel development and career paths, training, performance measurement and rewards.

Roberts[10] is of the opinion that specific techniques such as brainstorming and morphological analysis do not increase idea generation and that effective individual and group supervision, and maintenance of group diversity and task challenge as well as the linking of new employees into the communications networks seem to be more effective. In addition to focusing on the capabilities and skills of individuals, the composition of the group also needs specific attention. A balance between stability (comfort zone) and uncertainty and challenge (maintaining 'creative tensions') seems to be effective. Other important factors include the diversity of the group and the time for which the group has been working together. Multi-dimensional diversity heightens technical performance, and long-term stable technical groups become too self-secure, resulting in a decrease in their performance.

Katz[158] stresses the importance of motivating engineers and researchers in order to ensure optimum productivity and innovation. The stage of each individual's career should, in particular, be taken cognisance of in the motivational process. In the initial stage an employee must go through a socialisation phase in order to become productive. This is usually followed by an innovation phase during which the individual tackles challenges and contributes significantly to the development of the organisation. During the stabilisation phase the individual makes his tasks routine and solidifies his environment. Katz warns against the danger of staff remaining in the stabilisation phase too long and losing their innovative abilities and motivation. Such staff should be placed in a new environment where they can once again go through the phases of socialisation and innovation.

Dewett[159] discusses the importance of intrinsic motivation in people who are creative and states that it is an important antecedent to creativity. It is suggested that intrinsic motivation encourages exploration, persistence, flexibility, spontaneity and ultimately creativity. Such motivation is, however, usually coupled with the environment in which researchers work. Ryan and Hurley[160] indicated the importance of the research environment in the performance of researchers. In particular, in issues such as participative decision-making, management must be open to critique and be generally supportive of a collaborative environment.

Prajogo and Ahmed[161] found that the role of people in innovation is of paramount importance and that high innovation performance depends on the development of the right behavioural and cultural environment. In a favourable environment an organisation can then develop the innovation and R&D capacity required to stimulate innovation.

2.6.2 Structure of the R&D organisation

The structure of an organisation should ideally follow its strategy based *inter alia* on its inputs or environment (e.g. markets, customers and competition) as well as its outputs. Research has shown (Utterback[162]) that 60% to 80% of successful innovations are based on 'market pull', i.e. based on a perceived customer need or demand. 'Technology push' originates from a researcher's or company's introduction of new technology and, although important, it plays a secondary role. Interaction with customers through customer liaison personnel as well as by involving customers in the research and development process at an early stage is very important. These customers could be external or in another department in the same organisation (e.g. manufacturing). It is also imperative that, within an organisation, the R&D department has a strong alliance with the marketing and sales staff. The importance of management structure in the R&D productivity of a company was shown by an analysis done by Billings *et al.*[163] of 65 250 firm years of data from companies in the chemicals industry. They found that firms with significant stock ownership by directors produce relatively lower R&D output than their peers, particularly in government-funded research.

In organisations where technical advancement is important, excellence is achieved by grouping people of the same specialisation together. According to Roberts this is the functional or discipline-based organisation. Marquis and Straight[164] found that superior technical excellence is achieved by organising staff in functional structures. However, the group should still maintain a strong link with the outside world, not only through reading of literature, but especially through personal contact (Allen[165]).

Allen[166] also states that the structure of an R&D organisation should be closely related to the communication process desired within the organisation, which can either be:

- technical communication within the organisation in order to improve the R&D productivity in the organisation; or
- communication with the outside world in order to ensure that researchers remain abreast of technical developments.

Depending on which type of communication is most desirable for a specific company, the organisation should be structured to be either an input-focused organisation or an output-focused organisation. In an output-focused organisation, people are usually grouped around projects or programmes with the intention of pulling people of various disciplines together under a single leader in order to integrate all inputs towards well-defined outputs. In an input-focused organisation, people are usually structured around functions. However, according to Roberts, project-based structures have a serious flaw which affects many technical organisations, in that they tend to decrease the communication between people of the same discipline. In addition, the project leader is usually an expert in only one of the many disciplines that he/she has to manage. This sometimes leads to organisations electing to structure themselves in a matrix format in which technical experts report to both a leader in their technical field as well as to a project manager leading the project. This approach has the down side of lack of clarity on who is responsible for managing staff in terms of tasking, performance evaluation, the location of the individual, the longer-term career development of the person and general management. Although there is a trade-off between the two approaches, one of the two forms often dominates, causing the organisation to lean towards one or the other of the two.

The need to keep R&D staff connected to their area of discipline is related to the rate at which knowledge in that specific area is developing, as well as to the duration of the project that a person is assigned to (assuming that the project will remove the person from his discipline area). These two factors, plotted on a simple x-y diagram, are Allen's Organisational Structure Space (see Figure 2.22). If the situation in terms of project duration and rate of change in technology plots in the lower left-hand region of the space, then structuring around projects is likely to produce better results. On the other hand, in the top right-hand region of the space, functional organisations will yield better results.

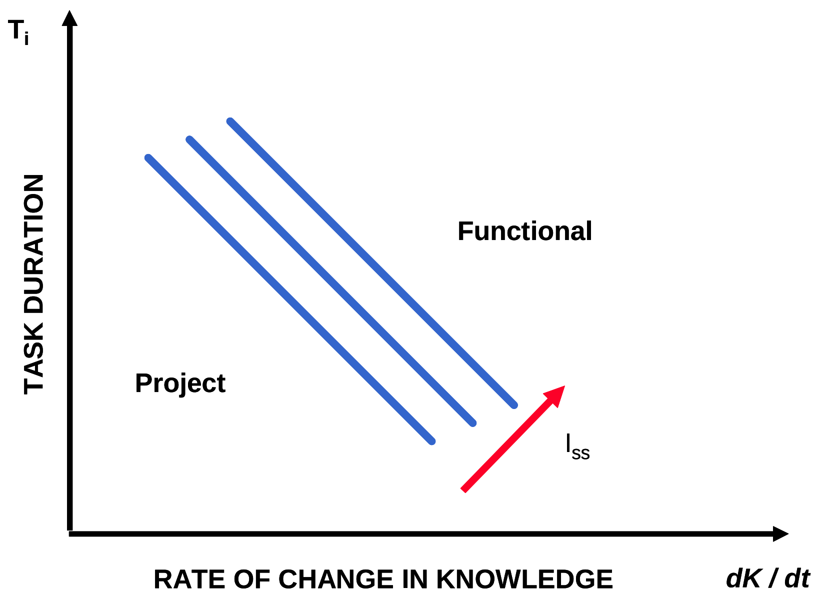

Figure 2.22: Organisational structure space (after Allen[166])

The position of the separating line in the space is determined by a third factor, namely the degree of subsystem interdependence (I_{SS}). I_{SS} relates to the need for and the complexity of project management as well as the dependence of a project phase on the outcome of a prior project phase. Increased I_{SS} moves the separating line in Figure 2.23 further to the top right region in the space.

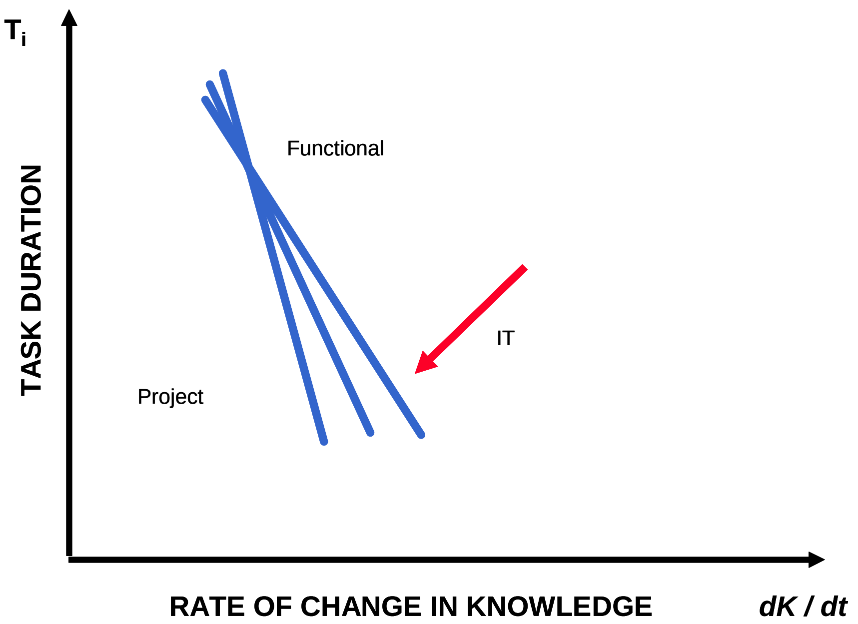

Figure 2.23: The effect of information technology on the organisational structure space (after Allen[166])

Note: In an R&D-focused organisation such as the CSIR or a university, the rate of staff turnover (young professionals coming and going) will also affect the position of the separating line (in the opposite direction from I_{SS}). This requires a special focus on human resource management in such organisations.

The explosion in the development of information technology has had an influence on the structuring of organisations because some of the functions traditionally addressed by organisational structure can be substituted by advanced information technology solutions. Information systems can simplify the process of keeping R&D staff up to date in their respective fields, improve communication with colleagues, as well as improve the coordination of projects through improved management systems. Allen[165] noted in 1986 that information technology will initially impact more on project coordination than on the need of R&D staff to remain knowledgeable about the state-of-the-art in their speciality fields. This implies that the net initial effect of information technology on the Organisational Structure Space will be to increase the functional area through a change in the slope of the separating line (see Figure 2.23).

According to Allen, there is no reason why both output and input-orientated structures cannot be used simultaneously in one organisation. The design of the organisational structure should take each individual case into consideration. Under certain conditions, matrix structures can be used effectively to address a balance between project focus and functional focus.

The managerial structure of an organisation has a major influence on the communication within the organisation. However, the physical structure (the layout or architecture) of an organisation has an equally important role to play (Allen[167]). The positioning of staff and the distance between their offices are important factors to be considered in optimising the communication within an organisation. Particular attention needs to be given to not positioning staff on different floors or further than approximately 30 m apart if they are to be working on the same project team.

Cobbenhagen *et al.*[168] conducted a study in the Netherlands to investigate the state of industry and to determine factors for successful change of industries into more innovative organisations. They used a sample of 62 companies in 35 branches of industry in the Netherlands. They indicate that the process of innovation is part of the organisational system and should be viewed as such. An organisation which successfully innovates must therefore not only possess technological core competencies, but also organisational and marketing competencies. This implies that client focus, quality, multi-disciplinary teams, cash-flow management, human resource management, partnering and strategic planning should be, *inter alia,* part of the process of successful innovation.

In their study they identified the differences between companies that are leaders (Dutch: Koplopers) and followers (Dutch: Pelotonleden). The following were the main conclusions:

- leaders manage to make breakthroughs ('shift the barriers') earlier and more regularly;
- leaders invest in organisational renewal which is essential to innovation;
- leaders are market and client focused and often get ideas for innovation from these sources;
- leaders find the optimum balance between developing technology and buying in technology;
- leaders usually have a strong organisational competency which is closely linked to their technological and marketing competencies; and
- leaders continuously conduct critical reviews of themselves.

According to Cobbenhagen companies should understand clients' needs in depth in order to go beyond providing what they ask for and also provide what they really need. Cobbenhagen concludes that, as in all strategic issues, timing is essential in innovation and that organisational change, leading to improved innovation, should be conducted using change models such as the socio-technical approach to organisational renewal.

Wang *et al.*[169] discuss the current trend of organisations to change from functional organisations into process organisations. They state that, although traditional functional organisations with pyramidal organisational structures are regarded as well suited to planning and control, communication problems often occur when projects span boundaries in the functional organisation – such structures could therefore inhibit innovation. They discuss various organisational structures which have been used to address the problems experienced. The structures include matrix organisations, centralised multi-divisional forms and product cell organisations. Process-complete departments can each conduct all the necessary tasks independently and can provide a complete package to the customer. Companies are moving towards flatter, process-orientated structures, the success of which depends on the ability of cross-functional teams to work together effectively. However, some barriers to cross-functional integration exist, mainly due to perceptual, cultural, organisational and language factors derived from an organisation's inherent inertia when it comes to change. Wang *et al.* suggest a framework for the process of organisational change.

2.6.3 Open innovation

Chesbrough[170], West and Gallagher[171] as well as Herzog and Leker[172] discuss the concept of Open Innovation and contend that it is a new paradigm of cooperation in R&D and innovation that can provide sustainable growth in the future. The process is defined as the use of inflows and outflows of knowledge to and from a company to accelerate internal innovation, and to expand markets for external use of innovation. Open Innovation also means a change in the way to use, manage, employ and also generate intellectual property. They describe Open Innovation as a holistic approach to innovation management as "…*systematically encouraging and exploring a wide range of internal and external sources for innovation opportunities, consciously integrating that exploration with firm capabilities and resources, and broadly exploiting those opportunities through multiple channels.*" Open Innovation focuses on the importance of using external technologies to advance internal innovation projects as well as using external means to commercialise a new product. Thus technologies or knowledge flow through the semi-permeable corporate membrane to external parties. According to Herzog and Leker[172], an Open Innovation approach requires a change in culture in a company, particularly as it pertains to attitudes of Not-Invented-Here and Not-Sold-Here syndromes. Von Hippel and Von Krogh[173] argue that free-revealing is central to Open Innovation practices.

Karanjikar and Wright[174] state that through Open Innovation a firm can enhance its innovation ability by connecting people in different firms where ideas can be recombined across disciplinary boundaries. However, it is important to balance the open innovation portfolio, and they discuss two concepts for achieving balance, i.e. a stratified model and a diversity model. The first model focuses on the stages of idea generation, proof-of-concept, prototype and licence-ready technology. The second model is based on the assumption that individuals bring different skills, knowledge and approaches to the table depending on their work practice, geographical location and academic discipline, thus enriching the innovation process. A company has to balance its portfolio of projects in terms of risk where the concept stage is the highest risk and requires the highest investment in company own capability. The ready-to-licence stage is the opposite but potentially with lesser return.

Chesbrough and Crowther[175] also found that open innovation principles are now being used by companies operating outside the high-tech industries.

2.6.4 Risk management

Managing the risk associated with large investments in R&D is a major issue for any company. Rese and Baier[176] discuss a real options approach to assist investment decision-making in hard product development. The use of a real options approach incorporates several developmental paths and outcomes in order to provide flexibility on final decisions to management at a stage as late as possible in the development process. This assists in minimising investment risk in a volatile market.

Thamhain and Skelton[177] discuss critical success factors for effective R&D risk management. They categorise the sources of risk and required actions by the organisation as follows:

- Risks within organisational processes – the capability of the organisation to simplify products, use effective project management, early feasibility testing and the ability to 'look ahead' to the market are some of the critical actions required to reduce these risks.

- Use of analytical tools and methods – the ability of the organisation to use tools ranging from simple brainstorming sessions to complex Monte Carlo analysis to determine the likely outcome of development processes.
- Risks within people - the quality of communications, level of trust, respect, credibility, minimum conflict, job security and skill sets are all factors influencing the ability of the organisation to deal with risk.

2.7 Technology development and innovation models

The discussion above highlighted the need for a new approach to the management of R&D in the road infrastructure sector. The overall objective of this thesis is firstly to assess whether existing technology management models can be modified to be suitable for managing R&D in road engineering. If not, then secondly, to develop a new conceptual R&D management model and decisions tools that are based on systems theory and take cognisance of complexity theory and cybernetics. This section assesses the characteristics of existing models for managing technology development. The applicability of these models for the management of R&D in road engineering is evaluated in Chapter 3.

Rothwell[178] categorised the types of technology management models as given in Table 2.2.

The early technology push models were linear in nature, describing a step-by-step process from basic work through to marketable product. An example of such a first-generation model is the Department Stage Model as discussed by Saren[179] (see Figure 2.24).

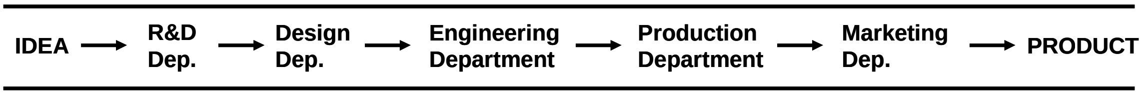

Figure 2.24: The Department Stage Model (Saren[179])

Table 2.2: Categories of technology management models (after Rothwell[178])

Generation	Type of model	Characteristics of model
First	Technology push	Simple linear sequential process. Emphasis on R&D. The market is the receptacle for R&D fruits.
Second	Need pull (market pull)	Simple linear sequential process. Emphasis on marketing. The market is the source of ideas for directing R&D. R&D has a reactive role.
Third	Coupling model	Sequential but with feedback loops. Push or pull or push/pull combinations. R&D and marketing more in balance. Emphasis on integration at the R&D/marketing interface.
Fourth	Integrated model	Parallel development with integrated development teams. Strong upstream supplier linkages. Close coupling with leading-edge customers. Emphasis on integration between R&D and manufacturing/design for makeability. Joint ventures.
Fifth	Systems integration and networking model	Fully integrated parallel development. Use of expert systems and simulation modelling in R&D. Strong linkages with leading-edge customers (customer focus at the forefront of strategy). Strategic integration with primary suppliers including co-development of new products and linked Computer Aided Design systems. Joint ventures, collaborative research groupings, collaborative marketing arrangements, etc. Emphasis on corporate flexibility and speed of development. Increased focus on quality and other non-price factors.

Forrest[180] states that these linear-sequential models are too simplistic and ignore many of the important aspects of innovation, including inputs from the environment, marketing factors and socio-economic factors.

Twiss[181] discusses a typical market-pull model (see Figure 2.25). The market pull models (2nd stage) put emphasis on the market, although the models were still very linear. In these models innovation is in response to identified market needs and R&D plays a reactive role. Forrest[180] states that the market-pull models are also too simplistic and that models should incorporate both market pull and technology push.

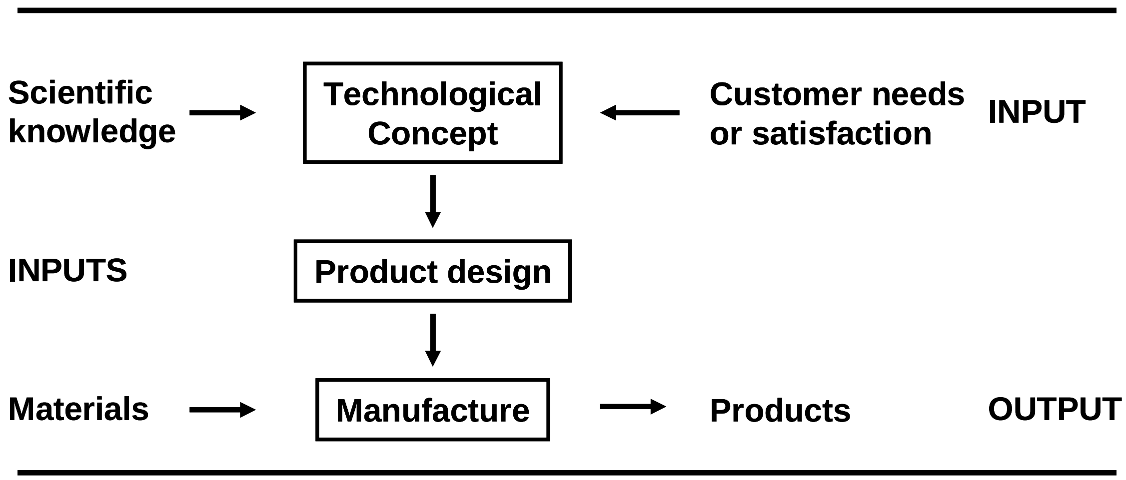

Figure 2.25: The market-pull model (Twiss[181])

In the 1970s models coupling science, technology and the market place were developed. In the Coupling Model of Innovation (see Figure 2.26) the process of innovation represents the confluence of technological capabilities and market needs within the framework of the innovating firm.

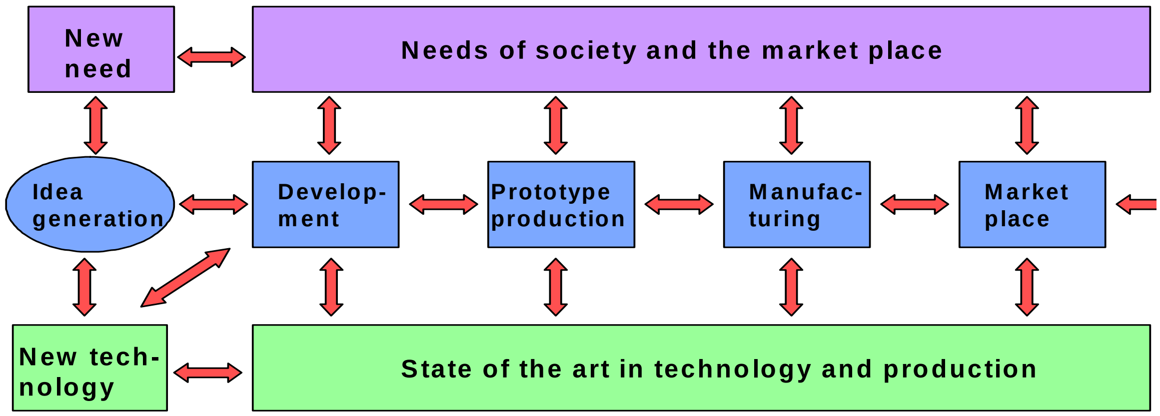

Figure 2.26: The coupling model of innovation (after Rothwell[178])

Twiss's Activity Stage Model (see Figure 2.27), an example of a 4th stage model, has been cited as one of the first to be a significant improvement on the early linear models[180]. In this model the activities in the innovation process and both the internal and external environment are recognised.

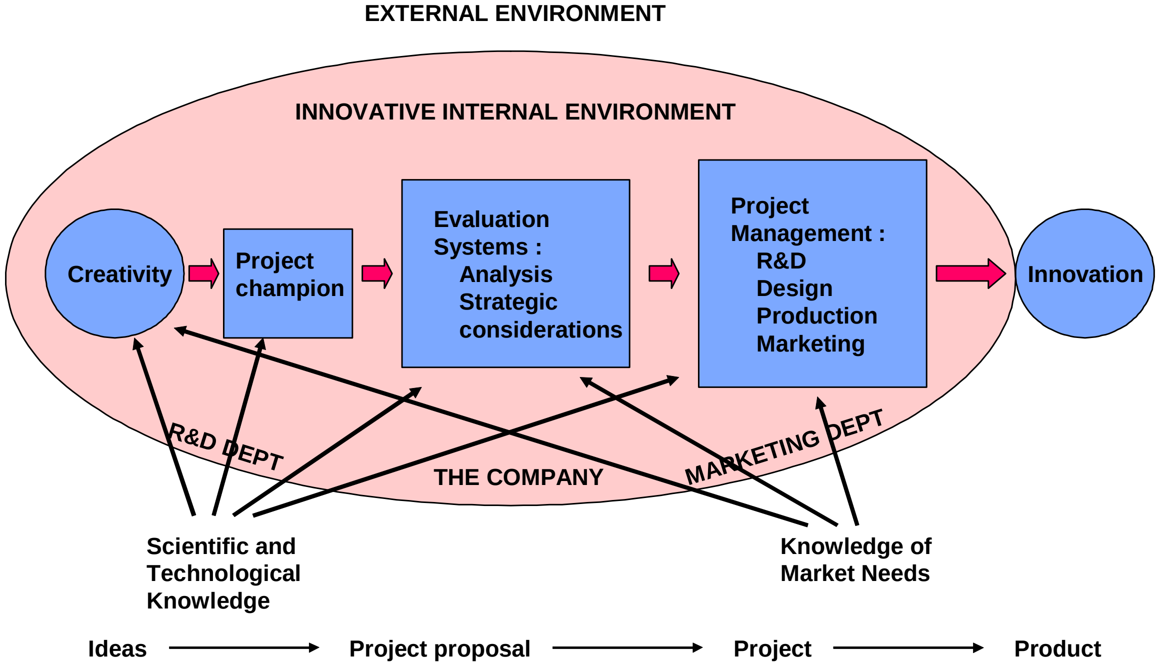

Figure 2.27: The activity stage model (after Twiss[181])

However, both these models (Rothwell and Twiss) are considered not to recognise the full complexities involved[180]. The so-called integrated models consider innovation as a parallel process involving R&D, prototyping and some manufacturing with a closer collaboration between manufacturers, suppliers and customers. Forrest[180] states that "*No model appears to be capable of being utilised as a generalised model of innovation*".

Brown and Karagozoglu[182] developed a systems framework for technological innovation in which they view technological innovation as taking place in a 'metasystem' of an organisation comprising various elements (see Figure 2.28). This is an example of a 5th generation model as described in Table 2.2. They emphasise the understanding of the whole system of innovation and the characteristics of the inputs as functions of the innovation goals of the organisation, radical new products, process innovation and efficiency.

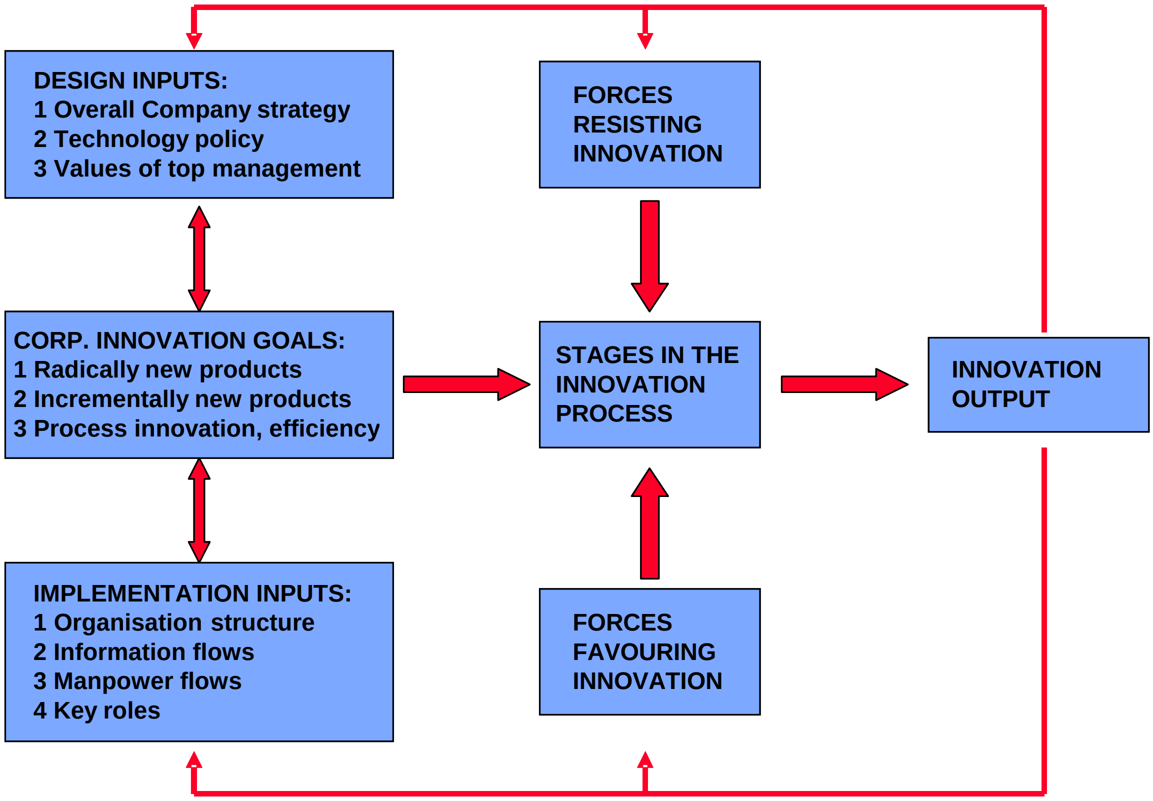

Figure 2.28: A systems framework of technology innovation (after Brown and Karagozoglu[182])

In the self-assessment guide and workbook[183] of the UK Department of Trade and Industry, Chiesa, Coughlan and Voss discuss a Process Model of Innovation (see Figure 2.29) – an example of a 5th stage model. This model comprises four core processes (product innovation, product development, process technology and technology acquisition) and three supporting processes (leadership, resourcing and systems and tools). They list four challenges that must be met in the management of innovation:

- translating requirements from each area into specifications for satisfactory results;
- linking together those, and only those, elements that need to be coupled;
- distributing responsibility and accountability for interactions; and
- integrating different perspectives on performance.

They state that:

"Understanding the relationship between innovation performance and competitive performance leads to an understanding of the relationship between the process of innovation and a firm's competitive or resource position. In turn, innovation performance is influenced by the characteristics of the business process, by the degree of interaction among processes and by the support to the core process of innovation. Each firm, given the particular characteristics of competitive strategy and of its industry, should understand these relationships and take the appropriate action in terms of business processes of innovation."

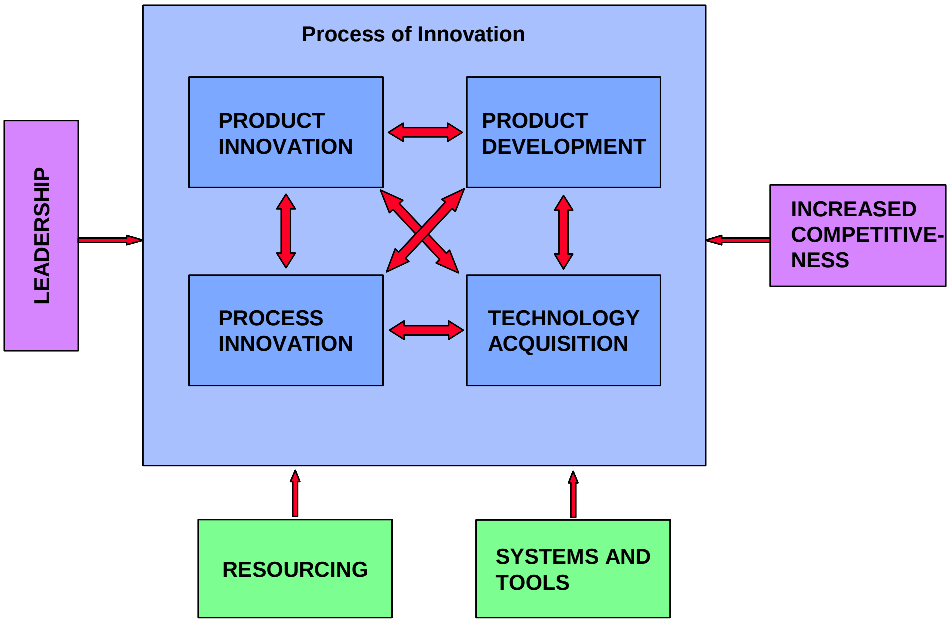

Figure 2.29: The process model of innovation (after Chiesa, Coughlan and Voss[183])

Brady[184] also discusses Bessant's model (see Figure 2.30) in which the main elements are:

- strategy, where opportunities and needs are identified;
- enablers, providing support for innovation;
- the acquisition/generation element where the competencies in innovation are situated;
- a product development system;
- a process development system;
- a linkage system, connecting the organisation to the outside world; and

- a learning system, which ensures that the organisation learns from its experience.

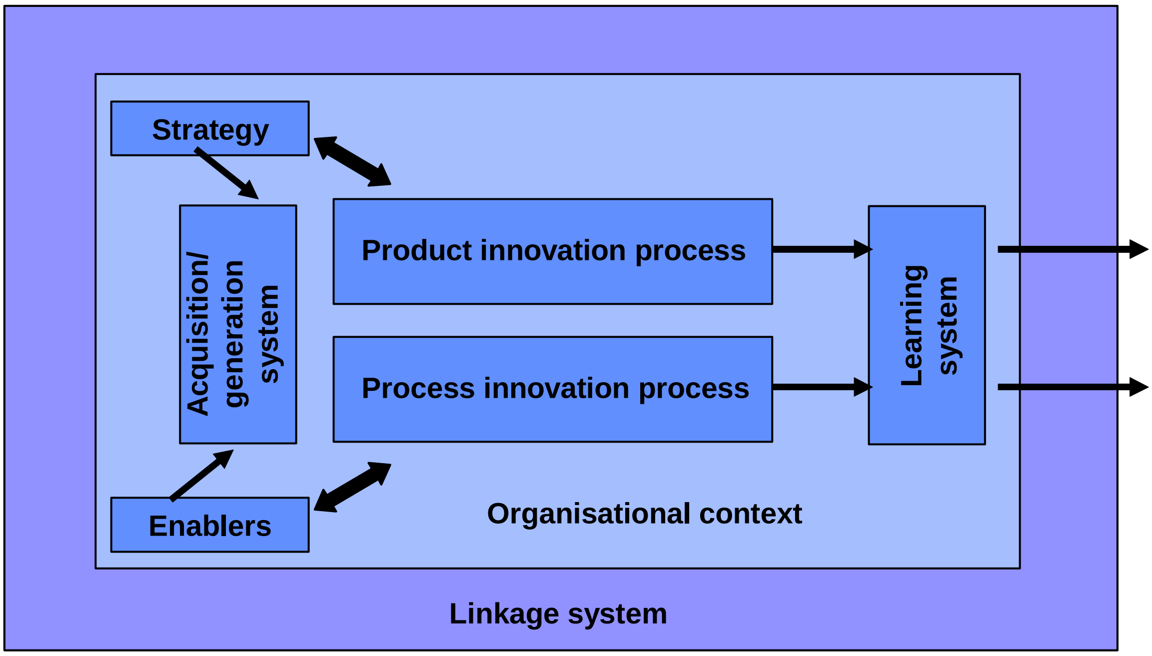

Figure 2.30: A model framework for the innovation system (after Bessant[184])

Gaynor[65] discussed a typical linear model for the process of technology development and diffusion (see Figure 2.31). The main elements in the model are:

- recognition of opportunity;
- idea generation, evaluation and selection;
- prototype product development;
- full-scale development; and
- technology utilisation and diffusion.

Although there are tentative feedback loops in this model (Gaynor[65]), it essentially remains linear with technology push being the main focus.

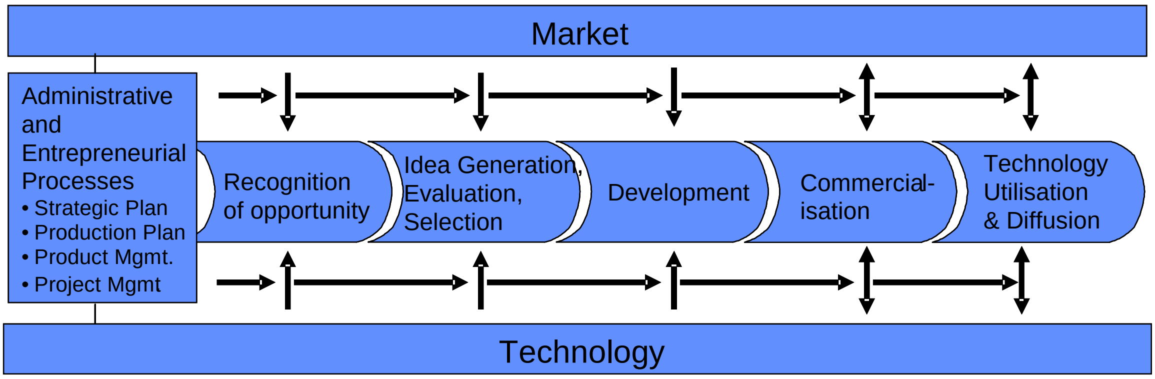

Figure 2.31: The innovative process and its interfaces with the market, technology and administrative subsystems (after Gaynor[65])

The applicability of these models for managing R&D in the road engineering sector is assessed in terms of selected criteria in Section 2.10. Although some of the above systems have moved away from the early linear models, they are not totally systems-based and still address mainly innovation in mass-produced hard products and are therefore not entirely suitable for managing R&D in the road infrastructure sector where most of the effort is aimed at developing new knowledge, engineering expertise and methodologies.

2.8 Diagnostic tools for assessing technology development performance

Diagnostic tools for assessing the success of technology development or innovation are relatively new and can range from simple checklists to sophisticated computer tools. Brady[185] discussed some of these tools and this information is summarised below.

The Innovation Management Tool Kit (IMTK)

The IMTK was developed for the UK National Economic Development Office in 1989 and was based on a study of best practice in 50 UK manufacturing companies. It consists of 13 handbooks designed to assist UK companies to become more competitive through innovation. It involves a series of tests in which managers and other employees assess their performance in relation to a set of ten key characteristics of companies which manage innovation successfully. These characteristics are related to company culture, employees, internal communication, organisation, customers, finance, suppliers, competitors, technology, new products and processes. The process involves the answering of a set of questions related to the above factors and is intended to allow a company to develop action plans to address its shortcomings. It also allows the benchmarking of a company against its peers.

The UK DTI workbook

The UK Department of Trade and Industry promotes a simpler process developed by March Consultants and based on the model developed by Voss *et al*.[183] Once again the process is based on a series of questions and involves benchmarking of the company.

The MINT programme

The Managing of Integration of New Technology (MINT) programme is an experimental scheme in the European Community SPRINT (Specific PRogramme for INnovation and Technology transfer) initiative. They have published a tools guide which includes the following tools:

- innovation audit;
- business review tool;
- diagnosis;
- technology audit;
- technology opportunity review;
- value-based innovation and diagnosis;
- product management audit; and
- quality management audit.

Technology mapping

Gaynor[65] (p13.5) discusses various mapping processes to analyse technologies. These include:

- *chronological mapping,* which is used to represent history and current state of knowledge in a specific discipline;
- *co-word-based mapping*, aimed at the quantification of knowledge growth based on numbers of publications and other bibliometrics;
- *cognitive mapping*, which is often used as a method of representation of personal knowledge; and

- *conceptual mapping*, which is used to represent a whole domain of knowledge.

Technology audits

De Wet[186, 187] discusses the use of technology space maps to:

- determine the scope and depth of present capabilities;
- determine the scope and depth of capabilities required to achieve goals implied by strategic objectives; and
- determine the scope and content of technology development and technology transfer activities to fill the gaps identified in the process.

2.9 Technology forecasting tools and techniques

Brady[184] discusses several technology forecasting techniques including:

- scenario writing;
- the Delphi process[188];
- relevance trees;
- trend impact analysis;
- probabilistic system dynamics; and
- morphological analysis.

Technology forecasting techniques are well developed. They have been reported on extensively and are not discussed in detail here.

Brady[184] also discusses various other techniques, including:

- value analysis and value engineering;
- quality function deployment;
- tools and techniques to assist project management (e.g. PERT, CPM);
- continuous improvement and quality;
- the capability maturity model; and
- software capability evaluation.

2.10 Discussion of models and tools

Brady concludes that, due to the specific nature of CoPS products, the applicability of the models, tools and techniques discussed above in managing innovation in CoPS projects is doubtful. This is due to the fact that most of these models and techniques were developed for products produced by mass manufacturing and are intended for the consumer market. Pavitt[189] also argues that the dynamics of innovation in products and the underlying body of knowledge supporting their development is significantly different.

The analysis of the models showed that some work has been done on the process of developing and managing products in the service industry. However, very little has been done on the management of R&D in terms of the definition given in Chapter 1, i.e. including engineering methodology, decision-support systems and new knowledge or know-how – particularly in the field of civil engineering technologies, methodology and materials. Current practice in technology management is mainly aimed at products for the consumer market (non-intelligent buyers) as opposed to the road infrastructure industry (intelligent buyers). Associated issues such as marketing and quality are therefore also mainly aimed at the manufacturing industry. The strategies are mainly aimed at the corporate level of a private company rather than at an industry.

However, even though the analysis of the above models did not provide a ready-made solution for the management of R&D in the road infrastructure field, a number of interesting observations can be made:

- The importance of the use of a systems approach to address the complex nature and non-linear behaviour of the R&D process in the road infrastructure industry was affirmed.
- A holistic approach that deals not only with the R&D process, but also the environment in which it takes place, should be taken into consideration. This includes issues such as industry strategy, human resource development and general training.
- Technology forecasting and foresight studies should be used to inform the long-term R&D strategy.
- Technology mapping processes can be used effectively in the understanding and managing of R&D.

2.10.1 Criteria for the assessment of technology management models

Brady[190] discussed the initiation of a project to develop technology and innovation management models and tools for Complex Product Systems (CoPS), which are defined as high-cost, customised, large-scale, engineering-intensive products such as flight simulators, telecommunications exchanges, aircraft and chemical process plants. CoPS have the following characteristics:

> *"Much of our understanding of the innovation process and its management has been derived implicitly from studies of sectors producing mass-produced goods such as motor vehicles and semiconductors. Similarly the models developed to describe the process and the tools and techniques developed to aid innovation management have often been derived from research in what we may call traditional sectors." - Brady*

- they are made up of many interconnected, often customised, elements organised in a hierarchical way;
- they exhibit non-linear and continuously emerging properties, whereby small changes in one part of the system can lead to large alterations in other parts of the system; and
- there is a high degree of user involvement in the innovation process, through which the needs of the economic environment feed directly into the innovation process (rather than via the market as in the standard model).

Brady stresses that much of our understanding of technology and innovation management stems from studies of the manufacturing sector, particularly mass-produced goods intended for the consumer market. The models and tools to assist technology management are similarly derived. Brady comments that these models and tools are unsuitable for managing technology development and innovation of Complex Product Systems.

Rothwell[191] listed a number of critical factors for successful innovation (author's emphasis in bold italics):

- the establishment of good ***internal and external communication and effective linkages with external sources of know-how***;

- treating innovation as a corporate-wide task, effective functional integration and ability to design for ***makeability***;
- implementing careful planning and project control procedures;
- efficiency in development work and high-quality production;
- ***strong market orientation***: emphasis on satisfying customer needs and, where possible, ***involving potential users in the development process***;
- providing a good technical service to customers, including ***training***;
- the presence of certain key individuals: effective ***product champions*** and technological gatekeepers (see Chapter 2);
- high-quality of management: dynamic, open-minded managers, ***a commitment to development of human capital***;
- the nature of the product, e.g. uniqueness, superiority;
- the nature of the market: intensity of market need, market growth and size;
- the achievement of technical and production synergies between the new product and existing products (i.e. the ***importance of cumulative know-how***);
- success is people-centred: ***innovation is essentially a 'people process'***;
- ***long-term corporate strategy*** in which innovation plays a key role, not an ad hoc role;
- ***long-term commitment to major projects*** based not solely on short-term return on investment considerations, but on future market penetration and growth; and
- innovation has to be seen as a ***system or total process*** which needs to be managed in an integrated way.

Germeraad[127] describes the four main waves of R&D management since the 1990s:

- re-engineering driving incremental R&D – where the focus was mainly on return on investment, market share, percentage of new product sales and other financial measures to determine the value of R&D;

- next-generation R&D – where the main focus was on technology forecasting and technology foresighting to deliver new future products that will yield higher financial returns;
- breakthrough innovation – in this period companies were in need of radical innovation and 'killer applications' in order to stave off competition; and
- leveraged R&D – the most recent period since 2002 (after the dot com crash), where the focus is on optimising R&D expenditure and value as well as external collaboration.

The analysis of the information from the literature survey in this chapter and the evaluation of R&D programmes and projects in Chapter 3 were used to define fourteen criteria used to assess the applicability of the models discussed here to manage R&D in the road engineering sector (see Table 2.3 below). The models were rated against the criteria on a five-point scale in terms of how well they complied with the criteria.

2.10.2 Evaluation of technology management models against criteria

Based on the above analysis, the models discussed above were evaluated (albeit only by the author) against the criteria defined in Section 2.10.1. The results are shown in Table 2.3 below. This analysis indicates that none of the models fully address the desired criteria. This was also confirmed in the analysis by Forrest[180].

Table 2.3: Evaluation of technology management models against the defined criteria

CRITERIA	Department stage model (Saren)	Market-pull model Twiss)	Coupling model (Rothwell)	Activity stage model (Twiss)	Systems framework (Brown)	Process model (Chiesa)	Model framework (Bessant)	Gaynor model	COMMENTS
Take cognisance of organisation strategy, technology foresight	1	2	2	2	4	2	5	5	Only the Brown, Bessant and Gaynor models had strong evidence of strategic planning
Based on a holistic, non-linear systems approach and complexity theory	1	1	1	1	1	2	2	1	Apart from some models that indicate feedback loops, there is no evidence of a complex systems approach
Balance between short-term and long-term objectives	1	1	1	1	1	2	1	1	Almost no evidence of any strategic balance in activities
Emphasis on a balance between invention and technology transfer	1	1	2	2	1	1	1	1	Almost no evidence of any strategic balance in activities
Use of cybernetic systems principles (feedback loops, self-organisation, self-reference and correction)	1	1	2	1	2	2	1	2	Very little evidence of any performance measurement that feeds back into the system and corrects itself
Integration of capabilities	1	1	3	3	3	3	2	1	Some models show some integration of capabilities
Portfolio management and balance	1	1	1	1	2	1	1	1	No evidence of portfolio management

CRITERIA	Department stage model (Saren)	Market-pull model Twiss)	Coupling model (Rothwell)	Activity stage model (Twiss)	Systems framework (Brown)	Process model (Chiesa)	Model framework (Bessant)	Gaynor model	COMMENTS
Balance between market pull and technology push	1	3	5	3	2	2	1	4	Some models balance market pull and technology push
Emphasis on human resource development (HRD)	1	1	2	1	2	3	1	1	Very little emphasis on human resource development
Stakeholder interaction and communication	1	4	4	3	2	2	2	4	Some models link to the market and their stakeholders
Use of impact measurement	1	1	1	1	1	1	3	2	Almost no evidence of impact assessment that feeds back to the management process
Use of open-innovation principles	1	1	1	1	1	1	1	1	No evidence of open-innovation principles
MEAN SCORE	1.0	1.5	2.1	1.7	1.8	1.8	1.8	2.0	

2.11 Concluding remarks

During the literature survey it was found that there is a significant focus on hard product development for the consumer market, particularly information and communications technology products. An analysis of the nature of the case studies in typical text books and journal articles on technology management confirms this situation. For example, Table 2.4 shows such an analysis of the articles in "Strategic Management of Technology and Innovation"[12] as well as in the 2006 and 2007 editions of "R&D Management".

Table 2.4: Number of case studies per output type

Category	Number of case studies
Hard products	53
Software	9
Services	10
Knowledge package	0
Other	1

Table 2.4 shows that 72% of the case studies and articles dealt with hard products and software development. The services case studies in the analysis above include, for example, ADSL services, broadband services, Internet services, financial trading services, online retailing, managerial consulting and digital print services. These fields are far removed from R&D in civil engineering and civil engineering technology and methodology in general.

Similarly, Table 2.5 indicates the trend towards electronics and Information and Communication Technology (ICT) case studies, with a lack of case studies in civil engineering and engineering methodology.

There is therefore an indication that published research on technology management does not address the issue of the development of engineering methodology or civil engineering technology and knowledge.

Table 2.5: Number of case studies per market sector

Market sector	Number of case studies
Electronics	11
Entertainment	4
ICT	29
Pharmaceutical	4
Materials	4
Other	15
Engineering methodology	0

The literature review highlighted a number of important aspects that should be taken into consideration in the development of an R&D management model for the road infrastructure sector in South Africa. These issues were used to define tenets[iii] or principles for the development of a new model. The analysis in Table 2.3 indicated that existing technology management models do not address the desired criteria for managing R&D in road engineering.

The issues and tenets are summarised in Table 2.6 in a number of categories. In Chapter 3 the 'mapping table' of tenets will be repeated with the new information, and the tenets based on the analysis in that chapter highlighted. These tenets are used as the basis for the development of the new R&D management model and tools discussed in Chapter 6. The eventual success of the model will finally be measured against these tenets.

[iii] According to Gaynor[65] a tenet is a principle based on observation, intuition, experience and, in some cases, empirical analysis. In this case these principles or tenets were derived from analysis of the information compiled from the literature review as well as observation over a number of years of implementation of the systems.

Table 2.6: Tenets and principles for the development of a new R&D management model

Category	Issue	Tenet
Scope of the model	Innovation is a chain from invention to exploitation.	The model should be based on a holistic approach that addresses the full innovation chain.
	R&D in the road infrastructure sector is complex and multi-disciplinary due to the nature of the work conducted and the mixture of product development and new methodology development.	The model should take cognisance of the principles of systems thinking, cybernetics and complexity theory with a specific emphasis on non-linearity to address the development of new engineering methodology and knowledge.
	There is a need for long-term strategic R&D, as well as for solving short-term technology needs.	The model should allow for a balance between long-term and short-term objectives.
	There is a need for enhancing the level of invention and creativity in organisations such as the CSIR and in South Africa in general.	The model should specifically emphasise creativity and invention.
	There is a need for the continuous transfer of technology to industry and government.	The model should place specific emphasis on technology transfer.
Systems approaches	First- and second-order cybernetics principles provide a sound basis for organisational design and management.	Cybernetics principles such as control and feedback loops, circular causality, self-organisation and self-reference should be taken into consideration in the design of the model.
	Systems approaches and cybernetic principles are more applicable to management models dealing with a complex environment.	The model should take cognisance of systems approaches, specifically the interaction between the elements of the system and their interdependence, and the interaction with the system environment.
		The interactive planning approach should be used to develop a new model to ensure participation of stakeholders.
		The model should address the inherent hierarchy of the system and the integration of capabilities.
	The environment of R&D in the road infrastructure sector is complex due to the variety of the activities and their interaction.	The model should take cognisance of complexity theory, specifically the non-linearity of the R&D process, some degree of informed reduction to deal with the breadth of the problem and the interaction of the elements in the model.
Strategic planning	R&D activities are an integral part of the business strategy of an organisation.	The strategic planning activity of an organisation should be a prominent element in the model.

Category	Issue	Tenet
	Technology strategy and the research agenda should be integral to business strategy and should take cognisance of issues such as portfolio balance.	The model should allow for the balancing of the research project portfolio to address strategic objectives.
		Both technology push and market pull should be taken into consideration in the model.
Technology transfer	Technology transfer is essential especially in an R&D organisation, the main focus of which is to develop new methodology and solutions for industry and government (i.e. external to the organisation).	Technology transfer should be an element of the model.
Process issues	Lead users are an important source of innovation.	The model should allow for interaction with stakeholders to define the R&D and technology development needs, to identify enhancements of technologies and methodologies and to continuously assess the usefulness of the outcomes.
	An understanding of core competencies, platforms and capabilities is valuable in optimising the effectiveness of the R&D programme and the eventual success of the technology deployment.	The model should incorporate the concepts of core competencies, technology platforms and capabilities.
	Quality management is an important aspect of successful R&D programmes.	The model should take cognisance of quality management principles in general and specifically in monitoring the quality of the output.
	It is important to measure the effectiveness of the R&D programme to ensure that processes are optimised and that stakeholders understand the programme impact.	The model should include processes for research effectiveness measurement and impact assessment.
	Information and communications technologies (ICTs) are playing an increasingly important part in the effectiveness of organisations.	The model should focus on the use of ICTs to enhance the effectiveness of information flow and knowledge dissemination.
Organisational issues	Skills balance in the team of professionals managing and conducting R&D is required for optimum efficacy.	The manpower pool should be linked to the model and play an important part in the model.
	A knowledge-intensive R&D organisation should be structured according to competency and not markets.	The model should allow for a focus on technical competencies and indicate their link to the relevant stakeholder needs.
	Principles of open innovation allow a holistic approach across a number of disciplines and organisations, thus enhancing the innovation chain.	The model should take cognisance of open innovation principles.

3 R&D MANAGEMENT IN THE SOUTH AFRICAN TRANSPORT INDUSTRY – AN ANALYSIS OF PAST RESEARCH PROGRAMMES AND PROJECTS

3.1 Introduction

In South Africa there have been a number of research programmes addressing the transport industry over the past 25 years. All the significant programmes that existed for more than five years were selected for analysis in this study. These are:

- the National Department of Transport (DoT) research programme prior to 1988 (the Steering Committee era);
- the DoT research programme between 1988 and 1993 (the Research and Development Advisory Committee era);
- the DoT research programme between 1993 and 1997 (the Centres of Development era);
- the Gauteng Department of Public Transport, Roads and Works research programme from 1995 to 2005;
- the Southern African Bitumen Association (Sabita) research programme from 1988 to 1997; and
- the CSIR Transportek (Division of Roads and Transport Technology) Parliamentary Grant research programme from 1988 to 2005.

All the DoT programmes and the Gauteng programme were resourced from public funding. The Transportek programme was grant funded from the Department of Science and Technology and the Sabita programme was private sector funded. This provided a cross-section of funding sources.

In addition, three significant research projects were analysed through case studies, namely the Heavy Vehicle Simulator (HVS), the development of capacitive mat axle weight sensors and related products, and the CSIR Transportek programme for developing technologies for labour-intensive construction (LIC). The purpose of this chapter is to conduct a critical analysis of these programmes and projects. Firstly, the history and context of the programmes are discussed and secondly, the management models used, the successes and failures and the lessons learnt that should influence the development of a new approach to an R&D management model for the road infrastructure sector are examined. The information provided here has been compiled from previous work carried out[192] as well as from personal discussions with Dr George Dehlen[193], who was a director of the National Institute for Transport and Road Research (NITRR) at the CSIR and a senior member of the Transportek management team. Dr Dehlen was also a member of many of the committee structures discussed in this chapter. Discussions were also held with Mr Keith Wolhuter[194] who served on the secretariat of the Navplan[iv] consortium for a number of years. A work group of experts was also used to confirm the results of the analyses conducted here.

Thirdly, the analysis of the six programmes was based on the trends in number of projects per annum, number of organisations doing research and average project size. The data presented in this chapter were compiled from the CSIR Transportek financial system as well as from the records of Navplan and then analysed to produce the trends discussed in Section 3.6. These trends are then compared with the successes and failures of the programmes.

Finally, some indications of the performance of the programmes in terms of their delivery are given to substantiate some of the conclusions drawn from the analysis.

3.2 The national Department of Transport (DoT) research programme

3.2.1 Background

Since 1951 CSIR Transportek has supported the DoT with the execution of research in transport-related topics. Up to 1994 the CSIR also assisted with the management of the research programme, after which the function of CSIR Transportek was limited to that of a research contractor. A detailed history of the DoT's research programme is given elsewhere[192].

[iv] Navplan was a consortium of CSIR Transportek, Bruinette, Kruger and Stoffberg Incorporated and Jordaan and Joubert Incorporated formed for the purpose of managing the RDAC era of the DoT research programme between 1988 and 1993.

The relationship between the CSIR and the DoT with regard to research management can be subdivided into three distinct periods. These are:

- the Steering Committee era (1953 - 1987);
- the Research and Development Advisory Committee (RDAC) period (1988 - 1993); and
- the Centres of Development (CoD) period (1993 - 1997).

In 1998, the DoT basically stopped research funding and focused on short-term investigative projects to solve immediate problems. Whereas this assisted the DoT in solving some urgent operational problems, it had a significant impact on R&D outputs and capability. Currently, the CSIR is conducting some limited knowledge application work for the DoT on a contract basis.

3.2.2 The Steering Committee era (1953 - 1987)

In this era, the R&D programme was managed with the help of the Road Research Advisory Committee (RRAC) and the Roads Steering Committee (RSC)[193]. The RSC consisted of senior officials from the NITRR as well as technical officials from the road authorities. The RRAC consisted of senior officials from the national and provincial road authorities, representatives from the consulting engineering fraternity, representatives from the construction industry as well as a representative from the oil companies. The RSC prepared a proposed research agenda which was then presented to the RRAC for review and advice to the Steering Committee on the final composition of the research programme[193].

The characteristics of the Steering Committee Era were as follows[192]:

- good communication between sponsors, users and researchers;
- guidance from a closely networked system of committees; and
- goodwill towards and trust in the Director of the then National Institute for Transport and Road Research to apply good research management practice in undertaking the research programme.

The funding was in the form of a stable grant, involving a minimum of formal controls (other than statutory accounting controls), and results were assessed as outcomes in the form of implementable and implemented findings, rather than mechanistically as work done. The meetings and site visits of these committees served an invaluable role in providing a channel for technical communication. The committees provided forums at which the researchers met with both the sponsors and the users of their research. This resulted in closely-knit teams of researchers, sponsors and users, which survived until 1988.

According to Dehlen[193] and Wolhuter[194] one of the weaknesses of the Steering Committee system was the split between the funding process and the R&D programme development process. This sometimes resulted in staff of the funding organisation lacking knowledge of or commitment to the research projects. During this era, projects were not managed according to tight deadlines, with the result that progress was often slow. The R&D programme was not based on a comprehensive R&D strategy, with the result that projects sometimes did not address real needs of the road authorities and the industry. In addition, the lack of a project-specific financial management system within the CSIR (then the NITRR) during the earlier part of the period made it difficult to quantify the costs of individual projects and to compare them with the benefits accruing from the findings.

3.2.3 The RDAC period (1988 - 1993)[192]

In 1986 the National Transport Commission (NTC) established the Research and Development Advisory Committee (RDAC). The RDAC process heralded a significant change in process in that it awarded projects mainly based on a lowest-cost tendering procedure. The RDAC reported directly to the South African Roads Board (SARB) and also liaised with the relevant departments in the DoT. The overall responsibility of the RDAC was to advise the SARB on research funding, to monitor and encourage research and to ensure that agreed research objectives were met and followed by implementation of the end-products. The RDAC thus effectively replaced the original CSIR Steering Committees which were then also disbanded during 1987. A consortium, first named Technoplan and subsequently Navplan, was created to assist the RDAC with administration. Navplan was a consortium consisting of CSIR Transportek and two civil engineering consulting firms.

The Navplan process focused mainly on the monitoring of progress and the control of research funding, and not on the R&D process as a whole. The intention was to incorporate the expertise and practical knowledge of practitioners in the industry into the research effort. To keep the process as transparent as possible, all research projects were awarded on the basis of a tendering process. This included both ‘client identified’ and ‘researcher identified’ projects. This sometimes led to a problematic situation where a research organisation would identify a need, develop a proposal for a methodology to address this need and would then subsequently lose the project on account of not being the lowest bidder in a tendering process. In this process, issues such as ownership of the intellectual property of the original ideas and work, as well as the parity between research organisations in terms of research capability, became very problematic. The response of the research organisations was to focus on reducing cost rather than on addressing needs with quality solutions. This resulted in a plethora of small unfocused projects and subsequent fragmentation of the research effort. It is shown in Section 3.6 that this had a severely detrimental effect on the impact and value of the research effort.

In addition, the problem of the complexity of using several different research organisations to address the widely divergent, and often conflicting, needs of a large body of stakeholders was never overcome. Many of these organisations had little experience of the research process. As new entrants into the field of research, their capabilities in this area were also largely unknown to the DoT or Navplan.

The process of awarding research contracts through the tendering system relied on the technical inputs of panellists. However, to give proper effect to their function, panellists had to be experienced people of stature in their chosen fields of interest. In an attempt to reduce demands on the panellists’ time, quality judgments were, in effect, replaced by administrative procedures which had to be transparent and impartial, as many researchers saw the Navplan consortium members as competition because some of the organisations to which the Navplan members belonged also tendered for research projects.

Thus the lack of a proper strategic approach incorporating a needs-determination process exacerbated the fragmentation of the research effort.

The process of inviting a wide spectrum of organisations to participate in the execution of research projects, as had been the case during the Navplan era, may have supported the short-term development of an extended corps of researchers. However, their commitment to R&D was questionable. The research contracts that were awarded were regarded purely as a source of income at a time when there was little infrastructural development taking place, and hence reduced opportunities of income generation elsewhere. Research projects were also subsidised in order to obtain some profile which would assist in winning the next consulting project. Research, in other words, was perceived as being a ‘stop-gap’ measure rather than a long-term commitment. At the end of 1991, the Navplan system collapsed (although in 1992 and 1993 two service contracts that did not involve significant R&D were awarded from this fund). After a hiatus of two years, it was replaced with a much lower-level programme, the COD programme discussed below. Any capability that may have been built up outside the CSIR was thus effectively lost.

Specific disadvantages of the Navplan process included[192]:

- the use of a lowest-price tendering system that focused on cost and not quality of the work done;
- shortcomings in strategic planning and a long-term view;
- it focused mainly on monitoring of progress and control of funding rather than on the R&D process and strategic objectives;
- the difficulty of using many different research contractors to address the needs of a large body of stakeholders was not addressed;
- the needs determination process was not inclusive because end users of the technologies were not consulted;
- the research effort became fragmented due to severe competition in the tendering process and a lack of strategic focus, which led to a plethora of small projects; and
- it did not focus sufficiently on invention and creativity, and most of the activity became knowledge application rather than knowledge generation.

3.2.4 Centres of Excellence/Development (1993 - 2004)[192]

Following the Navplan era and the two-year period (1991 to 1992) during which no research (or very little) was conducted by the DoT, it was decided to establish so-called 'Centres of Excellence'. A number of educational institutions as well as CSIR Transportek were invited to submit proposals for participation in the programme. The intention was that three Centres of Excellence would be created and located in Gauteng, the Western Cape and KwaZulu-Natal. A Centre was envisaged as comprising a grouping of universities and technikons that would participate, under the supervision of a Board of Control, in the process of addressing transport issues and the development of personnel and academic resources in the field of transport.

The main thrust of funding was towards knowledge enhancement and human resource development. The funding for these centres was, in essence, in the form of a research grant. The amount of funds for each centre varied depending on the number of staff involved and the extent of the centre's activities. In 1995, the 'Centres of Excellence' were renamed as 'Centres of Development' or CoDs. One of the more significant aspects of the concept of CoDs was that they effectively excluded the consulting practices from research, whereas during the RDAC/Navplan era, their input had been actively sought.

The needs identification process in this era was initially conducted by the researchers, which meant that a number of the projects did not address relevant topics. Subsequently, the DoT exercised its right to approve projects prior to execution. This process was, however, not strategically focused either. Research needs were identified by the line departments within the DoT and it mainly remained an in-house exercise with minimal input from other stakeholders.

During both the RDAC and CoD eras very little technology transfer took place[194].

3.2.5 Characteristics of the historical DoT research programmes to be taken into consideration

The following positive aspects of the DoT eras will be taken into account in the development of a new approach to R&D management:

- the use of steering committees to ensure proper strategic direction and management;
- proper progress monitoring and control systems as well as supporting information databases; and
- significant emphasis on the development of human resources.

One of the main disadvantages of the research programmes in all three of the above eras was that the R&D management process was very linear, i.e. it flowed from problem to research to solution without any structured feedback loops. This linear nature, combined with the fact that the strategic 'bigger picture' was not appropriately addressed, and that a comprehensive needs determination process was not followed, led to a situation of fragmentation and subsequent under-performance of the programme (see Section 3.6).

3.3 Gauteng Department of Public Transport, Roads and Works

The Gauteng Department of Public Transport, Roads and Works, or Gautrans (formerly part of the old Transvaal Provincial Administration), has, over the past decade, funded research at CSIR Transportek (which became part of the Built Environment Unit of the CSIR in 2005) on an annual basis. The most notable project was the Gautrans Heavy Vehicle Simulator (HVS) project which is currently still active[195]. This project is discussed in detail in Section 3.7.2.

The research work conducted for Gautrans is managed by a steering committee[196] and the work is championed in Gautrans by the Chief Engineer Materials. The steering committee consists of representatives of Gautrans, the CSIR, other provincial governments, the South African National Roads Agency and practitioners. The HVS project is relatively large (currently in the order of R6 million per annum). In earlier years, the project was also linked to the South African HVS programme through the HVS Steering Committee. Currently the programme also participates in the HVS International Alliance[197], a forum where research co-operation and information sharing is discussed by all members, including the California Department of Transport, Gautrans, the US Army Corps of Engineers (USACE), the Cold Regions Research and Engineering Laboratory of the USACE, VTT in Sweden and the Florida DoT. The official committee structure is augmented by regular project meetings, site visits and informal discussions. This communication channel is vital to the success of the project. One of the other characteristics of the Gautrans HVS programme over the past 20 years was the continuity of the funding for this project. Although the funding had to be decreased once or twice due to budgetary constraints in specific financial years, the budget amounts were significant and dedicated to a focused effort in the HVS project.

The HVS project was also complemented with materials testing, field surveys and trial construction projects - particular emphasis was placed on this in the latter part of the Gautrans HVS programme. This significantly enhanced the outputs from the HVS programme. Although consulting engineering firms and universities are involved in the Gautrans R&D work, the bulk of the work is conducted at CSIR Transportek.

Specific aspects that should be taken into consideration in the development of a new R&D management approach include:

- the continuity of funding which allowed for longer-term capability development and provided room for enhanced creativity;
- the fact that the project was well-focused with the result that outputs were implementable and useful in practice;
- the use of a steering committee to provide strategic direction for the project; and
- the fact that the HVS project was linked to other projects to enhance the body of outputs.

3.4 The Sabita research programme

3.4.1 Background

In 1988, the Southern African Bitumen and Tar Association (Sabita) embarked on a strategy-planning process during which the importance of generic R&D and technological development for the industry was acknowledged[198]. Sabita and the CSIR subsequently initiated a research and development programme for the asphalt industry, the Asphalt Research Programme (ARP). It was envisaged that the ARP would enhance asphalt technology in the industry, create an improved profile for the industry and enhance the industry's efficiency, thereby making the industry more competitive, and improving services and products to the industry's clients. The basis of the ARP was a needs-driven research programme based on the actual needs of the industry and its clients. Prior to the commencement of the programme, significant effort was put into the determination of research needs. A series of workshop-like meetings formed the Asphalt Research Strategic Taskforce planning process (AREST). The process was facilitated by the CSIR and included participants from the road authorities, the road industry as well as from local authorities and communities. The highest-priority projects emerging from the first AREST sessions focused on R&D, including work such as the Heavy Duty Asphalt Pavements and Appropriate Standards for Bituminous Surfacings projects. The industry's acceptance and prioritisation of projects was based on a benefit/cost assessment. The determining factor that facilitated the implementation of the programme was its foundation on actual research needs as identified by stakeholders in the road industry. The focus of the Sabita programme was on developing technologies for the benefit of South Africa in the future, as well as on training of practitioners and the implementation of research results. The implementation programme has yielded excellent results, particularly in the areas of large-aggregate mixes, porous asphalt and emulsion-treated bases, and in addressing social development needs[198].

Sabita and CSIR Transportek also jointly used the Bituminous Materials Liaison Committee (BMLC) meetings (which later became the Road Pavements Forum) as a forum for obtaining input into the R&D programme, sharing the results from the programme and endorsing results prior to implementation. Since 1995, the BMLC has become a seminar or mini-conference to which a much broader audience of interested parties are invited. The use of the AREST meetings to define general strategic direction and the BMLC as a forum to discuss research projects, results and implementation as well as to define detailed needs for research, was essential to the success of the Sabita programme. The needs determination process developed jointly by CSIR Transportek and Sabita was particularly successful. Examples of the use of these forums will be discussed in more detail in Chapter 7.

Sabita used a number of organisations, including CSIR Transportek, consulting engineering firms and universities to conduct R&D projects. However, a significant proportion (70%) of research projects was conducted by CSIR Transportek, either as the sole contractor or in co-operation with other parties. This allowed the creation of critical mass in terms of research capability within one main research organisation. A strong communication link was also established between CSIR Transportek and the Sabita Chair in Asphalt Technology at the University of Stellenbosch.

Thus the Sabita programme was based on a comprehensive strategy, addressed actual stakeholder needs and was focused on a number of large research projects that were managed as a portfolio. This ensured that the Sabita programme did not become fragmented but remained focused. The programme was estimated to have yielded high returns in relation to the investment[198]. The Sabita programme was used as an experiment to implement, test and improve the models and tools developed in this work (see Chapter 7).

3.4.2 Management structures and processes

The Sabita Asphalt Research Programme (ARP) Board consisted of six members nominated from Sabita, the asphalt industry, the CSIR and the road authorities. The ARP Board met two to three times per year in order to discuss the progress of projects and outputs from projects, to provide strategic direction to the Sabita research programme and to discuss the implementation of outputs and results. In addition to the role of the Board, a formal management system was established to ensure that the projects met their briefs as well as their deadlines. In order to ensure that individual projects were managed in sufficient detail to yield optimum results, a Sabita Technical Director and a Key Account Manager at the CSIR were appointed. The Sabita Technical Director liaised regularly with CSIR project leaders on technical issues and with the Key Account Manager on business issues. The roles of the above two persons were essential to the success of the Sabita R&D programme.

3.4.3 Beneficial characteristics to be considered

The following aspects from the Sabita programme should be taken into consideration in the development of a new R&D management system:

- strategic focusing through a process which includes wide participation by road authorities and industry;
- strategic direction provided through a steering committee;
- the use of a discussion forum to obtain research input, to share research results and to endorse findings prior to implementation;
- the development of a special needs determination process utilising the knowledge of a broad base of practitioners and stakeholders;
- the appointment of a dedicated technical director in Sabita which had the Sabita R&D programme as one of his main involvements; and
- the appointment of a Key Account Manager by CSIR Transportek to manage the business issues (including financial management, progress reviews and co-ordination) related to the projects conducted by CSIR Transportek.

Note: The Sabita R&D process was much more advanced than the DoT process or the Gautrans process, particularly in the period after 1995. Elements of systems thinking were used rather than a linear approach. The Sabita programme was used as an experiment for the implementation of the new concepts and techniques discussed in Chapter 6 as they were developed. This had a beneficial effect on the Sabita programme. The application of the new holistic approach in the Sabita programme and the benefits obtained are discussed in Chapter 7.

3.5 CSIR Transportek Parliamentary Grant programme

3.5.1 Background

The history of the Council for Scientific and Industrial Research (CSIR) is related in a book by Kingwill[199]. On 5 October 1945 the CSIR was formally established as a body corporate in terms of Scientific Research Council Act No. 33 of 1945 of the Parliament of the Union of South Africa. This meant that it became what was known as a statutory body. Initially the CSIR was wholly funded by parliament. In 1985, however, in line with changes in the scientific community world wide, the CSIR appointed a consultant to review its future. The results of this review led to a different approach by the CSIR to allow it to become more market orientated and less dependent on the parliamentary grant. Currently the parliamentary grant forms approximately only 40% of the CSIR's total income[200]. This strategy, although leading to financial success, did impact on the CSIR's science and technology base as was evident from the drop in academic publications and the increase in consultancy activity as opposed to research. In 2004 the CSIR embarked on a new strategy with renewed emphasis on building the quality of the science, engineering and technology base (the Beyond 60 strategy)[38] as well as on the delivery of SET outputs such as publications, patents and technology demonstrators[v]. The optimum investment of the parliamentary grant to build future technologies for South Africa has always been an important issue for the CSIR. This section describes the use and management of parliamentary grant funding related to the road building industry.

The Bituminous Binders Research Unit (BBRU) was formed in 1950 with sponsorship coming from the CSIR itself, the South African Torbanite Mining and Refining Company and Iscor. The BBRU was advised by a steering committee on the technical direction of the research programme. Following support from the National Transport Commission and the (then) provinces of Transvaal and Natal, the CSIR created the National Institute for Road Research in 1955. Subsequently the Institute added R&D programmes in transport and road safety and the name was changed to the National Institute for Transport and Road Research (NITRR). By 1985 the NITRR had grown into an organisation of 328 staff members.

In these initial years, virtually no funding (except that covering buildings and equipment) came from the parliamentary grant. In 1988, with the structural changes to the CSIR, the NITRR became the Division of Roads and Transport Technology (DRTT) and a small amount of parliamentary grant funding (also

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[v] A technology demonstrator is a significant novel technology that has been developed over a number of years, the application of which has been demonstrated in industry[292].

called Scientific and Technological Positioning funding or STEP funding) was allocated to the DRTT. This funding grew to an amount of R19.8 million in 2004 and is now termed Parliamentary Grant (PG) funding.

As part of the Beyond 60 strategy implementation, the CSIR Transportek Division was amalgamated with the CSIR Boutek Division to form a new Unit for the Built Environment in 2005. This section discusses the management of the PG funding in CSIR Transportek from 1988 to 2004.

3.5.2 Management structures and processes

Paterson and Kfir[201] reported that, after the redirection of the CSIR in 1988 to become more market orientated, its new operating philosophy stated that government funds were to be used to provide the organisation with the competencies that would allow it to improve the organisation's contribution to the development of South Africa and to improve its ability to earn income from contract research. At the time the CSIR therefore accepted the principle of utilising government funds as investments in the development of technology. Initially the Strategic Business Units simply submitted requests for parliamentary grant funding (STEP funding) as part of their annual business plan, giving some details regarding the projects to be conducted. However, the process was improved by the development of a number of systems to assist in the management of the parliamentary grant investment.

In 1991 a manual for the Management of Investments in Product Development (MIPD) was developed. The emphasis in the early years (1989 to 1993) was on changing the thinking of scientists from the purely scientific towards thinking about commercialisation and partnerships with industry. The MIPD process was designed to achieve this. It was initially aimed mainly at the development of hard products rather than the development of new technology and engineering know-how. The MIPD process was based on the monitoring and control of projects throughout their life cycle as depicted in Figure 3.1. However, this early model was very linear as it was developed along the same lines as classical technology management models as described in Chapter 2. According to Paterson and Kfir[201], one of the main problems with the MIPD process was that, although it called for portfolio management, it emphasised the project-product relationship by linking a specific product with one specific project. This led to severe fragmentation of the R&D effort into a plethora of small projects in a similar way to that of the DoT research programme during the RDAC era discussed above.

During 1996, using a Business Re-engineering Approach, a new process to aid the project selection process and the investment decision as well as to monitor the returns on investment was developed. This coincided with the formation of a technology manager's forum that served as a learning platform for members from all units in the CSIR. This process was based on a portfolio management approach in order to counteract the fragmentation that had occurred previously.

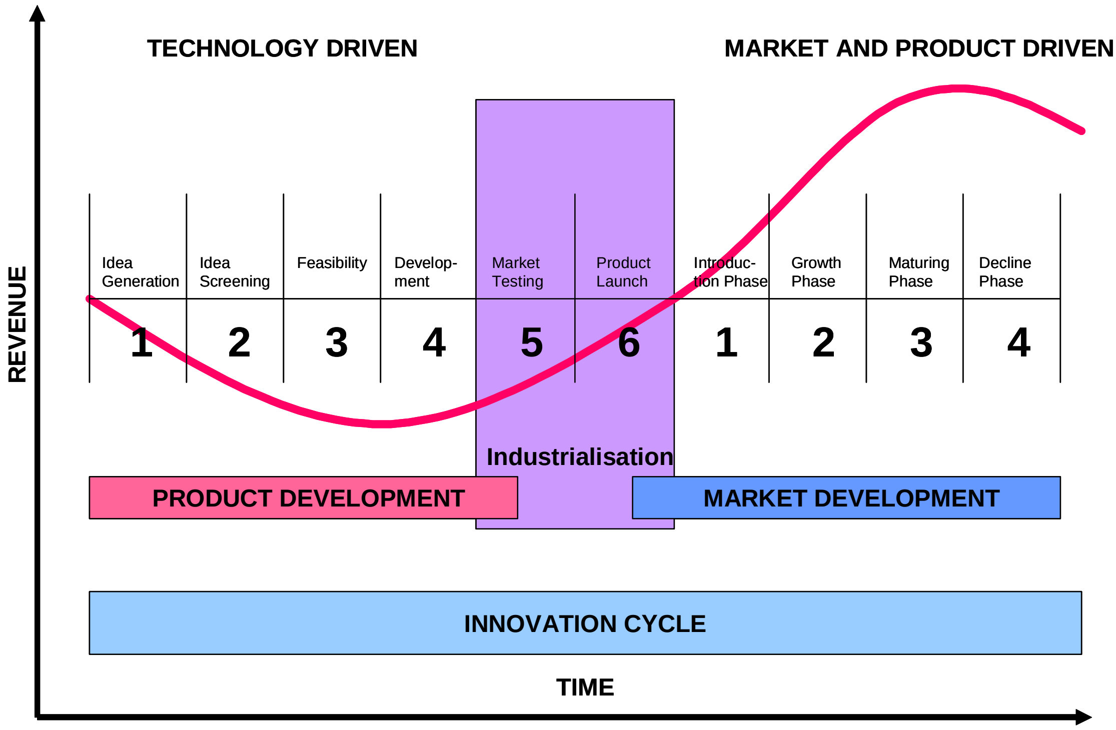

Figure 3.1: Project life cycle as depicted in the CSIR's Management of Investments in Product Development (MIPD) manual

The new investment decision was underpinned by three major themes:

- a direct link to market needs as a basis for the development of new offerings;

- the notion of portfolio management through technological thrusts[vi] rather than individual project management; and
- indirect ties between the investments and specific offerings or products.

The fragmentation of Parliamentary Grant (PG) projects in the CSIR's Division of Roads and Transport Technology (CSIR Transportek) was particularly severe due to the fact that the level of PG funding in this Division was very low initially. However, the PG investment in Transportek gradually increased to a level of about 35% of turnover. This higher level of funding placed emphasis on the need for the improvement of the processes of R&D management. This stimulated the work conducted for this thesis to develop a holistic systems approach and framework for managing R&D.

Note: In many ways the CSIR Transportek PG programme progressed through the same learning curve as the DoT programme regarding fragmentation. More recently systems thinking and a strategic focus were incorporated. As in the case of the Sabita programme, the CSIR programme was also used to test, evaluate and improve the new model. The detail and impact of this are discussed in Chapters 6 and 7.

3.6 Quantitative analyses of specific characteristics of the various programmes

The data analysed in this chapter were compiled from CSIR Transportek's financial system as well as from the Navplan records and then analysed to produce the trends discussed here.

In order to critically compare the above research programmes, specific characteristics of the programmes were analysed by plotting the following trends:

- number of projects in the programmes;
- number of organisations participating in the research programme (RDAC and Sabita programmes only);

[vi] A thrust comprises a group of related technologies and their offerings (products and services) which are offered to the market place and are managed as an entity.

- number of projects per organisation (RDAC and Sabita programmes only);
- total annual research budget in each programme;
- the average project size per programme; and
- the maximum project size in each programme.

The figures were adjusted to 2008 Rand values using the official Consumer Price Index figures (South African Department of Statistics[202]). These trends are shown in Figures 3.2 to 3.8 and are discussed in the following sections.

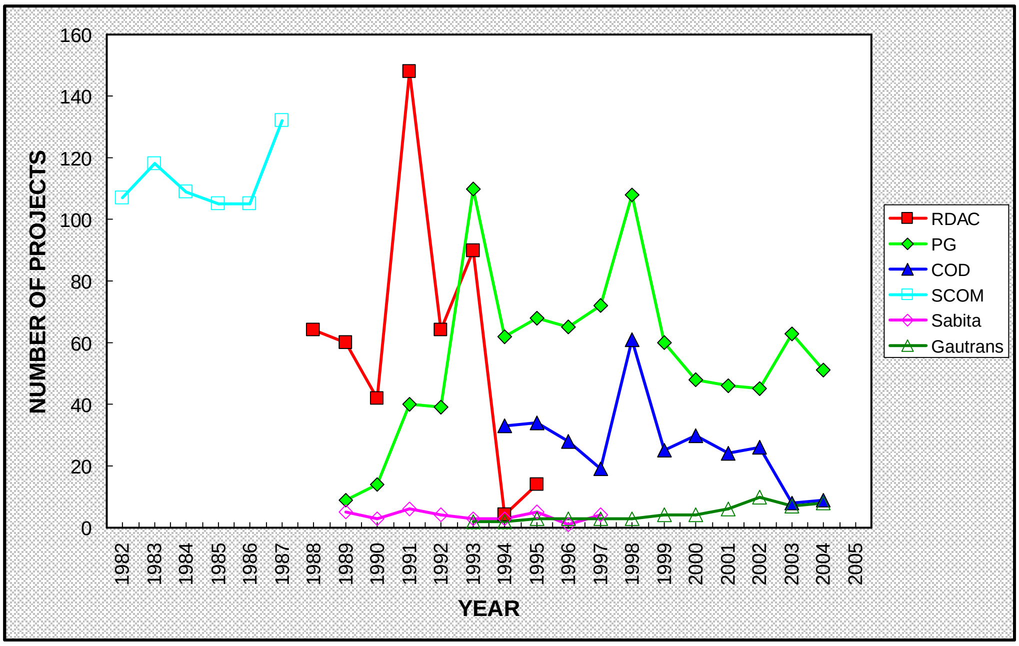

Figure 3.2: Number of research projects conducted per annum in each programme

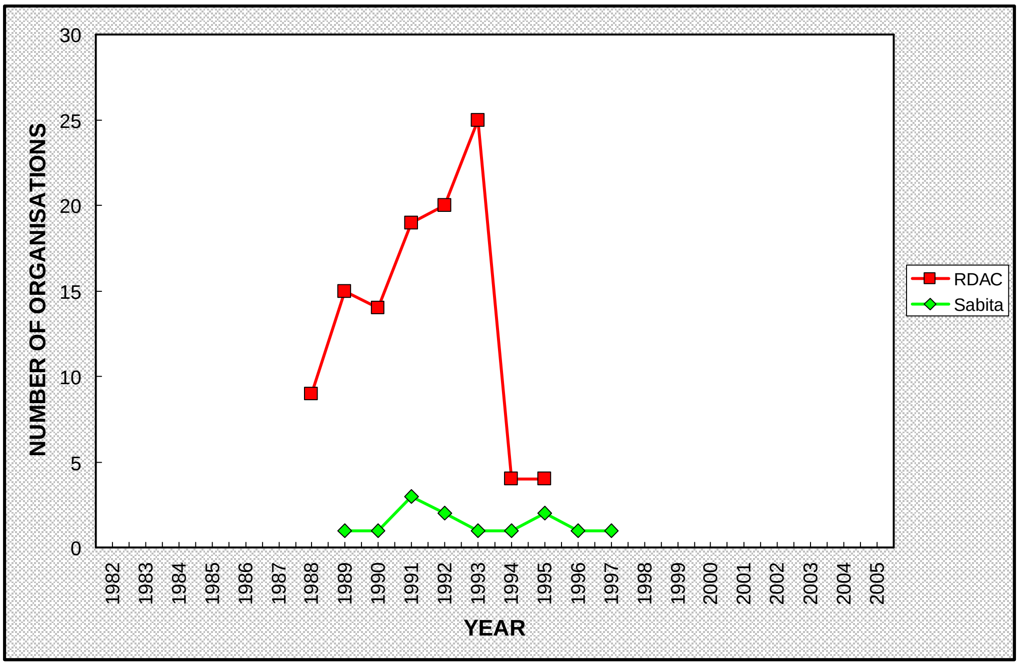

Figure 3.3: Number of organisations conducting research in the RDAC and Sabita programmes

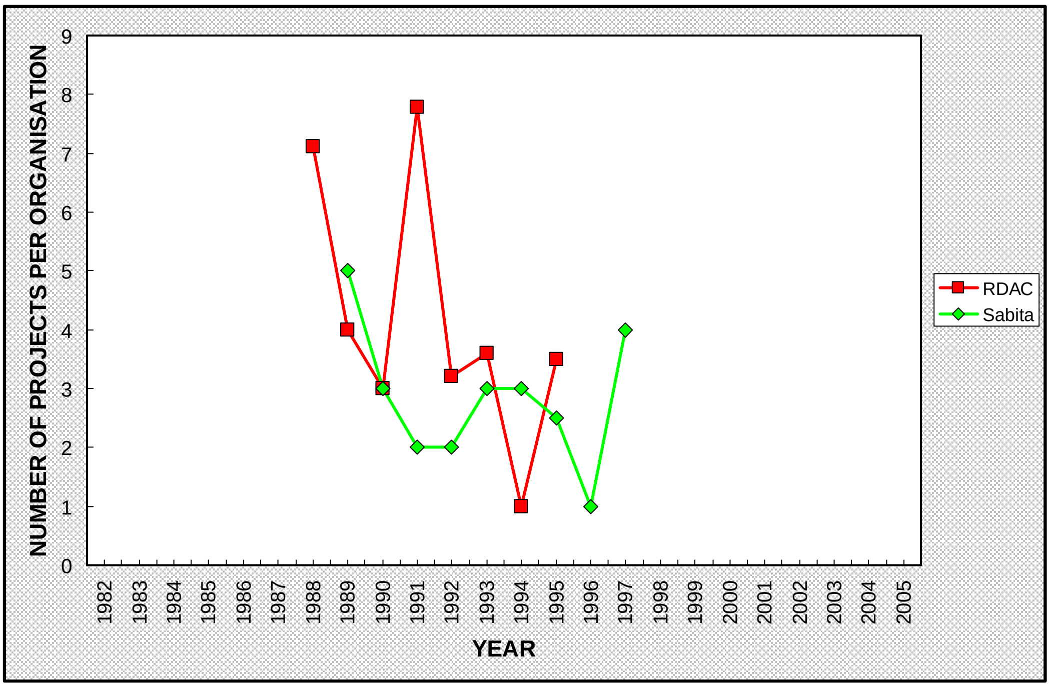

Figure 3.4: Number of projects per organisation in the RDAC and Sabita programmes

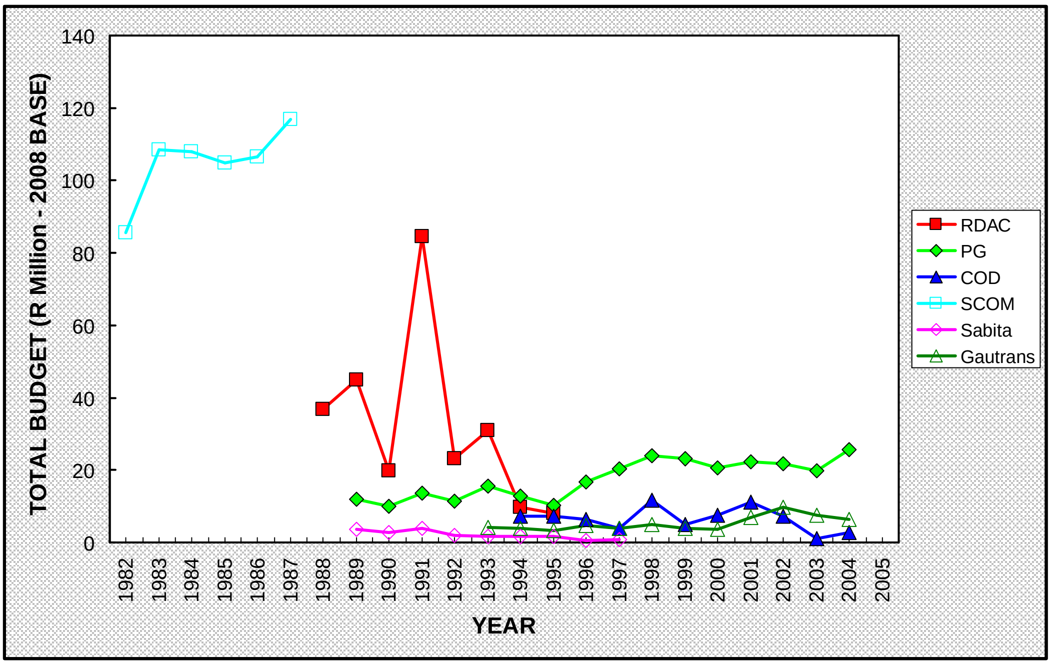

Figure 3.5: Total annual budget in the research programmes

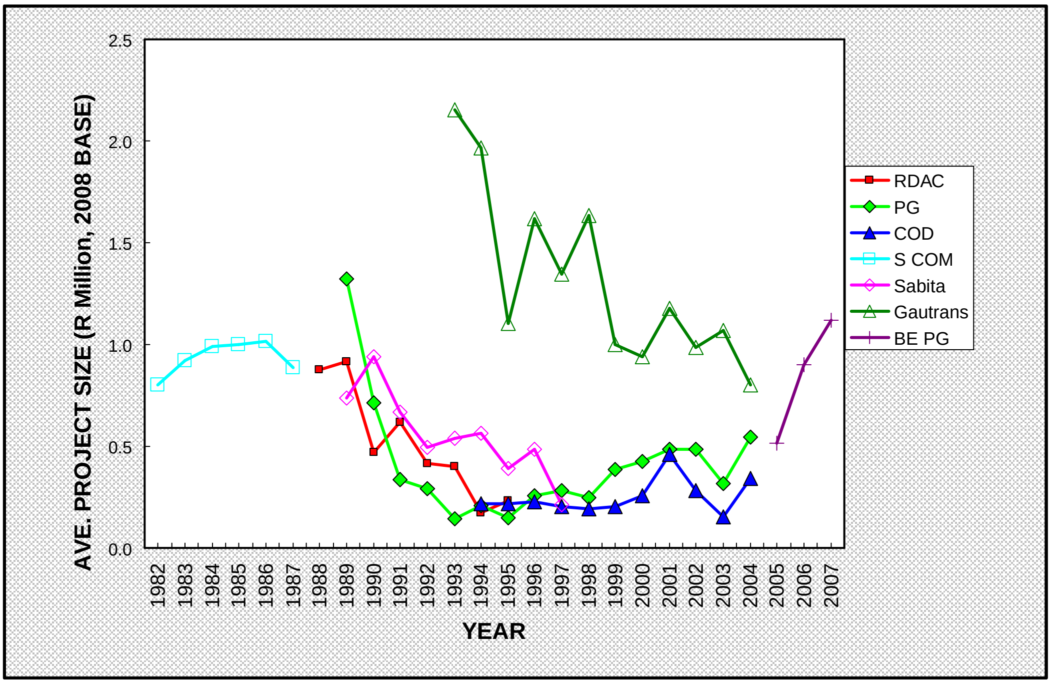

Figure 3.6: Average project size per annum for the research programmes (Built Environment Unit added)

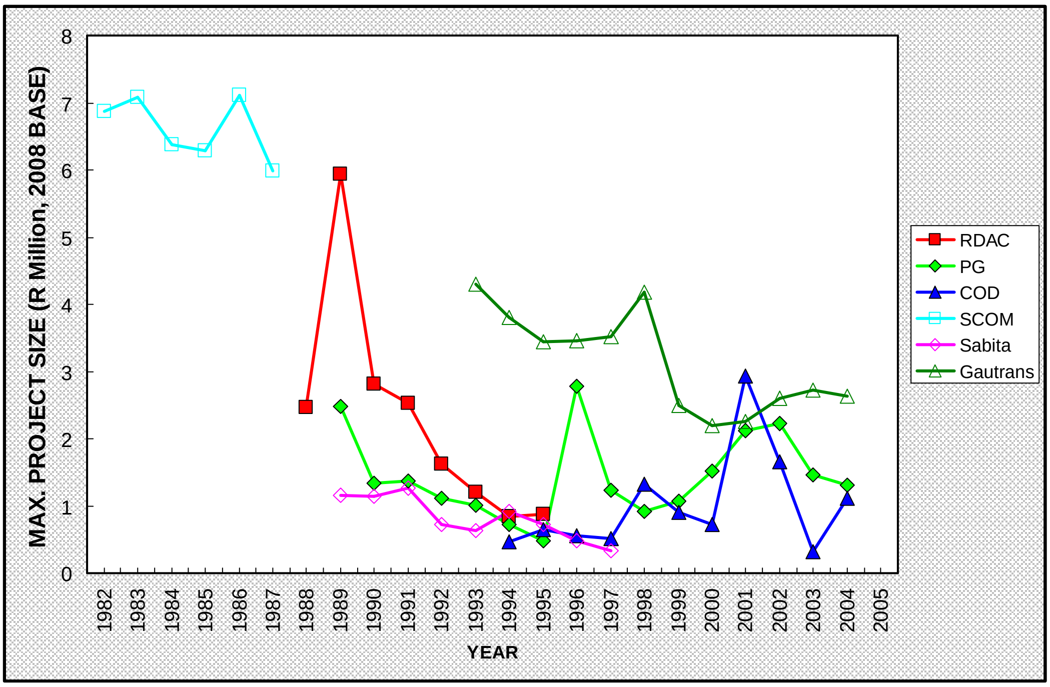

Figure 3.7: Maximum project size per annum for the research programmes

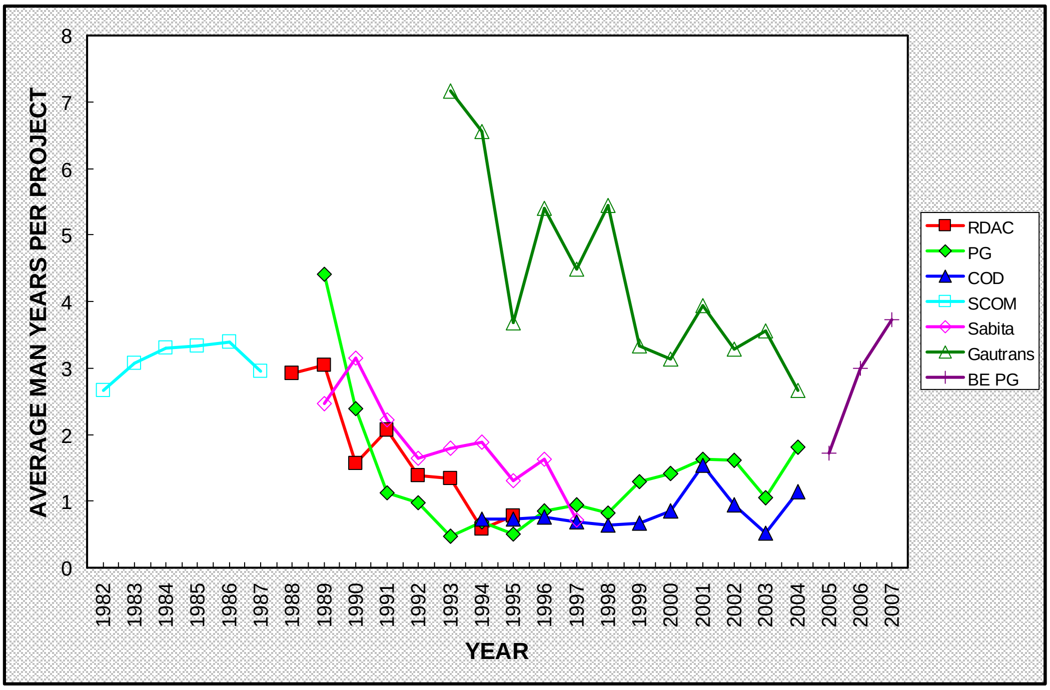

Figure 3.8: Number of man years employed per project for the research programmes (Built Environment added)

3.6.1 The Steering Committee era (pre-1988)

The following trends can be noted in Figures 3.2 through 3.8 (all figures in 2008 base Rand):

- the number of projects remained relatively stable compared with other programmes (see Figure 3.2);
- the total research budget increased slightly over time, but fluctuated less than that of other programmes (see Figure 3.5);
- the total budget was significant, growing steadily from R85 million to R116 million (2008 Rand) from 1982 to 1987;
- the average project size remained relatively stable (see Figure 3.6);
- the average project size was significant, varying from R800 000 to R1.16 million (2008 Rand);
- similarly the maximum project size remained stable and was significant, in the range of R6 million in 2008 Rand (see Figure 3.7); and
- the average number of man years per project was stable at approximately 3.0 (see Figure 3.8).

The Steering Committee era was a relatively stable period with stable, continuous funding. This period formed the basis of many of the successfully implemented research outputs for which South Africa became well known (see discussion in Section 3.5.7).

3.6.2 The RDAC era (1988 – 1993)

The trends in the RDAC era are very different from those during the Steering Committee era. The following can be noted:

- There was a significant drop in the number of projects in the transformation from the Steering Committee era to the RDAC era due to the budget decreasing to almost a third of what it was in the SCOM era (see Figure 3.2).
- In 1991 the research programme was opened up to a large number of consulting engineers and a tendering system was initiated - the result was a significant increase in the number of projects and number of organisations participating in the projects (see Figures 3.2 and 3.3).

- Although fewer projects were conducted in the subsequent years, the trend of an increasing number of participants continued, with the result that the number of projects per participating organisation continued to fluctuate, and finally decreased to a level between one and three (see Figure 3.4) - this contributed to the fragmentation of the research programme.
- The total budget dropped significantly from the Steering Committee era to the RDAC era (see Figure 3.5).
- The total budget showed a significant increase in 1991, in an attempt to increase the involvement of organisations outside the CSIR - however, subsequently the programme became fragmented and collapsed in 1994 (see Figure 3.5).
- The fragmentation as indicated by the average project size can be seen in Figure 3.6 - the average project size decreased from R914 000 to R173 000.
- The fragmentation into a greater number of smaller projects is also notable in the maximum project size (see Figure 3.7) - the maximum project size decreased from R5.9 million in 1989 to R0.84 million in 1996.
- The average number of man years per project also decreased from 3.0 to values of less than 0.58, thus not creating the opportunity for any manpower development (see Figure 3.8).

The above trends show the effect of the approach of the RDAC programme (particularly the introduction of the tendering process), which led to numerous small projects being conducted by 25 organisations, instead of focusing the majority (almost all) of the projects in one organisation, such as was done in the Steering Committee era. This reduced the possibility of the building of critical mass in specific research fields as well as the development of a high standard of research laboratories and equipment. The result was that the research programme did not deliver up to expectations and was finally stopped in 1996[192]. Ball and Butler[203] describe the allocation of research funding to universities in the UK through a series of research assessment exercises (RAE). They note that care should be taken in selecting the criteria for assessment (and therefore the allocation of funding) because it will change the behaviour of individuals and institutions. This phenomenon is also an indication that the larger R&D

environment and process is a ***complex system*** (as discussed in Chapter 2) and that a ***small change*** in the system can have a ***large, unforeseen effect*** on a different part of the system.

3.6.3 The CoD period (1994 – 2004)

The following trends can be noted:

- In general the CoD programme is a much more modest effort than the Steering Committee era or the RDAC era, with fewer projects and a much smaller budget (see Figures 3.2 and 3.5).
- The decrease in the number of projects is mainly due to a decrease in the total budget of the programme and not due to a refocusing strategy - this is confirmed by the fact that the average project size remained relatively constant.
- The average and maximum project sizes are significantly smaller than those of the other programmes (see Figure 3.6) and therefore the average number of man years per project is also very low - approximately 0.6.

Although the above trends should be seen in the light of the objectives of the CoD programme (including the fact that one of the main objectives of the programme was to develop human resources), it is notable that the projects were relatively small and that a solution to the fragmentation problem during the RDAC period was not found.

3.6.4 The Sabita programme

The Sabita programme was much smaller than the other programmes, but it was very successful in implementing results (see Section 3.6.7), and it may therefore be useful to note the trends in this programme. The data in Figures 3.2 through 3.7 only reflect R&D projects and not the associated implementation and marketing projects that Sabita conducted. The following trends can be noted:

- Although the total budget was relatively small compared with the budgets of other programmes, the funding remained relatively stable, apart from 1996 and 1997, when a lack of funding was experienced because of a drop in bitumen sales and industry instability.

- Relatively few projects were conducted per annum, but the average project size was greater than that of the much larger PG programme and RDAC programme over the same period (in spite of the fact that the annual budgets were relatively small) – (see Figures 3.2 and 3.6).
- Compared with the RDAC programme, fewer organisations were used to do the work, which gave a high degree of focus and enhanced implementation (see Figure 3.3).
- The number of man years per project, although initially above 3.0, also decreased with time to about 1.5, which is still higher than in some of the other programmes.

The Sabita programme seemed to be more focused and yielded significant results, as well as the implementation of these results (see discussion in Section 3.6.7).

3.6.5 The Gautrans programme (1993 to date)

The Gautrans programme is also relatively small and has focused mainly on the use of the Heavy Vehicle Simulator (HVS) to evaluate pavement structures and a few related projects. It has been successful in implementing results and the following trends can be noted:

- As in the case of the Sabita programme, the total budget was relatively small compared with other programmes, but the funding remained very stable (see Figure 3.5).
- Relatively few projects were also conducted per annum, and the average project size was significantly higher than that of all the other programmes (see Figure 3.6).
- Only one organisation was used to carry out the work, thereby also providing a high degree of focus and enhancing implementation.
- The maximum project size was the highest of all the programmes (due to the relatively large HVS project) - see Figure 3.7.
- The average number of man years per project was also significantly higher than that of the other programmes, varying from 7 to 2.5, which is the most important feature of the programme.

The Gautrans programme is focused, with significant project sizes and has yielded significant results and implementation of the results (see discussion in Section 3.6.7).

3.6.6 CSIR Transportek Parliamentary Grant (PG) programme (1990 - 2004)

In many ways the PG programme exhibited the same characteristics as those discussed above in the other programmes and it also become fragmented into a series of small projects. However, in 1996 a new approach was initiated (the so-called 'thrust' approach that focused on portfolios of projects) which assisted significantly in the refocusing of the PG research programme. Thrusts are essentially specific focus areas of research, building on specific capabilities. The new approach called for the management of thrusts as a portfolio of research investments rather than a focus at the project level. At the same time a first version of the new conceptual model and tools developed in this study was implemented. The development of the new approach to managing R&D is discussed in Chapters 6 and 7.

The analysis shows the following trends:

- As the annual budget initially increased, the number of research projects increased until 1996 after which the new approach to R&D management led to a more focused effort (see Figure 3.2). This is discussed in more detail in the following chapters.
- The average project size decreased as the programme lost its focus, however the initiation of a new approach to R&D management using *inter alia* the systems approach reversed this trend (see Figure 3.6).
- The average number of man years per project decreased from an initial value of 2 to below 0.6, after which an increase to approximately 2 can be seen since 1996 due to the implementation of the new approach to R&D management.

Figure 3.6 also shows average PG project sizes in the Built Environment Unit from 2005 to 2007. The major restructuring of the CSIR in 2005 (when the new Built Environment Unit was created) provided the opportunity for a comprehensive implementation of the new approach discussed in this thesis, with the result that the average project size increased to about R1 million and the man years per project to a value of more than 3.7 (see Figure 3.7).

Although the trends discussed above are very similar to those of the other programmes, indicating some fragmentation, the refocusing of the PG programme into thrusts of significant magnitude led to an increase in impact from the programme - this is discussed in more detail in Chapters 6 and 7.

3.6.7 Effect of fragmentation

The data and discussion above indicate that the various research programmes did not keep up with inflation. The total budgets decreased in real terms as did the average project size. This may have been due to general budget constraints. However, Wu *et al.*[204] found that, even in an economic downturn, firms that adhere to long-term strategic goals maintain technological differentiation and do not cut R&D funding in this period, and therefore perform better financially in the long run.

> *"Finally we must recognise the danger of fragmentation. In our race to meet all the challenges and ensure visible progress, we have not always made time to examine our priorities. We must guard against unrealistic wish lists by picking out the critical success factors. We must take the time to ensure that each department, province and local authority develops compatible policies and plans. We cannot afford to waste resources through contradictory actions." - Thabo Mbeki, November 1995.*

Figure 3.8 shows the average project costs of the programmes divided by an assumed average total cost of a researcher of R325 000 per annum, thus indicating the average number of man years spent per project. The data show that the fragmentation of the programmes had a significant effect on the number of man years employed per project, decreasing from as high as 4 to as low as 0.47 in the case of the PG programme. Taking into consideration the use of technicians and other support staff, this implies that instead of teams of two or three researchers working on a project, researchers were expected to work simultaneously on a number of projects. During this period a number of negative effects were observed[205]. These included:

- loss of focus by researchers;

- less effective mentoring of junior staff by senior researchers;
- less effective peer review of research results;
- less effective development R&D capability (specifically in the CSIR);
- less chance to use colleagues as a 'sounding board' for ideas and evaluation of results; and
- consequently, less effective innovation and loss of research staff.

Dimitratos and Plakoyiannaki[206], when studying organisational culture and entrepreneurship, also found that the lack of a holistic, systemic approach leads to fragmentation with the associated disbenefits. Nature[207] reported in 2000 that Germany had also realised that there was a need for a more systemic approach to counter fragmentation:

> *"The president of the Wissenschaftsrat, historian Winfried Schulze, says Germany must overcome the problems caused by the fragmentation of its research efforts that result from the independence of its universities and the existence of several science funding agencies, each with its separate budget."*

Similar intentions were expressed by the European Commission in 2003[208]:

> *"The core message of the European Research Area is the need to overcome the traditional fragmentation of research efforts in Europe through better co-ordination and co-operation, says European Research Commissioner Philippe Busquin."*

The effects of fragmentation on research activity were also reported in the case of marine research in the USA[209] and agricultural research in sub-Saharan Africa[210].

The question remains whether this fragmentation and the associated negative aspects impacted negatively on the delivery of outputs and results from the research programmes. To answer this question accurately, a comprehensive retrospective study is required. However, some indicative trends can be observed. In particular, the number of design guidelines and manuals produced under the auspices of government departments or private sector associations was analysed. These are considered to provide some indication of the implementation of research results and usage by practitioners in industry. ***These results are discussed in detail in Section 8.3 – some indicative information is given below.***

During the Steering Committee era, the DoT research programme delivered 23 Technical Recommendations for Highways manuals. These manuals are used by the South African transport industry and in some cases also internationally, for example in Australia and in the USA. Most of these manuals were developed in the 1970s, 1980s and early 1990s. Only five of these manuals were updated after 1995 and none since 1998. Similarly, the Technical Methods for Highways series consists of 12 manuals used nationally for materials and road structural testing. Only one of these was updated in 1997 and none since. In the case of the Urban Transport Guidelines series consisting a total of 11 manuals, the last updates were made in 1991 (see Section 8.3 for detail).

These manuals were developed based on years of research prior to 1990 and the current situation of low numbers of new manuals or upgrading of manuals is an indication of the negative impact of the implosion on the National Transport Research Programme. Some efforts have been made by the South African National Roads Agency to rectify the situation. However, if the expenditure on small and unfocused research projects during the RDAC era of more than R250 million (in 2008 Rand) from 1988 to 1993 is taken into consideration, it can be postulated that the fragmented research programme caused by the tendering process did not deliver up to expectations (see detail in Section 8.3).

In a similar period from 1990 to 1997, Sabita invested about R18 million (in 2008 Rand) in the asphalt research programme at the CSIR. In this period 26 design manuals were delivered which are currently still in use[211]. In contrast to the DoT programme, all these manuals were developed during the 1990s and updated after 1995, with five having being updated after 2000. The Sabita programme also yielded significant papers read at a number of international conferences, including the 7th and 8th International Conferences on Asphalt Pavements (ICAP) and the Conference for Asphalt Pavements in Southern Africa (CAPSA). In 1994 fourteen papers from South Africa were read at the 7th ICAP conference in Nottingham out of a total of 87 papers world wide. Eight of the South African papers originated from work conducted in the Sabita programme. Similarly, in 1997 seven out of fourteen South African papers at the 8th ICAP conference in Seattle originated from the Sabita programme.

The contrast between the DoT programme and the Sabita programme in delivery and value for investment is mainly due to the difference in the research and development process and management models. Many of the principles, models and techniques discussed in Chapter 6 of this thesis derive from the interactive experimentation with the conceptual model and tools in the Sabita programme. One of the main success factors for this development was the sound relationship and spirit of co-operation between the CSIR's Key Account Manager and the Sabita Technical Director who acted as champions of the process. Some of the early principles of this work were published in the Transportation Research Record in Washington DC[212].

This analysis indicates that a new approach to the management of an R&D programme should attempt to negate the negative effects discussed above. However, the answer does not necessarily lie in simply increasing research budgets, but rather in an innovative approach to managing the process.

3.7 Case studies of three significant research projects

3.7.1 General

A number of R&D projects that were conducted over the past 15 to 20 years were investigated and three significant projects selected for detailed analysis. Both positive and negative aspects were analysed and the lessons learnt from these projects were used to enhance the set of tenets or principles for a new management model for R&D as put forward in the previous chapters. The projects were selected on the basis of the following criteria:

- the breadth and depth of the impact that they have had on the local and international road infrastructure industry;
- the innovativeness of the developments;
- the fact that they were multi-year research programmes with dedicated funding for a number of years; and

- the balance of the portfolio of projects provided by their varying nature as discussed below.

The following projects were selected:

- the Heavy Vehicle Simulator (HVS) – development of new engineering methodology;
- the development of capacitive mat axle weight sensors and related products – hard product development; and
- the CSIR Transportek programme for developing technologies for labour-intensive construction (LIC) – practical application of new methodology and technology transfer.

3.7.2 The Heavy Vehicle Simulator (HVS)

Background

Accelerated Pavement Testing (APT) was brought to the fore in the late 1950s with the AASHO road test in the USA[213] and since then it has played an important role in road engineering. In APT, wheel loads are applied to a pavement structure over a very short period of time (usually two to three months), thereby making it possible to monitor the performance of the road pavement under accelerated traffic loading and then to predict the performance of the road over its full design life (usually 20 to 30 years). During an APT experiment, the pavement structure is instrumented in order to measure the response of the pavement to loading and changes in environmental conditions (temperature and moisture). The approach has significant economic benefits due to the fact that costly failures of new pavement design approaches can be prevented. Optimum rehabilitation and maintenance designs for in-service pavements can also be determined prior to design and construction, and it allows the development of an understanding of pavement performance principles and pavement engineering.

A number of full-scale APT facilities including circular tracks (e.g. the French system at Nantes, Westrack in Reno and the Cedex facility in Madrid) as well as linear tracks (e.g. the Lintrack system in Delft and the TRRL facility in Crowthorne) are in operation. In addition, mobile and semi-mobile facilities such as the Accelerated Loading Facility (ALF), the Mobile Load Simulator (MLS) and the South African Heavy Vehicle Simulator (HVS) have been used to evaluate pavement behaviour under accelerated traffic loading.

The South African HVS programme stems from development work during the late 1960s at the CSIR (Van Vuuren[214, 215]; Paterson[216]). The benefits arising from the HVS led to increased funding to manufacture three new production machines of improved design in 1972 (Mk III machines)[217] - funded respectively by the DoT, the then Transvaal Provincial Administration (TPA) and the NIRR. Road testing with the Mk III machines began in 1978. Figure 3.9 shows the TPA Mk III HVS. The Mk III test wheel carriage was designed to take normal dual truck wheels as well as aircraft wheels. The design also allowed for both uni- and bi-directional trafficking[218]. The three new production machines were operated by NIRR staff in close collaboration with the road authorities through advisory committees. This relationship has been a significant factor in the success of the programme, ensuring the earliest possible application of important findings[222].

The three machines each had somewhat different roles which reflected the differing priorities of the owners. The DoT machine was assigned to undertake specific DoT investigations that were of importance on a national level. The NIRR machine was generally more research focused with a longer-term view (investigating key factors influencing pavement performance). The TPA machine similarly focused on longer-term R&D but was geared to specific conditions in the province.

This balance of role was beneficial, enabling the findings from shorter-term specific investigations to contribute to and influence the longer-term programmes. Furthermore, there was a benefit to all the machines being operated by the same agency, not only in terms of economies of scale through resource sharing, but also in terms of the immediacy of communication between all those involved. Given the dynamic nature of the work, this ensured that new findings and developments could be rapidly evaluated and quickly disseminated. From the late 1970s and throughout the 1980s, the expanded HVS programme was able to underpin virtually all of the advances and developments in South African pavement engineering. These included the world-renowned use of highly compacted granular pavement bases (G1 material)[243] and the South African mechanistic pavement design method[237].

Figure 3.9: HVS Mk III – Gautrans HVS

For more than 30 years the HVS played a dominant role in the development of South African pavement engineering capability. The extent of this influence is well illustrated by the contributions to international conferences, on both direct HVS applications and the associated development of rational analysis/design methods and their practical implementation (Freeme *et al.*[219], Viljoen *et al.*[220], Horak *et al.*[221], and Rust *et al.*[222]). Horak estimated the benefit-to-cost ratio of the HVS programme to be in excess of 12[242].

The success of the South African HVS programme and increased international interest in the technology led to the export of the technology to the USA and Europe since 1994. The first international HVS programme was funded by the California Department of Transportation (Caltrans), and the R&D using two Mk III HVSs was conducted as a joint venture between the University of California at Berkeley (UCB), Dynatest Consulting (a US consulting engineering firm) and CSIR Transportek. The Californian APT programme (CalAPT) delivered useful results in a very short period of time. The success and initial results have been reported by Nokes *et al.*[223]

The rising interest in APT internationally boosted further development of HVS technology, and a new generation HVS, the Mk IV, was developed in a joint venture between CSIR Transportek, Dynatest Consulting and Reumech Ermetek. The new HVS Mk IV (see Figure 3.10) remained closely aligned to its forerunners, but was modernised with full computer control and limited simulation of dynamic loading. The first HVS Mark IV was ordered by the Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers and a second new HVS for joint work between the national Road Research Laboratories in Finland and Sweden (VTT and VTI respectively) was delivered in June 1997.

Figure 3.10: HVS Mk IV – CRREL HVS

In a parallel development, a double-sized HVS for testing of airport pavements was designed for the Waterways Experiment Station (WES) of the US Army Corps of Engineers. Apart from its physical size, the fundamental difference between the new HVS–A (dubbed ‘Bigfoot’) and the Mk IV is the loading capability - it can load the test wheel up to 450 kN, whereas the HVS Mk IV can only apply 200 kN. The HVS–A is also designed to utilise an aircraft wheel bogie. This machine was delivered to WES in 1998 (see Figure 3.11). A new

HVS Mk IV+ was also designed for CSIR Transportek, and was delivered in March 1999. The HVS Mk IV+ is based on the HVS Mk IV, but the frame and loading beam have been strengthened to allow the simulation of full dynamic loading. Subsequently an HVS Mark IV+ was also delivered to the Florida Department of Transportation. In 2007 an HVS MK IV+ was ordered from Dynatest by the CRRI in India and a Mk VI, a modular and less expensive machine, by the University of Chang 'An in China.

Figure 3.11: HVS Mk V - WES HVS

Philosophy, aims and objectives of the SA HVS programme

The HVS machines each played a different role in the SA HVS programme. Initially the work of the CSIR machine was more research focused, addressing basic materials modelling and design method evaluation (Rust *et al.*[222]). Towards the late 1980s this machine was, however, also being used to address specific project-related problems such as the alkali-aggregate reaction distress experienced on the N2 concrete road near Cape Town. The DoT machine was used to attend to specific project-related and national needs, including work on thick asphalt bases, jointed concrete pavements and recycled asphalt materials. The TPA HVS, now operated for the Department of Public Works, Roads and Transport of Gauteng Province (Gautrans), on the other hand, focused on specific provincial needs, alternating between basic and applied work.

It should be emphasised that APT is one of a number of tools available to the pavement engineer. Figure 3.12 (after Hugo *et al.*[224]) demonstrates the place of APT in bridging the gap between laboratory work and long-term pavement performance (LTPP) studies. The respective cost implications and likely benefits are also shown.

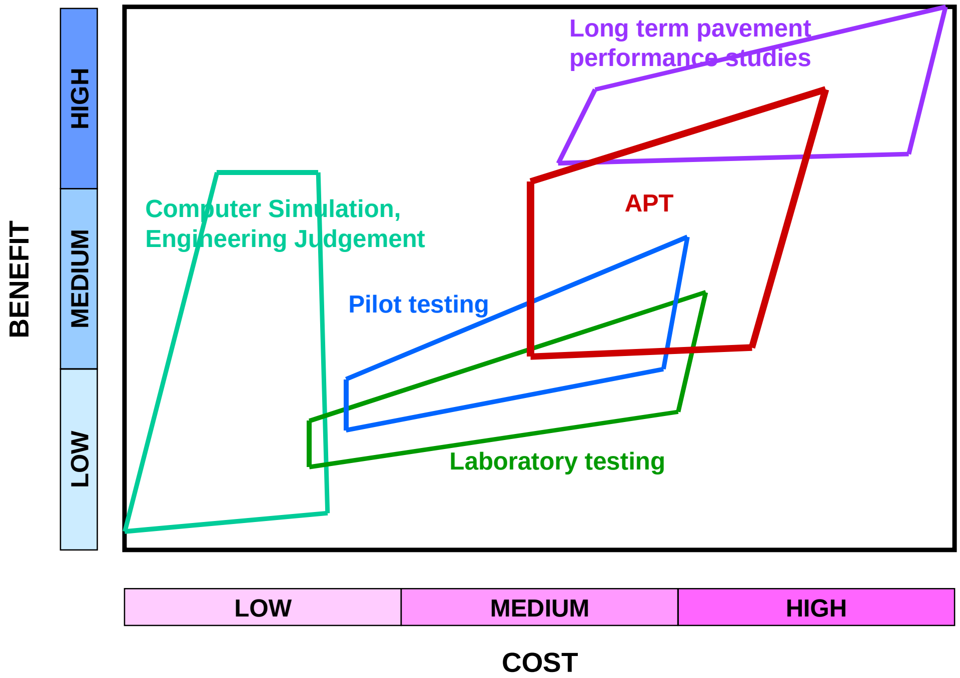

Figure 3.12: APT as the bridge between laboratory work and LTPP

In the mid-1990s, the changes in South Africa demanded a new look at the role of APT in pavement engineering developments, particularly with respect to the role of the HVS in the development of technologies that would benefit poverty alleviation. Particular emphasis therefore needed to be placed on aspects such as labour-intensive construction, implementation of new findings and technology transfer in order to ensure the effective delivery of relevant solutions to the road industry. As part of the early work conducted for this thesis, the strategy and philosophy of the Gautrans HVS programme were adjusted and enhanced accordingly, and early in 1996 a new strategic plan for the Gautrans HVS was finalised (Rust *et al.*[225]). This plan also included the strategic planning for future work on evaluation of basic pavement upgrading options, some of which had been constructed labour-intensively. The main strategic objectives of the Gautrans HVS programme were to develop and evaluate the following:

- the design and performance of pavement structures suitable for basic access roads and collectors and rural road networks;
- Labour Intensive Construction (LIC) pavement compositions;
- techniques for upgrading and maintenance of existing low-volume pavement structures;
- the use of innovative, cost-effective materials and methods, optimising the use of in situ materials (both treated and untreated);
- technologies for the preservation of the existing road network in order to extend its service life;
- technologies for the optimisation of the use of scarce road-building materials; and
- calibration of pavement deterioration models.

The Gautrans HVS programme therefore included not only HVS testing of new road sections, but also enhanced data analysis based on the database of historical HVS data. In addition, advanced data analysis is conducted in order to facilitate the implementation of results, and to provide inputs to pavement management systems.

Outputs from the SA HVS programme

As mentioned above, the South African HVS programme has formed the core of R&D in pavement engineering over the past three decades. The HVS fleet was used to address a multitude of problems in the road industry, and although the respective roles of the three machines differed, in essence basic pavement engineering materials and design were evaluated in order to develop and enhance understanding of their behaviour under accelerated trafficking and changes in environmental conditions. These results were used to improve material and structural design methodologies, criteria and specifications. From 1995 to the early 2000s, apart from the changes outlined previously, there was a shift in emphasis in the SA HVS work towards lower-class pavements, often with more marginal materials. The South African road network comprises some 207 000 km of national and provincial roads and 103 000 km of tertiary roads. Shaw and Van Huysteen[226] estimated that there are also approximately

200 000 km of unproclaimed roads in the urban and rural developing areas of South Africa that are in dire need of upgrading to improve basic access. In addition, in the late 1990s, the DoT identified a number of major roads that needed upgrading. These included, *inter alia*, National Route No. 1 (the N1) north of Pretoria and the Maputo corridor which links Gauteng Province with Mozambique. However, due to a scarcity of funds, these initiatives needed cost-effective and optimal use of available resources and thus provided much of the impetus for the research and development activities discussed below.

Operational developments

Developments relating to the improvement of HVS operations include:

- an improved data acquisition system, which facilitates ease of data acquisition, trouble shooting and preliminary data processing. It consists of specialised hardware and software (currently in use in South Africa as well as at UCB);
- improvements in environmental control, including a temperature-control chamber to control the pavement surface temperature between -5 ℃ and 60 ℃; and
- the development of new measurement equipment, including the 3D stress sensor (De Beer *et al.*[227]) and a laser profilometer for measuring the deformation of the road surface under trafficking[228].

Materials-based developments

Developments relating to pavement materials include:

- a materials design method for large-aggregate mix bases (LAMBs) highlighting the promising behaviour and the technical benefits of these base types (Rust *et al.*[229], Sabita[230]);
- a materials design and structural design method for Granular Emulsion Mixes (GEMs) or emulsion-treated bases (De Beer[231], Sabita[232]);
- an approach to rehabilitation measures for lightly cemented base pavements (Steyn *et al.*[233]);
- treatments for phased upgrading of unpaved roads (Steyn[234]);
- comparison of bases constructed by labour-enhanced techniques, including penetration macadam, emulsion-treated natural gravel, slurry-bound macadam and clinker ash;

- a design method for porous asphalt (voids in excess of 20%) (Sabita[235]);
- the evaluation of wandering vs. channelised traffic on pavement performance, particularly asphalt rutting for the California Department of Transportation (Caltrans) as might result from Intelligent Transport System applications (Rust *et al.*[236]);
- evaluation of the Caltrans practice of replacing a full thickness of conventional asphalt with a half thickness of a semi-open graded bitumen-rubber asphalt (Rust *et al.*[236]); and
- the development of a number of new test methods for materials such as the erosion test for cementitious materials, the crack movement simulator for evaluating crack reflection and the refinement of the dynamic creep test for asphalt deformation.

Developments in design, analysis and performance characterisation

Developments in structural pavement design and analysis include:

- the updating of the South African pavement structural design method (Technical Recommendations for Highways, TRH4) to include the latest information from the HVS programme, particularly information on the improvement of the SA mechanistic design method, SAMDM (Theyse *et al.*[237]);
- improvements in the modelling of permanent deformation in pavements, including a new approach to estimating permanent deformation of pavements from HVS data (Theyse[238]);
- improved modelling of in-depth deflection bowls, including a back-calculation method based on actual responses measured during HVS testing (Horak[239]);
- comparison of HVS-predicted behaviour with actual pavement performance (Jooste *et al.*[240]); and
- enhancement of Pavement Management System procedures such as the adoption of visual cracking as a trigger for resealing.

Developments in HVS-related technologies

A number of HVS-related technologies and products have also been developed, for example the 3D stress sensor to characterise tyre/pavement interface stresses to enable more accurate modelling of pavement stresses and strains

(De Beer[227]), and the K-mould for improved characterisation of fundamental road material properties (Semmelink *et al.*[241]).

Direct financial benefits

Attempts have been made in the past to assess the financial impact of the HVS programme. In 1992 Horak *et al.*[242] assessed the benefit/cost ratio of the HVS programme to be as high as 12.8. In 2005 Jooste and Sampson[243] estimated the benefit of HVS testing on G1 road bases in South Africa to fall in the range from 2.4 to 10.2 depending on the assumptions made. These estimates show significant benefit even though it should be appreciated that such economic quantification, in this instance attempting realistically to compare the 'with HVS' and 'without HVS' scenarios, is invariably both imprecise and conservative (the latter to minimise possible contention).

Rust *et al.*[222] reported specific examples of direct benefits obtained from the results of the HVS programme, including the application of large-aggregate mixes for bases and granular emulsion mixes (LAMBs and GEMs) mentioned above. In each case, the HVS programme played an important part in the process, allowing certain optimisations and implicit cost savings. In the case of GEMs (a marginal, in situ material upgraded to base standard with emulsion and a small quantity of cement) it was shown that savings of up to R30 000 per kilometre (1996 Rand) could be achieved. This technology is being used extensively in parts of South Africa where good aggregate sources are scarce. In the Free State Province alone, GEMs could be used on 2 000 km of road in the future, implying a significant saving. The HVS testing cost was R630 000, which is a very favourable return on the research investment.

In the case of LAMBS, HVS testing validated the performance of this material, which can bring about a 40% binder saving by using large aggregates in the base mix. LAMBS technology has now been used in a number of projects (Rust *et al.*[244]).

The discussion above indicates that the HVS programme was very successful in that it has not only had a major technical impact in the roads industry, but has also resulted in significant cost savings and direct financial benefit to the roads industry.

Management structures

One of the key success factors of the HVS programme was that each of the HVS projects was strategically managed through a steering committee consisting of stakeholders from road authorities, consultants, academic institutions and the CSIR. These steering committees met three to four times a year to discuss the general strategic direction and objectives of the programme, to assess the progress and early findings and to prioritise future projects.

Detail planning at the project level was conducted by the CSIR project leader in conjunction with a designated person from the road authorities who acted as champion for the project and played the following specific roles:

- to provide a strong communication link between CSIR technical staff and their road authority counterparts;
- to conduct regular visits to the HVS test sites in order to visually observe pavement behaviour under HVS traffic;
- to give regular feedback to management and political leaders;
- to ensure early implementation of results;
- joint publication of reports and papers read at conferences by champions; and
- ‘living’ with the project on a day-to-day basis in order to ensure quality decision-making on issues such as change of test variables, when pavement response readings should be taken, etc.

In the case of the Gautrans HVS, an operational committee was added in later years to ensure improved day-to-day management of the project. This committee consisted of the road authority champion and relevant CSIR technical staff. Broad dissemination of results and information took place through an Accelerated Pavement Testing (APT) forum.

Analysis of critical success factors

All historical HVS publications (more than 350) were reviewed in order to determine the success and failure factors for each of the HVSs. These are summarised below.

Success and failure factors for HVS 2 – CSIR-owned

Successes:

- directed by an external steering committee and focused on a needs-driven programme;
- the uniqueness of the concept, providing a mobile test facility to test real roads;
- excellent co-operation between road authorities and researchers;
- development of unique HVS-associated equipment to measure pavement response; and
- value of results well communicated to stakeholders.

Failures:

- the machine did not spend enough time on test sites (the machine was moved too soon);
- high cost of logistics of operating far from home base;
- technology transfer through reports were inadequate; and
- not sufficient focus - testing too many different pavement types for short periods of time.

Success and failure factors for HVS 3 – DoT-owned

Successes:

- directed by an external steering committee and focusing on a needs-driven programme;
- the uniqueness of the concept, providing a mobile test facility to test real roads;
- excellent co-operation between road authorities and researchers;
- flexibility in testing programme allowed the evaluation of urgent problems; and
- focus on specific critical (often crisis) situations for the road authorities.

Failures:

- lack of a longer-term strategy - changing direction too often to address urgent problems;
- validity of technical results questioned due to frequent changes in direction and the briefness of the tests; and
- high cost of logistics of operating far from home base.

Note: The lack of longer-term strategic focus encountered in the National DoT research programme discussed above is once again also observed in the DoT HVS programme.

Success and failure factors for HVS 4 – Gautrans-owned

Successes:

- directed by an external steering committee and focusing on a needs-driven programme;
- the uniqueness of the concept, which provides a mobile test facility to test real roads;
- excellent co-operation between road authorities and researchers;
- dedicated and knowledgeable champions from the road authority and the CSIR;
- well-defined strategic direction and goals;
- relatively lower cost of operating the machine closer to home base;
- longer-term strategy allowed for longer periods to be spent on each test section, thus taking them to full failure;
- focus on data storage and retrieval;
- investigation of pavements with a proven long-term performance record in order to advance knowledge; and
- the recent focus on improved marketing through newsletters, electronic media (CD-ROM) and publications.

Failures:

- lack of data recording and processing personnel; and
- some difficulty in convincing political leaders of importance.

The Caltrans project

As discussed before, in 1994 the California Department of Transport decided to obtain two refurbished HVSs from South Africa (refurbished HVS2 and HVS3). In its short lifetime the project has shown significant successes and some of the critical success factors and failures are also discussed below.

Successes:

- the dedication of the client champion from Caltrans;
- the high quality of the team which initiated the project (consisting of members from Caltrans, the University of California at Berkeley, Dynatest consulting and CSIR Transportek);
- the strategic management of the project through a steering committee to involve stakeholders and the quality of the strategic leadership in the project;
- the willingness of Caltrans to use the existing knowledge base in South Africa in order to accelerate their own learning curve;
- the co-operation between Californian and South African researchers in a technology transfer project;
- the co-operation with an academic institution;
- the relatively high level of funding (compared with that in South Africa) made available by Caltrans;
- the interactivity between the HVS testing programme and a fully-fledged laboratory testing programme; and
- the visibility of the project in the USA.

Failures:

- some problems experienced due to changes in the client championship; and
- as yet insufficient measurement of the impact of technology transfer to industry and practice in the USA.

Common success factors

The common factors leading to the overall success of the HVS programme were:

- sound strategic planning in most of the cases, directed by an external steering committee;

- the focus on client-identified needs to address urgent issues with some of the HVSs;
- the focus on longer-term knowledge-accumulation testing in some of the HVS tests;
- the balance in the overall HVS programme using the fleet of HVSs to address both urgent needs and longer-term technical objectives;
- the quality of the communication between researchers and stakeholders through the steering committees, technical meetings, the APT forum, seminars and conferences;
- the quality of and visibility of internationally published papers;
- the successful and quick implementation of results as they became available;
- the success of the link with academic institutions (16 PhD degrees and 28 Masters' degrees);
- the focus on people development combined with technology development; and
- the review of the impact of the HVS programme from time to time.

3.7.3 The development of capacitive mat axle weight sensors and related products

Background

The Steering Committee of the National Institute of Road Research (NIRR) recognised the need to assess axle loading in terms of Equivalent Standard 80 kN Axles (E80s) carried on South Africa's roads as early as the late 1950s. The defined need was for portable equipment that could be used for field evaluation of traffic loading across the country and, seeing that no such equipment was available internationally, it was decided that the CSIR should initiate a project to develop a prototype.

Product development

Kühn *et al.*[245] reported the development of a portable sensor based on capacitive principles – the Series 5 sensor, patented in 1968. The sensor, 1 800 mm x 450 mm x 12 mm in size, was called the Series 4 sensor - the first prototype capacitive mat axle weighing sensor. Initial use of the Series 4 sensor found that the sensor was too thick, thus causing impact effects when a truck tyre passed over it at speed and subsequent inaccuracy and speed dependency of the readings. The sensor was then redesigned using plate electrodes with a soft dielectric of natural rubber, thus reducing the thickness to 8 mm. The sensor consisted of three electrode plates cast in a natural rubber dielectric and had a neoprene outer cover.

Manufacturing rights were given to Rubber Products and Mouldings and the system was first marketed by Plessey and then by Electromatic. Over a 25-year production cycle more than 1 500 sensors were manufactured and sold internationally. During this time only minor changes were made to the design of the sensor in order to benefit from improved materials that became available.

Subsequent to the above developments, international interest in Weigh-in-Motion (WIM) technology increased significantly. In 1977 the NITRR Steering Committee decided that a new development, the Traffic Data Logger (TDL), should be developed to complement the Series 5 sensor[245]. The TDL consisted of two electromagnetic loops and an axle load sensor connected to a hardware and software system that could record vehicle speed, vehicle length, number of axles, individual axle loads, axle spacing and tyre contact length. The initial trials of the TDL showed that the sensitivity of the Series 5 sensor was not adequate for this new application. The sensor was upgraded to the Series 8, by making use of a castable elastomer as dielectric (see Figure 3.13). Although the Series 8 sensor was more expensive, the sensitivity was greatly improved and it was easier to manufacture.

In 1993 an agreement between the CSIR and TRAFFTRANS was signed for the manufacturing of the Series 8 sensor, and by the mid-1990s, approximately 450 Series 8 sensors had been sold.

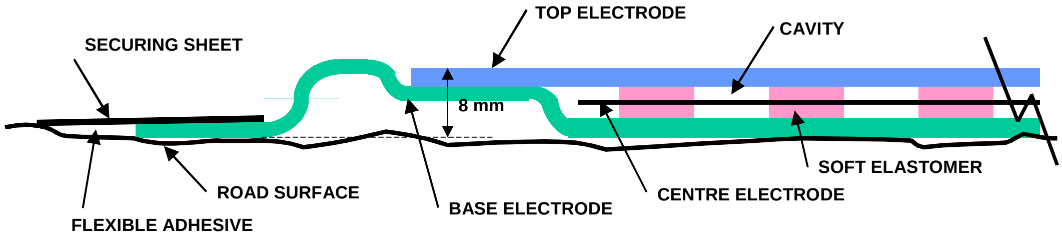

Figure 3.13: Cross-section of Series 8 sensor

The early development of the capacitive mat sensors was followed by the development of a flush-mounted permanent sensor (the Series 9 sensor), which measured 2 000 mm x 500 mm x 16 mm and was installed in a pan that was permanently cast into the road surface. The sensor could be removed for use elsewhere and a dummy installed in its place. The sensor performed very well in the trials[246] and was approximately half the cost of a German sensor which had a similar accuracy (approximately 95% accuracy if calibrated on site).

A number of customers indicated that they would prefer a sensor which was lighter and easier to install, even if they could not obtain the high accuracy of the Series 9 sensor. This prompted the development of the Series 9b sensor, which measured only 1 800 mm x 150 mm x 16 mm. The sensor was also less expensive than the Series 9. Apart from local use, the Series 9b sensor has also been used in Germany and in Italy. By the mid-1990s, more than 50 Series 9 and 9b sensors had been sold.

In response to the need for a portable sensor for truck screening at low speed, the Series 11 sensor was developed in 1978. The sensor had the following characteristics:

- it measured only 1 000 mm x 500 mm x 8 mm and could therefore fit into the luggage compartment of a traffic officer's car;
- it weighed only 15 kg and could therefore be handled by one person; and
- it had a convenient carrying handle and was packaged neatly with all its related equipment in an easy-to-handle container.

The data logging system for the Series 11 sensor was developed by Mikros Systems which was marketed as the Vehicle Load Monitor (VLM). To date, more than 100 Series 11 sensors have been sold.

Customer feedback on the Series 8 sensor showed that the high cost of installation and removal from the road were factors of concern. This was mainly due to the manpower required to handle the sensors and divert traffic for a lengthy period of time. A Series 8b sensor, which measured 1 800 mm x 200 mm x 8 mm and weighed 10 kg, was developed to address this concern. The cost of manufacturing the sensor was less than half that of the Series 8 sensor. Its accuracy was less than that of the Series 8 sensor, but was still acceptable to customers.

Discussion and critical evaluation

The development of the series of hard products based on capacitive mat technology was very successful, both technically and from a business point of view. In terms of Roberts' definition[10] significant exploitation of the invention occurred and thus it can be viewed as a successful innovation. There are a number of reasons why the development was so successful, one of the most important being that it was based on the development of significant competency in the required technologies, both within CSIR Transportek and externally with partners in industry. The series of key products (solutions) that were developed were based on the development and enhancement of a single platform, i.e. the capacitive mat technology platform. Even though the researchers did not realise it at the time and most of the management was done intuitively, this is an excellent example of the use of a technology platform to produce a series of key products cost effectively as described by Meyer and Utterback[247].

The following important aspects from this case study can be observed:

- the fact that a steering committee was involved in the decision to develop the technology not only ensured that the technology was readily accepted by and implemented in the market place, but also ensured that long-term funding was available for the development and maintenance of the competency required for a successful innovation;

- at a very early stage parties external to the CSIR (TRRL in the UK) were involved in the assessment of the developments;
- industrial partners (Plessey, Electromatic and Rubber Products and Mouldings) were involved at an early stage and they provided competencies not available at the CSIR;
- the development team was able to respond rapidly to market requirements (e.g. in the case of the development of the Series 9 sensor) due to the fact that the technology platform was well developed;
- the development team was able to utilise related technological development (e.g. new materials becoming available) to enhance the quality of the technology platform;
- as defined by Roberts[10], idea generators, gatekeepers, sponsors and product champions were involved in the process;
- some of the financial returns from the products developed were re-invested to enhance and build the competency and technology platform; and
- the total dedication and drive of the main inventor and gatekeeper (Basson).

A number of negative factors were, however, also observed, including:

- the fact that the Programme Manager (as defined by Roberts[10]) or Business Inventor was either absent or not very effective, thus leading to the problems experienced with contracts and returns on the products;
- the developments were mostly reactive to market needs and not proactive, thus leading to a rather lengthy period where almost no enhancement of the technology platform took place (apart from the use of new materials);
- very little human resource development took place and the expertise and competency were only based in a few critical people, which made the technology platform vulnerable; and
- marketing rights of the products and their improvements were allocated exclusively, thus allowing the external partner to prescribe the utilisation or otherwise of a new enhancement (e.g. the Series 8b sensor).

3.7.4 The Transportek labour-intensive construction technology programme

Background

Historically, in the apartheid era, the CSIR focused mainly on the issues important to the government of the time. In the case of CSIR Transportek, this implied that the main focus was on First World transport issues, including a focus mainly on major highways, both rural and urban. However, at the time of the CSIR's restructuring in 1988, the organisation's strategic planning process recognised that in the changing South Africa, significant emphasis should be placed on the needs of the majority of the people of South Africa. CSIR Transportek's first business plans took this into account, which led to the formulation of the Low Volume Roads programme. This programme focused mainly on materials and was incorporated into the Road Engineering programme at a later stage. In 1992 CSIR Transportek realised that increased effort was needed in the issue of job creation in the road building industry and the associated labour-intensive construction technologies. The importance of labour-intensive construction, and especially its role in creating jobs in a developing country, were also highlighted by McCutcheon[248, 249].

In addition, the same realisation flowed from the strategic planning processes in the Sabita Research Programme (see Chapter 7). This led to the incorporation of the Labour-Intensive Construction (LIC) focus area and the Small Contractor Development focus area in CSIR Transportek's technology development programme as described in Chapter 7.

The need for technology development focused mainly on:

- materials design and specifications for LIC;
- the design of structures that were LIC friendly;
- the behaviour and performance of LIC pavements;
- LIC construction methods;
- training modules for LIC; and
- LIC pilot training projects.

Some of the most important projects and lessons learnt from the above aspects are discussed in the sections below.

Overview of selected LIC and Small Contractor Development projects

Several projects related to LIC and SMMEs were conducted by CSIR Transportek during the 1990s. These projects were mainly funded by Sabita, the DoT, Gautrans, some private sector companies and the CSIR Parliamentary Grant. Some of the most important projects are listed and briefly discussed below.

Dust control (1988 to 1998)

There are more than 600 000 km of unsealed roads in South Africa, of which many are in urban developing areas. Jones[250] indicated that, apart from being a nuisance factor, dust also causes environmental and social impacts. The research conducted at CSIR Transportek focused mainly on modelling the problem, measurement of dust generated by traffic, criteria for designing gravel roads to minimise dust and the use of various materials to control dust caused by traffic. Such materials included hygroscopic salts, lignosulphates, modified waxes, polymer emulsions, tars, bitumens and sulphanated oils. The work has led to solutions which have been implemented very effectively, especially in developing communities. A number of pilot projects were also successfully completed. The success of the work was mainly due to the commitment of CSIR product champions and the fact that a co-ordinated, holistic approach was followed with both government departments and the private sector supporting the research effort.

Labour-intensive construction training modules (1994 to 2004)

Initial work on LIC at CSIR Transportek focused on the development of training modules for prospective small community-based contractors utilising LIC techniques. The modules covered topics such as road building materials, basic surveying techniques, basic calculations and construction techniques. The first project, which was conducted at Phutaditjaba in the Free State, was later repeated in the Vaal Triangle. The projects were initially funded from the Parliamentary Grant and later supported by a number of government departments. The success of these projects was due to the capabilities and commitment of internal product champions, the political profile of the projects and the level of community interaction that took place.

The use of Sasol ash as road construction material (1995 to 1998)

In 1995 Sasol commissioned CSIR Transportek to investigate the feasibility of using coarse clinker ash, which is a by-product of the coal-to-fuel process, as a road building material. Due to the light weight of the product, the project soon focused on the special advantages of using the material in LIC. The project work included:

- a feasibility study[251];
- a materials design study focusing on the use of the material in its neat state at well as modified with emulsion;
- a structural design phase which focused on structural design parameters for the material;
- Heavy Vehicle Simulator testing of various pavement compositions using the material; and
- a cost analysis, including an economic hauling distance analysis.

The project idea started off as a simple investigation into the use of the material in a small-scale LIC project[252]. The use of a holistic planning approach and technology trees (see Chapter 6) as part of the work conducted for this thesis led to:

- the inclusion of Gautrans and Sabita in the research programme to provide additional funding to conduct HVS testing and advanced materials testing of the product;
- the development of a comprehensive project plan and implementation plan; and
- an enhanced implementation phase that included modifications to the Sasol plant to render the ash more effective in terms of materials properties.

The project therefore grew from a simple basic materials testing exercise (budget of about R200 000) to a comprehensive multi-year research programme of more than R2 million (in 1998 Rand) that yielded significant outputs. This project was particularly successful in co-ordinating research activities from a number of funding agencies[252]. Figure 3.14 shows labourers constructing an ash base by hand.

Figure 3.14: Labour-intensive construction of HVS test sections at Cullinan

HVS testing of LIC pavement structures

In 1996 Gautrans initiated a project to evaluate the performance of a number of LIC pavement structures under HVS testing to compare their performance with a conventionally constructed 100 mm thick G1 base pavement[253]. In addition, the different materials and techniques used were evaluated in terms of constructability, and the finished surfacings were evaluated in terms of rideability. The project focused on emulsion-treated bases, waterbound macadam bases and the use of coarse Sasol clinker ash untreated and treated with emulsion.

The performance of the sections was discussed by Theyse[254]. The project was well managed and included a holistic approach emphasising co-operation between Gautrans and Sasol, a fact that added to the success of the project.

Case studies of NDWP pilot projects (1996 to 1998)

The National Department of Public Works (NDPW) initiated 12 pilot projects relating to the development of infrastructure to initiate the reorientation of government expenditure on infrastructure. CSIR Transportek was commissioned by the NDPW to monitor and assess these projects to compile information that could be used by governments at national, provincial and local level to improve their infrastructure development processes. In addition, the information was used to develop guidelines and provide technical information[255]. This was a relatively large project that included workshops to disseminate information and obtain inputs from participants. The project was successful due to the fact that it was a significant investment and included participation of stakeholders, the community in particular.

Lubisi development project (1995 to 1999)

In 1995 the CSIR initiated a project to address general development in the area of the Lubisi Dam near Queenstown in the Eastern Cape Province. The work was conducted in co-operation with the Lubisi Dam Development Forum, a community-based structure which the CSIR assisted in creating. The main objective of the project was to create sustainable villages where people would, for instance, collect their waste material and use it to generate power. By-products from the process are also used for agricultural purposes, thus enhancing self-sufficiency in energy and food supply. Currently 19 villages consisting of 55 sub-villages are represented in the Development Forum. CSIR Transportek's involvement in the project focused on training local people in gravel road construction, material stabilisation techniques, concrete road and parking area construction and the construction of road kerbs.

The most important lessons learnt from this work include the following:

- the logistic problems of conducting a project in such a remote area should not be underestimated;
- tasks such as construction should be scheduled taking into account delays caused by the remoteness of the site;
- workers should be paid according to a piece-work system instead of on a daily basis; and
- full-time supervision on site is essential in order to ensure that trainees remain effective.

In spite of the logistical problems experienced, the project was very successful as it formed part of a large corporate initiative, specific staff members were dedicated to the project and the project consisted of training based on a significant base of knowledge and information developed over a number of years.

Contractor development simulation package (1998 to 2004)

This project was aimed at the development of a computer-based package for use by small contractors to assist them in the technical and business management of their operations. Apart from training in technical topics such as base construction and surfacing of roads, it includes aspects such as costing and estimating for tendering purposes, programming and progress charts, and costing and budgeting. In essence, the project is about the packaging of the knowledge gained by CSIR Transportek in labour-intensive construction and small contractor development over a period of ten years.

The Amadiba Road project (2003 to 2004)

Transportek was approached by the Mbizana Local Municipality, situated in the OR Tambo District in the Eastern Cape Province, for assistance with upgrading their main access road[256]. Mbizana is considered to be the poorest local authority in the entire country, and the unemployment rate stood at over 75% at the time. Labour-intensive construction techniques developed at CSIR Transportek were used to assist the community to upgrade this access road. In a post-construction analysis, Mashiri[256] found that almost 70% of the cost of the project was earned in wages by the community, and thus it had a significant impact on their livelihood. Longer-term effects included the training of community members in construction techniques, better mobility of the community, lower transport costs and fees and a marked improvement in access for and response time of emergency vehicles. Once again one of the main success factors of the project was the level of community interaction.

Discussion of LIC projects

The above discussion indicates that CSIR Transportek's LIC programme started out in a similar fashion to that of the research programmes described in Chapter 3. Initially a few successful large projects were conducted in direct response to market needs, thus focusing only on 'market pull'. However, this period was followed by a short-term outlook which focused only on immediate needs. The result was that the projects (both Parliamentary Grant funded and externally funded) started fragmenting into smaller projects with lesser impact.

Some of the main lessons learnt include:

- the importance of champions in the research organisation which will ensure final technology transfer (dust control);
- projects with a high political profile (addressing issues of national importance) are more likely to succeed due to significant funding (Lubisi Dam);
- the importance of a 'bigger picture' approach (holistic approach) which will ensure that research efforts from more than one funding organisation are co-ordinated and managed as a whole to achieve maximum impact (Sasol project);
- the importance of community interaction in projects in rural areas to ensure effective technology transfer (Amadiba Road and Lubisi Dam); and
- the importance of post-analysis of the impact of technology transfer and implementation on communities (Amadiba Road).

3.7.5 Main aspects from case studies to be considered

The projects in the three case studies discussed above varied in nature and included a hard-product development case (the capacitive axle weighing mats), an engineering methodology development and transfer case (the HVS technology package) and a programme with the main emphasis on implementation, technology transfer and training (the CSIR Transportek LIC programme). In spite of their varied nature, the technology management lessons learnt from these projects are very similar. The main aspects that were deemed to have a positive impact include:

- sound strategic planning, directed by an external steering committee where appropriate;
- the fact that various steering committees were involved in the decision to develop the technologies not only ensured that the technologies were readily accepted by and implemented in the market place, but also

ensured that long-term funding was available for the development and maintenance of the competencies required for successful innovation;

- the balance between a focus on client-identified needs to address urgent issues and a focus on longer-term research capacity development and new knowledge generation;
- the quality of the communication between researchers and stakeholders through the steering committees, technical meetings, the APT forum, seminars, conferences and community interaction;
- the early involvement of external partners in the development of the technologies, thus providing competencies not available at the CSIR;
- the ability of the development team to respond rapidly to market requirements (e.g. in the case of the development of the Series 9 sensor) due to the fact that the technology platform was well developed;
- as defined by Roberts[10], idea generators, gatekeepers, sponsors and product champions were involved in the process;
- some of the financial returns from the products developed were re-invested to enhance and build the competency and technology platform;
- the quality and visibility of internationally published papers;
- the successful and quick implementation of results as they became available;
- the use of a ‘big picture’ or holistic planning approach to combine the research efforts of several organisations to achieve an enhanced output;
- the success of the link with academic institutions which resulted in several post-graduate degrees;
- the focus on people development combined with technology development;
- the attempts to review the impact of the projects from time to time;
- the importance of the interaction between stakeholders and community in the strategic planning as well as the technology transfer phases (even if they were not technically trained); and
- the importance of the political profile achieved by focusing on national priorities.

These points were used to update the set of tenets as indicated in Table 3.3. The new additions are shaded in grey.

3.8 Evaluation of the R&D programmes against criteria for R&D management

3.8.1 Criteria for assessing research programmes

The analysis of the information above was used to define a number of criteria that can be used to compare the six R&D programmes. The criteria deal with the following aspects:

- the level of strategic planning and long-term vs. short-term focus;
- communication with steering committees and users of research results;
- the level of focus vs. fragmentation in the R&D programme;
- human resources development activities;
- management processes and structure; and
- the use of R&D management tools and processes.

The detailed criteria are shown in Table 3.2 below.

3.8.2 Assessment of research programmes

A work group was formed to rate the degree to which each of the programmes and projects fulfilled the criteria discussed above. The work group consisted of government officials, consulting engineers and researchers who had managed and had been involved in the R&D programmes. The members of the work group, their affiliation, historical role and field of expertise are given in Table 3.1. The work group rated the degree to which each of the programmes fulfilled a specific criterion on a five-point scale (where 5 indicated the highest score). The mean, median and standard deviation are given. Due to the small sample size, the median values are more appropriate for consideration.

Table 3.1: Members of the evaluation work group

Name	Organisation	Historical role	Field of expertise
Coetzee, L	DoT	Research Management	Transport planning
De Beer, M, Prof.	CSIR	Researcher	Pavement engineering and design
Du Plessis, L	CSIR	Researcher	Accelerated pavement testing
Hendricks, PJ	CSIR	Researcher and Director of Transportek	Pavement engineering, LIC
Horak, E Dr	Kubu Consulting	Researcher, research management	Pavement engineering and design
Paige-Green, P Dr	CSIR	Researcher	Pavement materials
Rust, FC	CSIR	Researcher, research management	Pavement engineering, pavement materials, research management
Sadzik, E	Gautrans	Research management	Public sector management of roads
Sampson, L	CSIR	Researcher, research management	Pavement materials
Steyn, W, Prof.	CSIR	Researcher	Pavement engineering
Verhaeghe, B	CSIR	Researcher, research management	Pavement materials, asphalt technology
Wolhuter, K	CSIR	Member of Navplan	Research management, geometric design

Table 3.2: Results of work group evaluation

	DoT, SCOM			DoT, RDAC			DoT, CODs			Sabita			Gautrans			CSIR PG			AUTHOR'S COMMENTS
CRITERIA	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	
Programme based on comprehensive strategy	3.4	3.5	0.7	2.6	3.0	0.9	2.0	2.0	0.8	4.7	5.0	0.5	4.1	4.0	0.7	4.7	5.0	0.5	The DoT programmes, particularly after 1988, were based on short-term needs and not on strategic objectives. The CSIR PG programme and the Sabita programme were based on significant strategic planning exercises.
A long-term strategic view of the programme and its objectives	3.4	4.0	1.3	1.8	2.0	0.8	1.6	1.0	0.8	3.8	4.0	0.4	4.1	4.0	0.8	4.6	5.0	0.5	The public-funded programmes (SCOM era, Gautrans and CSIR PG) took a long-term view of R&D and its benefits. This view was, however, lacking significantly in the RDAC and CoD programmes. The private-funded Sabita programme was based on sound strategic planning but had more emphasis on medium-term problem solving and technology transfer.
R&D direction obtained from a steering committee, contact with external parties through linkages and communication	4.1	4.0	1.0	2.6	3.0	1.1	1.7	1.0	1.0	4.4	4.0	0.5	4.3	4.0	0.6	4.4	4.0	0.5	Strategic direction from a steering committee was a strong feature of the SCOM era; the Sabita programme (AREST process), the Gautrans programme (HVS steering committee) and the CSIR PG programme (Research Advisory Panel).
Strategic focus and R&D capacity building in selected organisations (little fragmentation)	4.0	4.0	0.9	1.7	1.0	0.9	2.9	3.0	1.1	3.8	4.0	0.8	4.1	4.0	0.8	4.3	4.0	0.7	The SCOM, Sabita, Gautrans and CSIR PG programmes focused on medium to long-term outputs, thus building R&D capacity in a few organisations only. The RDAC programme in contrast used many R&D organisations and a large number of smaller, short-term projects.

	DoT, SCOM			DoT, RDAC			DoT, CODs			Sabita			Gautrans			CSIR PG			AUTHOR'S COMMENTS
CRITERIA	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	
Interaction with technology users to determine research needs through a formal process, market orientation	3.0	3.0	0.8	2.2	2.0	1.0	1.6	2.0	0.5	4.3	4.0	0.7	3.9	4.0	1.1	4.2	4.0	0.7	The Sabita, Gautrans and CSIR PG programmes used the formal needs determination process developed for this thesis. In contrast the RDAC and COD programmes were based almost purely on researcher-defined topics.
Good communication between funders, users and researchers	3.0	4.0	1.4	2.0	1.0	1.2	1.4	1.0	0.5	4.6	5.0	0.5	4.1	4.0	0.5	4.0	4.0	0.9	The Sabita and CSIR programmes used the Road Pavements Forum (RPF) to determine R&D needs and communicate results to users. Gautrans uses the international HVS user group as well as the RPF.
Emphasis on human resources development (HRD)	3.1	3.0	0.6	1.9	2.0	0.9	3.3	3.0	1.3	3.1	3.0	0.8	3.5	3.0	0.7	4.4	5.0	0.7	The main focus of the COD programme was HR development. In the CSIR PG programme-specific funds were 'top sliced' for HR. Due to the short-term nature of the RDAC programme there was very little focus on HR development.
Presence of programme champions	3.3	3.5	1.3	2.4	2.0	1.1	2.1	2.0	0.9	4.4	4.0	0.5	4.4	4.0	0.7	4.4	4.0	0.5	In the Sabita, Gautrans and CSIR PG programmes, programme champions were appointed in both the R&D and the client organisations. This occurred to a lesser degree in the other programmes.
High level of project management and control	1.8	2.0	0.7	4.4	4.0	0.5	2.7	3.0	1.0	4.1	4.0	0.6	4.2	4.0	0.8	4.0	4.0	1.0	The RDAC programme focused strongly on project management and control due to the short-term nature of the projects. In contrast the SCOM era programme had very little control to the extent that some projects never achieved their targets or were sometimes years behind schedule.

	DoT, SCOM			DoT, RDAC			DoT, CODs			Sabita			Gautrans			CSIR PG			AUTHOR'S COMMENTS
CRITERIA	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	Me	Md	s	
Long-term funding and continuity of funding	4.1	5.0	1.4	1.7	2.0	0.7	2.1	2.0	0.7	3.2	3.0	0.7	4.3	4.0	0.8	4.3	5.0	0.9	The RDAC programme was the only research programme that allocated funding based on lowest cost through a tendering process. The other programmes were either grants or sole supplier R&D contracts.
Use of R&D management models and tools	1.6	2.0	0.5	2.1	2.0	0.9	2.0	2.0	1.1	3.7	3.0	1.1	3.4	3.0	0.8	4.3	4.0	0.7	The CSIR PG programme was used for implementation of the models and tools developed for this thesis. Some of the tools were also implemented in the Sabita programme.
Use of portfolio management	2.3	2.5	0.9	2.1	2.0	1.1	2.0	2.0	0.9	3.7	4.0	0.7	3.2	3.0	0.6	4.6	5.0	0.5	The CSIR PG programme used the tools and models developed for this thesis. Some implementation of these tools also occurred in the Sabita and Gautrans programmes.
Use of technology foresight studies	1.5	1.0	0.8	1.3	1.0	0.7	1.3	1.0	0.5	2.8	3.0	1.0	2.6	3.0	0.9	4.4	4.0	0.5	Several technology foresight studies have been conducted for the CSIR PG programme.
Use of impact assessment	1.5	1.0	0.8	1.1	1.0	0.3	1.0	1.0	0.0	3.6	4.0	0.5	4.2	4.0	0.9	3.4	4.0	0.7	Gautrans has conducted significant studies on the benefits of HVS testing, the results of which were published internationally. Some impact assessment work was done in the Sabita and CSIR PG programmes. In contrast no work was done in the DoT programmes.

Discussion of results

Table 3.2 gives the mean, median and the standard deviation of the ratings of the user group. The ratings indicate that the RDAC and COD programmes scored significantly lower than the Sabita, Gautrans and CSIR Parliamentary Grant (PG) programmes. The SCOM programme scored average. The main differences are that whereas the RDAC and COD programmes were mainly short-term focused with no strong link to a longer-term strategic plan, the Sabita, Gautrans and CSIR programmes were strongly linked to a longer-term strategy with inputs from a steering committee. This difference led to significant fragmentation in the RDAC and COD programmes that was not present in the other programmes. Thus the CSIR, Sabita and Gautrans programmes had strong interaction with the users of technology, and there was also good communication between the researchers and funders of research. The fragmentation into smaller projects in the RDAC and COD programmes did not allow emphasis on mentoring and human resources development whereas, according to the user group, this was a strong feature of the other programmes. The RDAC programme did have a high level of project management and control which was essential for a short-term focused programme. The SCOM and COD programmes scored low on project management. Of significance (but not surprising) is the difference in scores for the long-term funding criterion, indicating that the RDAC programme, and to a lesser extent the COD programme, did not have any long-term view of R&D objectives. The CSIR programme is the only one that scored higher than 4 for the use of R&D management models and tools, portfolio management and technology foresight studies.

This analysis confirms the characteristics, both positive and negative, of the programmes as analysed in Sections 3.2 to 3.6 of this chapter. In particular the user group ratings agree with the aspect of fragmentation in the RDAC and COD programmes as discussed above.

3.9 Concluding remarks

3.9.1 General comments

The analysis in this chapter and the user group evaluation in Section 3.8 indicate that the RDAC and COD-related programmes lacked a strategic, holistic approach to R&D management. The fragmentation of these programmes had a severe effect on their ability to deliver results. In contrast were the Sabita, Gautrans and CSIR R&D programmes which used focused strategies and had relatively large average project sizes. The latter programmes were used, in their middle to late stages, to implement some of the concepts, models and tools developed for this thesis. These programmes also had good track records in terms of implementation of results. The following are important points to be considered in the development of a new approach to R&D management:

- A mechanism for providing strategic direction to researchers and to create an environment for communication between researchers and a wide representation of stakeholders should form an essential part of the R&D management structure - this can be provided by steering committees (such as the CSIR Research Advisory Panels) or discussion forums such as the Bituminous Materials Liaison Committee (currently the Road Pavements Forum).
- The research objectives and project contents should be linked to the overall strategy and needs in the industry which, in turn, should be determined by a well-managed needs determination process.
- The R&D management process (including the investment decision process) should take cognisance of the balance between long-term strategic developments ('technology push') and solving of short-term problems ('market pull').
- The process should be structured to enhance implementation, and the efficacy of the process should be adjudicated on the implementation of results.
- A minimum level of stable funding is vital to stimulate innovation and allow the development of people.
- An alternative to an open tendering process should be utilised for the allocation of projects and/or funding to organisations.

- The research programme should be controlled sufficiently to ensure that overall objectives are met, but the control should not inhibit creativity, invention and innovation.
- The process should be well monitored, utilising appropriate systems to record investment and output, and to determine the impact of the investment.
- The process should have a strong emphasis on the development of human resources.
- Implementation channels such as the use of a discussion forum, information technology and other delivery systems should be an essential part of the process.
- It is important to use a portfolio management approach in addition to individual project management.
- The programmes displayed the characteristics of a complex (cybernetic) system and therefore systems thinking should be incorporated into a new conceptual R&D management model and tools.

The above points were added to the mapping table (see Table 3.3 – new issues are shaded in grey) and were used as the principles for the development of the new model discussed in Chapter 6.

3.9.2 The cybernetic systems nature of the R&D programmes

The characteristics of the R&D process as a complex system were discussed in Chapter 2. The behaviour of the research programmes discussed here correlates well with these characteristics. For example:

- the process involved a large number of players (elements) that interacted richly with each other;
- the boundaries of the process/system were porous, with information as well as players flowing in and out;
- there was a significant flow of information into and out of the R&D process;
- historical trends had a significant influence on the process;

- the creation of a ‘thermometer’ or sensor in the system (the price of R&D projects on tender) inadvertently created a feedback loop that changed the behaviour of the process/system significantly;
- a small change (tender process) caused a large, unforeseen effect (fragmentation and disintegration); and
- strong central control alone (especially in the RDAC programme) did not yield the desired results.

It can therefore be postulated that the group of research programmes analysed here, which formed part of the total R&D effort in road engineering R&D, displayed the characteristics of a complex (cybernetic) system. It is therefore essential to take cognisance of systems characteristics in the development of a new model and tools for managing the process.

The work in this chapter highlighted a number of pitfalls in the management of R&D that must be avoided. However, a number of positive characteristics in the programmes were also identified, and many of these are important for a new approach to the management of an R&D programme in the road infrastructure industry (see Table 3.3). The most important desired characteristics for an R&D management system were included in the user survey discussed in Chapter 5.

Table 3.3: Enhanced set of tenets based on analysis of R&D programmes and projects

Category	Issue	Tenet
Scope of the model	Innovation is a chain from invention to exploitation.	The model should be based on a holistic approach that addresses the full innovation chain.
	R&D in the transport sector is complex and multi-disciplinary due to the nature of the work conducted and the mixture of product development and new methodology development.	The model should take cognisance of the principles of systems thinking, cybernetics and complexity theory, with specific emphasis on non-linear thinking to address the development of new engineering methodology and knowledge as opposed to the development of hard product for the consumer market.
	There is a need for long-term strategic R&D, as well as for solving short-term technology needs.	The model should allow a balance between long-term and short-term objectives.
	There is a need to enhance the level of invention and creativity in organisations such as the CSIR and in South Africa in general.	The model should specifically emphasise creativity and invention.
	There is a need for the continuous transfer of technology to industry and government.	The model should place specific emphasis on technology transfer.
Systems approaches	First- and second-order cybernetics principles provide a sound basis for organisational design and management.	Cybernetics principles, such as control and feedback loops, circular causality, self-organisation and self-reference, should be taken into consideration in the design of the model.
	Systems approaches and cybernetic principles are more applicable to management models dealing with a complex environment.	The model should take cognisance of systems approaches, specifically the interaction between the elements of the system and their interdependency, and the interaction with the system environment.
		The interactive planning approach should be used to develop a new model to ensure participation of stakeholders.
		The model should address the inherent hierarchy of the system and the integration of capabilities.
	R&D in the road infrastructure environment is complex	The model should take cognisance of complexity theory, specifically the non-

Category	Issue	Tenet
	due to the variety of the activities and their interaction.	linearity of the R&D process, some degree of informed reduction to deal with the breadth of the problem and the interaction of the elements in the model.
Strategic planning	R&D activities are an integral part of the business strategy of an organisation.	The strategic planning activity of an organisation should be a prominent element in the model.
	Technology strategy and the research agenda should be integral to business strategy and should take cognisance of issues such as portfolio balance.	The model should allow the balancing of the research project portfolio to address strategic objectives.
		Both technology push and market pull should be taken into consideration in the model.
	Impact from research output is more effective, as a longer-term view of research programmes is taken especially as regards funding of the programme.	The model should allow optimum balance between addressing short-term needs and longer-term strategic research agendas.
Technology transfer	Technology transfer is essential, especially in an R&D organisation, the main focus of which is to develop new methodology and solutions for industry and government (i.e. external to the organisation).	Technology transfer should be an important element of the model.
	It is important to involve communities in technology transfer activities and planning of projects.	Community interaction should be taken into consideration in the strategic planning as well as the technology transfer phases of the project.
Process issues	Lead users are an important source of innovation.	The model should allow interaction with stakeholders to define the R&D and technology development needs, to identify enhancements of technologies and methodologies and to continuously assess the usefulness of the outcomes.
	An understanding of core competencies, platforms and capabilities is valuable in optimising the effectiveness of the R&D programme and the eventual success of the technology deployment.	The model should incorporate the concepts of core competencies, technology platforms and capabilities.
	Quality management is an important aspect of	The model should take into consideration quality management principles in

Category	Issue	Tenet
	successful R&D programmes.	general, and specifically monitoring the quality of the output.
	It is important to measure the effectiveness of the R&D programme to ensure that processes are optimised and that stakeholders understand the impact of the programme.	The model should include processes for research effectiveness measurement and impact assessment.
	Information and communications technologies (ICTs) are playing an increasingly important part in the effectiveness of organisations.	The model should focus on the use of ICTs to enhance the effectiveness of information flow and knowledge dissemination.
	Small, unconnected projects such as those that arise if the research programme becomes fragmented have little impact and do not allow strategic capacity building.	The model should encourage larger, multi-disciplinary projects that deliver higher-order solutions, and allow the building of research platforms with critical mass in terms of manpower.
	Stakeholder needs are strategically important in setting a research agenda.	The model should allow a needs determination process that ensures broad participation in defining technology needs on which the research agenda is based.
	Regular communication with stakeholders ensures effective participation.	The model should incorporate mechanisms though which stakeholders can have a dialogue with researchers in order to ensure two-way communication that results in enhanced solutions and ease of final implementation.
	Unique and novel technologies are likely to have a high impact eventually, provided that enough lead time is allowed (e.g. the capacitive mat products).	The model should stimulate invention, and should allow longer-term focus on the development of new, unique technologies without clouding the effort of the need for short-term delivery.
	Involvement of technology partners is essential to ensure maximum success of the research programme.	The model should ensure that the environment within which the research and development take place is linked to the programme of work.
Organisational issues	Skills balance in the team of professionals managing and conducting R&D is required for optimum efficacy.	The manpower pool should be linked to the model and play an important part in the model.
	The quality of the research team is essential to the eventual success of the programme.	The model should allow a central role for the manpower pool.

Category	Issue	Tenet
	A knowledge-intensive R&D organisation should be structured according to competency and not according to markets.	The model should allow a focus on technical competencies and indicate their link to the relevant stakeholder needs.
	Principles of open innovation allow a holistic approach across a number of disciplines and organisations, thus enhancing the innovation chain.	The model should take cognisance of open innovation principles.
	Stakeholder interaction is very effective when it is formalised through a steering committee or similar structure.	The model must incorporate leadership from a steering committee, research panels or similar structures.
	Effective research programme management is required, both in the funding organisation as well as in the research organisation.	The model should incorporate organisational champions who ensure effective co-operation between funders, stakeholders and research organisations.
	Enhanced manpower development both inside and outside the research organisation is critical for general capacity building in new engineering methodology and know-how.	The model should ensure that the intellectual capacity pool is integral to its operation and that new entrants are sufficiently mentored to ensure professional growth.
	It is important to show the short-term and long-term benefits of the research programme.	The model should allow an impact assessment process as well as the management of research effectiveness.
Funding issues	A minimum level of continuous funding is required in order to build long-term capacity.	The model should ensure that grant funding and contract R&D funding are managed holistically to ensure minimum funding levels in the longer term.

4 PROBLEM STATEMENT, RESEARCH QUESTIONS, RESEARCH DESIGN AND METHODOLOGY

4.1 Introduction

The previous chapters discussed the problem regarding R&D management in the transport and road engineering sector. In this chapter the problem is summarised and then the research questions and thesis statement given in Chapter 1 are discussed in more detail. The research approach, data and analysis methods mentioned in Chapter 1 are also discussed in detail.

4.2 Summary of the problem statement

R&D in transport and road engineering was affected by the decline in R&D expenditure in South African in the 1990s. A number of studies[257, 258, 259] have indicated that the transport sector and the construction sector in South Africa have come through a period of underinvestment by government and a lack of service delivery from government. This environment led to a number of survivalist strategies which impacted negatively on R&D programmes (see Chapter 3). The result was a focus on direct, immediate problem solving rather than on R&D-based activity with a view to building competencies for the future. In addition, the Department of Transport (DoT) implemented a regular tendering process for awarding research projects and therefore the emphasis shifted from quality of output to project cost. Consequently, in the early 1990s, the Director General of Transport in South Africa expressed the opinion that the national transport research programme had become fragmented with very little focus and subsequently did not deliver up to expectations[260]. Funding decreased in real terms and the focus was narrowed down to special investigations related to short-term problem solving (see Chapter 3). This situation has, to date, not improved and currently the DoT budget for R&D is less than 0.02% of their annual budget[261], which is 50 times less than the target of 1% set in the National R&D Strategy.

The analysis in the previous chapters indicated that:

- SET and R&D in the transport sector are particularly important in a developing country such as South Africa, which is in need of both economic and social development.
- Past transport R&D programmes have underperformed for a number of reasons which include the use of simplistic linear management models (see

detail in Chapter 3) and tendering processes that led to fragmentation of the programmes and eventually their demise.

- The R&D process as such is a complex system and includes a number of organisations that are themselves complex systems. Therefore a simplistic linear management model is unlikely to yield the desired results.
- The analysis in Chapter 3 emphasised this notion, and it was indicated that the R&D programmes which were analysed exhibited many of the characteristics of a complex system, specifically the fact that a small change (implementation of tendering procedures) led to a large, unforeseen effect (the fragmentation of the programme and its subsequent demise).
- Traditional R&D and innovation management models were developed for hard product development and are linear in nature. They follow the steps of idea, research, development, engineering, manufacturing and marketing and do not comply with the set of desired characteristics defined in Chapter 2.
- More than 72% of the case studies in a typical technology management handbook and series of journal articles deal with hard product development and most of the remainder with software development – none deal with R&D in infrastructure or transport (see Chapter 2).
- Traditional R&D management models do not take cognisance of the complexity of the process of developing new knowledge, engineering methodology, know-how, expertise and capacity building such as that needed in the transport and road engineering sector.

In addition, R&D for the transport industry and the road engineering industry in South Africa is different from product development for the consumer market in a number of ways, including the following:

- it involves the spending of public sector funding and therefore the expected outputs should be related to the needs of the people of South Africa rather than the profitability of a company;
- it focuses on the generation of knowledge, expertise and methodology rather than on product development for the consumer market;
- there is a direct focus on capacity development and human resource development; and
- it involves co-operation between several organisations rather than in-house product development.

The need for a different approach was also highlighted by Gaynor[262], who states that:

- technology is not merely machinery and advanced electronics, but rather any means to accomplish a purpose in a broad, holistic sense;
- the management of technology is not an exclusive practice, independent of other variables, but is rather a complex, interconnected systemic process; and
- suboptimal solutions are created when an enterprise focuses solely on the easiest and most logical remedy to a problem, and fails to see a broader proposal of viable solutions from a systemic standpoint.

Da Mota Pedrosa[265] further emphasises the fact that very little research has been done in innovation management in the services (soft products) sector. In addition, a holistic R&D process is much broader than mere research activities and should encompass the total R&D process, including strategic business development, technology networks and alliances, thus reducing risk and uncertainty (Kosmider[263]).

The difference in approach required for innovation in 'hard' as opposed to 'soft' products was also emphasised by Birchall and Tovstiga[264]. Da Mota Pedrosa[265] highlights the importance of innovation in the ***non***-manufacturing sector, including services. According to Dolfsma[266] there are major differences in innovation between the goods sector (hard products) and the services sector (soft products), and the innovation process of services and goods must be different, thus implying a demand for new concepts, methods and models. Berg and Einspruch[267] highlighted the fact that there has been a lack of focus on technology management in the services sector in spite of the fact that it comprises 80% of the gross domestic product in the USA. Not unlike the transport sector and specifically road engineering, most of the business is based on Intellectual Property which is not protected through patents. This requires a ***different approach*** in the services sector (road engineering is mainly a professional service) to that in the goods or manufacturing sectors.

4.3 Research questions and thesis statement

The review and analysis done in the previous chapters indicated that there is a need to develop a new R&D management model and decision-support tools for the road engineering sector. This work was conducted by answering the following research questions:

- To what extent are currently used technology management practices and models applicable to the management of R&D in the road engineering field?
- What are the critical success factors for an effective R&D management model in the road engineering field?
- What are the critical principles and required elements of a systems approach to such a model?
- What are the appropriate decision-support tools required for managing complex, multi-disciplinary research programmes in the road engineering field?
- If a new approach and management model are implemented, what effect will they have on the research output of the road engineering research programme?

The overall objective of this work is firstly to assess whether existing technology management models can be modified to be suitable for managing R&D in road engineering. If not, then secondly, to develop a new conceptual R&D management model and decision-support tools that are based on systems theory and take cognisance of complexity theory and cybernetics. Thirdly, the objective is to implement such models in a number of R&D programmes to assess their applicability. Lastly, the work should determine whether such implementation has had any significant impact on the R&D outputs from the programme.

The following thesis statement is therefore defined:

> ***The development and implementation of a systems-based conceptual management model and decision-support tools in a road engineering research programme will lead to an increase in research effectiveness in terms of number of outputs and long-term growth in the R&D programme.***

4.4 Scope and limitations of the work

4.4.1 Scope

This thesis focuses on the following aspects:

- a review of classic R&D management and innovation management processes and models as described in the literature;
- a review of past R&D programmes and selected projects in the transport industry in South Africa and a quantitative analysis of associated data;

- the definition of a set of tenets as the basis for the development of a new R&D management model and tools;
- the development of a new model for managing R&D for the road infrastructure industry in South Africa (including a strategic-level conceptual model, decision-support tools and a system for evaluating research effectiveness);
- an analysis of the implementation of the proposed model in a number of research programmes and the lessons learnt in this process; and
- the development of an implementation protocol for R&D management.

4.4.2 Limitations

This thesis is limited to R&D management in the road engineering industry and does not cover aspects related to marketing and business development which are usually seen as part of the broader innovation process. The models and tools developed here have not been tested in environments other than road engineering.

4.5 Research design and method

The success of the implementation of a new R&D management model is dependent on the co-operation of a large number of stakeholders in the R&D process. A new model should thus be developed interactively with stakeholders to include their insights and opinions. The models and tools developed were implemented in, and evaluated by, industry from time to time in order to enhance the ultimate value of the end result and to facilitate final implementation.

4.5.1 Research method

The work conducted here is a mixed research model employing both qualitative as well as quantitative analysis of information and data. Mixed methods are often used when additional quantitative substantiation is sought for conclusions that are derived from the qualitative analysis[268]. More specifically, a developmental research approach as described by Thomas[53] as well as a case study approach[54] was followed. According to Thomas, developmental research comprises three phases:

- analysis of the problem (Part 1 in the thesis map – see Figure 1.2);
- development of the solution (Part 2 in the thesis map); and
- evaluation of the implementation of the solution (Part 3 in the thesis map).

In this thesis therefore, firstly the problem of managing the complex process of R&D in the transport sector and road engineering is analysed. Secondly, a new conceptual model and supporting decision tools are developed that are tailor-made for the development of new engineering methodology as opposed to hard product development. Thirdly, the implementation of these models in two local research programmes and a large research project is evaluated and the effect thereof determined. Lastly, an implementation protocol for the management of R&D is developed, presented and used to analyse challenges in the Labour-Intensive Construction field.

The quantitative and qualitative analyses of the literature, existing innovation management models and case studies were utilised to develop a set of ***tenets*** for the development of a conceptual R&D management model and supporting decision tools. Throughout the thesis the table of tenets is used to summarise the learning in a specific chapter and to facilitate the link to subsequent chapters. The information in the tenet table was analysed and reduced to form 12 main tenets on which the development of the model and tools was based. The model and tools were developed interactively through discussions and trials in research programmes in the public as well as the private sectors.

4.5.2 Research instruments

In this work the following research instruments were used:

- *document analysis* – qualitative analysis of information in the literature, including international publications on technology management and R&D management, project reports as well as internal publications of the CSIR;
- *case studies* – case studies of six historical research programmes and three significant projects to determine success factors;
- *personal interviews* – interviews with fellow researchers, administrators of R&D programmes and managers in the public and private sectors;
- *work group sessions* – discussions were held with members of a work group to validate the qualitative analysis in Chapter 3 with quantitative ratings;
- *survey* – an e-mail survey was conducted amongst international R&D managers to determine to what extent they use the proposed elements of a new model as well as the importance of such aspects;

- *interactive workshops* – workshops were held with members of the road engineering industry to evaluate the validity of the model and tools as well as to determine future research directions; and
- *presentations* to local and international members of the road engineering academia, the public sector and the private sector to solicit feedback and input.

4.5.3 Data collection

The qualitative data used in this work were collated from literature reviews, case studies, personal interviews, surveys, interactive workshops, project reports, internal CSIR publications as well as CSIR and Navplan[vii] financial records. The quantitative data were generated from the analysis of the financial records of the CSIR as well as from the records of the Navplan organisations. Information regarding the number of research outputs from the road engineering programme was compiled from CSIR records as well as the Southern African Bitumen Association's website.

4.5.4 Analysis

The quantitative and qualitative analyses of the literature, existing innovation management models and case studies were utilised to define a set of tenets for the development of a conceptual R&D management model. In Chapters 2 and 3 the table of tenets summarises the learning in each chapter. Important aspects of the findings were evaluated through a survey of international R&D managers and statistical analyses of their responses (using SPSS version 16.0) to inform the development of a set of twelve final tenets which formed the basis of the conceptual model and decision tools.

Due to the complexity of the work undertaken, it was difficult to measure the success of the implementation of the new systemic model and tools developed. The problem was, however, approached in the following manner:

- Firstly, the characteristics of the final model and tools were evaluated by mapping the function of the model and tools against the tenets developed in the previous chapters and describing the process through which the model and tools address these tenets.

[vii] Navplan was a consortium of organisations appointed by the Department of Transport to manage the transport R&D programme in the mid-1990s.

- Secondly, a number of measurements were used to assess the effect of the implementation of the new model and tools. This included analysing the following trends (assessing the situation before and after the implementation of the model):
  - the number of academic publications;
  - number of post-graduate degrees awarded;
  - the number of national guidelines and design manuals delivered, with specific emphasis on the difference between the Sabita programme and the RDAC programme;
  - the average size of research projects (using 2005 Rand as a base); and
  - growth in CSIR contract research and development funding related to the road infrastructure sector.

Elements of the research effectiveness measurement model described in Chapter 6 were used with the data above to evaluate the overall impact of the new R&D management model and tools. The Mann-Whitney U Test was used as an indicator in the analysis of the data before and after the implementation of the model (see Chapter 8) to evaluate the validity of the thesis statement defined in Chapter 1.

4.5.5 Interviews, presentations and workshops

The models developed were presented to and discussed with a number of stakeholders (organisations and individuals) throughout the development process. Based on their inputs, the models and techniques were enhanced and modified as well as added to. These interviewees and presentations are summarised in Appendix B in the companion document to this thesis.

4.6 Conclusion

In this chapter the research approach and research methods used in this work are presented. A developmental research approach was followed. The research instruments included document analysis, personal interviews, a survey and interactive workshops. The study employed a mixed research method using both qualitative and quantitative data analysis. Statistical analysis was conducted using SPSS version 16.0.

5 A SURVEY TO DETERMINE THE EXTENT OF USE AND THE IMPORTANCE OF R&D MANAGEMENT CHARACTERISTICS

5.1 Context

The analysis conducted in Chapters 2 and 3 resulted in the identification of a number of important aspects to be considered in the management of an R&D programme. These characteristics were determined from the literature review and from the analysis of past R&D programmes and projects in the transport sector in South Africa. In addition, a number of tools reported in the literature were discussed. The purpose of this chapter is to assess the 'extent of use' of these characteristics and tools by R&D managers and researchers, as well as how important managers and researchers consider them to be. To this end a survey was designed and sent to a number of R&D managers operating both in South Africa and internationally. This chapter describes the design of the survey, the target group, the results obtained and the interpretation of the results. The results of the quantitative analysis confirm the findings of the qualitative analysis discussed in the previous chapters.

5.2 Design of the survey

The survey was designed to provide an indication of the 'extent of use' of a number of prominent characteristics of an R&D management process as defined in Chapters 2 and 3, and how important they are considered to be by survey respondents. In addition, the extent to which R&D management tools are used was evaluated. The following characteristics were included in the survey:

- the link of the R&D programme and projects to an overall strategic plan;
- the differentiation in management processes of longer-term basic R&D projects and shorter-term development projects;
- the use of portfolio management tools to balance the research project portfolio;
- the use of formal technology transfer projects to ensure the implementation of research results;
- the formal assessment of impact (effectiveness) of R&D programmes and projects;
- the use of integrated, system-based approaches in R&D management, including feedback loops to ensure team learning;
- the use of a formal investment decision process to allocate funding to projects;

- the use of formal planning of human resource development; and
- the use of formal project management processes.

The extent to which the following tools were used was also evaluated:

- scenario planning;
- technology foresight studies;
- stakeholder needs analysis;
- technology road mapping;
- technology trees; and
- causal maps.

The technology tree tool developed by the author as part of the work for this thesis was included in the survey specifically to assess the novelty of the tool, and to allow the use of the tool to be compared between researchers not exposed to its use and those in the Built Environment Unit of the CSIR (CSIR BE Unit) who had been exposed to the use of the tool. The survey was also designed to assess both the extent of the use of the characteristics and their perceived importance, thus allowing for analysis of the 'gap' between importance and extent of use. A five-point Likert scale was used for both the extent and importance evaluations. The survey questionnaire is shown in Appendix C.

5.3 The target group

The exact extent of the population of organisations that conduct R&D in transport, roads and construction was not known at the start of this study. A significant effort was made to include R&D organisations in the road infrastructure and transport fields in the target group, and although the final list of 126 organisations cannot be guaranteed to be the full population, it is an extensive list. No sampling was done on the target group and the survey was sent to the whole group. The respondent group of 45 (being those that responded voluntarily) can therefore not be viewed (in a formal way) as a statistically representative sample of the total population that originated from a formal sampling technique (e.g. random sampling, systematic sampling or stratified sampling). The analysis and results discussed in this chapter are thus of an indicative nature, complementary to the qualitative analyses in the previous chapters. However, the 45 respondents represent 42 independent R&D programmes (in three cases researchers in a programme as well as their managers responded), and as such the information obtained is regarded as significant.

The survey was sent to R&D managers in a number of local and international organisations operating across a variety of research fields, but concentrated mainly in the transport, infrastructure, road engineering and construction fields. The contact details were sourced from Internet searches, websites of international organisations such as the Transportation Research Board in the USA and the Forum of European National Highway Research Laboratories (FEHRL), and from personal contacts. In addition, the survey was circulated to ten managers and researchers in the CSIR BE Unit who have been using the model and tools developed in this thesis for at least three years (see implementation discussion in Chapter 7). Their responses were analysed separately as an indication of an 'after implementation' case study and is also used for the analysis in Chapter 8.

5.4 Responses

At the time of the analysis, 35 responses from outside the CSIR BE Unit and 10 from within the Unit had been received. The profile of external respondents is depicted in Figure 5.1 in terms of the following characteristics:

- number of responses per region (Australia, Europe, the USA and South Africa);
- number of responses per management position category;
- number of responses per organisation type; and
- number of responses per research field.

The pie charts in Figure 5.1 indicate both the number of respondents in each category as well as the percentage. The detailed responses are shown in Appendix D. Figure 5.1 indicates that:

- 54% of the respondents were from South Africa and the remainder from international organisations;
- 63% of the respondents were R&D managers and the remainder general management or researchers;
- 40% of the respondents were from educational institutions, 31% from state-owned enterprises (government research laboratories) and only one (3%) from the private sector; and
- 63% of the respondents were from infrastructure-related R&D programmes.

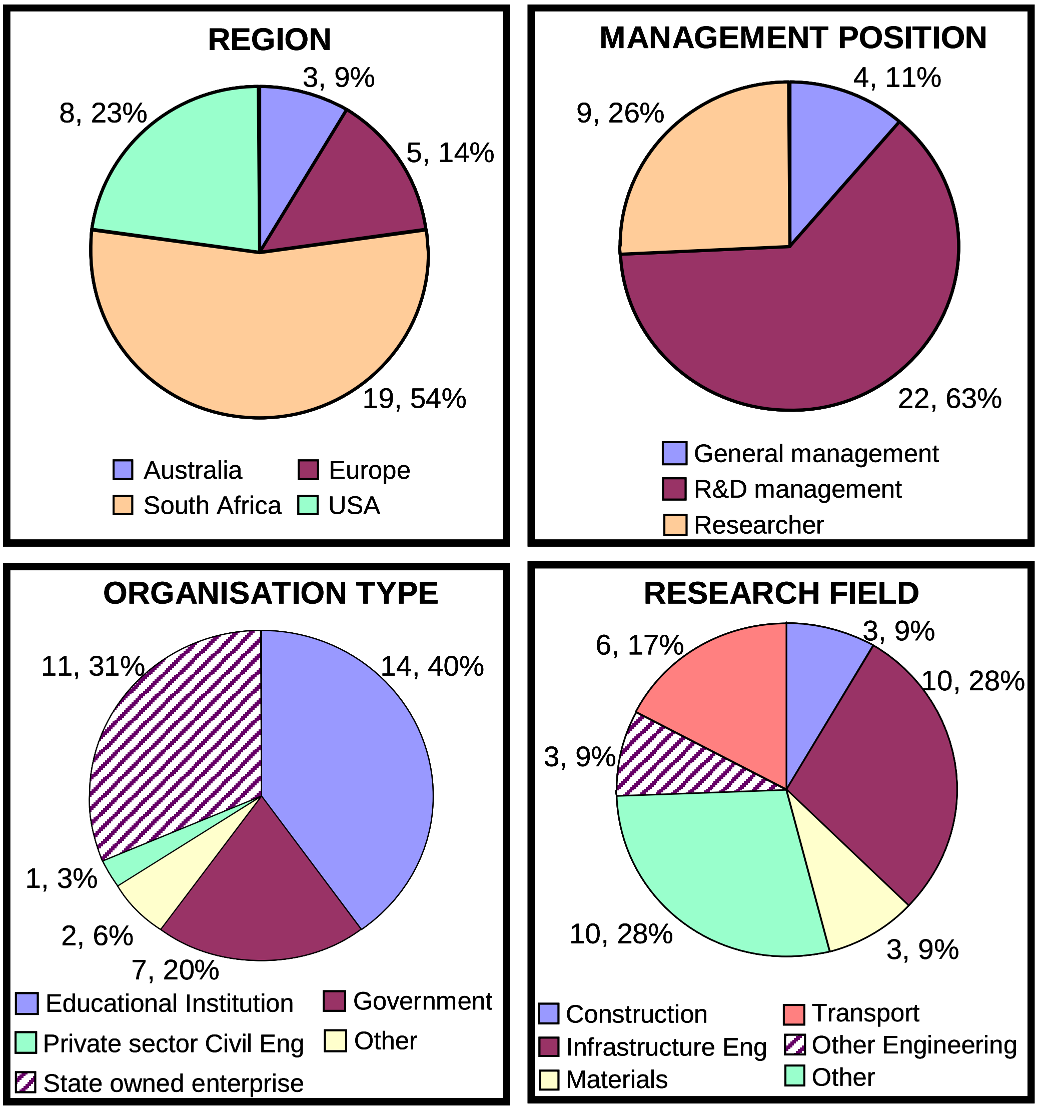

Figure 5.1: Profile of survey respondents (excluding CSIR BE Unit respondents)

5.5 Annual budget and number of researchers

The average annual budget of each of the respondents as well as their number of researchers and number of projects were analysed. Figure 5.2 indicates the distribution of R&D budget in US dollars and the number of researchers in each R&D group.

Figure 5.2 indicates that there was a spread of budget sizes and research team sizes. The survey included a number of large R&D programmes (in excess of $10 million per annum and more than 100 researchers).

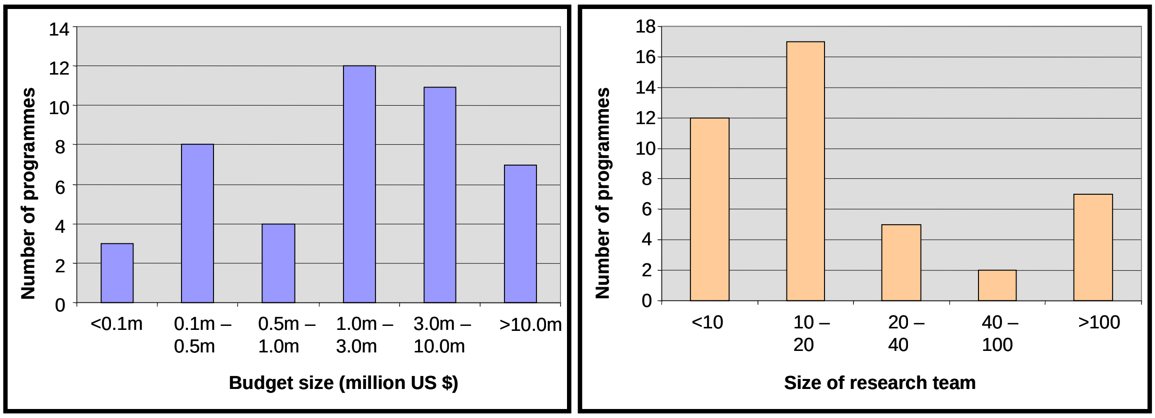

Figure 5.2: Histogrammes of budget size and size of the research team

In addition, the budget in US dollars per researcher and the budget per project were calculated, as well as the number of researchers per project. These indicators are shown in Figure 5.3 for each of the four regions defined: Australia, Europe, the USA and South Africa.

The budget per researcher shows that South Africa is the lowest at US$ 81 536, followed by Australia at US$ 136 043, Europe at US$ 247 067 and finally the USA at US$ 703 883 per researcher. The results from South Africa and Australia are aligned with the value of the currency in those countries as compared with the US dollar. The US value was inflated due to the fact that two of the organisations that responded manage large R&D programmes but outsource most of the R&D work and thus indicated a low number of researchers. If these two organisations are excluded from the calculation, the US figure drops to US$ 278 409 which is very similar to the figure for Europe. These differences are also influenced by the difference in manpower cost in the various regions.

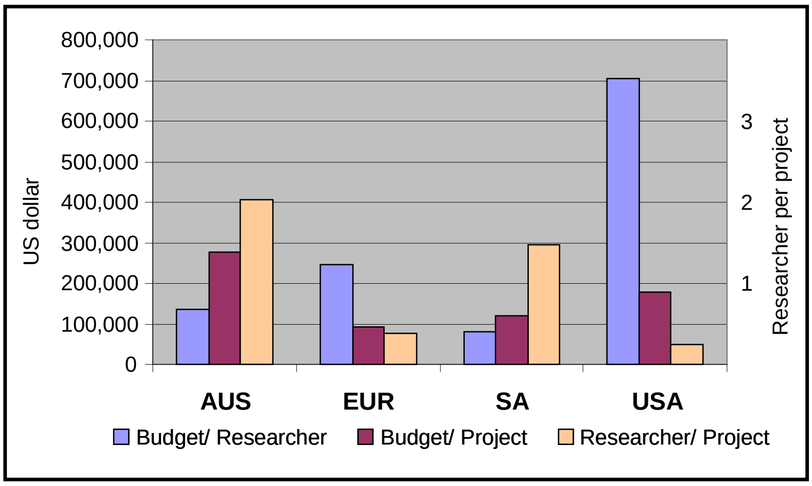

Figure 5.3: Financial and human resource utilisation ratios per region

In terms of the average budget per project, the data indicate that Australia was the highest (US$ 276 337), followed by the USA (US$ 177 262) and South Africa (US$ 120 989). Europe, in spite of relatively higher manpower costs compared for example with South Africa, have smaller projects at only US$ 93 533.

In order to achieve some parity in the comparison between regions, the budget figures were normalised using the Purchasing Power Parity indicator as given in the Economist Pocket World in Figures[269]. The financial data were normalised by dividing the data with the ratio of a country's Purchasing Power Index to that of the USA (the value of which is 100). The result is shown in Figure 5.4. The figure indicates that South Africa and Australia have significantly higher average budgets per project. This pattern will be investigated in more detail below.

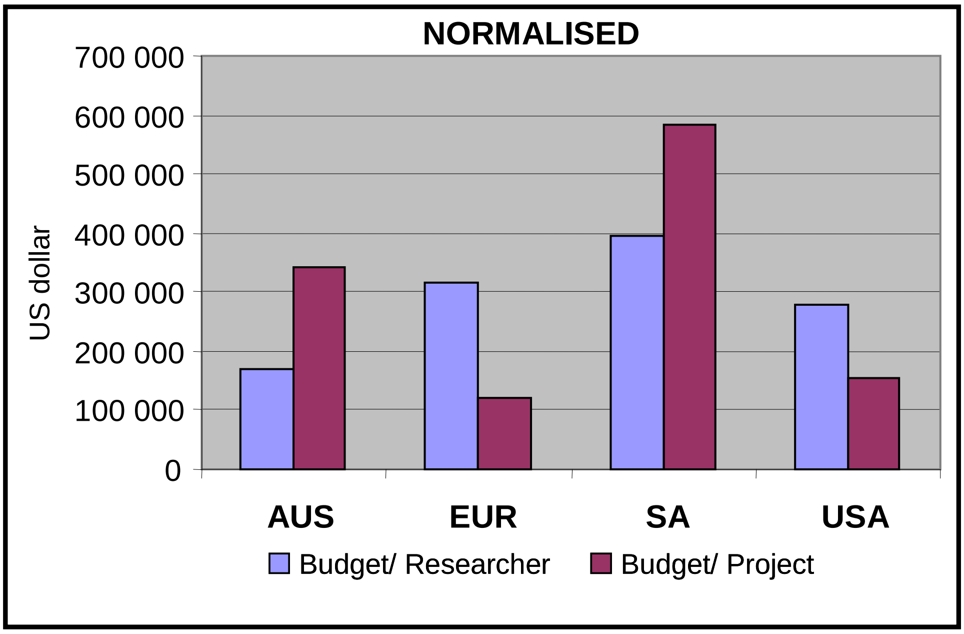

Figure 5.4: Normalised financial and human resource utilisation ratios per region

Finally, the number of researchers per project in Australia and South Africa is higher than in Europe and the USA (see Figure 5.3). This could lead to increased fragmentation of the R&D effort in Europe and the USA, and is confirmation of the observations made in Chapter 3 (see Section 3.6.7).

5.6 Exploratory analysis of the data

5.6.1 Comparison of basic statistics

For the statistical analysis, the five-point Likert scale was converted into a numerical scale where 1 is the lowest score and 5 the highest. The data obtained from the survey from respondents were processed using SPSS version 16.0 and Excel 2003. The data were analysed for two cases:

- Case 1: only respondents who had not been exposed to the work discussed in this thesis (excluding respondents from the CSIR BE Unit).
- Case 2: all respondents.

The data analysis for Case 1 is shown in Table 5.1. The average response to each of the nine characteristics of R&D management (in terms of the extent of their use by the participants as well as their perceived importance) is shown. The table shows the skewness value of the data (as calculated by SPSS), the mean, the standard deviation, the median, the minimum value and the maximum value. The table furthermore also shows the 'gap in application' by subtracting the 'extent of use' score from the 'importance' score.

Case 1: Data distribution

In the case of the R&D management characteristics, the skewness value is generally below one, indicating that the data set is roughly normally, or at least symmetrically, distributed. One exception is the case of the 'extent of use of impact assessment', where the value is 1.14. Nevertheless, both the mean and the median (abbreviated as 'med.' in the table) values are reported and were used in the summary, particularly because the sample is relatively small.

In the case of the R&D management tools, several of the skewness values were higher than one, in which case the median values were used in the data analysis.

Table 5.1: Summary of responses to the survey for Case 1: excluding CSIR BE Unit respondents

		Extent of use						Importance						Gap	
Characteristics	N	Skew[viii]	Mean	St Dev	Med.	Min	Max	Skew	Mean	St Dev	Med.	Min	Max	Mean	Med.
Strategic planning	35	-0.59	3.97	0.95	4	2	5	-0.05	3.43	0.65	3	2	5	-0.54	-1
Long-term vs. short-term projects	35	-0.23	3.37	0.97	4	2	5	0.85	2.91	0.82	3	2	5	-0.46	-1
Portfolio management	35	0.81	2.03	1.25	1	1	5	0.83	2.26	0.98	2	1	5	0.23	1
Technology transfer	35	0.56	2.66	0.97	2	1	5	-0.40	2.94	0.73	3	1	4	0.29	1
Impact assessment	35	1.14	2.06	0.91	2	1	5	0.35	2.83	0.86	3	1	5	0.77	1
Use of systems approach	35	0.43	2.43	1.22	2	1	5	-0.07	2.74	0.85	3	1	4	0.31	1
Investment decision process	35	-0.12	2.97	1.29	3	1	5	0.00	3.00	0.87	3	1	5	0.03	0
Human resources development	35	-0.10	3.23	1.14	3	1	5	-0.04	3.03	0.71	3	2	4	-0.20	0
Project management	35	0.02	3.14	1.38	3	1	5	0.00	3.00	1.14	3	1	5	-0.14	0
Tools (extent of use)	N	Skew	Mean	St Dev	Med.	Min	Max								
Scenario planning	35	0.00	2.17	0.82	2	1	4								
Foresight studies	35	1.25	2.17	1.01	2	1	5								
Needs determination process	35	0.09	3.29	1.02	3	1	5								
Technology roadmaps	35	1.06	2.11	1.13	2	1	5								
Technology trees	35	1.55	1.51	0.74	1	1	4								
Causal maps	35	0.93	1.54	0.70	1	1	3								
Other	35	2.65	1.40	0.88	1	1	5								

[viii] Skewness value as calculated by SPSS version 16.0

Case 1: R&D management characteristics

The mean and median values of the R&D characteristics given in Table 5.1 indicate that the following characteristics are used most often:

- Linkage of R&D programme and projects to a strategic plan;
- management of longer-term basic R&D projects vs. shorter-term development projects;
- the use of a formal investment decision process to allocate funding to projects;
- the use of formal planning of human resources development; and
- the use of formal project management processes.

In terms of importance, all the characteristics were rated as relatively important with the exception of portfolio management.

The gap between ’importance’ and ‘extent of use’ (assessing both mean and median values), was highest for the use of portfolio management, formal technology transfer projects, the formal assessment of impact, and the use of integrated, system-based approaches in R&D management. This gap indicates that there could be a need for the development of new knowledge, processes and tools in these three areas.

Case 1: Use of R&D management tools

The data in Table 5.1 indicate that the use of R&D management tools is relatively low, with the exception of ‘needs determination processes’. In particular the data indicate that the use of technology trees rated close to a value of one, indicating almost no use at all. Two of the 35 respondents rated a value of 3 for technology trees, indicating ‘regular’ use (see Appendix D). Both these respondents work in units of the CSIR other than the CSIR BE Unit and had been exposed to the use of technology trees as developed for this thesis. One respondent (the manager of the Gautrans R&D programme) rated the use of technology trees at a level of 4 (indicating ‘most of the time’), but as indicated in Chapter 7, the Gautrans R&D programme was one of the programmes used for the implementation of the tools developed for this thesis and the manager was exposed to the use of technology trees.

Case 2: Data Distribution

Table 5.2 shows that, as in the Case 1 data set, the skewness values for the Case 2 data set are relatively low, except for the use of R&D management tools where several values are above one. Both the mean and median values are also reported for this case.

Case 2: R&D management characteristics

The highest scores for the extent of use of characteristics (see Table 5.2) remained ostensibly the same as that for Case 1, except for slight increases in the mean and median values for 'portfolio management', 'technology transfer' and 'use of systems approaches'. This is due to the fact that the CSIR BE Unit respondents (although in the minority) were exposed to the work done for this thesis during the implementation phase discussed in Chapter 7. As in Case 1, both the mean and median values indicate that all the characteristics are important. The highest 'gap' was for 'impact assessment'. The median of the gap for 'use of systems approaches' was reduced due to the influence of the CSIR respondents.

Case 2: Use of R&D management tools

Once again the use of technology management tools is rated low in general. However, compared to Case 1, an increase can be seen in 'use of technology trees' and 'foresight studies' owing to the inclusion of the respondents from the CSIR BE Unit. The statistical significance of the difference between the two groupings ('before exposure' and 'after exposure') is discussed in more detail in Section 8.7.

Table 5.2: Summary of responses to the survey for Case 2: all respondents

		Extent of use						Importance						Gap	
Characteristics	N	Skew[ix]	Mean	St Dev	Med.	Min	Max	Skew	Mean	St Dev	Med.	Min	Max	Mean	Med.
Strategic planning	45	-0.63	4.04	0.93	4	2	5	-0.16	3.47	0.63	3	2	5	-0.58	-1
Long-term vs. short-term projects	45	-0.49	3.47	0.89	4	2	5	0.60	3.07	0.84	3	2	5	-0.40	-1
Portfolio management	45	0.55	2.13	1.16	2	1	5	0.62	2.53	1.12	2	1	5	0.40	0
Technology transfer	45	0.41	2.87	1.04	3	1	5	0.07	3.11	0.80	3	1	5	0.24	0
Impact assessment	45	0.91	2.11	0.86	2	1	5	0.45	2.98	0.89	3	1	5	0.87	1
Use of systems approach	45	0.12	2.62	1.19	3	1	5	-0.10	2.96	0.90	3	1	5	0.33	0
Investment decision process	45	-0.37	3.22	1.28	3	1	5	-0.17	3.09	0.85	3	1	5	-0.13	0
Human resources development	45	-0.25	3.40	1.12	3	1	5	-0.03	3.20	0.76	3	2	5	-0.20	0
Project management	45	0.10	3.11	1.32	3	1	5	0.08	3.04	1.19	3	1	5	-0.07	0
Tools (extent of use)	N	Skew	Mean	St Dev	Med.	Min	Max								
Scenario planning	45	0.36	2.38	0.98	2	1	5								
Foresight studies	45	0.57	2.47	1.10	2	1	5								
Needs determination process	45	0.03	3.47	1.06	3	1	5								
Technology roadmaps	45	1.29	1.93	1.07	2	1	5								
Technology trees	45	0.96	2.13	1.38	2	1	5								
Causal maps	45	1.23	1.58	0.75	1	1	4								
Other	45	2.62	1.38	0.83	1	1	5								

[ix] Skewness value as calculated by SPSS version 16.

5.6.2 Basic statistics per region, position and organisation type

The mean values and standard deviation of the responses were analysed based on the following groupings:

- region;
- career position of respondent;
- organisation type; and
- field of research.

For first-order comparison, the total 'extent of use' score, total 'importance' score and total 'use of tools' score per respondent were calculated. For the 'extent of use' and 'use of tools' score the analysis excluded respondents from the CSIR BE Unit. For the 'importance' score all the respondents were considered. The mean values, median values and standard deviation per grouping are shown in Figure 5.5 below.

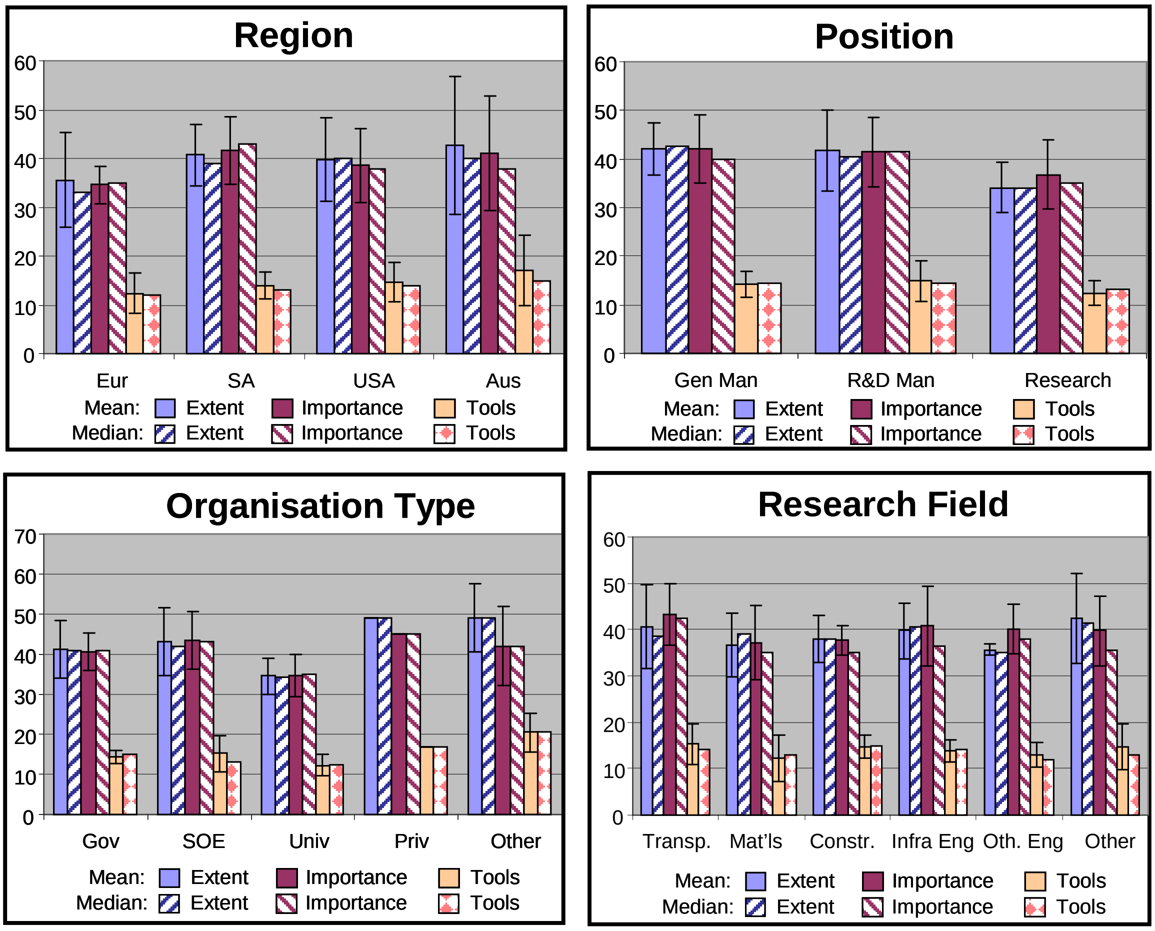

Figure 5.5: Mean score, median score and standard deviation per grouping

The following are indicated by the data in Figure 5.5:

- In terms of region, Europe has a lower total average score for extent of use, importance and use of tools – the other regions are very similar;
- In terms of career position, general managers and R&D managers scored higher than researchers. This could be because they are more involved in the management process than researchers;
- In terms of organisation type, universities scored lower than government and state-owned enterprises (the number of respondents was very low for private sector and other) – this pattern is analysed in more detail below; and
- For research field, the scores were marginally higher for transport, infrastructure engineering and other – but there is no strong relationship between research field and total score.

A between-groups analysis of variance (ANOVA) was conducted to explore the influence of the four independent grouping variables on the Total Score for extent of use. The ANOVA results are shown in Table 5.3 below.

Table 5.3: Results of between-groups ANOVA

Dependent Variable: Total ScE					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2 931.554a	31	94.566	3.331	0.012
Intercept	34 016	1	34015.997	1198.318	0.000
Region	46.609	3	15.536	0.547	0.659
Position	200.394	2	100.197	3.530	0.060
Organisation	568.374	3	189.458	6.674	0.006
Research Field	267.569	5	53.514	1.885	0.165

The significance column indicates that 'Organisation type' had a statistically significant influence on the total score for 'extent of use' (F = 6.67, p = 0.006); with 'Management Position' (F = 3.53, p = 0.06) being marginally significant. There was no significant influence from 'Region' or 'Research field'. This confirms the visual observations from Figure 5.5 above.

A one-way between-groups ANOVA was conducted to further explore the impact of 'Organisation type' on the total score for 'extent of use' of the R&D management characteristics. For the purposes of this analysis the one respondent in the private sector was added to the 'Other' group. There was a statistically significant difference at the 95% level in Total Score for 'extent of use' (F = 9.5, p = 0.000). Post hoc comparisons using the Tukey HSD test indicated that the mean score for Universities (M = 34.5, SD = 4.5) was significantly different from the mean scores for 'State Owned Enterprises' (M = 46.7, SD = 8.0) and the 'Other' group (M = 49.0, SD = 6). There was no statistical difference between the means of Universities and the Government group.

Based on the above analysis, and to investigate the effect of the organisation type in more detail, the respondents were divided into two groups: universities and the rest. The characteristics were analysed individually by comparing the medians of the scores of the two groups of respondents using the Mann-Whitney U Test. This non-parametric test was preferred to the T-test for comparison as that the sample size was relatively small and therefore the normality assumption required for the T-test could potentially be violated. The results are shown in Table 5.4. Variables for which a statistically significant difference between universities and other organisations were found (i.e. with a *p*-value of less than 0.05), are shaded.

The results in Table 5.4 indicate the following general findings:

- universities generally have smaller budgets, smaller projects and smaller budgets per researcher (using normalised figures);
- the data indicate that universities had fewer researchers per project (using normalised figures); and
- regarding the total score for the extent of use of characteristics, their importance and the use of R&D management tools, universities scored significantly lower than other organisations.

Table 5.4: Comparison of ratings from universities with other organisations

	Non-Universities		Universities						
	N	Median	N	Median	Median Diff	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)
Budget ($US normalised)	26[x]	9,327,992	14	490,947	8,837,045	25.5	130.5	-4.44004	0.000
Budget / res. ($US norm.)	26	392,758	14	98,189	294,568	65.5	170.5	-3.30489	0.001
Budget / proj. ($US norm.)	26	623,035	14	130,919	492,116	45	150	-3.88699	0.000
Researcher per project	26	1.4	14	1	0.4	110	215	-2.17697	0.029
Total score 'extent of use'	31	46	14	34.5	11.5	46.5	151.5	-4.185	0.000
Total score 'importance'	31	43	14	35	8	67.0	172.0	-3.691	0.000
Total score 'use of tools'	31	16	14	12.5	3.5	77.5	182.5	-3.44	0.001
Strategic planning (ext)	31	4	14	4	0	122.0	227.0	-2.464	0.014
Strategic planning (imp)	31	4	14	3	1	191.0	296.0	-0.714	0.475
Long-term vs. short-term (ext)	31	4	14	4	0	215.5	711.5	-0.04	0.968
Long-term vs. short-term (imp)	31	3	14	3	0	205.0	310.0	-0.32	0.749
Portfolio analysis (ext)	31	3	14	1	2	80.5	185.5	-3.529	0.000
Portfolio analysis (imp)	31	3	14	2	1	95.0	200.0	-3.139	0.002
Technology transfer (ext)	31	3	14	2	1	102.0	207.0	-2.962	0.003

[x] The five organisations that outsource their R&D were omitted from this analysis (see Section 5.5)

	Non-Universities		Universities						
	N	Median	N	Median	Median Diff	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)
Technology transfer (imp)	31	3	14	3	0	121.0	226.0	-2.609	0.009
Impact assessment (ext)	31	2	14	2	0	120.5	225.5	-2.574	0.010
Impact assessment (imp)	31	3	14	3	0	170.0	275.0	-1.242	0.214
Systems approaches (ext)	31	3	14	2	1	112.0	217.0	-2.648	0.008
Systems approaches (ext)	31	3	14	2	1	120.0	225.0	-2.509	0.012
Investment decision (ext)	31	4	14	2	2	30.0	135.0	-4.722	0.000
Investment decision (imp)	31	3	14	2	1	108.0	213.0	-2.842	0.004
HR planning (ext)	31	4	14	3	1	159.5	264.5	-1.458	0.145
HR planning (imp)	31	3	14	3	0	124.5	229.5	-2.451	0.014
Project management (ext)	31	3	14	3.5	-0.5	193.5	689.5	-0.594	0.552
Project management (imp)	31	3	14	3	0	199.5	304.5	-0.442	0.659
Scenario development	31	3	14	2	1	161.5	266.5	-1.427	0.154
Foresight studies	31	3	14	2	1	107.5	212.5	-2.818	0.005
Needs determination	31	3	14	3	0	159.0	264.0	-1.496	0.135
Technology roadmaps	31	2	14	1	1	159.5	264.5	-1.505	0.132
Technology trees	31	2	14	1	1	49.0	154.0	-4.389	0.000
Causal maps	31	1	14	1.5	-0.5	207.5	703.5	-0.262	0.793
Other	31	1	14	1	0	187	292.0	-1.013	0.311

Differences in the extent of use as well as importance of R&D management characteristics include the following:

- portfolio analysis is lower for universities, both in extent of use and importance;
- the extent to which technology transfer projects are used is lower in universities;
- systems approaches are lower in extent of use and in importance;
- the use of an investment decision process is lower in extent of use and in importance; and
- foresight studies are also used significantly less.

For the extent of use of strategic planning, the importance of technology transfer, the extent of use of impact assessment and the importance of HR planning, the Mann-Whitney U test indicates a significant difference even though there does not appear to be a difference in the median values for these characteristics.

From the above it is apparent that the mandate and culture of universities are different from those of other R&D organisations. Universities usually also have a different funding mechanism from a contract R&D organisation with different monitoring and control mechanisms. Universities seem to be more internally focused and their R&D activities are managed on a project rather than a portfolio basis, taking little cognisance of the potential return-on-investment of R&D activity. This is probably due to the fact that students are used for a significant portion of the R&D activity as part of their Masters' and Doctoral studies (which is the main purpose of R&D at universities). This should be taken into account in setting up R&D management systems at universities.

5.7 Principal component analysis

Factor analysis or Principal Component Analysis (PCA) is often used in an exploratory manner to determine the interrelationships between variables of a data set[270]. The data set for the respondents, excluding the CSIR BE Unit, was subjected to PCA using SPSS version 16.0. In addition to investigating the interrelationships of the variables, the purpose of this exercise was also to assess the potential of reducing the number of characteristics from the original nine to a lower number which would simplify further statistical analysis. For the purpose of this analysis only data from the respondents external to the CSIR BE Unit were analysed. The 'extent of use' and 'importance' scores were analysed separately.

The correlation matrices for the two cases showed many coefficients of 0.3 and above. Table 5.5 indicates that the Kaiser-Meyer-Olkin values were 0.51 and 0.68 respectively - the recommended minimum is 0.6.[271] Bartlett's Test of Sphericity[272] reached statistical significance supporting the factorability of the correlation matrix.

Table 5.5: Kaiser-Meyer-Olkin values and Bartlett's test

KMO and Bartlett's Test for 'Extent of use' variables		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		.511
Bartlett's Test of Sphericity	Approx. chi-square	76.985
	Df	36.000
	Sig.	.000
KMO and Bartlett's Test for 'Importance' variables		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.684
Bartlett's Test of Sphericity	Approx. chi-square	65.300
	Df	36.000
	Sig.	.002

The PCA indicated three components with eigenvalues of more than one in the case of the 'extent of use' group of variables and four components in the case of the 'Importance' group of variables (see Table 5.6).

However, in both the 'extent of use' and 'importance' cases the cumulative percentage variance explained by the principal components with initial eigenvalues above one only reach 63.5% and 71.5% of the total variance respectively, which is relatively low. This is confirmed by the scree plots for the two cases shown in Figure 5.6. In the case of 'extent of use' there is no distinctive break in the plot. In the case of the 'importance' data, there is a distinctive break after component one.

Table 5.6: Initial eigenvalues for both groups of variables

Extent of Use				Importance			
Component	Initial Eigenvalues			Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %		Total	% of Variance	Cumulative %
1	2.5	27.772	27.772	1	3.108	34.529	34.529
2	1.702	18.916	46.689	2	1.176	13.065	47.595
3	1.519	16.877	63.566	3	1.144	12.707	60.301
4	0.943	10.478	74.044	4	1.01	11.218	71.52
5	0.829	9.207	83.251	5	0.882	9.796	81.316
6	0.613	6.814	90.065	6	0.541	6.011	87.327
7	0.404	4.488	94.553	7	0.442	4.911	92.237
8	0.3	3.334	97.887	8	0.396	4.402	96.639
9	0.19	2.113	100	9	0.302	3.361	100

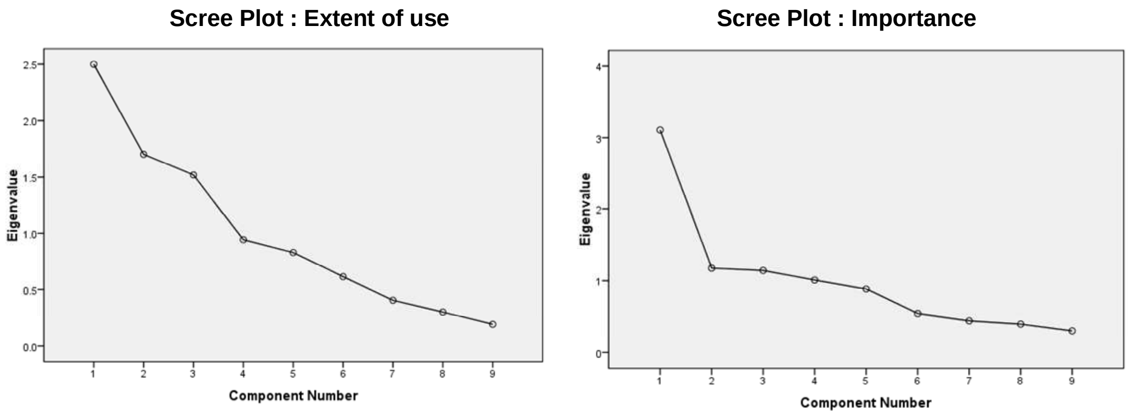

Figure 5.6 Scree plots

The matrices for the first three components of the two variables are shown in Table 5.7. The weights or loadings of variables on the components of the ‘extent of use’ data do not seem to lead to any practical or logical interpretation and, as also indicated by the scree plot in Figure 5.5, all these variables should be retained as individual variables for further analysis.

Table 5.7 Component matrices for 'extent of use' and 'importance'

Component Matrix: Extent of Use				Component Matrix: Importance				
	Component				Component			
	1	2	3		1	2	3	4
TechTransE	0.805		-0.381	SystemI	0.756			
SystemE	0.689		-0.355	ProjManI	0.719			-0.417
PortfolE	0.593		0.361	ImpactI	0.71			
StratPlanE	0.562	0.368		InvesDecI	0.655	-0.309	-0.344	
ImpactE	0.513			LongShortI	0.614	-0.501		0.365
LongShortE		0.76		PortfolI	0.601		-0.455	0.416
ProjManE	0.355	0.704	-0.406	HumResI		0.84		
InvesDecE	0.508	-0.578	0.369	StratPlanI			0.824	
HumResE			0.847	TechTransI	0.454			-0.6

Inspection of the components for the 'importance' data reveals that the variables can be grouped together into four components that make some logical sense:

- Component 1: ***Systems approach,*** which includes a number of the variables that describe the use of a holistic systems approach in R&D management.
- Component 2: ***Human resource development***, which is also influenced by the investment decision (of which funding for HR development is a part), as well as by long-term versus short-term projects (longer-term projects allow room for HR development);.
- Component 3: ***Strategic planning***, which includes some elements of the investment decision and portfolio management.
- Component 4: ***Technology transfer***, which includes some elements of project management, long-term versus short-term projects (technology transfer projects are shorter-term projects), as well as portfolio management.

This analysis indicates that these four aspects of R&D management can be seen as potential groupings within the 'importance' data. It can therefore be postulated that the respondents indicated that these four characteristics are important for an R&D management process.

5.8 Dominant factors influencing level of R&D management

Complementary to the data collected from the survey, the following variables were added to the data set from the Economist Pocket World in Figures[269]:

- Gross Domestic Product per head in the country of the respondent.
- The Purchasing Power Parity, which equalises exchange rates based on a standard basket of goods.
- Human Development Index as defined by the United Nations Development Programme.
- Most used road network index in vehicle-kilometre per year per kilometre of road.

The purpose was to determine whether these general region-related factors influence the level of R&D management as described by the R&D characteristics analysed in this survey.

In addition, the previously defined variables of Budget per Project, Budget per Researcher and Researcher per Project were used in the same analysis. In order to achieve some parity in comparison between regions, the budget figures were normalised using the Purchasing Power Parity values as discussed above.

The variables in this analysis are continuous (as opposed to categorical) and therefore it was decided to conduct a correlation analysis using Pearson product-moment correlation coefficients.

Furthermore, a multiple regression was applied to these data. The purpose of the regression analysis was to investigate the correlation between the independent variables (GDP per head, budget per project, etc.) and the dependent variable (Total Score for 'extent of use of characteristics'). Preliminary analysis was done to ensure no violation of the assumptions of normality, linearity and homoscedasticity. The emphasis was ***not*** on the building of a predictive model but rather to investigate the influence of the independent variables on the 'quality of R&D management' as indicated by the dependent variable.

The regression coefficients are shown in Table 5.8 and the model summary in Table 5.9.

Table 5.8: Correlation coefficients

	N	R (TotalScE)	Sig. (1-tailed)
TotalScE	45	1	.
N-GDP per Head	45	-0.263	0.040
HDI	45	-0.277	0.033
Road Use	42	-0.325	0.018
N-Budget per Researcher	40	0.613	0.000
N-Budget per Project	42	0.681	0.000
Researcher per Project	41	0.381	0.007

Table 5.9: Regression model summary

	Unstandardised Coefficients		Standardised Coefficients		
	B	Std. Error	Beta	t	Sig.
(Constant)	39.758	11.678		3.405	0.002
NGDPperHead	0.000	0.000	0.518	1.211	0.235
RoadUse	-0.017	0.008	-0.467	-2.027	0.052
BudPerRes	0.000	0.000	0.078	0.287	0.776
BudPerProj	0.000	0.000	0.927	2.194	0.036
ResPerProj	-3.850	2.926	-0.411	-1.316	0.198
HDI	-0.101	0.272	-0.157	-0.372	0.713

R Square	Adjusted R Square	Std. Error of the Estimate
0.581	0.497	6.141

The results in Table 5.8 show the correlation coefficients for each of the independent variables individually and the correlation coefficient of the Total Score for Extent of Use (TotalScE). Although these results are from a relatively small sample size and for a limited number of countries, the results indicate the following:

- The normalised GDP per Head, Road Use and Human Development Index variables are ***negatively correlated*** with the Total Score for 'extent of use of characteristics', which means that higher values for these variables are associated with lower values of the Total Score for ‘extent of use’. This can be interpreted as a pattern that ‘richer’, more developed countries do not manage their R&D programmes as effectively as the ‘poorer’ countries, probably due to R&D funding being more readily available in richer countries. The extent of the correlation is classified as medium to small[273].

- The normalised ‘Budget per Researcher’ and ‘Budget per Project’ variables show a strong ***positive correlation*** ($r > 0.6$)[273]. Therefore higher values for these variables are associated with higher values on the Total Score for ‘extent of use’.
- The ‘Researcher per Project’ variable was ***positively correlated*** at the medium level ($0.3 < r < 0.6$)[273].
- All the p-values were statistically significant at the 95% confidence level (i.e. all $p < 0.05$).

Although not indicated in the above tables, the correlation coefficients did show a statistically significant interrelationship between the N-GDP per Head, Road Use and HDI variables, indicating that they could be combined into one variable or could be used interchangeably for regression analysis. This is confirmed by the regression model results in Table 5.9. The right-hand column indicating the significance measure shows that only the Road Use variable had a significance of $p \sim 0.05$ with the other two not being statistically significant. This result means that, given the presence of Road Use in the regression model, the other two variables make no significant additional contribution to the model.

A similar argument may be followed for the three variables Budget per Researcher, Budget per Project and Researcher per Project. The data in Table 5.9 indicates that, in the regression model, only the normalised Budget per Project variable had a significant influence ($p = 0.036$), while the coefficients of the other two were not statistically significant.

5.9 Summary and concluding remarks

The survey was designed to investigate the validity of the findings of the qualitative research in Chapters 2 and 3 through a survey and quantitative analysis. The responses represent a relatively small data set, but this should be seen in the light of the fact that they represent 42 independent R&D programmes locally and internationally. The results from the survey confirmed to a large degree the qualitative results. One of the new findings from the survey was that the organisation type (in terms of culture, mandate and funding mechanism) could influence the extent to which the organisation uses important R&D management characteristics and tools.

In particular, the following was found for the specific data set analysed here:

- South Africa and Australia, on average, conduct larger research projects than Europe and the USA (based on costs normalised with the Purchasing Power Parity index).
- South Africa and Australia have three to four times more researchers per project than Europe and the USA.
- The following R&D management characteristics are used most often:
  - Linkage of R&D programme and projects to a strategic plan;
  - management of longer-term basic R&D projects vs. shorter-term development projects;
  - the use of a formal investment decision process to allocate funding to projects;
  - the use of formal planning of human resource development; and
  - the use of formal project management processes.
- In terms of the importance of the R&D characteristics, respondents rated all of the characteristics as being relatively important, with the exception of portfolio management.
- In terms of the 'gap' between importance and extent of use of the characteristics, the difference in the respective responses (excluding the CSIR BE Unit) yielded the highest gap (highest potential for improved processes) in the following areas:
  - portfolio management (although not highly important);
  - formal technology transfer projects;
  - the formal assessment of impact; and
  - the use of integrated, system-based approaches in R&D management.
- The 'extent of use' scores of the R&D management tools showed that the Technology tree tool developed for this study was not known to the

respondents, except for those respondents from the CSIR Built Environment Unit or those who had been exposed to the method during the implementation phase of this study, indicating that it is a novel approach.

- In terms of the independent variables in the study, an ANOVA indicated that 'Region' and 'Research Field' had no influence on the total score of the 'extent of use' of R&D characteristics.
- The management position of the respondents had a marginally significant influence, in that the researchers generally rated the extent of use lower than the two management categories.
- The most significant difference was in 'Organisation Type' where the total 'extent of use' score for universities was significantly lower than that for other organisations.
- Universities particularly scored lower in the following aspects:
  - portfolio management;
  - the extent to which technology transfer projects are used;
  - the use of systems approaches;
  - the use of an investment decision process; and
  - the use of foresight studies.
- Possible explanations for the different score from universities include funding mechanisms, the nature of their mandate and their culture.
- A Principal Components Analysis of the 'Importance' ratings of all respondents indicated that four groups of characteristics seem to emerge and therefore should be considered in the development of an R&D management process:
  - systems approaches;
  - human resources development;
  - strategic planning, and
  - technology transfer.
- A regression analysis between the dependent variable 'Total Extent of Use Score' and a number of independent variables indicated the following:
  - Normalised GDP per Head, Road Use and Human Development Index variables are negatively correlated with the Total Score for 'extent of use of characteristics', thus indicating that, for this data

set, ‘richer’ countries do not seem to manage R&D programmes as well as ‘poorer’ countries;

- The normalised ‘Budget per Researcher’ and ‘Budget per Project’ variables show a strong positive correlation, indicating that larger projects go hand in hand with a higher level of R&D management (this supports the findings in Chapter 3).
- The ‘Researcher per Project’ variable was positively correlated at the medium level, which also supports the findings in Chapter 3.

In conclusion, the quantitative analysis of the survey data supported the findings of the qualitative analysis in Chapters 2 and 3. The characteristics identified and evaluated in this analysis are therefore taken forward in the ensuing chapters as the basis for the development of a new, systems-based R&D management model.

6 A PROTOTYPE MODEL FOR A SYSTEMS APPROACH TO THE MANAGEMENT OF R&D IN THE ROAD INFRASTRUCTURE INDUSTRY

6.1 Introduction

> *"Initial research in the Technology Management Initiative supports the idea that the more complex and difficult a tool is to use, the less likely it is to be applied. Some of the most powerful tools are simple methods for promoting structured communication among people." Brady – University of Sussex*

In the previous chapters the problem of management of R&D in the road infrastructure industry was highlighted. The process is complex, as it focuses on the development of engineering methodology and knowledge rather than on consumer products.[9] The models discussed in the literature survey do not fulfil the requirements for the management of a complex process.[51] Several characteristics of a model for managing such a process were defined through the literature study and the analysis of historic research programmes and projects. The importance of these characteristics was evaluated through the ratings of the managers of 43 local and international R&D programmes obtained from a survey. These characteristics were summarised in tenets or principles. In this chapter the development of a new model and tools for the management of R&D in the road infrastructure industry, based on these tenets, is discussed. The use of a conceptual model supported by supporting tools is in line with thinking by Phaal *et al*.[274].

This chapter focuses on the following:

- The argument for using a systems approach that also incorporates elements of cybernetics and complexity theory is made. This is motivated separately because a systems approach is a central theme in this thesis.
- The tenets defined in previous chapters are summarised to explain the basis on which the model and tools were developed.
- The approach, which consists of a conceptual model (upper level) supported by decision-support tools (middle level), which are in turn supported by basic data (lower level), is described.

- The development of the conceptual model and tools and the rationale for their design are discussed.
- The tools developed consist of:
    - a needs determination process that incorporates interaction with practitioners, officials and stakeholders, technology foresight activities and international networking;
    - the technology tree concept and tool that is used to understand elements of the SET base and their interaction, to develop the link between the SET base and key solutions that satisfy the needs defined, to assess the balance in the R&D portfolio and therefore to identify R&D needs; and
    - a Research Effectiveness measurement tool based on perceived value of the output, outcome and impact of R&D activity.
- Other processes related to the management process such as:
    - technology transfer and delivery systems; and
    - the education and training process.
- The link of the model to internal and external management structures.
- The processes for using the model and tools.
- Lastly, a reflection on the cybernetic systems characteristics of the model and tools.

This model was developed in phases in parallel with the implementation of some of the aspects of the new approach in a number of research programmes in the road infrastructure industry (see Chapter 7). The model and tools presented in this chapter can therefore be regarded as prototypes that were enhanced during the implementation process discussed in Chapter 7. The status of the approach as it is currently applied in the CSIR Built Environment Unit is also discussed in Chapter 7.

6.2 Essential elements of a new approach to the management of R&D

6.2.1 The argument for a systems approach

The previous chapters highlighted pertinent aspects of previous South African R&D programmes. Some of the main disadvantages of the previous programmes were the lack of a holistic management process, the use of open tendering processes for procurement (based on lowest cost allocation), the lack of stable funding streams and a short-term view. In addition, the problem was exacerbated by individuals defining their own research topics and problems with no 'bigger picture' view. This resulted in the fragmentation of the research programme into small projects addressing small detailed problems and therefore not achieving the desired outcome and impact. The negative impact of fragmentation in research programmes was also identified in a number of international research programmes[207, 208].

In Section 2.3.3 the R&D process is analysed as a complex system based on work done by Cilliers[50]. It was shown that the R&D process displays the characteristics of a complex system. In particular, the emerging behaviour of the historic R&D programmes where a small change (the lowest-cost tendering process) caused a large, unforeseen effect (fragmentation and demise) is one of the key characteristics of a complex system. The literature study in Chapter 2 highlighted the fact that existing international R&D management models are very linear in nature[51], i.e. they focus on the stages of idea, research, development, product commercialisation and marketing as consecutive steps with minimal feedback to enhance the process. Furthermore, most of these models and tools were developed for consumer product development processes. In the road infrastructure sector (and the bigger transport sector) research programmes focus on the generation of new knowledge, engineering methodology and solutions, as well as algorithms and software tools, and therefore the management process is much more complex[9]. Aspects such as the implementation of the solution should therefore be considered before the research work is conducted. A simple linear model is therefore unlikely to be sufficient for the management of the R&D process. Berkhout *et al.*[275] also stress the importance of moving away from linear models for innovation management.

Management processes designed with systems thinking in mind allow interaction between elements as a continuous process and indeed also interaction of the elements with their environment, leading to a non-linear process or non-consecutive occurrence of events. The importance of viewing innovation as a non-linear process is also stressed by Verhaeghe[276]. Non-linearity encompasses the following aspects:

- The activities in the process do not occur consecutively but are executed simultaneously as and when value can be added (e.g. implementation should be planned simultaneously with research project planning).
- Elements of the process may be omitted in order to achieve the objectives cost-effectively (e.g. research is not necessary if existing knowledge is sufficient to solve the problem at hand).
- The interaction between the elements and the addition of value due to this interaction are actively sought (e.g. implementation plans and target market should influence the approach to the project).
- Cognisance is taken of the environment within which each activity takes place and the influence of the environment is actively sought (e.g. resources external to the research environment are used to maximise usability and impact).
- The elements of the process interact and are connected through feedback loops, thus influencing each other's performance.
- Small changes in the process can cause big effects elsewhere in the process.

Contrary to what researchers are generally comfortable with, the above process may require some 'reverse thinking', i.e. the researcher should visualise the end product and think through its implementation prior to planning the approach to and details of the project.

In addition, to prevent a narrow outlook by researchers focusing on their 'pet topics' and to maximise the outcomes of research conducted by a number of organisations, a more holistic approach, taking the 'bigger picture' into account is required (the Sasol Ash project discussed in Section 3.7.4 is a good example of such an approach). Although many definitions exist, holism in essence means that the whole is more than the sum of the parts[277]. The use of a holistic approach implies that:

- R&D and technology development needs should be determined in a process taking cognisance of the market for which the technologies are intended and of non-technical factors (e.g. political, social and cultural issues) which will influence its implementation;

- the R&D activities of organisations in a particular field should be planned co-operatively where possible (at a national level);
- a relevant representation of stakeholders interested in the R&D activity should be involved and consulted (including end users);
- planning should not focus only on the technical problem at hand, but should take cognisance of the longer-term development of the competency within which the R&D takes place;
- planning should consider the implementation of the final result and specifically the required delivery system to the stakeholder;
- all the elements of the R&D process should be taken into consideration at the initial stages;
- the likely outcome and impact of the R&D should be taken into account; and
- project planning and costing should include activities such as implementation, training and impact measurement.

As motivated in Chapter 1, the use of a systems approach will yield a model that is more suitable for the management of R&D in the road infrastructure sector than the older, linear models used for managing the development of consumer products. This is of particular importance in a field where multidisciplinary, complex problems are addressed, as is also confirmed by Minderhoud and Fraser[278]. This chapter is dedicated to the description of the development of an R&D management model and tools that address these issues.

6.2.2 Key requirements for a new approach

The process for managing R&D in the road infrastructure sector should be designed to yield maximum benefit for the transport industry, the economy of the country as well as users and communities. In the previous chapters a broad set of tenets for the development of such a process were defined. However, for these to be used as the basis for the development of a new model, they need to be summarised and ordered. The information in Table 3.3 and the results of the survey discussed in Chapter 5 were used to derive the set of summarised tenets discussed below.

Tenet 1: A holistic approach should be integral to the model

As discussed in Section 6.2.1, the model should be based on a holistic approach which implies that the model should take account of the broader environment within which the programme takes place, which includes the needs of stakeholders and communities. The importance of a holistic approach when developing a framework for R&D management was emphasised by Adams *et al*.[60]. Interaction with all role players is essential and the R&D efforts of these should be co-ordinated. The process should take cognisance of the full innovation chain, including the eventual impact of the programme. This implies that the principles of open innovation should be used to ensure effective co-operation between research organisations to enhance the outcome from the process.

Tenet 2: The model should be based on a systems approach

The model should take cognisance of the principles of systems thinking (see Section 6.2.1), cybernetics and complexity theory with a specific emphasis on:

- non-linear thinking to address the development of new engineering methodology and knowledge as opposed to the development of hard products for the consumer market;
- the interaction between the elements of the system and their interdependency;
- the interaction of the system with the system environment;
- feedback loops that allow control, self-reference and self-organisation;
- circular causality which means that the system can impact on itself;
- the fact that small changes can cause large effects elsewhere in the system; and
- some degree of informed reduction to deal with the breadth of the problem.

Tenet 3: Integration of elements or levels of the model should be used to enhance the value and quality of the outcome from the research process

Integration of a number of disciplines is required to address the complexity of the process to develop solutions for the road infrastructure industry that are implementable, usable by stakeholders and acceptable to communities. The integration of basic pockets of expertise to deliver higher-order key solutions that will provide long-term impact should be emphasised.

Tenet 4: The manpower pool should be central to the model

The effectiveness of any R&D programme depends to a large degree on the quality of the researchers and practitioners involved in the process, particularly where innovation in technical organisations is concerned[279]. The quality of the manpower pool should therefore be integral to the model and the research programme should be linked to future manpower development through education activities.

Tenet 5: Strategic planning must be a core element of the model

The strategic planning and vision for both the road industry as well as the research organisation must form an integral part of the model. The model must also allow for a body (e.g. a steering committee) that provides strategic direction to the programme.

Tenet 6: The research and development programme must be balanced

Balance implies that there should be a strategic view of the balance between solving short-term problems and building new technology and knowledge platforms in the long term. As such there should be a balance between 'market pull' and 'technology push'.

Tenet 7: Core competencies and platforms should be integral to the model

The concept of core competencies and technology platforms should form an integral part of the model to ensure that long-term R&D capability is developed, that critical mass in terms of human resources is developed and that stakeholder needs are addressed effectively.

Tenet 8: The model must stimulate creativity and invention

It is important to allow enough room for researchers to be inventive to ensure that new knowledge generation is effective.

Tenet 9: The model should counter the effects of fragmentation

The model should stimulate the formulation of larger, multi-year and multidisciplinary projects that will ensure increased return of value for the investment made.

Tenet 10: The model should measure the effectiveness of the R&D process

The model must allow the measurement of the effectiveness of as well as the impact of the R&D programme.

Tenet 11: Stakeholder interaction and technology transfer are essential

The involvement of stakeholders and communities in the planning as well as the technology transfer stages of the process are essential to ensure that stakeholder needs are addressed and that implementation is facilitated. This is particularly important where new solutions are implemented that will affect the daily lives of people in communities. The model should allow interaction with such stakeholders and communities to ensure that the final solution will be acceptable and implementable. Information and Communications Technology (ICT) should be used optimally to ensure effective technology transfer.

Tenet 12: The model and tools should allow effective internal and external communication, including the motivation for stable long-term funding

It is important that the model should allow researchers to communicate effectively about research activities across the boundaries of a number of disciplines. The programme of work should also be linked to the stakeholder needs to ensure that stakeholders understand the need for and the objectives of the R&D programme. The funding of contract R&D is the function of several organisations in the road infrastructure industry of South Africa. The model cannot prescribe such funding, but can facilitate the process by developing comprehensive R&D strategies and agendas based on a systems approach that would provide a strong motivation for long-term funding.

The above summary tenets were used as a guide in the development of the framework for a new approach, conceptual model and tools as discussed in the sections that follow.

6.3 A conceptual model to manage R&D

6.3.1 Main elements of the proposed model

One of the main findings of this study is that R&D should take place in a framework based on a systems approach and taking into account the bigger picture (holistic approach). The model should be viewed as a system with elements that are linked, interact with each other through feedback loops and interact with their environment to ensure an effective, interactive process.

R&D management can be viewed at the three levels shown in Figure 6.1. These are:

- the strategic level;
- the operational level; and
- the basic data and information level.

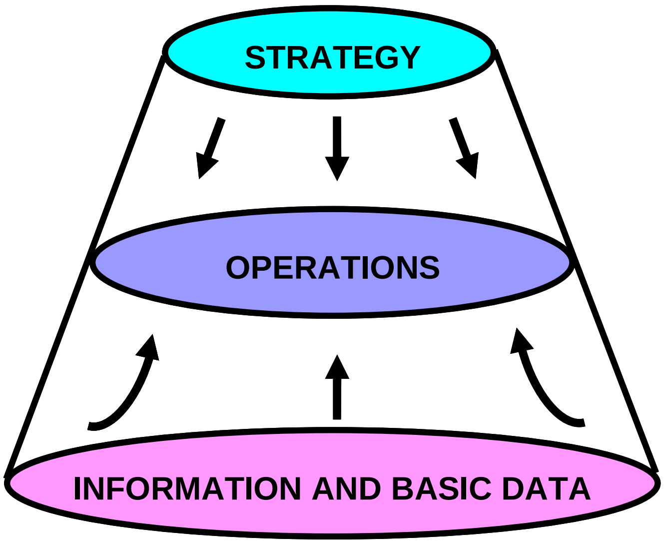

Figure 6.1: Levels of R&D management

In essence, the management process should take cognisance of strategic drivers ('top-down' process) as well as basic data from the results of the process ('bottom-up' process). The operational level is where tools and techniques are used to analyse basic data and information and to measure the results against the strategic drivers. This study focused on the development of a strategy-level conceptual management model, the supporting analysis techniques and the accumulation of data used in these techniques.

The model developed in this study is viewed as a system as defined by Flood and Jackson[74] (see Chapter 2), consisting of main elements which interact with each other and are interdependent. Flood and Jackson state that a system comprises elements which are linked to one another through a series of relationships. If a group of elements are richly interactive a boundary can be drawn around them separating them from their environment. A system also has inputs and outputs with feedback loops that influence the operation of the system and therefore the whole is usually more than the sum of the parts.

Beer[280] showed a schematic of a dynamic system as being a circular diagram (see Figure 6.2). The notion of a circular representation of a management model is valuable in view of the fact that circular causality holds true in a cybernetic system (i.e. the system can impact on itself).

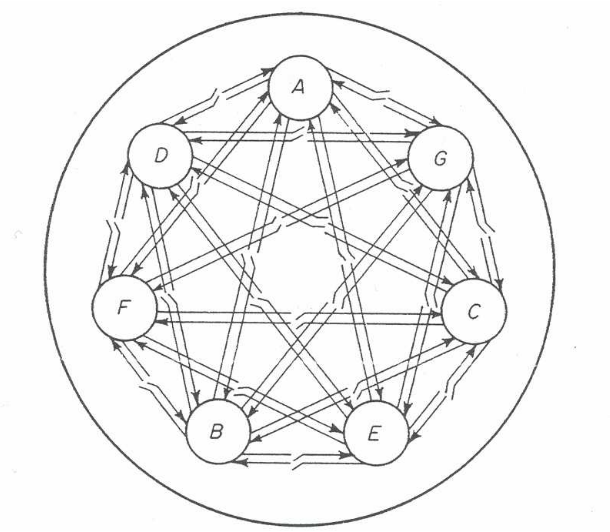

Figure 6.2: A dynamic system as depicted by Beer[280]

Based on Beer's notion and the characteristics in the twelve tenets above, the conceptual model in Figure 6.3 was developed.

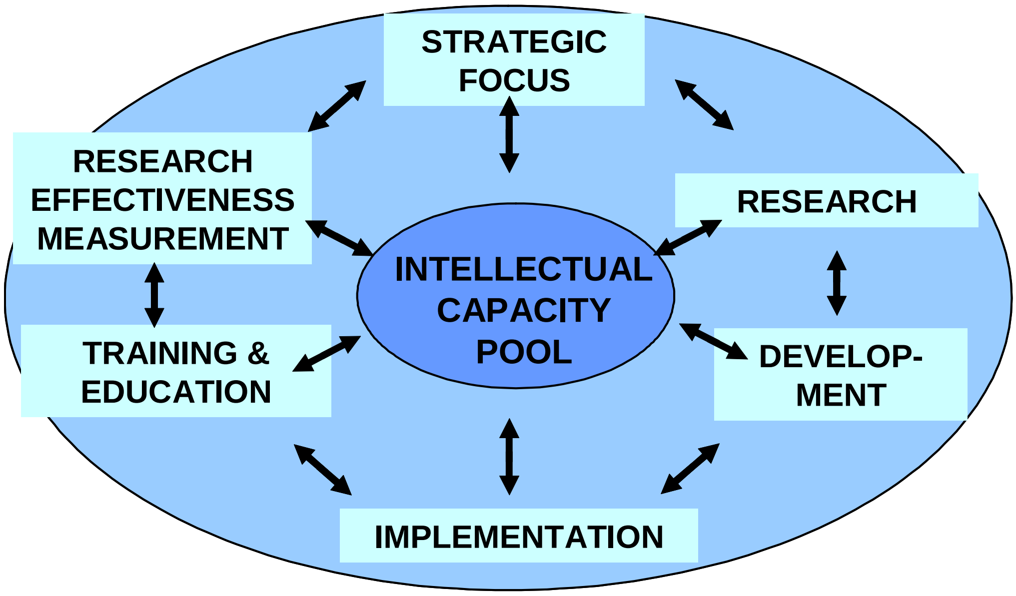

Figure 6.3: Main elements of the conceptual R&D management model

Figure 6.3 shows the main elements of the conceptual model for the management of R&D developed for this thesis. Central to the process is a pool of intellectual capacity consisting of expertise, knowledge and know-how throughout the entire industry (client bodies, public sector authorities, educational institutions, research organisations and the private sector) that is vital to the success of the process. The R&D process must ensure that the quality and strength of the pool of intellectual capacity are maintained. The elements of the system around it are:

- strategy and strategic focusing;
- the research process;
- the development process;
- implementation and technology transfer activities;
- education and training activities; and
- research effectiveness measurement.

These elements are discussed in more detail below.

Strategy and strategic focusing

As indicated in the analysis in Chapters 2, 3 and 5, R&D should be linked to strategy in order to achieve maximum benefits. As stressed by Roussel[81], the selection of a balanced portfolio of research and development projects should be directed by the focus of the R&D strategy which, in turn, should be an integral part of the business strategy of the organisation or industry concerned. In an organisation such as the CSIR it is essential that both the overall strategy of the organisation as well as the strategic direction of the industry it is serving should be taken into account. Techniques such as technology scanning and forecasting should be used to guide the technology development strategy. These techniques are well known and will not be discussed in detail here. However, strategic planning processes usually include some or all of the following steps:

- a situational analysis of the external environment in which the organisation operates as well as the internal environment of the organisation;
- an assessment of the Political, Economic, Sociological, Technological, Legislative, and Environmental trends (the so called PESTLE analysis – also named PEST or STEEP in earlier versions) in the environment in which the organisation operates;
- an assessment of the organisation's Strengths and Weaknesses as well as the Opportunities and Threats facing it (so called SWOT analysis);
- an assessment of the organisation's or industry's strength vs. the attractiveness of the markets and technologies it would like to venture in; and
- the development of a strategic plan and action plan to ensure growth and long-term viability for the organisation or industry.

Research and Development project portfolio

A sustainable research and development (R&D) programme should consist of a balanced portfolio of projects that will address both long-term strategic objectives and short-term immediate needs. Research projects are viewed separately from development projects in the model, due to the fact that they should be managed differently. Chiesa *et al.*[281] describe the difference between research processes and development processes in terms of cultural differences as follows:

- Research:
  - creation of a positive environment (freedom to express scientific opinion and flexibility in reviewing projects);
  - open door policy;
  - accept mistakes; and
  - direct communication
- Development:
  - clear-cut priority setting;
  - identify and solve areas of weakness;
  - play for speed; and
  - formal communication.

Thus research projects are by nature more basic in their approach than development projects and aim to ‘break new ground’. Research projects should therefore be managed with clear strategic direction, but not with schedules that inhibit creativity. Development projects, on the other hand, usually have clear briefs, aims and deadlines as well as tight budgets and should be managed accordingly. Weggeman and Groenveld[282] highlighted the importance of finding management models that are suitable to the research environment and researchers, allowing sufficient room for creativity rather than standard business management and quality control models.

Note: The tight management of research projects through the use of, for example, a lowest-cost tendering system in the RDAC period discussed in Chapter 3, was probably one of the main reasons why the process, in the long run, did not deliver new breakthroughs and in essence became a set of consulting projects rather than strategic research that did not live up to the expectations of the stakeholders.

Implementation and technology transfer

This element of the R&D management system is vital to ensure that research outputs lead to outcomes and eventually impact (see Section 6.4). The importance of this was highlighted in Chapter 2 by the discussion of Roberts' view[10] that innovation has only occurred once exploitation of the new technology has taken place.

Implementation should not be limited to the publication of R&D results, but should include *inter alia* the following aspects:

- dissemination of information and management of information databases;
- design codes, manuals, specifications and procedures;
- conferences, seminars and workshops;
- teaching at tertiary institutions;
- demonstration projects;
- commercialisation of new products;
- community interaction and information sharing; and
- media releases.

In the implementation process, the target audience of the information needs to be identified clearly and the appropriate delivery system used. Figure 6.4 shows a schematic diagram of the interaction of the various elements of the implementation process.

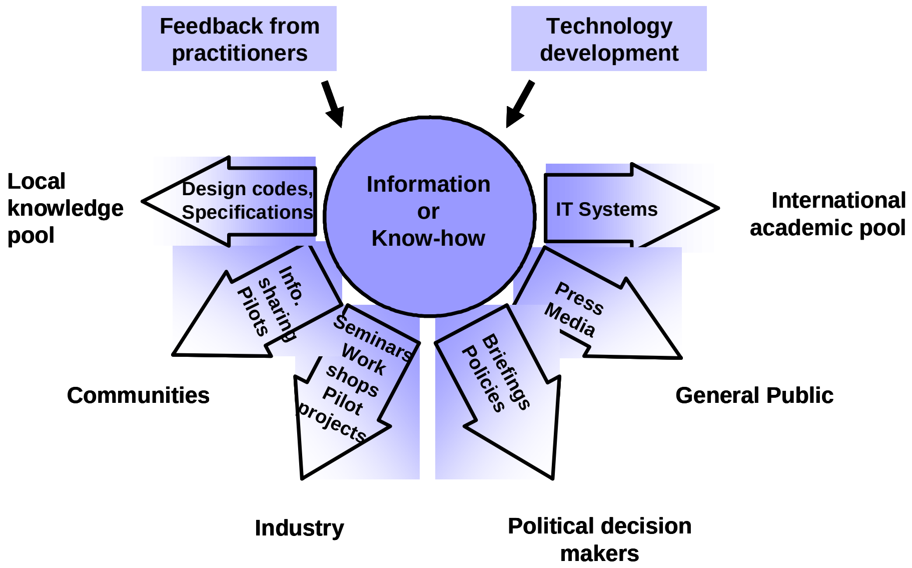

Figure 6.4: Information dissemination in the implementation process

In this figure, the central pool of information and know-how should continuously be added to from new R&D results as well as from continuous feedback from practitioners. This pool of information should then be disseminated to, for example, the following target areas (examples of delivery systems in brackets):

- industry (conferences, seminars, pilot projects);
- communities (information sharing, demonstration projects);
- general public (press releases, articles);
- decision-makers (briefings, policy formulation);
- local knowledge pool (design codes, specifications, models); and
- international academic pool (publications, information management).

The use of appropriate delivery systems in each case is essential to the successful implementation of the technology. Information and Communication Technologies (ICTs), and particularly the Internet, should be taken into consideration in the planning of implementation projects.

Education and training

Education and training of members of the industry are essential to the successful final implementation of technology. Such education should take place at tertiary educational institutes as well as through training of practitioners in industry. Figure 6.5 shows the main elements of this process.

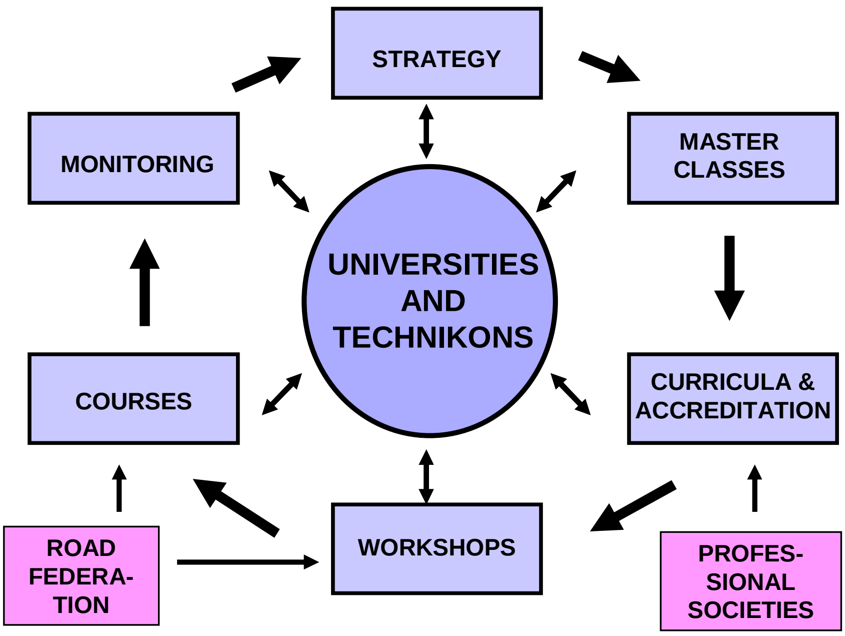

Figure 6.5: The education process

Central to the process are the tertiary education institutions. The main elements of the process include:

- a strategy and policy to ensure that transport technology is addressed adequately at educational institutions;
- the development of courses for master classes in order to transfer new technology and knowledge to lecturers;
- refresher courses and workshops for members of industry; and
- a monitoring process to ensure that the strategy and policy are effective.

The education and training process is vital to the development of the intellectual capacity pool and its value should therefore not be underestimated.

Research effectiveness and impact measurement

The R&D management model must include a measurement process to assess the effectiveness and impact of the programme in relation to the strategic objectives defined initially. This assessment forms the final link back to (and will therefore influence) the strategic focus and direction. The approach to measuring research effectiveness and impact developed in this study is discussed in Section 6.4.4.

Interaction of the elements

The model is a based on a non-linear systems approach which implies that the elements are interlinked and interact with and influence each other. The activities in the elements do not necessarily follow sequentially but can take place non-linearly. As a simple example, the definition of a problem in the strategic process is not necessarily followed by a comprehensive research project. If existing basic knowledge is sufficient, then the process can be short-circuited and a solution developed with no or little new knowledge generation. Thus the process flows from the 'strategy' element to the 'intellectual capacity pool' to 'development' and finally to 'technology transfer'. Sometimes all that is necessary is 're-packaging' of existing knowledge and thus the process will flow from 'strategy' to the 'intellectual capacity pool' to 'technology transfer'. In a slightly more complex example, the outputs and deliverables from the process need to be monitored continuously and measured against the strategic objectives to ensure that the research and development project portfolios are geared to address needs as they arise from the strategic process. Thus the knowledge generation process can follow numerous paths through the model – one of the characteristics of a complex system. The R&D management process should therefore take cognisance of the fact that the individual elements of the process interact with and therefore influence each other. This implies that all the elements of the process should be taken into account at all times. Aspects such as implementation, impact, balance of the R&D portfolio and the intellectual capacity pool should be kept in mind when strategic and detailed project planning take place.

Efficacy in the R&D programme can only be achieved if the process is viewed holistically. The typical linear thinking of problem, research, development, and only then followed by implementation, often leads to rework or solutions that are not practical. The systems approach forces the researcher into ‘reverse thinking’ i.e. starting at the end, visualising the solution and its implementation first to direct thinking at the early stages of planning a project. It is essential to recognise that technology transfer and implementation are much more effective if they form part of the R&D management system.

The process also impacts on the intellectual capacity pool through the development of human resources and expertise. The quality of the intellectual capacity pool, in turn, impacts on the quality of the R&D process - forming a strong positive spiral. The model can also be seen as a ‘wheel of R&D’ which turns around the axis of the intellectual capacity pool. However, if either the intellectual capacity pool or elements of the process are neglected, the consequent negative spiral can cause severe detrimental effects in the programme, as was indicated during the RDAC period discussed in Chapter 3.

Note: The fragmentation that took place in the RDAC period discussed in Chapter 3 had a negative influence on both the R&D process and the intellectual capacity pool. This caused some long-term damage in terms of human resource development which will take some time to recover and rebuild.

Although the proposed model for managing research and the development of technology and knowledge in the road infrastructure sector is a systems approach at the strategic level, its success depends largely on the quality of the underlying techniques and tools at the operational level and the quality of the underpinning data collection and database management as shown in Figure 6.1. These underpinning techniques will be discussed in Section 6.4 below.

6.3.2 The environment around the system

According to Flood and Jackson[74], a system consists of a set of elements which interact with each other and interacts with its environment. This is depicted in Figure 6.6. The environment relating to the main elements is discussed below.

Environment around strategic focusing

During strategic planning the most important factors to be considered are:

- the input into the R&D process by stakeholders including organisations in the public and private sector as well as in academia and the research environment;
- the input into the R&D process by stakeholders such as users of technology, communities and the tax payer;
- current and likely future technology trends; and
- the identification of current and future needs for R&D, technology development and solutions, through a facilitated process.

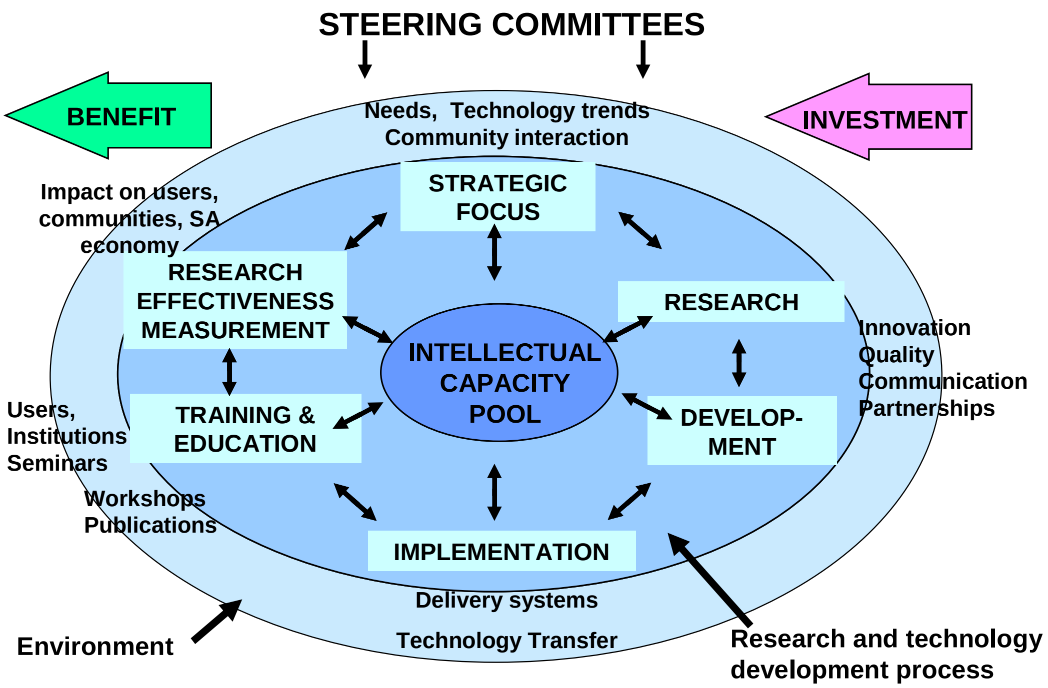

Figure 6.6: The environment around the conceptual management model

Environment around research project portfolio

During the process of planning and executing a well-balanced portfolio of research projects, the following are essential elements in the environment:

- an organisational culture that will stimulate creativity and innovative thinking;
- the development and maintenance of a human resource pool that provides sufficient critical mass to stimulate innovation;
- the development of an organisational structure that allows for the development of people on multiple career paths, thus allowing senior research staff to grow their career paths separate from the management structure of the organisation;
- the physical layout of the organisation to stimulate effective communication;
- techniques for stimulating innovation in an organisation;
- techniques to ensure that the research and development portfolios are balanced and will address the needs defined; and
- systems to manage and track the generation of new ideas.

Environment around development project portfolio

During the development phase of the R&D process, the emphasis shifts from creativity and knowledge generation to engineering (soft and hard systems), process design, specifications and prototyping. The following aspects pertaining to the 'environment' are therefore essential:

- partnerships with industry in order to ensure that the products or processes developed are in line with industry expectations and are indeed implementable and practical;
- the use of expertise in industry (not necessarily existing in the research organisation) e.g. engineering design and specification development; and
- a quality management system to ensure that the deliverables are acceptable to users and are of a high standard.

Environment around implementation and technology transfer

In the implementation phase the emphasis moves to the packaging of results and to outputs and their delivery into the market place. The following are therefore important aspects pertaining to the 'environment':

- a process to review whether the final product addresses the original need;
- the packaging of products to suit specific needs of specific market sectors;
- the development and maintenance of a suite of delivery systems (e.g. workshops, seminars, conference papers, software, web-enabled systems) to deliver outputs and results into the market effectively; and
- the development of resources (staff, equipment an processes) to achieve the above.

Environment around education and training

In essence education and training can be seen as part of the implementation and delivery systems discussed above. However, R&D in the road infrastructure industry is different from that in other industries in that its main output is the generation of new knowledge and methodology rather than new consumer products. In this process the following ‘environmental’ factors are very important:

- the development and maintenance of a technology awareness programme at school level in order to start developing the young professionals of tomorrow (taking cognisance of demographic drivers);
- a strategic alliance with local tertiary educational institutions to ensure that new technologies and knowledge are taken up into curricula;
- master classes for lecturers at tertiary educational institutions in order to ensure that they remain abreast of new technologies and knowledge; and
- special delivery systems such as ICT-based systems and the Internet in order to ensure ease of access to students and lecturers.

Environment around research effectiveness and impact measurement

One of the most important aspects of the R&D process is to measure the effect of the process at various levels. These could range from the level of the research organisation itself through the level of industry that it is serving to the level of macro economics. Important aspects are:

- the impact and effect on the general public, users of the technology and practitioners;
- the impact of the technology on the industry in which it is being deployed - both practitioners and client authorities; and

- the impact of the technology on a national level mainly in terms of economics and human resource development.

These aspects are discussed in more detail in Section 6.4.4.

6.3.3 Management structures that form part of the R&D management process

The importance of linking the R&D management approach to the industry or sector it is serving was shown in Chapter 3. To ensure that both strategic direction and technical integrity are maintained, steering committees at two levels are suggested: a main steering committee to address the strategic focus and direction, and functional discipline committees to address project formulation and planning.

These committees should be formed under the auspices of government structures in the relevant government departments (e.g. the DoT and SANRAL). It is proposed that the following functional discipline areas be defined:

- transport policy formulation and strategic planning, including transport economics, urban passenger transport, rural transport, freight transport and transport systems;
- transport operations (including road safety and intelligent transport systems);
- maritime and air transport; and
- roads, including pavement engineering, construction (both conventional and labour-intensive construction) and road maintenance.

Main steering committee

The main steering committee should include representatives (possibly the chairperson) of the functional discipline committees, as well as one member representing provinces and one member representing metropolitan authorities. Consideration should be given to the inclusion of non-government stakeholders, i.e. users of transport, educational institutions, research organisations and the private sector. The functions of the main steering committee should be:

- to provide strategic direction for R&D (including ‘hard’ technology development, knowledge generation, and projects to aid decision support and policy formulation) taking cognisance of the needs of the industry and stakeholders;

- to secure sources of funding for the R&D programme;
- to make budget allocations for each functional discipline steering committee; and
- to evaluate the business plans developed by the functional discipline committees.

Functional discipline committees

The functional discipline committees should have representatives of provincial and local governments, experts and users of transport technology, where required. The experts will form teams to plan and guide the R&D process, including paying attention to implementation, dissemination of information, and education and training activities in each focus area. The functions of these committees should include:

- actively managing a process for determining the needs for R&D;
- defining specific fields of R&D that need to be addressed (Technical Focus Areas or TFAs);
- defining objectives for these TFAs;
- determining budget allocations for each TFA;
- submitting business plans to the main steering committee for approval;
- reviewing the overall progress in the functional area and reporting to the main steering committee; and
- managing the delivery and implementation process.

Note: The proposal for steering committees was implemented in CSIR Transportek through the establishment of five Research Advisory Panels that assisted with research direction and also evaluated the quality of outcomes from the Parliamentary Research Programme. The Pavement Research Advisory Committee was initiated in 2003 to co-ordinate research at national and provincial level. This is discussed in more detail in Chapter 7.

These committees are essential to ensure that the R&D programme yields optimum results. However, care must be taken that the system does not become so cumbersome and bureaucratic that it collapses, as was the case in the RDAC programme (see Chapter 3).

6.4 Techniques and tools to support the strategy-level R&D management model

Each of the elements of the conceptual model is underpinned by processes and analysis techniques and tools at the operational level. These utilise databases and information at the basic level. The processes and techniques are discussed below in relation to each of the elements of the conceptual model.

6.4.1 A needs determination process to support strategic focusing

As discussed above, strategic planning is essential to the success of an R&D programme. One of the aspects of developing a strategy for an organisation or industry is to determine their R&D needs. Figure 6.7 shows how the needs-determination process links to the strategic planning process.

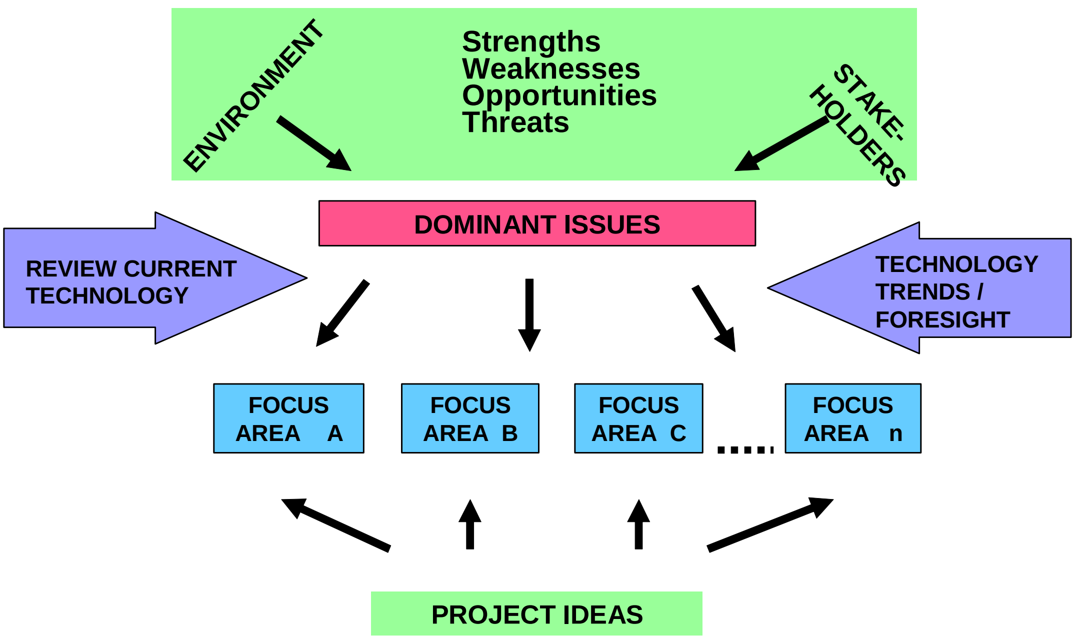

Figure 6.7: The needs determination process

The needs-determination process was developed through interactions mainly with Sabita[xi] and through the process of managing the Parliamentary Grant programme in CSIR Transportek and the Built Environment Unit. The steps in the process are:

(i) An extensive consultation process with selected representatives from stakeholder organisations and groupings (these are the 'lead users' as defined by Von Hippel[91] – see Section 2.5.1). This is a facilitated process during which strengths and weaknesses as well as threats and opportunities to the industry are formulated. The process should take cognisance of the environment in which the road infrastructure industry exists.

(ii) Formulation of the key strategic issues (dominant issues) facing the industry. Key focus areas for R&D can then be distilled from these issues. The process of defining key focus areas should be conducted taking cognisance of existing knowledge, international technology trends and technology foresight studies. This is a top-down strategic planning process.

(iii) The next part of the process consists of the accumulation of innovative project ideas from practitioners in the industry as well as from participants in the R&D process. This is a bottom-up participative process. The project ideas are then categorised into the key focus areas. Room should be made for innovative ideas (wild cards) which may lead to significant new technology advances.

(iv) Finally, objectives and action plans should be determined for each focus area within the overall strategic framework. The project ideas should then be used to develop comprehensive plans that will address the objectives of each focus area.

The 'top-down' strategic planning process which results in the formulation of the dominant issues facing the organisation or industry is as important as the 'bottom up' process. The formulation of the key focus areas that will help the organisation or industry address the dominant strategic issues should also be conducted

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[xi] Mr Rob Vos, technical director at the time, participated in this process

through a facilitated process, but could be achieved using a smaller, more technically orientated group. The focus areas should be clearly linked to the dominant issues. As an example, if job creation is a dominant issue in the road building industry, then labour-intensive construction is likely to be a key focus area for R&D.

The ‘bottom up’ approach is usually facilitated by the use of any of the group techniques currently used by management consultants (e.g. the nominal group technique). During implementation of this work in the Sabita programme, it was shown that experienced facilitators should be used to achieve optimum results (see Chapter 7). The aim of the bottom-up approach is to allow the development of a set of R&D problems, shortcomings or R&D ideas as perceived by professionals in the industry. These problems or ideas are then combined into the key focus areas.

The next step is to develop a focused R&D plan for the programme as a whole and for each key focus area, based on both strategic inputs and the problems and ideas generated by the ‘bottom up’ process. These plans should focus on significant projects that will deliver significant results rather than the plethora of small tasks addressing individual project ideas which characterised the fragmented approach that was utilised in some research programmes in the past. These significant projects can then be addressed properly through the formulation of teams of the best individuals available in the industry, from more than one organisation. This approach is preferable to allocating small projects to a number of organisations which results in the problem of collating the respective results into a comprehensive deliverable and leads to fragmentation.

The implementation of the above approach is discussed in Chapter 7.

6.4.2 The use of technology trees to balance the research and development project portfolio

A sustainable R&D programme should consist of a balanced portfolio of projects that addresses both long-term strategic objectives and short-term immediate needs. The prioritisation and final selection of projects should therefore include an analysis of the balance of the project portfolio. Project portfolio management can be conducted using a number of techniques such as those discussed by Roussel[81]. One of the new tools developed for this thesis is the technology tree. The technology tree is a powerful tool to address issues such as balance and project priorities. Figure 6.8 shows a simplified schematic diagram of a technology tree. Detailed examples of technology trees are given in Chapter 7.

The technology tree consists of the following levels:

- key focus areas and their related identified needs as determined from the needs-determination process;
- key products or key solutions to address the identified needs;
- a technology platform;
- applied technologies or capabilities;
- base technologies; and
- basic science and infrastructure.

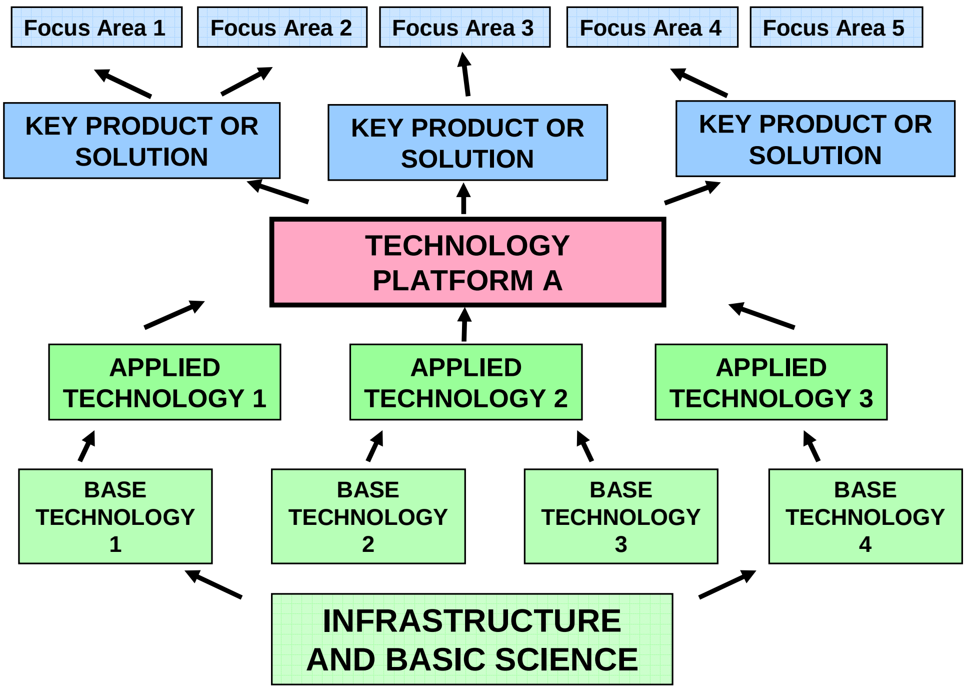


Figure 6.8: Simplified schematic of a technology tree

Definitions of terminology used in the technology tree diagram are given below.

Key focus areas (needs) are obtained from the needs-determination process and should address the strategic dominant issues facing the industry. An example of a strategic dominant issue for the roads industry in South Africa is job creation and the supporting needs focus area is labour-intensive construction.

Key products or key solutions are integrated knowledge or technology packages to address the specific needs determined. Linking to the above example of labour intensive construction, these could, for instance, be design methods for user-friendly asphalt materials, small compaction equipment and a catalogue of LIC road pavement designs and specifications.

Technology platforms

The technology platform forms the centre of the technology tree. As discussed in Chapter 2, Utterback[162] defines a technology platform as an innovative process, methodology or base product that facilitates the development of a family of products or solutions to fulfil a set of market needs. The advantage of technology platforms is that they focus the R&D effort on significant developments that will have a significant impact. The function of the technology platform is to ***integrate*** the research and development activity taking place at the lower levels of the tree and to add commercialisation processes and delivery systems to these activities in order to ensure effective key solution development, technology transfer and ultimately the desired impact. The importance of integration in large, complex projects is also emphasised by Nehme *et al.*[283] – particularly the role of a systems integrator with a high level of expertise that integrates the core capabilities of an organisation. The technology platform thus forms the conduit through which several key products or key solutions can be delivered from the same science, engineering and technology base (applied technologies, base technologies and research infrastructure) in a cost-effective manner.

As discussed in Chapter 2, Meyer and Utterback[102] quote the case of Black and Decker's power tool business as an example of the use of technology platforms. In 1970 Black and Decker (B&D) had hundreds of products in the market using more than 30 different motors, 60 different motor housings, and dozens of different operating controls. Each product also had a unique armature. The B&D management realised that, to remain competitive, it would have to decrease its cost of goods by a third. They then embarked on a $20 million development programme to design product families based on a shared platform. The platform consisted of a standard motor that could serve all their power tool needs, standard motor housings and controls and a standardised adhesive bonded armature. Subsequently, each product family was re-engineered (drills, jigsaws, sanders, etc.) and several key products delivered from the same platform. The results were dramatic: a reduction of 50% in product costs, a market share increase from 20% to a dominant share and a reduction in the number of competitors from more than 20 to three.

An example of a technology platform in the road infrastructure sector is construction technology.

An applied technology (or capability as defined by Patterson and Kfir[201]) is the compilation of a number of base technologies in order to form a certain capability or competency in an organisation. Garcia-Muiña and Navas-López[284] state that the development of capabilities based on technological knowledge is considered to be one of the basic foundations of business competitiveness, especially in technology-intensive industries. This level of the technology tree usually also requires significant critical mass in terms of human resources with specialised expertise and knowledge. An example of an applied technology is labour-intensive construction techniques.

Base technologies comprise the basic tools and techniques that support the applied technologies. An example of a base technology relating to the construction platform is quality control methods.

Infrastructure includes research infrastructure such as equipment, software, models, databases and basic science.

Examples of technology trees that make the above definitions clearer are shown in Chapter 7.

The technology tree can be used to obtain a holistic visualisation of the process to develop key solutions and/or products that will address the defined needs. Verhaeghe and Kfir[285] stressed the importance of visualising the innovation and

R&D process to generate a common understanding amongst researchers and stakeholders about the processes and expected outcomes of an R&D programme. A technology tree achieves this end, but in a layered structure that allows the analysis of the balance of the project portfolio as described below.

A technology tree also assists in focusing the planning process on the elements of the technology tree that need attention and then identifying projects to address those elements. It is also a powerful tool to assist with the prioritisation of projects. Examples of technology trees and their use are given in Chapter 7.

As mentioned above, an essential element of a sustainable R&D programme is to balance the portfolio of projects. Statistics of the project portfolio (number of projects, cost of projects, etc.) can be plotted on the technology tree at the various levels. Adding the numbers horizontally will give an indication of the vertical balance in the portfolio (basic work vs. applied work and solutions). Similarly the numbers can be added vertically in order to assess the horizontal balance in the portfolio, i.e. effectively assessing the balance in addressing the respective needs identified. This method of assessing balance raises strategic questions regarding the focus of the programme, thus ensuring that available funding is utilised optimally whilst taking cognisance of strategic objectives.

Technology trees can also be used to focus the planning process on the gaps in the technology tree and on the identification of projects to address these gaps (in contrast to the tendency of researchers to want to work on ‘pet topics’). Technology trees also constitute a powerful tool to assist with the prioritisation of projects based on their importance in the technology tree rather than simply a voting or rating process. In the planning process the logical sequence of projects based on their position in the technology tree (i.e. a project lower on the technology tree supporting a higher-order project) is therefore taken into account.

A further use of technology trees is to assess the quality of the science and technology base and particularly the human resource component by plotting the number and category of researchers in each area on the tree. This indicates areas of low critical mass or areas where too many researchers are active in relation to the identified needs and the strategy, thus allowing enhanced planning of the development or recruitment of human resources.

As described by Utterback[162], technology platforms should be planned into the future thus providing a picture of second and third-generation developments of the same technology family as the technology is improved (see Figure 6.9). This ensures that the development team remains abreast of emerging technologies and it also assists with multi-year project planning. The technology trees supporting the technology platforms overlap at the basic and applied levels, but each of the platforms should represent a distinctive improvement in technology or change in direction of the development. This notion is particularly important in industries where the rate of technology development is very fast (such as the ICT industry). Akella *et al.*[286] emphasise this by stating that it is important to understand that the time factor is a major driver in innovation in technology-based companies but not so much in relatively slow-moving industries – of which the roads industry is one.

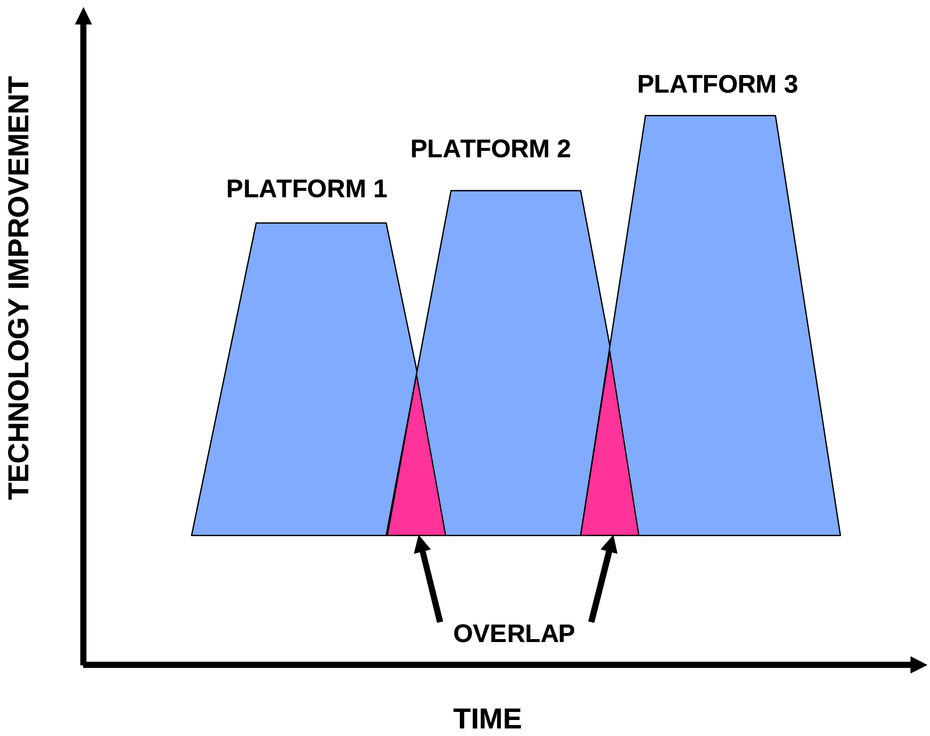


Figure 6.9: Planning of technology platforms over time

Technology trees were used to address issues in the Beyond 60 strategic planning process of the CSIR during 2004 and 2005. The quality of the Science, Engineering and Technology (SET) base of the CSIR and its link to impact and benefits to the community and stakeholders were critically assessed. One of the major benefits of the technology tree tool is the visualisation of the link between the SET base and the eventual need in the market place. This is emphasised by the concept of 'value innovation' as defined by Aiman-Smith *et al.*[287] which provides the link between R&D and what buyers want; it indicates the importance of the link between the early stages and the later stages of the innovation cycle. Value innovation emphasises that R&D alone is not enough for a company to be successful. In a survey of 32 industries, Makri and Lane[288] found that a sound science base is playing an increasingly important role in innovation and therefore growth. In particular, they found that a solid science base supports the development of new technology platforms.

As depicted in Figure 6.10, technology trees were used to develop an understanding of the relevance of basic and applied research (top-down process) by linking these activities to desired outputs, products and key solutions.

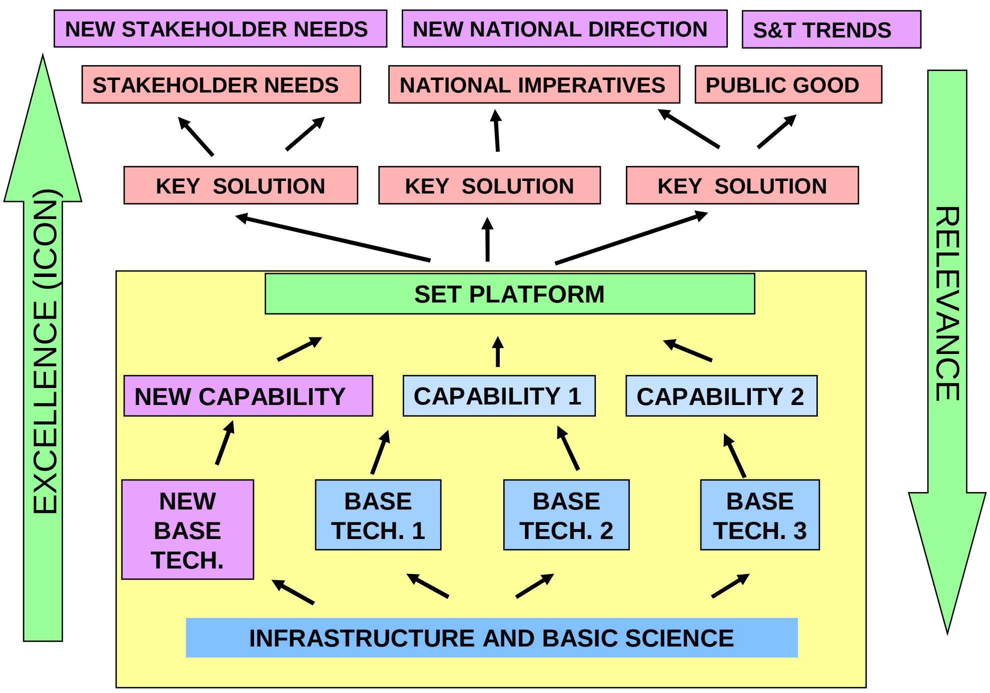


Figure 6.10: Use of technology trees to indicate relevance versus research excellence

This link is essentially a market-pull process. The quality of the SET base (depicted in the yellow block below the platform) was assessed by plotting the capabilities and base technologies in each CSIR Unit (details are given in Chapter 7). The process of developing new capabilities, thus enhancing the SET base and subsequently delivering new cutting-edge knowledge and key solutions, was also plotted. This technology-push process, if successful, will lead to excellence and 'icon status' which is one of the objectives of the CSIR Beyond 60 strategy (see Section 3.5). This technology-push activity may then lead to the creation of new stakeholder needs and even new S&T trends.

As part of an extended literature review conducted for this thesis, the use of the words 'technology tree' as it relates to technology management in an article by Heiss[289] was noted. Although this was published after the first article on technology trees[212] emanating from this work, it is worthwhile to compare the two concepts here. Heiss discusses the use of a concept which he calls a technology tree in Siemens Austria (in the electronics and ICT field) to achieve the following (see Figure 6.11):

- formalising how technologies outside the company are introduced into the company;
- setting up a set of levels of networks ranging from a 'call for network' through an 'expert net: professional' to a 'strategic support centre';
- utilising these networks to operate across borders in the company to develop in-house knowledge about these technologies and then to select the ones that grow and become valuable to the company; and
- thus using the 'technology tree concept' mainly to stimulate communication about new technologies imported into the company - it is *"a driving force for cultural changes towards knowledge sharing, cooperating across the borders of business units, and opening top-down bottlenecks*."

Heiss depicts this as a tree with knowledge networks as the leaves, the branches representing company divisions and the fruit depicting new potential technologies to be incorporated into the company (see Figure 6.11). Therefore Heiss' concept depicts the stimulation of communication about new external technologies whereas the technology tree tool developed for this thesis is a portfolio management tool incorporating concepts such as the technology platform, and a stratified S&T base. Thus the only similarity between the two concepts is the name ‘technology tree’.

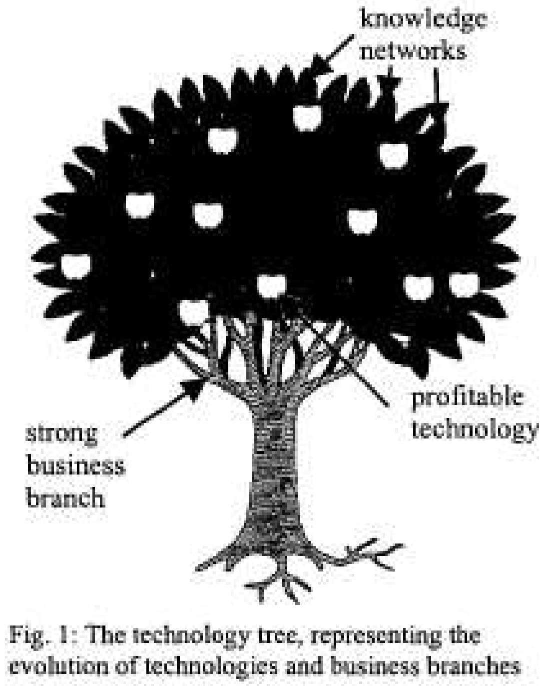


Figure 6.11: Heiss’s ‘technology tree’ concept

6.4.3 The development of delivery systems to support implementation

As mentioned above, the development of delivery systems is essential to the success of implementation of new technology, especially in a field such as the transport industry where the main focus is on the development of knew knowledge and soft solutions rather than on the development of hard products for the consumer market. The process of transferring a new technology into the market place can be categorised into two phases, i.e.:

- the immediate, short-term activity to present the new technology to the industry, typically through seminars, workshops and pilot projects, and
- the longer-term activity of managing information for future reference which is strongly linked to educational processes.

Often implementation is considered to have been completed after seminars or workshops covering the topic have been conducted. However, to ensure ease of access to new information and knowledge, the following additional structures should be put into place:

- management systems and database software for recording the details of projects and their outcomes, including project plans and financial detail;
- processes and funding for producing manuals, design codes and specification documents;
- systems for managing information in electronic format including search engines which allow ease of access; and
- information technology systems, particularly the Internet to allow the technical community and students to access information and technologies.

It is important to realise that the activities related to implementation can often be as costly as the activity of developing the technology and this should be taken cognisance of during budgeting for a systems-based R&D programme.

6.4.4 A research effectiveness measurement system

Background

In the transport field (and the road infrastructure sector) impact measurement is particularly complex because of the diverse nature of R&D, ranging from basic science, materials science and engineering to transport planning research and even social research. It was therefore necessary to develop a unique approach to the measurement of research effectiveness and impact.

As discussed in Chapter 2, research effectiveness is defined as a combination of elements relating to:

- inputs (resources);
- outputs (useful, transferable results);
- outcomes (effects on funders, recipients of outputs, and directly involved stakeholders); and
- impacts (permanent short and long-term result of the outcomes that can be assessed at the global, national, sectoral or company level).

To add value to this study, it was decided to use the CSIR Built Environment Unit as the reference framework for developing the research effectiveness system. The Built Environment Unit was formed during the Beyond 60 restructuring process in 2005 by combining the Transportek and Boutek Divisions of the CSIR. This Unit focuses on the following fields of research:

- planning support systems (including access planning, design of sustainable human settlements, geographic information systems, sustainability science, etc.);
- infrastructure engineering (including pavement engineering and materials, port design, design of structures);
- construction (including conventional and labour-intensive construction and construction materials);
- architectural science (including a focus on schools and hospitals as well as design of sustainable buildings);
- infrastructure operations (including passenger and freight transport, network asset management, intelligent transport systems);
- logistics and quantitative modelling (including logistics analysis, modelling of built environment problems, complexity theory); and
- rural infrastructure and services (including rural access, transport, sanitation, water and energy supply).

Although the diversity of the focus areas above adds a level of complexity to the measurement of research effectiveness, it is considered to provide an excellent opportunity to evaluate the system developed.

Current status in the CSIR

Prior to this study, the process of measuring research performance at the CSIR included the following:

- the setting of Unit level targets for Key Performance Indicators (KPIs), based on the CSIR and Unit strategy and operations plans;
- the aggregation of targets for KPIs at CSIR level;
- the evaluation of Unit-level value derived from five 'return on investment' indicators (see Table 6.1);
- CSIR and Unit-level peer review studies; and
- unit-level anecdotal information gathering of success stories.

The Unit-level KPIs include a number of input measures such as[290]:

- balance of the research programme in terms of Frascati definitions[291];
- research governance issues such as the appointment of a Research Advisory Panel and processes for managing Parliamentary Grant funding;
- distribution of demographics and researchers' qualifications; and
- operational issues such as injury frequency rate and energy consumption.

A limited number of indicators pertaining to research effectiveness are also included. These are:

- number of publications;
- number of patents and technology demonstrators;
- number of organisations collaborated with in research projects; and
- revenue earned from intellectual property commercialisation.

In addition to the above, the value derived from Parliamentary Grant research is also determined through a 'return on investment' calculation (after Walwyn[292]) as shown in Table 6.1 below.

Table 6.1: CSIR measures of value derived from Parliamentary Grant investment

Measure	Equivalent Value (R/Item)
Publication equivalents	500 000
PhD degrees conferred	1 500 000
Patents registered	12 000 000
Royalty income	Same as income
Technology demonstrations	10 000 000
Contract research income	15% of total to count

The above equivalent values were derived from analysis of research programmes at US and South African Tertiary Educational Institutes, as well as the CSIRO in Australia[292]. One of the key indicators is the number of new PhDs conferred. The importance of this indicator was also emphasised by Basu[293]. In an analysis of indicators of science, technology and development in India and in

Asian countries, Basu found a correlation between positive economic growth and a focus on science, engineering and technology. He concludes that the number and quality of SET outputs are directly related to the number of PhDs in a particular country. Walwyn (*ibid*) used the analyses mentioned above to calculate the net present value of a PhD to the economy of a country on the basis that the differential income of such a person through his or her lifetime is an indication of the value of a PhD to the economy.

However, Walwyn's measures (see Table 6.1) contains only limited evaluation of research effectiveness as defined above (including output, outcome and impact). The current processes for evaluation of research activity are mainly based on input measures, governance issues and bibliometrics. Whereas this is a very good start, outcome- and impact-orientated measurement needs to be added to obtain the full picture of research effectiveness. In the work conducted in this study, these values were used as benchmarks for developing a more comprehensive research effectiveness measurement tool.

Proposed approach to monitoring of research effectiveness

General principles

Rather than focusing on input, output and impact separately, a system for evaluating total research effectiveness was developed. Some of the aspects of evaluating research effectiveness were already included in the CSIR and Unit level KPIs as well as the 'Return on Investment' evaluation described above. Additions to current practice at the CSIR to achieve a more holistic evaluation of research effectiveness are suggested here. This notion is also confirmed by Dissel *et al.*[130] who states that financial analysis on its own is insufficient and that many companies supplement quantitative models with techniques that incorporate qualitative assessments using scoring models.

Cozzens[294] reported on the assessment of US federal research programmes and listed one of the lessons learnt from a history of more than 20 years was that the simpler the system the better. Furthermore she notes that the link between research outcomes and socio-economic impact is complex and difficult to determine. Osawa and Yamasaki[295] also noted that R&D performance indices are difficult to develop and that they should be easy to understand and commonly understandable to the R&D and other divisions.

It should be noted that the system developed in this work was purposefully not designed to be complicated in order to facilitate its use.

As discussed in literature survey in Chapter 2, effectiveness and impact assessment is not an easy task nor is it an exact science. The US National Research Council of the National Academies states[296]:

> "*Industry has long used metrics to gauge progress in meeting business objectives and to identify where adjustments should be made to optimise performance and increase profits. Federal agencies are increasingly relying on metrics, either to manage programs or to increase their accountability to Congress and the public. The latter motivation was strengthened by the Government Performance and Results Act of 1993, which required federal agencies to set strategic goals and to measure program performance against those goals. Finally, academia uses metrics to supplement peer evaluation in decisions to hire or promote faculty members, allocate resources among departments, or compare the performance of departments at different universities*."

Based on a comprehensive study, the US National Research Council defined the following principles for development of metrics related to research effectiveness:

- Good leadership is required if programmes are to evolve towards successful outcomes.
- A good strategic plan must precede the development of metrics. Such a plan includes well-articulated goals against which to measure progress as well as prioritisation of these goals.
- Good metrics should promote strategic analysis. Demands for higher levels of accuracy and specificity, more frequent reporting, and larger numbers of measures than are needed to improve performance can result in diminishing returns and escalating costs.
- Metrics should serve to advance scientific progress or inquiry, not the reverse. Good measures will promote continuous improvements in the

programme, whereas poor measures could encourage actions to achieve high scores (e.g. ‘teaching to the test’) and thereby lead to unintended consequences.

- Metrics should be easily understood and broadly accepted by stakeholders.
- Promoting quality should be a key objective for any set of metrics.
- Metrics should assess process as well as progress.
- A focus on a single measure of progress is often misguided.
- Considerable challenge should be expected in providing useful outcome or impact metrics for science.
- Metrics must evolve to keep pace with scientific progress and programme objectives.
- The development and application of meaningful metrics will require significant human, financial and computational resources.

In this work it is therefore proposed that impact assessment forms part of a research effectiveness evaluation process that addresses process, input, output, outcome as well as impact.

However, it is important to note that some elements of the system will be exact measurements and can therefore be quoted as such, whereas some will be indicative of nature and can only be used to improve internal strategic planning processes. The main purpose of this work is to improve the strategic planning process and care should be taken in ‘claiming’ impact and communicating results to stakeholders.

The following elements of evaluation should therefore be part of the research effectiveness monitoring process:

Process measures

These entail the evaluation of the processes used with respect to the following:

- the strategic planning process and its link to stakeholder needs, national priorities, market trends, science and technology trends and foresight studies;

- the development of a research agenda based on the above as well as on consultation with stakeholder groups, forums, the Research Advisory Panel, collaborating research partners, etc.;
- the management of the portfolio of research projects using a portfolio approach to ensure the appropriate balance and to maximise outcomes and eventual impact; and
- project management and governance issues such as managing overheads and running expenditure per project, timely delivery of outputs, quality of delivery, etc.

In the CSIR, the process measures are, to a large extent, catered for in the current KPI set of the Units. However, portfolio management and project management issues need some attention.

Input measures

These entail the evaluation of the resources employed in the R&D process, including the following:

- the human resource component – number, qualifications and transformation issues;
- the balance in the application of research funding for the respective Frascati categories of research[291];
- the amount of funding employed for research infrastructure; and
- the number of collaborative partnerships.

In the CSIR, these factors are also catered for in the KPI process.

Output measures

Output measurement should focus on:

- bibliometrics (number of articles, papers and books);
- other important publications (national design guidelines, selected CSIR reports approved by the internal SET leadership committee, etc.);
- selected contract R&D reports (approved by the internal SET leadership committee);
- number of new post-graduate qualifications;
- patents; and

- technology demonstrators.

In the CSIR, these factors are mostly accounted for in the current KPI process, but measures should be put into place to monitor publications and reports other than journal articles, refereed conference papers or books.

Outcomes measures

Outcomes are more difficult to monitor and record than outputs. It is suggested that the outcome of an R&D portfolio should be investigated annually through the following:

- specific outcomes evaluation projects that will provide qualitative and quantitative analysis of the results of a multi-year research programme;
- peer review processes that should include reviews by, for example, a research advisory panel;
- interaction with key stakeholders through an anonymous questionnaire focused on the outcomes of the R&D process; and
- quantification of outcomes through a set of measurements and indicators as discussed below.

Impact assessment

Impact assessment is the most difficult part of the R&D effectiveness evaluation process since it may sometimes take years or even decades for real impact to manifest. The following are suggested:

- retrospective studies to determine current impact resulting from R&D over the past 10 to 15 years;
- the development of a database to record events to facilitate future evaluation of impact; and
- the development of some impact indicators that can be used in trend analysis to inform the strategic management process.

General aspects of the system

In general, the following should be considered:

- the system should mainly be used for internal strategy planning instead of for ‘claiming’ impact – the results from anecdotal and qualitative analysis from retrospective studies can be used for public release;

- multi-year trend analysis should be used and the emphasis should be on determining the trend rather than on obtaining 100% accuracy of the data;
- to compare tangibles with intangibles and to do trend analysis, the use of an 'equivalent value point' system should be considered; and
- multi-level analysis based on the same database, but approached differently for different users, should be implemented.

Levels of data analysis and presentation

Research effectiveness analysis results can be used at various levels to assess the performance of a research programme. To make it possible to use the system for both strategic planning purposes as well as reporting to stakeholders, the following three levels are considered relevant:

- the political level, where anecdotal and qualitative information is used to provide feedback to decision-makers about the success of a research programme;
- the strategic level, where the above as well as quantitative data and indicators play an important role to inform strategic level decisions about future direction; and
- the project level where all data are analysed at project or portfolio level to understand trends and lessons learnt, and to provide feedback to researchers to improve their research processes and outputs.

In a research effectiveness analysis system, the above analysis should be supported by a comprehensive database with information on input, output and, outcome, as well as impact. The data and analysis can then be presented to suit the level (as discussed above) that is being addressed. The building blocks of the system are data collected at project level and then processed and collated at portfolio level to calculate indicators.

Trend analysis in impact assessment

Guidi[297] as well as Chiesa and Frattini[145] emphasise that a critical choice in the design of a performance management system for R&D is the identification of the objectives of the measurement system. As indicated above, the most difficult part of the research effectiveness monitoring process is impact assessment. It is proposed that impact assessment be conducted mainly to inform the strategic investment decision and not to 'claim' impact. Therefore the analysis and presentation will focus on strategic trend analysis and portfolio analysis over the lifetime of a portfolio of projects. Suomala[298] emphasises the importance of assessing products over the whole life cycle in order to determine performance. This implies that the development needs to be monitored from the early stages of discovery through to launch of the product and eventually the demise of the product. The view of product performance measurement in conjunction with life cycle principles is likely to reduce the short-termism typically associated with new product development.

Even so, it is difficult to compare tangible with intangible results in an impact analysis process. One way of addressing this problem is to use an equivalent value point system (similar to that which is currently used in the CSIR to monitor the value derived from Parliamentary Grant investment) and to analyse the changes in equivalent points based on trend analysis. These trends can then be used to inform strategic management and investment decisions as well as to develop indicators that can be used at the political level. The advantage of this approach is that the focus is not on the accuracy of the measurement, but rather on the trends. This fact prevents endless arguments about the exact way in which the impact should be measured. Trend analysis also prevents strategic decision-making based on a singular situation during a specific time window, thus providing greater depth of understanding of the performance of a portfolio of projects.

The general trends that are important for the strategic management process fall into the following categories:

- financial outcomes and impact at national and stakeholder level;
- human resource development;
- science, engineering and technology excellence enhancement;
- social impact;
- environmental impact; and
- technology transfer and knowledge dissemination.

The approach should also be to monitor indicators where the equivalent value is normalised by dividing by the relevant input parameters. Wang and Huang[299] suggest a lag of three years between R&D investment and output measurement. This is also in line with the CSIR's current three-year planning cycle and it is proposed that a similar approach be used here, i.e. that the ratio of the R&D effectiveness calculation and the R&D investment in a portfolio of projects three years prior be used as an indicator of R&D effectiveness.

It is proposed that initially the following indicators be used at the macro level:

- economic impact score/research Rand;
- human resource development score/research Rand;
- score for science, engineering and technology enhancement in the CSIR/ Parliamentary Grant Rand (specific to the CSIR strategic planning process);
- science, engineering and technology enhancement scorer/number of researchers;
- social impact score/research Rand;
- environmental impact score/research Rand; and
- technology transfer score/research Rand.

As mentioned above, the degree of difficulty in measuring the above factors varies significantly. Generally, it is much easier to measure at the organisational level than at the macro level. Similarly, technological impacts and financial impacts are usually easier to quantify than social impact. As such, the development of a research-effectiveness (RE) measurement system is a difficult task and the accuracy and applicability of any system can be questioned. Therefore the emphasis is not on the actual values obtained from the system, but rather on the monitoring of changes and trends in scores and indicators that can be used to direct the strategic planning and investment decision process.

As indicated in Figure 6.12, the important aspect is whether the indicator trend is increasing, remaining the same or decreasing, and not the actual value of the indicator. Figures 6.13 to 6.15 show schematics of trends for specific project types. It is important to realise that the type of project should be taken into consideration when comparing projects for making the investment decision.

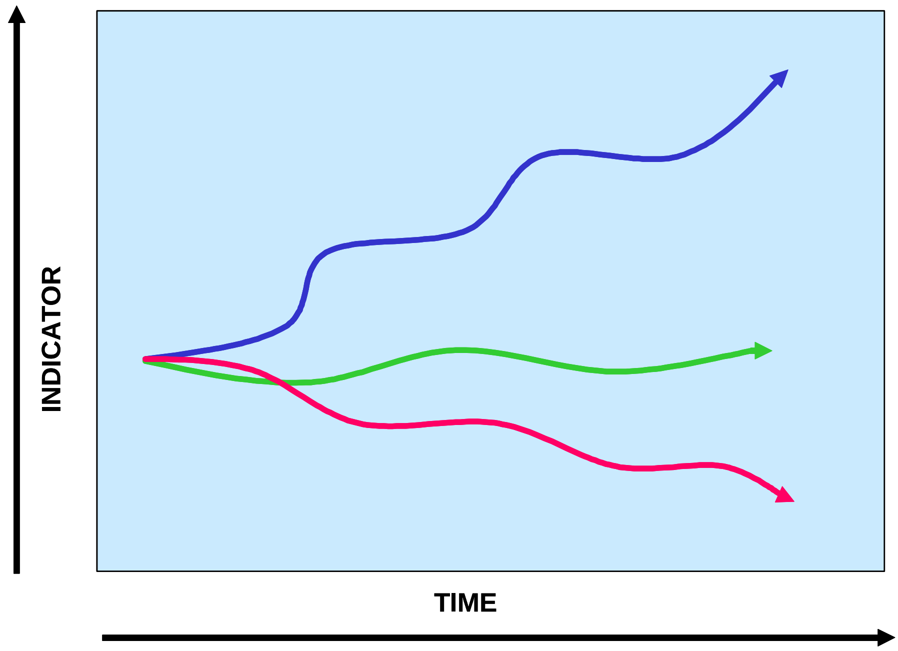


Figure 6.12: Schematic of indicator trends

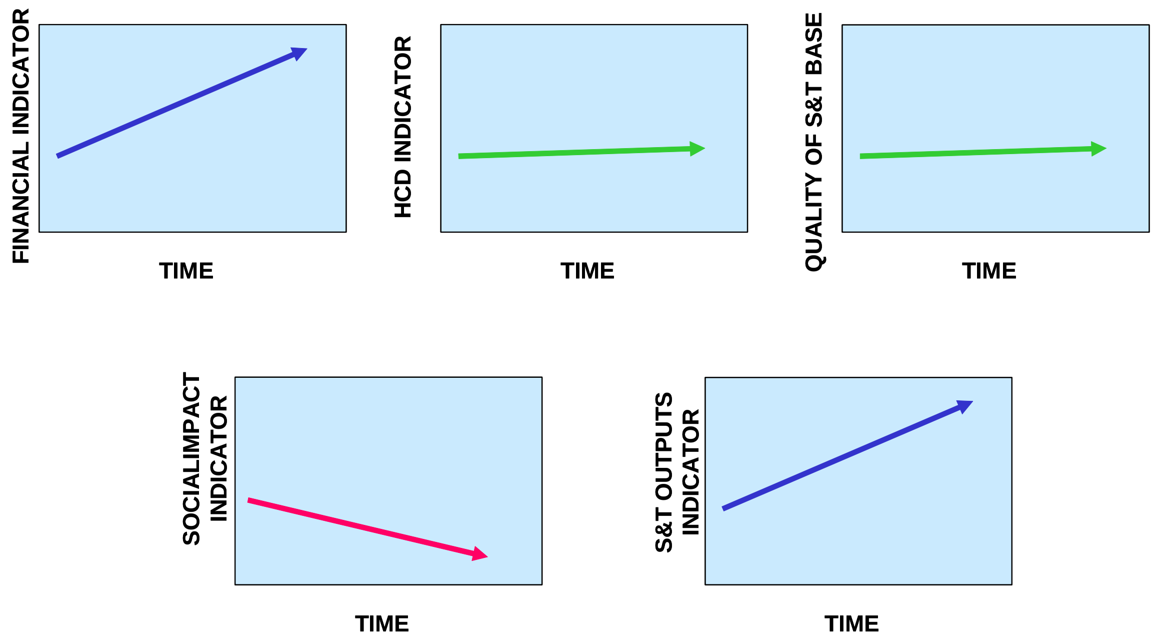


Figure 6.13: Example of a typical project focusing on income generation

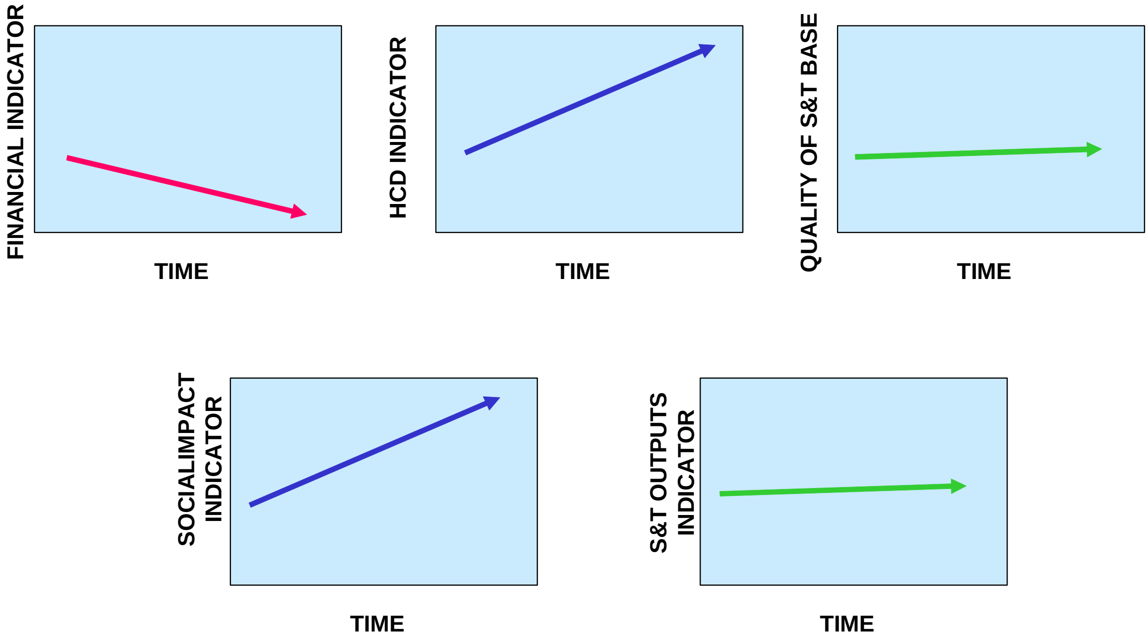


Figure 6.14: Example of a typical project focusing on social impact

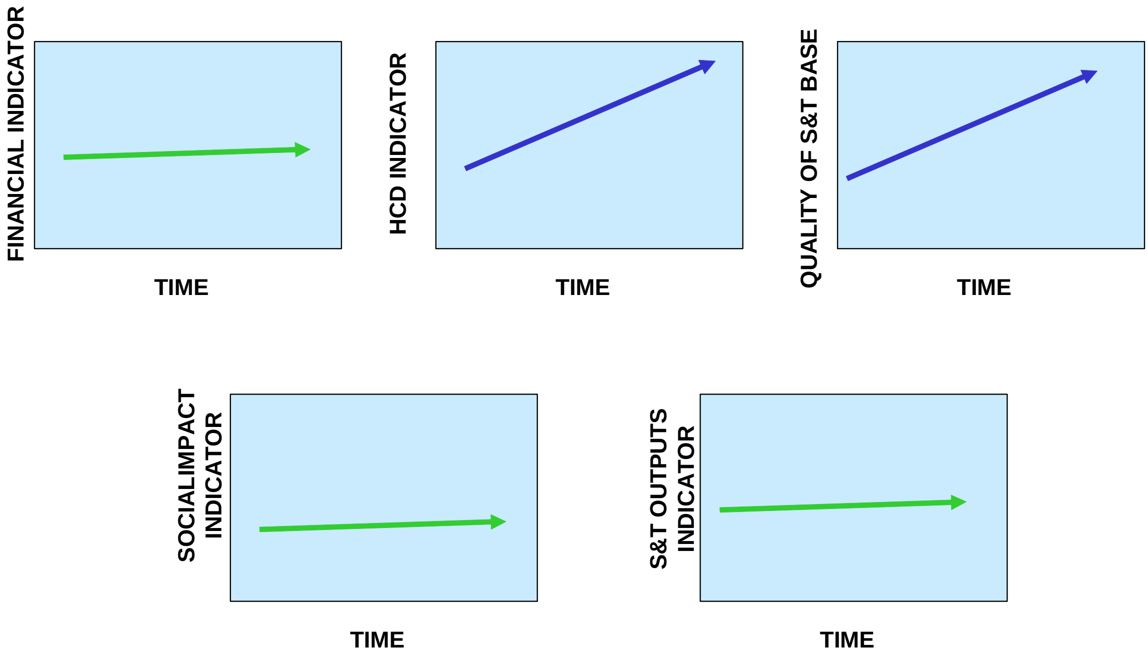


Figure 6.15: Example of a typical project focusing on Strategic Human Capital development

Proposed scoring system

In considering the development of an equivalent point scoring system, two issues need to be addressed:

- the relative value of various factors measured (e.g. 1 patent = 8 PhDs as in the current CSIR system), and
- whether the relationship is linear or non-linear (e.g. if one patent equals eight PhDs then should two patents be worth sixteen PhDs or should it be more or less?).

For the purposes of this discussion, both the linear and non-linear relationship approaches were considered and these are briefly discussed below.

Non-linear relationship approach

If it is assumed that the relationships between factors measured (e.g. bibliometrics, PhDs, patents, savings to industry, foreign income earned, etc.) are non-linear, then one approach to the measurement problem is to define discrete intervals of equivalent points and then decide on the targets in each interval for each factor. This approach was recently tried in the CSIR Built Environment Unit but was found to be too complicated. The advantage of such an approach is that more accuracy can be achieved in terms of the ratio between factors. However, the approach leads to some anomalies, particularly where the unit counts are relatively low. For example, it forces ratings into discrete intervals and one, two and three PhDs both score the same value. In addition, one extra PhD, i.e. moving from three to four PhDs, causes a jump to the next category of equivalent value. It is therefore proposed that for now a linear relationship approach should be used.

Linear relationship approach

For the purposes of this study it was therefore assumed that the relationships between factors measured are linear. The factors can of course be weighted to take cognisance of specific strategic objectives in the shorter term. The basis of the work conducted here was to develop a set of ***perceived equivalent value*** indicators that relate to the value of outcomes and impacts as perceived by the stakeholders of the Built Environment Unit. The approach was to develop an initial set of potential measurements or indicators based on existing practice, the literature review, the work conducted by Walwyn[292] and discussions with key staff and then to verify these values through discussions with the CSIR Built Environment Unit Research Advisory Panel (RAP). The proposed set of measures is therefore a form of a Balanced Score Card as discussed in Chapter 2 (Bremser and Barsky[124] and Kaplan and Norton[300]). Yawson *et al.*[301] described the use of a Balanced Score Card approach to measure the performance of the Food Research Institute which is a unit in the Council for Scientific and Industrial Research in Ghana. This organisation is very similar to the CSIR in South Africa and is faced with similar problems of research funding, delivery of research output and commercialisation of products. They have found that the approach provides a good basis for setting organisational goals and for determining R&D performance targets.

Brent and Pretorius[302] emphasised the importance of including sustainability concepts in technology management practices, thus incorporating the three pillars of sustainability (economic issues, environmental issues and social issues) into technology management. It is important to incorporate these aspects into a research effectiveness measurement tool.

From the above analysis, the following categories of metrics were suggested:

- *financial metrics* to assess direct and indirect return on investment as well as the stimulation of economic growth;
- *strategic human* capital development to assess the success of the R&D programme in achieving this strategic goal for South Africa;
- *quality of the SET base* to assess the potential of the programme to deliver cutting-edge solutions;
- *SET outputs* to assess the quality of the outputs from the R&D process;
- *social impact* to assess the potential benefit to a range of stakeholders; and
- *environmental impact* to provide an assessment of the contribution of the R&D process to sustainability.

These categories are therefore a mixture of indicators of input, output, outcomes and impact issues.

An initial list of measurements and their equivalent points were developed and then discussed in a facilitated work shop with the CSIR Built Environment's Science, Engineering and Technology (SET) committee which consists of 15 senior researchers from the Unit. In this process the number of indicators was reduced from an initial 42 to 26 and the SET committee rated the indicators individually in terms of their perceived value. As a second step, the reduced list of indicators was then rated in terms of their relative equivalent value by the BE Unit Research and Advisory Panel (RAP) through a questionnaire and subsequent discussion. The RAP consists of academics and practitioners in the built environment sector. Appendix E (see companion document) shows the questions asked.

The final result of the exercise is shown in Table 6.2. This table shows the average of the rating by six people on the Built Environment RAP and six people on the Built Environment SET committee. The standard deviation of the ratings is also shown. It can be noted that in some instances there was a high degree of variance in the ratings. It is therefore proposed that the ratings in Table 6.2 be used as initial values, and that further work be conducted through, for instance, a Delphi process[188] to refine the relative scores.

To enhance the understanding of these values, typical current scores in the CSIR Built Environment Unit are also shown. The last column in the table shows the equivalent number of PhD degrees (based on the CSIR benchmark that a PhD degree is equivalent to 1.5 million points).

As can be noted from Table 6.2, it is proposed that some factors should be monitored annually and some calculated cumulatively after retrospective studies have been done. Trend analysis will then be conducted to support strategic decision-making.

The research effectiveness measurement system of the Built Environment Unit as designed in this work is therefore based on the following:

- the development of a score card in which the concept of equivalent scores is used to make it possible to compare scores and indicators in and across a number of categories (e.g. to be able to say that x number of papers are equivalent to y number of patents or to z percentage of R&D contract income);

- the calibration of the scores based on the perceived value (to researchers, stakeholders and users) of categories of research outputs, outcomes and impacts; and
- the monitoring of the trends in the change in these scores and indicators.

The equivalent scores are defined as the 'equivalent Rand value' of the achievement as perceived by stakeholders, e.g. researchers, practitioners and academics.

The data required for the indicator analysis can be recorded in the following ways:

- project-level recording of inputs, events, outputs and anecdotal success stories;
- portfolio-level retrospective research effectiveness analysis projects to determine outcomes and impacts and to collect anecdotal information;
- unit-level recording and analysis of Human Resource data, research infrastructure data, citations, etc;
- peer-review exercises (including evaluations by the RAP) to validate processes, output and outcome information as well as impact assessment; and
- research effectiveness analysis studies (three-year cycle).

Table 6.2: Final result of perceived equivalent value points

Factor	Average	Std Dev	CoV	Final Value	Typical Result	Score	PhD Eq.
CAT. 1: FINANCIAL INDICATORS							
Contract research income to CSIR	15	0		15%	80 000 000	12,000,000	8
Royalty income to CSIR	100	0		100%	1 000 000	1 000 000	0.7
Estimated savings to government and industry	21	10	48.63%	21%	50 000 000	10 500 000	7
Estimated business increase to industry	18	6	32.21%	18%	20 000 000	3 600 000	2.4
CAT. 2: STRATEGIC HUMAN CAPITAL DEVELOPMENT							
No. of PhDs conferred	1 500 000	0	0.00%	1 500 000	2	3 000 000	2
No. of people trained p.a. (external to CSIR)	12 108	11 782	97.30%	12 000	300	3 600 000	2.4
No. of masters degrees conferred	619 615	234 196	37.80%	600 000	3	1 800 000	1.2
No. of new professional registrations	407 083	285 748	70.19%	400 000	2	800 000	0.5
CAT. 3: QUALITY OF SET BASE							
Value of research infrastructure and equipment	15	0	0.00%	15%	60 000 000	9 000 000	6
Total unit citations of publications	3 906	2 787	71.36%	4 000	1 000	4 000 000	2.7
No. of external co-authored publications	75 840	54 833	72.30%	75 000	25	1 875 000	1.3
Committee memberships & keynote addresses	96 880	85 176	87.92%	100 000	20	2 000 000	1.3
CAT. 4: SET OUTPUTS							
Peer-reviewed conference paper	250 000	0	0.00%	250 000	40	10 000 000	6.7
Paper in refereed journal	500 000	0	0.00%	500 000	20	10 000 000	6.7
Book chapter	500 000	0	0.00%	500 000	5	2 500 000	1.7
PCT international patent	12 000 000	0	0.00%	12 000 000	1	12 000 000	8
Techn. demonstrator international application	10 000 000	0	0.00%	10 000 000	2	20 000 000	13.3

Factor	Average	Std Dev	CoV	Final Value	Typical Result	Score	PhD Eq.
CSIR-published technical report	210 833	264 180	125.30%	200 000	40	8 000 000	5.3
National design guideline	3 454 545	1 947 662	56.38%	3 500 000	1	3 500 000	2.3
South African provisional patent	2 320 833	1 593 275	68.65%	2 300 000	1	2 300 000	1.5
Technology demonstrator local application	4 729 167	2 124 898	44.93%	4 700 000	4	18 800 000	12.5
CAT. 5: SOCIO-ECONOMIC INDICATORS							
Estimated no. of external jobs created (direct)	6 215	6 102	98.17%	6 200	500	3 100 000	2.1
No. of significant socio-economic projects where technology is deployed	1 741 667	1 349 974	77.51%	1 700 000	2	3 400 000	2.3
Rand value of socio-economic projects where technology is employed	18	6	35.04%	18%	50 000 000	9 000 000	6
CAT. 6: ENVIRONMENTAL IMPACT							
No. of significant environmental projects where technology is employed	1 500 018	2 061 540	137.43%	1 500 000	1	1 500 000	1
Rand value of environmental projects where technology is employed	15	4	29.81%	15%	15 000 000	2 250 000	1.5

Definitions:

Peer-reviewed conference paper is as per the Department of Education policy[330]

Paper in refereed journal is as per the Department of Education policy[330]

Book chapter is as per the Department of Education policy[330]

Patent Co-ordination Treaty (PCT) patent filing is a co-ordinated process to obtain a patent subjected to examination

CSIR-published technical reports are important reports published by the CSIR on approval of a Unit Director

National design guideline is a design guideline prepared by the CSIR under the auspices of a peer review committee and published by a government department or industry organisation for national use

South African provisional patent is a local patent filing (non-peer-reviewed)

A technology demonstrator is a hardware or software solution based on a significant multi-year research project (value of investment more than R2 million), the application of which has been demonstrated in government or industry

Applying the system at various levels

The above approach should of course be applied with care so as not to create unwanted behaviour. One example of such behaviour is the use of these trends to set performance targets for individuals which can lead to superficial over-emphasis of certain aspects to the detriment of others. Table 6.3 gives a summary of the proposed information reporting and indicators at the project/thrust[xii], strategic and political levels.

Implementation of research effectiveness measurement system

The use of the above system will involve significant effort and it is suggested that progress towards full implementation be achieved through the following steps:

- use the simple data form for collecting information about projects as part of an official project closing-down procedure;
- develop a database to manage the information and develop an electronic interface for data collection;
- process the first round of data and refine data requirements;
- ensure that project planning takes cognisance of the research effectiveness assessment procedure and sets targets for projects at the initiation stage;
- define and complete an initial retrospective project to analyse past performance and determine the baseline status; and
- review the efficacy of the system and refine where necessary.

[xii] A thrust comprises a group of related technologies and their offerings (products and services) which are offered to the market place and are managed as an entity.

Table 6.3: Proposed information reporting and indicators

	Project / Thrust level	Strategic level	Political level
Input	Collaborative partnerships; Frascati category split; link to strategic objectives; project level detail.	Human resource profile; portfolio balance (e.g. in terms of Frascati categories); funding for research infrastructure; portfolio investment information.	No additional input information.
Output	Bibliometrics (number of articles, papers and books related to project); other important publications and contract R&D reports as described above; number and class of patents; number and class of technology demonstrators[xiii]; lessons learnt; number of educational packages and interventions; number and value of active collaborations at project level.	Bibliometrics (number of articles, papers and books related to focus areas); other important publications; selected contract R&D reports; patent portfolio analysis; technology demonstrator portfolio analysis, HR profile and demographics, number and value of active collaborations at focus area or portfolio level.	Selected ‘flagship’ publications (at sector level), e.g. annual State of Logistics Report; selected contract R&D reports with political impact; high-level HR profile and demographics indicators.

[xiii] A technology demonstrator is a significant novel technology that has been developed over a number of years and the application of which has been demonstrated in industry.

Outcome	Financial information on additional contract R&D and income generated from intellectual property; industry financial gains and savings; exports; number of industry applications of technology and value thereof; technology transfer indicators.	Financial information on additional contract R&D and income generated from intellectual property at portfolio level; portfolio analysis of technology transfer indicators; portfolio output balance; aspects of outcome and impact trend analysis.	Strategic-level financial indicators; strategic-level technology transfer indicators
Impact	Recording of basic impact data; special retrospective projects to assess impact.	Outcomes and impact trend analysis and indicators, special retrospective projects to assess impact.	Strategic-level social impact indicators (e.g. job creation, education); strategic-level financial impact indicators
Proposed indicators	Trend analysis of factors in Table 6.3 at thrust level (excluding S&T indicators which are recorded only at the organisation level).	Trend analysis of all categories in Table 6.3 at organisation level and thrust level.	Anecdotal information and qualitative statements regarding outcomes from research; HR profile changes normalised with research Rand; estimation of industry benefit normalised with research Rand; technology transfer statistics.

6.4.5 Evaluation of the decision support tools in the systems paradigm

Cilliers[79] and Geyer[73] discussed the characteristics of a complex system (see Section 2.3.3). The technology tree tool (see Section 6.4.2) displays many of the characteristics of a complex (or cybernetic) system in the following way:

- The technology tree tool consists of a number of elements that interact with each other and are dependent on each others performance or behaviour.
- There are feedback loops (e.g. the top down process as discussed above) that influence both the content of the tree as well as the links between the elements of the tree.
- A small event (e.g. an error in basic research or a new discovery) low in the technology tree may have a significant impact elsewhere in the tree.
- The technology tree is a 'living' tool and its repetitive use enhances the content of the tree as well as the expertise of the observer (which is part of the complex system). This also means that the technology tree represents a history over a number of years – it has a 'memory'.
- The nature of the interactions between the elements, particularly in the integration of applied technologies to deliver a specific key solution, determines the outcome (the characteristics of the final product).

As discussed by Pretorius and De Wet[75] the technology tree also displays a hierarchy and structure. This implies that the nature of the technology tree resembles many of the characteristics of a complex system.

Similarly the needs determination tool (see Section 6.4.1) involves many players that interact with each other. Repetitive use of the tool provides feedback to stakeholders on the success of the R&D process and leads to redirection of the process – thus the process has a 'memory.' Small events such as the recognition of a new need or opportunity (often recognised by only one of the stakeholders) can have a large effect in terms of the strategic direction of the R&D programme.

As discussed by Geyer[73] the model and tools can be seen as a system with sub-elements that form a hierarchically nested set of systems that interact with each other. These two tools thus display the nature of a complex system and therefore are eminently suitable as part of a larger R&D management model and process that is based on systems thinking.

6.5 The investment decision

One of the most important issues in R&D management is how to invest funds to yield optimum returns. In the manufacturing sector the focus is mostly on increased profits and therefore approaches such as real options analysis are used. According to Rese and Baier[176] a real options approach allows companies several developmental paths and outcomes in order to provide flexibility on final decisions to management at a stage as late as possible in the development process. This assists in minimising investment risk in a volatile market. In developing new knowledge and engineering know-how, the notion of planning more than one path to arrive at the research objective could be useful in selecting the right approach.

Linton *et al.*[303] describe the use of data envelopment analysis (DEA) to prioritise and select research projects. The system usually uses input parameters such as product life cycle, intellectual property life cycle, and required investment and output measurement parameters focusing on three net present value calculations based on the most pessimistic, most likely and most optimistic scenario. The method is more applicable to a portfolio of a large number of potential research projects, and in such cases is used to stratify the projects into levels of similarly efficient frontiers. This allows the categorisation of a large number of projects into several groups that are not easy to compare so that projects can be compared with each other on an equal footing. As can be seen from the input and output measures, the method, however, focuses mainly on research projects aimed at developing hard products for a consumer market.

However, a more comprehensive and holistic focus (other than financial results) is required in the road-building industry utilising decision factors that would cover the whole impact sphere of R&D and therefore should include a number of decision factors that address public good, technological progress, portfolio management aspects as well as some financial considerations. The investment decision factors given below were developed interactively with the management team of CSIR Transportek over a number of years.

6.5.1 Market need for R&D

As discussed above, one of the drivers behind R&D programmes should be identified needs in the market place - the so-called 'market pull' process. This is essential to ensure that researchers do not get involved (and sometimes remain involved for years) in their 'pet topics' and that the overall objective of the R&D programme remains to address real market and industry needs. The needs-determination process described in Section 6.4.1 ensures that this objective is met.

6.5.2 Strategic positioning

The emphasis on R&D in response to market needs should, however, be balanced by an equal drive to stimulate creativity, new ideas and thus innovation in order for the organisation to remain viable in the long run. The innovation drive should be defined in response to the organisation's strategy and should not simply be a compilation of innovative ideas from researchers. It sometimes requires a leap of faith by management to invest in a new idea, but it is essential to keep an organisation at the cutting edge of technology. If well managed as part of a portfolio of projects, this can be very successful provided that it is accepted that some projects will succeed and some will fail.

6.5.3 Knowledge and technology gaps

The technology trees discussed in Section 6.4.2 should be used to assess the quality of existing knowledge in the domain under consideration and can thus indicate 'gaps' in knowledge, competencies or technologies. Sufficient investment emphasis should be placed on these gaps to ensure that new knowledge is generated as opposed to the refining of existing knowledge or even worse, the repeating of work already done. One of the disadvantages of not implementing a holistic approach to R&D management is that sometimes work is repeated without the funder or the researcher realising it - this was particularly apparent during the fragmentation that occurred during the RDAC research period discussed in Chapter 3.

6.5.4 The thrust portfolio management approach

The holistic approach to R&D management requires that projects be managed as part of an R&D programme. The fragmentation of the effort, as was indicated in Chapter 3, can be very detrimental. At the CSIR[201], R&D projects are managed in strategic R&D thrusts rather than as individual projects. A thrust comprises a group of related technologies and their offerings (products and services) which are offered to the market place. This implies that a defined thrust is linked to the dominant issues in the strategic plan of the CSIR Unit conducting the work and that a portfolio of projects in the thrust addresses the objectives of the thrust in a synergistic manner. The thrust usually aims to develop one or more technology platforms and its related applied and basic technologies as discussed in Section 6.4.2. This approach allows interaction between projects and also ensures that some 'wild cards' can be added to stimulate creativity and therefore innovation. This also implies that the success of the investment is considered at the thrust level. Therefore it may be successful even though some projects may fail to produce the expected results.

The investment decision should therefore take cognisance of the principles of thrust management, including the following:

- the development of a research plan at the thrust level with strategic objectives which gives direction to the development of a portfolio of projects to address the objectives;
- the go-ahead decision for some 'wild card' projects if they are likely to address the strategic objectives of the thrust to balance the portfolio of projects (on a simple short-term return on investment basis, these projects would never be selected and thus the opportunity for creativity and innovation is significantly limited);
- 'basic research' projects which, although not directly linked to market needs, are positioned at a low level in the technology tree and will create competencies for the organisation that will provide future strategic advantages; and
- the assessment of the success of the investment at the thrust level which allows some projects to succeed and some to fail.

6.5.5 Balance in the project portfolio

Balance in the project portfolio is extremely important to minimise risk in investment and optimise short- to medium-term returns on the one hand, and on the other hand to allow creativity and innovation as well as to ensure the long-term viability of the organisation by ensuring that its technological base remains relevant. As discussed in Chapter 2 and Section 6.4.2, the balance of the project portfolio can be seen as the following:

- balance of investment in technologies vertically in the technology tree, i.e. balance between investment low in the technology tree vs. high in the technology tree (basic technologies and infrastructure vs. key solutions);
- balance of investment in technologies horizontally in the technology tree i.e. addressing all the strategically dominant issues adequately or optimally;
- balance between projects in domains with a proven track record and the so-called 'wild cards'; and
- balance in the project portfolio as suggested by Roussel[81] (discussed in Chapter 2), i.e. maturity of the technology vs. competitive position, returns vs. probability of success and knowledge of the technology in the organisation vs. knowledge of the market it is intended for.

Technology trees as well as the matrices suggested by Roussel (*ibid*) should be used to ensure balance in the investment project portfolio. The application of some these principles is discussed in Chapter 7.

6.5.6 Impact track record and impact projections

In addition to the above, the track record of the focus area and its projections for the future should be considered in the investment decision. This should be addressed by evaluating the financial and other returns versus the investment in the area. The trends in the impact measurement indicators discussed in Section 6.4.4 should be used to support this decision-making process. Future projections of trends can also be introduced to aid the process.

6.5.7 Development time vs. envisaged benefit

In a scenario of world economic uncertainty and a need for immediate problem solving to address the needs of the poor, there is increasing pressure on R&D funding and the need to optimise value for money from R&D investment is ever-increasing. In addition, the rate of change of technology in fields such as computerisation is increasing rapidly - to the extent that traditional methods of R&D may take so long that the new technology will be obsolete on completion of the project. New ways of shortening development time must be considered, and therefore the approach to be followed as well as the projected time to completion should form part of the input into the investment decision.

6.6 Stimulating creativity and innovation

Essential elements of a successful R&D management system are creativity and innovation. These terms were defined in Chapter 1. Roberts[10] defined the process of innovation as consisting of invention and exploitation. Thus the process of innovation (the development of new technologies or knowledge) starts with new ideas generated by creative people. In an improved R&D management process it is therefore essential to allow stimulation of creativity and thus idea generation and innovation. In the R&D management model this places emphasis on people, who are shown as central to the model at the strategic level (see Figure 6.3). The following aspects are important in this process:

- the development of people to be creative and innovative;
- the development of a culture of creativity and innovation in the organisation;
- organisational design, (organisational structure, physical layout and business processes) to stimulate creativity and innovation;
- the development of techniques to stimulate creativity and innovation; and
- a system to record and monitor new ideas.

The topics of creativity and innovation are dealt with at length in the literature and a detailed discussion will not be repeated here. However, some of the above factors merit a brief discussion.

As discussed in Chapter 2, the environment in a successful organisation should be conducive to creativity and innovation. This includes an organisational structure which places emphasis on the importance of R&D. In the CSIR, R&D management and information management are represented at CSIR Executive level. In each of the research Units R&D management is controlled by a Strategic Research Manager who is a member of the management team and reports directly to the Director of the Unit. In addition, the importance of the physical layout of offices and laboratories to stimulate communication and thus creativity must be recognised. Business processes such as financial systems, strategic planning processes and reward systems must be designed in such a way that they contribute towards stimulating creativity by encouraging and rewarding the right behaviour.

To stimulate creativity and idea generation, companies that are in the business of hard product development for the consumer market often create a 'skunk works' as discussed in Chapter 2. A skunk works usually consists of a laboratory where staff can use some organisation and private time to 'play and discover' – an activity that often leads to the development of innovative ideas. However, in the transport industry much of the development focuses on the generation of new knowledge, methodologies, processes and techniques, rather on than hard product development. To stimulate creativity and innovation in this environment a discussion forum which can be seen as a 'virtual skunk works' was created in the CSIR Transportek Unit. The purpose of the virtual skunk works is to get expert researchers to present controversial ideas and stimulate technical discussion in a relaxed environment so that opportunities are created for the generation of new ideas.

The process followed in a virtual skunk works discussion usually consists of:

- one or two short technical presentations (often controversial and with opposing view points) on a selected topic;
- a facilitated process to discuss the advantages and disadvantages of the approach or approaches;
- a 'think tank' process to address shortcomings and problems highlighted during the discussion; and
- recording of ideas and issues by a scribe.

In addition to the overall objective of stimulating creativity and innovation, the virtual skunk works process has the following advantages:

- it ensures that senior technical staff allocate time for group discussions on important technical issues;
- it allows the sharing of new ideas amongst technical staff;
- it acts as a sound boarding for new ideas in a group process;
- attending and participating in discussions on topical and relevant technical issues is an important learning process for new staff (especially young professionals); and
- it serves as training for young professionals by developing their skills in cognitive thinking and technical presentation.

6.7 Conclusion

This chapter discussed the development of a framework, model and tools for a systems approach to the management of R&D in the road infrastructure. The development of the system was based on:

- the analysis of relevant elements of technology management practice;
- the analysis of the critical success and failure characteristics of historic research programmes and projects;
- the analysis of the suitability of selected technology management models found in literature;
- the evaluation of the importance of proposed elements of a new R&D management model through a survey and associated statistical data analysis;
- the development of a set of principles or tenets for a new approach based on the above analysis;
- many interactions and discussions with stakeholders and practitioners in the road infrastructure industry; and
- specific emphasis on relevant elements of cybernetics, systems thinking and complexity theory.

6.7.1 The model as a complex cybernetic system

The conceptual model has many of the characteristics of a complex system and a cybernetic system such as:

- it is a circular model, thus indicating that the system can impact on itself in a 'circular causality' mode;
- the research effectiveness element acts as a 'sensor' that measures the effectiveness of the system both in terms of the outcomes from the programme as well as the quality of the human resources base;
- the research effectiveness element then provides feedback to the system through a number of loops and causes corrective action typically in the strategic planning and manpower pool element;
- the interactions between the elements of the system are rich and non-linear;
- the system is sensitive to changes that can have large effects elsewhere in the system;
- the boundary to the system is porous and it has a rich interaction with its environment;
- the supporting decision support tools also display characteristics of complex systems and, combined with the conceptual model, they can be seen as a higher level complex system with a set of nested sub-systems;
- the tools in the system in particular contain a 'history' or 'memory' over time; and
- the collection of performance data produces an element of self-reference and self-correction.

The implementation of the model and tools in the R&D programmes of the CSIR and Sabita is discussed in Chapter 7.

7 IMPLEMENTATION OF NEW MODEL AND TOOLS

7.1 Introduction

The need to reassess the process of R&D management for the South African transport sector was highlighted by a series of events, including the fragmentation of the South African Department of Transport's (DoT) research programme, the political changes in South Africa and the subsequent restructuring of the DoT, as well as the increasing scarcity of funds and the subsequent need to optimise return on investment (see discussion in Chapters 1 and 4).

The models and tools presented here were developed in a phased approach and interactively in consultation with industry, consultants and academics. The quality of the implementation of the work therefore improved with time. The applications discussed below deal with the implementation of the model and tools in the following research programmes:

- early implementation of concepts in the Sabita programme;
- the work conducted in the CSIR parliamentary programme since 1996;
- the planning of joint projects between the CSIR, Sabita and the DoT; and
- the planning and development of a new South African Hot-Mix Asphalt Design method.

The purpose of this chapter is to assess the degree to which the model and tools developed in Chapter 6 could be implemented in practice, as well as to determine the lessons learnt in this process. Finally, the status of the approach as it is currently used in the new CSIR Built Environment Unit is discussed.

7.2 Managing the Sabita research programme

7.2.1 Introduction

As discussed in Chapter 3, in 1988 the Southern African Bitumen and Tar Association (Sabita) embarked on a strategy planning process, during which the importance of a generic research and technological development programme for the industry was realised[198]. The Asphalt Research Programme (ARP) was subsequently initiated. It was envisaged that the ARP would enhance the use of asphalt technology in the industry, create an improved profile for the industry and enhance the industry's efficiency, thereby making it more competitive. The industry also needed to improve its services and products. At the outset Sabita made it clear that the ARP should be a needs-driven research programme based on the real needs of the industry and its clients. Some of the early thinking in a new systems approach to R&D management was introduced into the planning process and will be discussed against the backdrop of the strategic model and tools described in Chapter 6. The information provided here has been summarised from unpublished documents such as the minutes of the meetings of the ARP Board, the Asphalt Research Strategy Task team (AREST) workshops and from personal discussions with members of the Sabita staff[304].

7.2.2 Strategy

It was clear to Sabita that their members would demand an R&D programme that was aligned with the strategies and agendas of its individual members[198]. However, the specific details of the strategic plans of the individual companies were confidential. Sabita therefore decided to develop an R&D strategy for the industry as a whole. A series of workshop-like meetings formed the Asphalt Research Strategy Task team planning process (AREST). The process was facilitated by the CSIR and involved participants from the road authorities, the road industry, consultants, local authorities, communities and other stakeholders. The purpose of the process was two-fold: firstly to develop scenarios for the future of the asphalt industry within which R&D could be assessed and, secondly, to determine R&D needs. In 1988 this process simply involved scenarios and the rating of a series of predefined research projects.

The AREST process was repeated from time to time and in 1990 the industry's R&D programme was redirected to position the asphalt industry for the imminent socio-political changes in South Africa. The emphasis was on issues such as socio-economic development needs, road needs studies, labour-intensive construction and job creation. In this process classic strategic planning processes, such as scenario development, SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) and PEST analysis (Political, Economic, Sociological, Technological), were used. Vision and mission statements were also developed.

During the AREST meeting held early in 1995 it was concluded that the asphalt industry should focus on three main areas in the subsequent years[198]:

- 'emergency plans' to position the industry to deal with a sudden flow of development-orientated funds for the construction of roads in communities;
- a proactive approach to new stakeholders in order for the industry to present its skills to new stakeholders; and
- actions to sustain the industry until the expected new opportunities arose.

In terms of R&D, the focus was therefore on technologies for the benefit of the future South Africa, specifically on technologies that could be used in providing roads in developing communities, as well as on training and the implementation of research results. The implementation programme yielded excellent results, particularly in the areas of large-aggregate mixes, porous asphalt and emulsion-treated bases, and in addressing social development needs.

As discussed in Chapter 3, the Asphalt Research Programme Board (ARP Board) was created in order to fulfil the function of a steering committee that would provide strategic input as well as to monitor progress. In addition, the Bituminous Materials Liaison Committee (BMLC) was used as a broad representation of the users of new technology to provide practical input, to act as a sounding board for new ideas and to endorse findings and results.

The Sabita R&D programme was therefore based on strategic plans developed in conjunction with the industry and users of technology. In addition, in line with the principles discussed in Chapter 6, technology users were involved in the process from the planning stages through to implementation.

7.2.3 Application of the strategic R&D model to the Sabita programme

The specific focus of the Sabita programme on technology transfer of practical solutions and the need to satisfy shareholders in terms of bottom-line in combination with the need to ensure that the industry enhances its technology base at the time, needed to be taken into consideration in the implementation of aspects of the new R&D management model in this programme. In discussions with members of Sabita[304], it was realised that there are specific 'levers' that would ensure the success of the R&D programme. In a simple way, the R&D process can be seen as a turning wheel with the axis of the wheel (core of the model) being the intellectual capacity pool. If the interaction between the elements of the system is neglected, the wheel no longer turns efficiently. The momentum of the process is provided through the 'levers' (see Figure 7.1) causing a positive (clockwise) spiral in the process building the intellectual capacity pool.

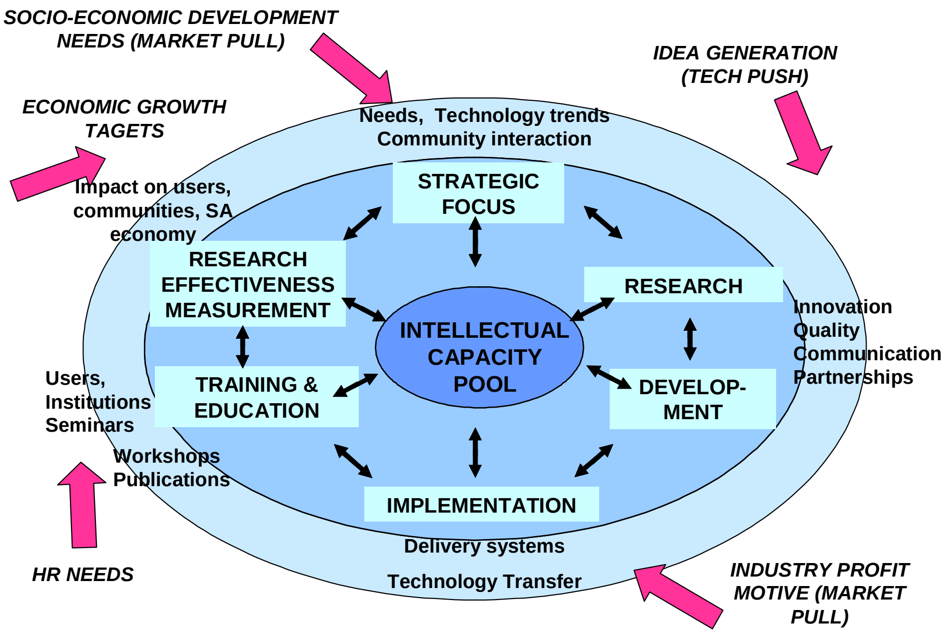


Figure 7.1: Levers in the research and technology management model for the Sabita programme

However, neglecting the systems approach and ignoring some of the elements in the system (through, for example, fragmentation of the process as discussed in Chapter 3) can cause a counter-productive result to the detriment of the value derived. The levers in the model are:

- *socio-economic development needs (market pull)* which drives the strategic process in the model and influences the needs-determination process and the research agenda;

- *idea generation (technology push)* which occurs during the strategy and early R&D phases and drives invention, thus also influencing the research agenda;
- *industry profit motive* which impacts on the implementation element in the model and drives the research agenda;
- *human resource development needs* which drives the education/training element in the model and influences the HR development process; and
- *the national economic growth target* which drives the research effectiveness and impact measurement elements.

The Sabita R&D management process took cognisance of the effect of these levers or drivers.

7.2.4 Needs determination in the Sabita programme

The needs-determination process described in Chapter 6 was used in the later stages of the Sabita programme and is currently still being used[212]. In order to enhance the process and facilitate speedy results, a small core group from the industry was formed – the Sabita Education and Technology Committee (E&T Committee). The Sabita E&T Committee consisted of seven technical experts from the industry and the Technical Director of Sabita. As the name indicates, in addition to R&D, specific emphasis was placed on education and training activities. The following forums and processes were used:

- the AREST meeting to determine the dominant strategic issues facing the industry ('top-down' process);
- the BMLC to identify problems in detail and to generate ideas for projects; and
- the Sabita E&T Committee to consolidate the information and determine the Technology Focus Areas (TFAs) for addressing the dominant issues.

The AREST meeting in 1995 identified the following issues as being strategically dominant in the industry[198]:

- preservation of the existing road network;
- optimisation of investment into the road network;
- industry effectiveness;

- community roads; and
- job creation.

Subsequently, the following Technical Focus Areas (TFAs) were defined by the Sabita E&T Committee to address these issues:

- asphalt mix design for new roads and rehabilitation;
- effective thin surfacings for maintenance;
- industry quality;
- technologies for low-volume roads; and
- labour-intensive construction.

In the early stages of the Sabita programme the TFAs defined were simply intended to address the dominant issues on a one-to-one basis.

The approximately 80 people who attended the BMLC were asked to generate a list of the problems being experienced and project ideas. The attendees were split into five groups of about 15 people, each with a facilitator. They were asked to identify the issues and problems facing them on a day-to-day basis, as well as to list some project ideas that could help to address these problems. Appendix F (see companion document) contains a list of the project ideas generated. The rating of these projects is discussed below. The Sabita E&C Committee and researchers from the CSIR also added some project ideas.

7.2.5 Defining the Sabita R&D portfolio

The inputs described above were used to define technology platforms and technology trees for Sabita in an interactive process with the Sabita E&T Committee. The following were identified as technology platforms from which key solutions could be developed to address the strategic issues:

- High-performance Asphalt Technology;
- Surface Treatment Technology;
- Quality Systems;
- Bituminous Stabilisation Technology; and
- Construction Technology.

Figure 7.2 shows the technology platforms and their links to the dominant issues. Using a facilitated 'think tank' process, the key solutions to addressing the dominant issues were identified for each of these platforms (see description below).

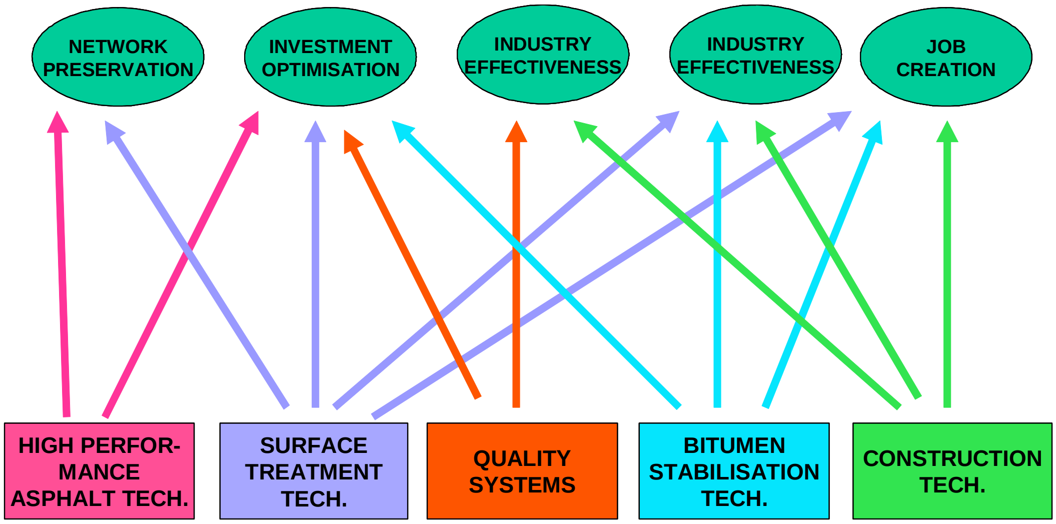


Figure 7.2: Sabita technology platforms and links with dominant issues

Key solutions for the High-performance Asphalt Technology platform

- high-stability asphalt wearing courses;
- durable thin surfacings;
- heavy-duty asphalt bases;
- flexible asphalt surfacings;
- thin-layer asphalt technology, and
- road user-friendly products.

Key Solutions for the Surface Treatment Technology platform

- technology for maintenance and holding actions;
- skid-resistant surfacings;
- durable seals;
- flexible seals; and
- technology for dust palliation.

Key Solutions for the Quality Systems platform

- innovative product certification systems;
- product guarantee systems;
- health, safety and environment strategy;
- improved materials specification systems;
- Product Performance Guarantee Systems; and
- quality control for labour-intensive construction.

Key Solutions for the Bituminous Stabilisation Technology platform

- Granular Emulsion Mixes (GEMS);
- foamed bitumen;
- flexible surfacings;
- low-cost roads; and
- penetration macadam.

Key Solutions for the Construction Technology platform

- guidelines for labour-intensive construction;
- training modules for labour-intensive construction; and
- manuals for construction practices.

Figure 7.3 shows an example of the High-performance Asphalt Technology tree, its key solutions and their links to dominant issues. The remainder of the technology trees can be seen in Appendix G (see companion document).

The Sabita E&T Committee was also used to rate the key solutions. They were rated in terms of the need for R&D and their likely impact. Both the ratings and the ranking (1 being the most important and 5 being the least important) are shown in Appendix H (see companion document). In the early stages during 1990, the focus was on the core business of the Sabita members, i.e. asphalt technology and emulsion stabilisation, with the result that labour-intensive construction and other social issues ranked very low. However, the strategic inputs from subsequent AREST meetings led to a redirection of the programme and to the initiation of several projects in this category.

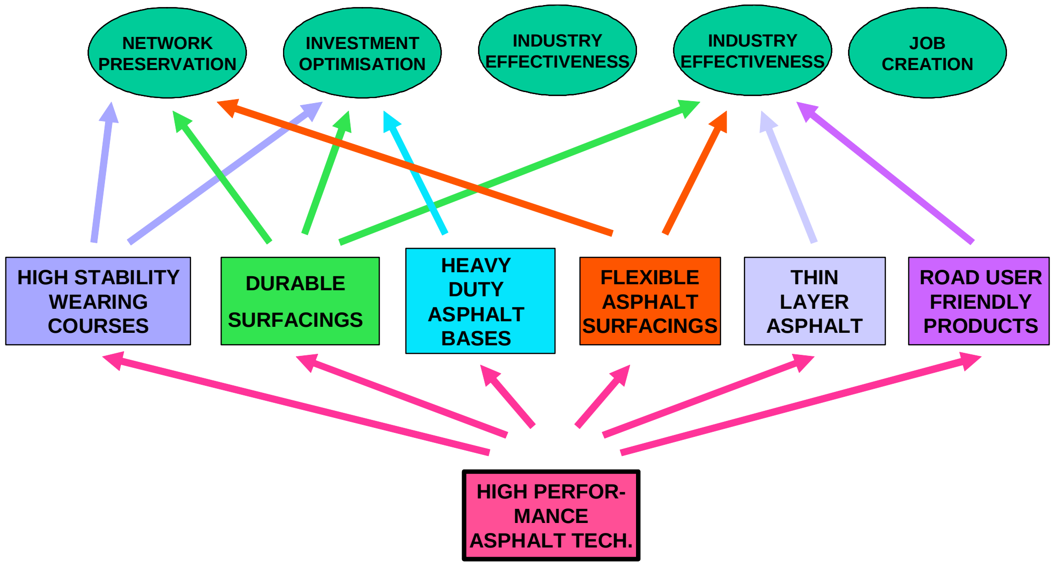


Figure 7.3: The Sabita High-performance Asphalt Technology platform, its key solutions and their links to the Sabita-dominant issues

Technology trees for each of the platforms were then developed by the author and presented to the Sabita E&T Committee for comment and approval. An example of a final technology tree (for High-performance Asphalt Technology) is shown in Figure 7.4. The remainder of the technology trees are shown in Appendix G. Appendix I gives a summary of the key solutions, applied technologies and base technologies for each of the platforms.

Appendix F (see companion document) gives the project ideas generated from the BMLC workshops and their rating of importance as determined by the delegates. Five groups of about 20 people each were used. The project ideas were rated in the following categories:

- technological benefit;
- benefit to the road authorities (client bodies);
- benefit to developing communities; and
- benefit to the asphalt industry.

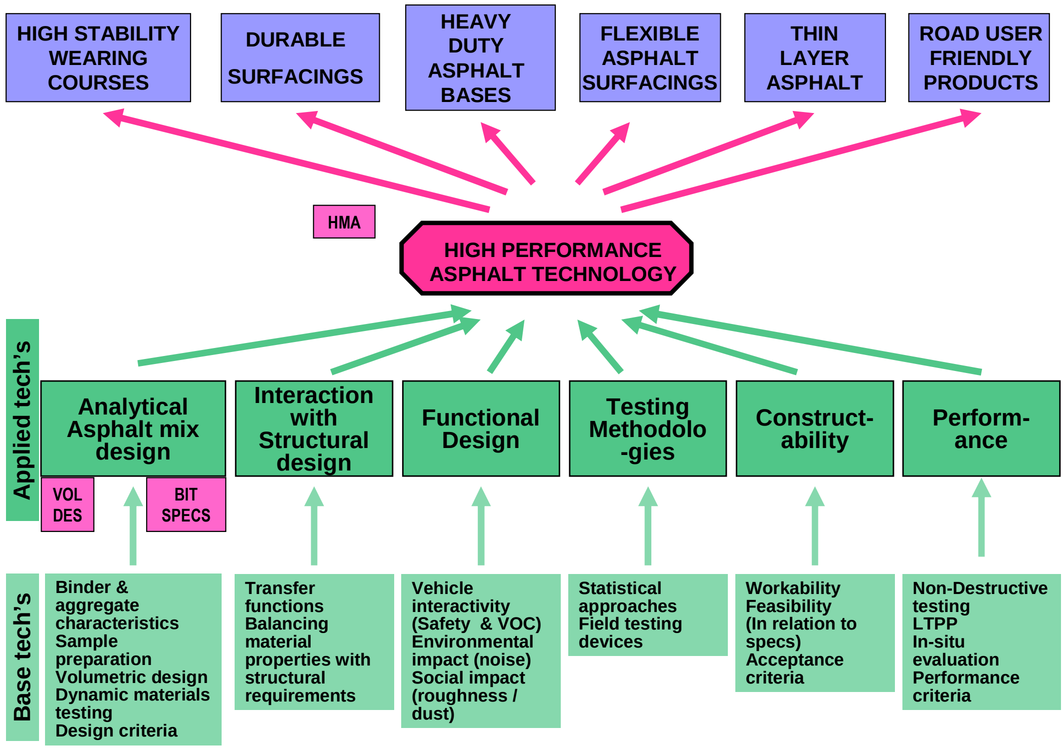


Figure 7.4: The Sabita High-performance Asphalt Technology tree with the positions of projects shown

A five-point rating scale was used (5 being very high). During the rating process, the members of certain groups added project ideas to the list. The projects were then ranked on the basis of total score – see Appendix F. At this stage the importance of techno-social issues, such as labour-intensive construction, became evident and consequently several projects aiming at techno-social or socio-economic issues related to roads were conducted during the next period (1991 to 1994).

Detailed project plans in the Sabita portfolio were developed from the project ideas generated by the BMLC and by assessing their importance in the technology trees. Due to the fact that Sabita is a private sector organisation, they tended to fund projects higher up in the technology tree, i.e. closer to the key solutions, especially during the period 1996 to 1998. The nature of these projects was often that of incremental change or implementation of results rather than that of developing new basic technology. In this situation, balance in the project portfolio can be achieved only if the projects are complemented by other programmes. This is discussed further in Section 7.3.

Appendix J (see companion document) gives brief descriptions of the projects defined since 1989. In the latter part of the Sabita research programme (1995 to 1998) the main projects defined were:

- volumetric principles for the design of asphalt mixes (VOLDES);
- design and performance of bitumen-emulsion treated materials (ETBs);
- revised National specification for bitumen (BITSPECS);
- guidelines on Health, Safety and Environmental issues in the use of bituminous products (HSE);
- quality systems for the asphalt industry (QUAL);
- the effect of the road environment on road traffic safety (SAFE);
- design of foamed asphalt bases (FOAM);
- design of highly flexible surfacings(FLEXSURF); and
- a new South African Hot-Mix Asphalt design method (HMA).

It can be seen from the above that during this period (1995 to 1998) the strategic direction of the Sabita programme was once again adjusted. The focus was mainly on quality issues, the impact of road condition on road safety and, once again, on hard-core asphalt technology. It is notable that the strategic direction and redirection of the programme contributed significantly to its success. The positions of the defined projects on the technology trees are shown in Figure 7.4 (for High-performance Asphalt Technology) and in Appendix G. The majority of the projects were positioned relatively high in the technology tree.

7.2.6 Implementation and technology transfer

As mentioned before, the Sabita programme defined during the initial AREST meeting in 1989 focused on technical research projects and was then redirected during subsequent AREST meetings. In the last couple of years of the programme much of the effort was focused on implementation of research results. The project descriptions in Appendix J also list the implementation actions. These focused mainly on:

- dissemination of information through presentations at the ARP Board meeting and the BMLC;
- reports and technical papers;
- articles in technical and general media;
- seminars;
- workshops; and
- pilot projects.

The work was co-ordinated mainly by the Sabita Technical Director, with assistance from the researchers conducting the projects. A significant number of papers were published and presented at international conferences showing some measure of international review of the work conducted. From the early years implementation of results from the Sabita programme had been very successful, as reported by Rust et al.[198].

7.2.7 Education and training

Apart from the implementation actions given above, Sabita also embarked on specific educational and training activities. These included:

- the funding of the Sabita Chair in Asphalt Technology at the University of Stellenbosch;
- a series of training videos intended for technicians in the asphalt industry; and
- special training courses such as the Asphalt Testers Course presented by the Pretoria Technikon.

Once again the activities were co-ordinated through the Sabita Technical Director and were very successful[198].

7.2.8 Impact measurement

Although Sabita has not been driving a formal process for determining the impact of their programme, the achievements and benefits to industry had been reviewed at the AREST meetings (see Appendix J) and in the form of a technical paper discussing the return on research investment in the asphalt industry[198].

However, the information available can be used to initiate the development of an impact measurement system such as is discussed in Chapter 8.

7.2.9 General discussion

The Sabita programme followed the principles and the model discussed in Chapter 6 reasonably well. The success of the programme emanated from the quality of the strategic planning process and the implementation activities. However, the following aspects could have been improved:

- the development of an events and outcome database for measurement of research effectiveness and the calculation of impact indicator trends over time;
- improved use of technology trees to prioritise projects and to ensure that the project portfolio remains balanced; and
- the development of a more formal process to support the investment decisions, thus decreasing the influence of 'strong players' on the prioritisation of projects.

As mentioned above, Sabita, being a private sector organisation, focused most of its efforts on projects positioned relatively high in the technology tree, i.e. relatively close to key solutions. In addition, a significant proportion of its funding was spent on the packaging of key solutions and their implementation. This led to an apparent imbalance in the project portfolio, but was somewhat compensated for through co-operation with the DoT and CSIR Transportek on broader research programmes. This is discussed in more detail in Section 7.4.

7.3 Planning and execution of the Parliamentary Grant funding programme in the CSIR Transportek Unit

7.3.1 Introduction

The CSIR Parliamentary Grant (PG) programme is discussed in detail in Chapter 3. The Grant is provided by the Department of Science and Technology through the CSIR Board. In CSIR Transportek this funding amounted to about 30% of the total income – the remainder came from contract research work and royalties. At the unit level in CSIR Transportek, the PG was managed by the Technology Manager and the Thrust Managers (see Chapter 3). In the new CSIR

Built Environment Unit this position has been modified to include the strategic planning for the Unit and renamed as Strategic Research Manager. The nature of the funding implies that much of the work conducted is aimed at the lower end of the technology tree (in contrast with the Sabita programme). However, in accordance with CSIR strategy, the work needs to be aimed at supporting technology development in response to market and user needs.

CSIR Transportek conducted R&D in three main areas:

- transport policy, planning and operations;
- traffic safety and engineering; and
- road infrastructure provision and maintenance.

The above covers a wide and diverse field and in the interest of brevity, the main focus in the following sections will be on applications and examples in the road infrastructure field. The process of planning and managing technological development through PG funding is discussed below in relation to the model and techniques described in Chapter 6.

7.3.2 Strategy

The planning of R&D in CSIR Transportek was closely linked to the unit's business strategy. The process of strategy development will not be discussed in detail here, but some of the relevant R&D-related aspects will be highlighted.

In CSIR Transportek the usual, classic strategy planning processes were used, including scenario development, a vision statement, a mission statement, definition of Key Strategic Issues, a research fund investment plan, a Human Resources development plan and a budgeting process.[305, 306] Key Strategic Issues included:

- effective linkages with stakeholders, international experts through selective partnerships and alliances;
- sustainable growth from new South African markets (provincial, agencies, etc.) and a focused Africa drive and international drive;
- enhancing Human Resource (HR) capacity:

- harnessing the information and communications technology (ICT) revolution, and
- environmental issues in transport planning, infrastructure provision and maintenance, as well as transport operations.

The role of R&D management as a holistic process can be noted from the objectives of growth through competency development, linkages to markets and external experts, the development of Human Resources (intellectual capacity pool), and the emphasis on communication, delivery systems and ICT.

It was found that the conceptual model developed in Chapter 6 fitted well into the strategy planning processes of CSIR Transportek. The R&D strategy for CSIR Transportek was embedded in the business strategy and the key investment areas (thrusts) were based on this business strategy. This is discussed in more detail in the sections below.

7.3.3 Needs determination

As discussed above, the PG programme in CSIR Transportek was intended to develop new solutions and technologies for South Africa, with the emphasis on positioning the CSIR to address market and user needs for technology. This implies that needs determination for the CSIR Transportek PG programme had to focus on:

- the needs of users of transport systems and infrastructure;
- the technology and knowledge needs of road authorities in providing and maintaining transport infrastructure;
- the technology needs of the consulting engineering fraternity;
- the need to assess the appropriateness of international emerging technologies in the South African transport sector; and
- the need to stimulate in-house innovation and creativity in order to develop cutting-edge new technology and knowledge to position CSIR Transportek to address the needs of the market and users.

In addition to the needs-determination process followed by Sabita, CSIR Transportek also used the following processes and channels to determine current and future needs for technology knowledge and competencies in the transport sector:

- formalised needs-determination processes as discussed in Chapter 6 and as indicated by the example of the Road Materials Committee (RMC) below;
- a set of five Research Advisory Panels that provided input into the formulation of the research agenda;
- inputs from other needs-determination processes such as those conducted by Sabita;
- representation on and participation in DoT committee structures such as the Committee of Land Transport Officials (COLTO), the Roads Co-ordinating Committee (RCC) and the Road Materials Committee (RMC);
- organising, managing, participating in and obtaining inputs from other committee structures such as the Bituminous Materials Liaison Committee (BMLC), which later become the Road Pavements Forum (RPF), the Cementitious Pavements Forum, the Accelerated Pavement Testing (APT) Forum and the Heavy Vehicle Simulator (HVS) Steering Committee;
- participation in international conferences and scanning of new technology developments at these conferences;
- links with international organisations through joint projects (e.g. the University of California at Berkeley (UCB) and Dynatest Consulting in the USA as discussed in Chapter 3);
- links to the Transportation Research Board (TRB) activities in the USA through attendance of their annual conference and participation in TRB committees;
- selected overseas study visits to assess new research, technology development and innovation;
- education of CSIR Transportek staff at local and international universities and obtaining technical input from them; and
- technology foresight studies which indicated future trends in technology and market needs[307].

Some of these activities are briefly discussed below with the emphasis on those pertaining to the road infrastructure field.

Needs determination for the Road Materials Committee (RMC)

The Road Materials Committee (RMC) was a sub-committee of the Roads Co-ordinating Committee of COLTO. Its members consisted of representatives of the national and provincial road authorities, as well as CSIR Transportek. The needs-determination process described in Chapter 6 and implemented by Sabita was used in an abbreviated from to determine research needs for the RMC in a facilitated workshop in November 1996. The following dominant strategic issues were identified:

- preservation of the existing road network;
- inadequate funding for roads;
- optimisation of investment in the road network;
- provision of new facilities / provision of community roads;
- efficiency and quality in the road building industry;
- capacity-building;
- job creation; and
- image of roads as an engine for economic growth.

There was significant overlap between these strategic issues and the dominant issues determined by Sabita. Based on these dominant issues, the following Technology Focus Areas (TFAs) were then identified:

- asphalt mix design;
- bituminous binders;
- chemical stabilisation;
- management systems;
- quality control;
- Long-Term Pavement Performance (LTPP);
- Product Performance Guarantee Systems (PPGS);
- pavement deterioration models (performance);
- granular materials design;
- environmental issues;
- pavement design;

- material component testing;
- construction techniques and maintenance; and
- Accelerated Pavement Testing (APT).

Appendix K (see companion document) contains a list of the project ideas defined for each of the TFAs above. These ideas were used to draw up a list of important projects based on a simple rating process. The following projects were considered to be urgent:

- tyre contact pressure and related pavement design issues (Project RMC1);
- a new South African hot-mix design method (RMC2);
- patching for flexible pavements (methods, life, quality control, etc. – RMC3);
- design of bitumen-treated materials (GEMS and foamed bitumen – RMC4);
- laboratory management and quality control (RMC5);
- performance acceptance criteria for Product Performance Guarantee Systems (RMC6);
- Long-Term Pavement Performance: establishment and management at project level (RMC7);
- upgrading of community roads (RMC8); and
- synthesis of drainage practice (RMC9).

The position of these projects on the technology trees is discussed in Section 7.4.

Research Advisory Panels

In 2001 the CSIR Transportek also structured five research advisory panels to assist with the formulation of the PG research agenda and the evaluation of the outputs from the programme. These panels focused on:

- roads infrastructure research;
- Intelligent Transport Systems (ITS);
- passenger transport;
- traffic safety; and

- transport policy, decision support and rural transport planning.

These committees were used to develop the research agenda in CSIR Transportek in 2001 and 2002. The committees identified the dominant issues facing their sector, future challenges to the sector and knowledge gaps that need to be addressed. Appendix L (see companion document) contains the detailed information from these work sessions.

Participation in international conferences

CSIR Transportek's participation in international conferences was deemed to be important to remain abreast of new emerging technologies, to identify areas of technology development that South Africa should invest in for future competitiveness and to identify opportunities for co-operation. These conferences included *inter alia*, the annual meeting of the Transportation Research Board (TRB) in Washington DC, USA; the International Conference on Asphalt Pavements (5-year intervals) and the Conference on Asphalt Pavements in Southern Africa (5-year intervals.

Links to TRB committees

CSIR Transportek participated in the following TRB committees related to road infrastructure:

- the Flexible Pavement Design Committee;
- the Accelerated Pavement Testing Task Group; and
- the Research Management Committee.

International students

CSIR Transportek annually funded several students in Civil Engineering, Transport Economics, Urban Planning, Social Sciences and other related fields, at both the undergraduate and post-graduate level. Several post-graduate students were sponsored to study internationally at universities such as the University of California at Berkeley, the University of Illinois and the University of Leeds. This had a major advantage in that these students were in a position to provide input regarding emerging technologies at these universities into the planning of the R&D programme.

Transportek Foresight Study

CSIR Transportek conducted a Business and Technology Foresight Study[307] in order to enhance its decision-making process regarding the investment of its PG funding. The study included a desk study of international trends and workshops to develop scenarios as well as to identify future trends and challenges. Furthermore, an analysis of the offering portfolio was done and its relevance and robustness in relation to five future scenarios assessed.

The desktop study[308] defined the following main drivers in the transport industry:

- Political drivers:
  - new government policy and government funding and initiatives such as NEPAD.
- Societal drivers:
  - continued population growth and urbanisation;
  - rising conflict and security issues; and
  - changes in the nature of the demand for mobility.
- Economic drivers:
  - continued globalisation of markets and production;
  - growing regional co-operation in Africa and the SADC countries;
  - continuing growth of private sector involvement in governance.
- Sustainability drivers:
  - growing pressures of environmental, economic and social sustainability.
- Technological drivers:
  - advances in energy;
  - advances in vehicle technology;
  - advances in transport infrastructure technology; and
  - adoption of Information and Communications Technologies (ICT).

One of the main outputs from the study was the development of five possible future scenarios for South Africa. These were:

- *Doldrums* (a very low road scenario with little progress, economic stagnation and minimal social development).

- *Utopia* (the high road scenario with a strong economy in a politically stable environment with significant social development and minimal environmental side-effects).
- *Social progress* (a scenario in which social reforms are successfully implemented and initiatives such as NEPAD are very successful, but economic success lags behind.
- *Commercial drive* (a scenario in which economic growth and prosperity become paramount at the cost of social reform and environmental issues).
- *Balancing act* (a scenario in which social reforms are slow, but significant economic growth takes place although strongly balanced with environmental concerns and focus).

These scenarios were then used to evaluate and review Transportek's research agenda, and shortcomings were identified. The project portfolio was evaluated for robustness against the set of scenarios and the recommendations made. This is depicted in Figure 7.5.

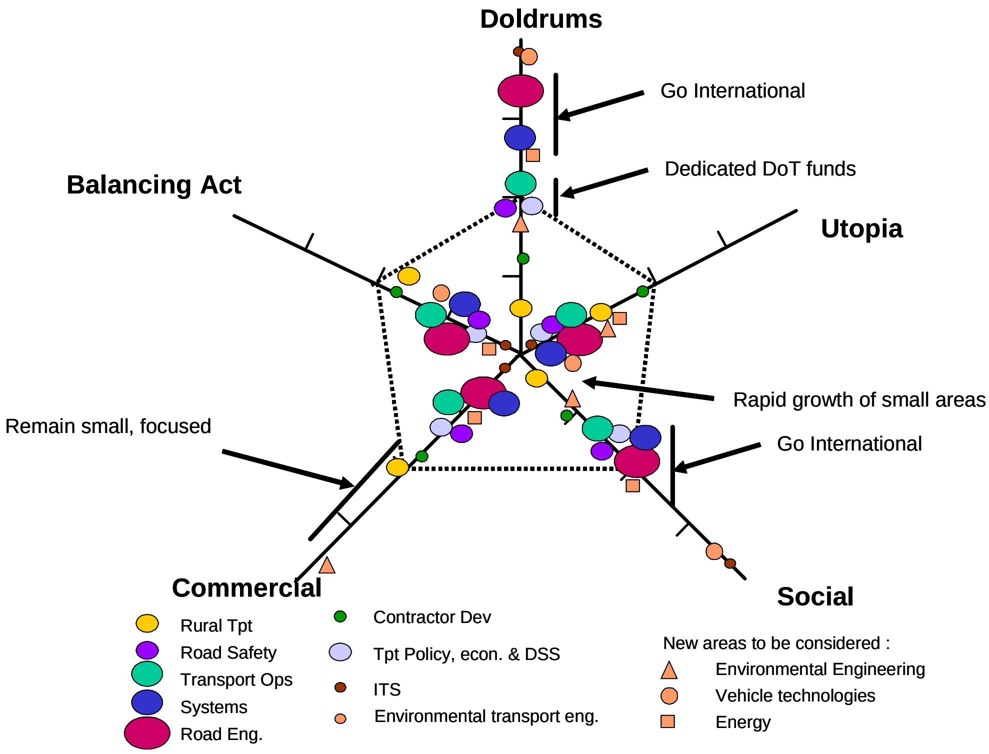


Figure 7.5: Scenarios from the Transportek Foresight Study, project portfolios and suggested strategic actions

Rather than being a once-off process, needs determination at CSIR Transportek was therefore ongoing and the understanding of the needs and trends was enhanced and refined over a number of years. This process then provided input into the planning of CSIR Transportek's PG investments, as discussed in Section 7.3.4 below.

7.3.4 Developing the R&D portfolio

In developing an R&D portfolio for CSIR Transportek's Parliamentary Grant programme, the main aims were firstly, to develop new solutions and technologies that were related to needs identified by users and stakeholders and, secondly, to develop new knowledge that would enhance Transportek's position to enable it to address the future technological and research needs of the transport sector. The thrust approach discussed in Chapter 6 was used to ensure that fragmentation into small projects did not occur. A thrust is a significant, focused investment in a specific technology area and consists of one or more technology platforms and a set of projects aimed at achieving a common goal. Based on its strategic planning process, Transportek conducted R&D projects in the following thrust areas (focus areas):

- transport policy, economics and environmental issues;
- spatial development and transport planning;
- transport operations and logistics;
- traffic engineering and safety;
- integrated management systems;
- pavement evaluation and design;
- pavement materials evaluation and design; and
- pavement construction.

The thrusts related to roads, i.e. the last four in the list above, were all positioned in the Road Engineering competency. A distinction must be made between existing competencies and platforms and the new knowledge and capabilities generated through thrust investments to address specific objectives within a competency area.

The process of developing a technology platform could be either radical, such as when a new 'green field' area is initiated, or incremental if existing knowledge is enhanced or expanded. External contract R&D projects were therefore often conducted in parallel to and integrated with the generation of a new platform. This implies that, from CSIR Transportek's point of view, 'market offerings' could be positioned at any level in the technology tree. For example, key solutions were integrated products delivered at the top of the technology tree, while offerings from the lower levels of the tree could consist simply of testing materials and providing the results, without any value addition. This thinking implied that external parties were often involved in the development of a technology platform in a 'get the customer on board early' mode. Apart from obtaining valuable input from external sources (lead users as defined by Von Hippel[91]), this also facilitated the subsequent implementation of the technologies and solutions developed due to 'buy-in' and ownership amongst the eventual users of the technology.

In CSIR Transportek's 1998/99 business plan[309] the following were defined as technology platforms in each of the thrust areas related to infrastructure engineering:

- Pavement Evaluation and Design thrust:
  - pavement structural design methods
  - long-term pavement performance technology
  - accelerated pavement testing technology.
- Pavement Materials Evaluation and Design thrust:
  - materials component testing technology
  - modification and stabilisation technology
  - unbound materials design
  - product quality
  - maintenance materials technology
  - seal design
  - high-performance asphalt technology
  - asphalt mix design linked to structural design and performance.
- Construction Technology thrust:
  - Labour-intensive construction (LIC) techniques and small contractor development

- construction quality management.
- Integrated Management Systems thrust:
  - infrastructure management systems.

The last two platforms under the Pavement Materials Evaluation and Design thrust were developed specifically to address the Hot-Mix Asphalt Design project discussed in Section 7.5.

The above platforms and the user and stakeholder inputs described in Section 7.3.3 were used to develop and enhance a set of technology trees in the roads field. Figure 7.6 shows an example of the technology tree for pavement structural design methods. The key solutions developed for this tree are shown in Figure 7.7. The remainder of the trees and key solutions are shown in Appendix G (see companion document).

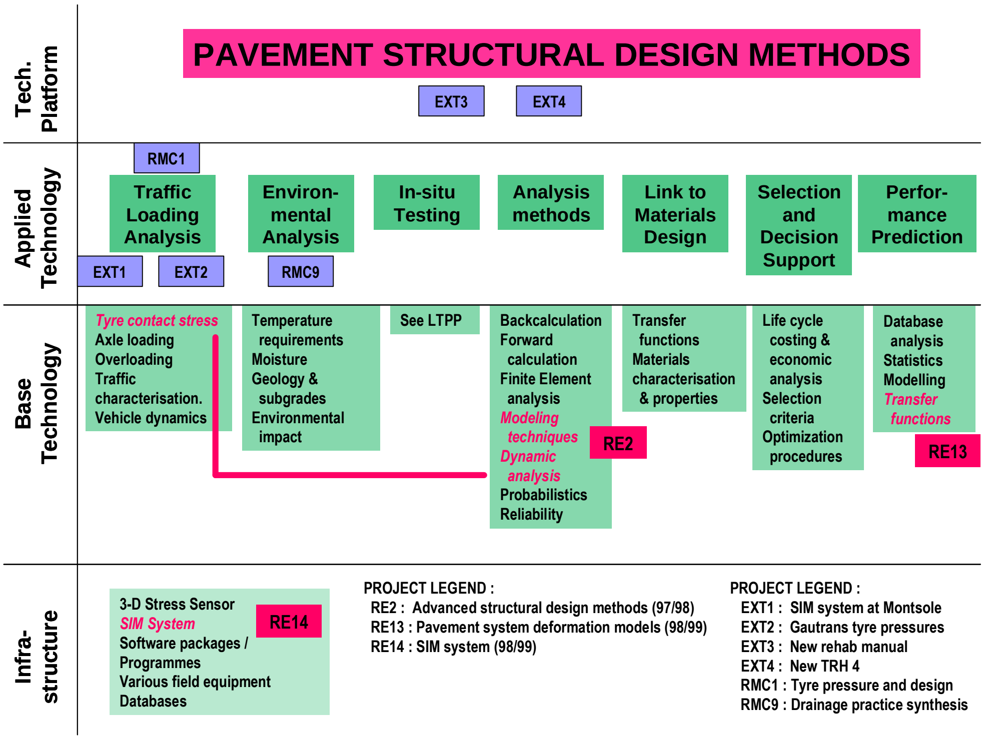


Figure 7.6: The CSIR pavement structural design methods technology tree showing PG projects (red) and contract R&D projects (blue)

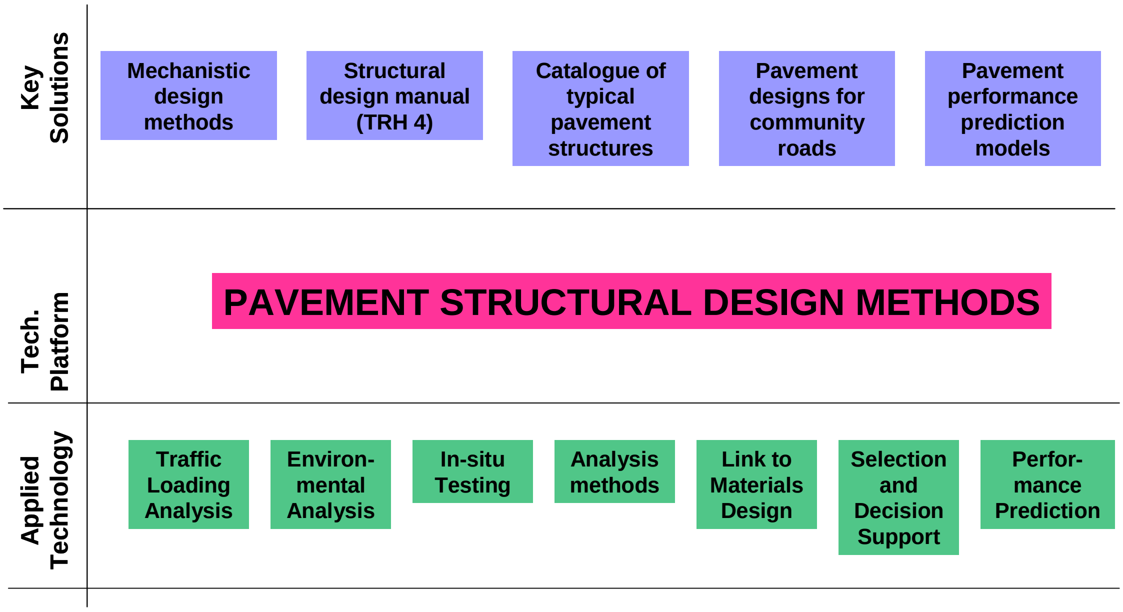


Figure 7.7: The CSIR pavement structural design methods technology platform showing key solutions

Descriptions of the elements of the technology trees are given in Appendix M (see companion document). It is interesting to note that, in contrast to the Sabita example, the technology trees were developed first (although taking cognisance of market and user needs) and then the possible key solutions were defined. This is due to the fact that PG funding was deliberately used to develop new capabilities at the lower end of the technology tree, which implies a slightly greater emphasis on 'technology push' and researcher creativity than in the case of the Sabita example where member or user needs played a dominant role in a 'market pull' mode. As explained in Figure 6.10, a second, 'top-down' iteration is then required to ensure that the key solutions are addressing the strategic needs adequately.

The technology trees discussed above, showing the external needs and projects, were used to develop the PG project portfolio for each investment cycle. The investment decision factors discussed in Chapter 6 were used to assess thrust-level business plans and project plans. This is discussed in more detail in Section 7.3.5. Appendix N (see companion document) gives the projects initiated in the 1997/98 and 1998/99 financial years as examples of projects emanating from the planning process.

7.3.5 The investment decision

The investment decision process as described in Chapter 6 was used to assess proposed investments to be made in CSIR Transportek's PG project portfolio. The investment decision process is linked to the strategic planning process and consists of the following steps:

- the development of thrust-level business plans linked to the CSIR Transportek Business Plan;
- the evaluation of the thrust-level business plans according to the criteria described in Chapter 6;
- the allocation of funding at the thrust level, based on the above evaluation (this ensures that the balance in the funding in the thrust portfolio is aligned with the strategy);
- the development of detailed project proposals in each thrust, based on the research objectives in the plan;
- the evaluation of project proposals according to the criteria given in Chapter 6;
- the allocation of funding to approved projects, and
- the monitoring of progress and results on a quarterly basis with a view to redirecting the funding or changing the focus of projects where necessary.

Table 7.1 shows the rating against the investment criteria for each thrust as determined during the 1998/1999 strategic planning process. The ratings and subsequent investment percentages were determined through discussion and group consensus among the CSIR Transportek management team.

Table 7.1: Ratings of thrusts according to investment decision process (1998/1999)

	Transport Policy	Spatial Develop.	Freight Transport	Passenger Transport	Transport Eng.	Traffic Safety	Man systems	Pavement Eval.	Materials Eval.	Construct.
Average annual % investment	4	6.7	New	6	12.9	New	16.8	11.3	12	7.1
Average annual investment (R x 1 000)	419	698		620	1 334		1 735	1 175	1 245	737
Investment 98/99 (R x1 000)	845	995		1 020	2 155		965	1 490	2 020	1 560
Average annual income (R x 1 000)	1 188	1 360		764	1 743		2 749	6 106	1 843	1 396
Market need	3	3	5	4	4	5	5	5	4	3
Strategic positioning	4	4	2	3	4	3	2	5	5	3
Corporate objectives	4	4	3	4	3	4	3	4	4	3
Technological gaps	4	3	4	2	5	3	4	2	2	3
Impact track record	4	4	3	3	3	3	4	5	4	4
Development time vs. benefits	4	4	4	4	4	4	5	3	4	4
TOTAL SCORE	23	22	21	20	23	22	23	24	23	20
Proposed investment (%)	5.5	9	3.8	5.5	9	14.3	10	14.8	18.5	10
Proposed investment (R x 1 000)	585.75	958.5	404.7	585.75	958.5	1 522.95	1 065	1 576.2	1 970.25	1 065

7.3.6 Implementation

Implementation projects and activities as part of CSIR Transportek's technology development programme included, *inter alia*, the following:

- the management of all publications and providing ease of access to these publications to the transport sector and other interested parties;
- technical papers and presentations at various conferences;
- user manuals for the use of new technologies (e.g. the LAMBs manual, the GEMs manual, the Porous Asphalt manual, the Labour-Intensive Construction manuals for the Department of Public Works and the updating of the TRH series for the Department of Transport);
- assistance with the modification of specifications (e.g. the bitumen specification and the CSRA specifications);
- dissemination of information at forums such as the BMLC and the APT forum;
- seminars, often in co-operation with funders of the work (e.g. the Appropriate Standards and Modified Binders seminars with Sabita and a seminar on the new rehabilitation manual for the DoT);
- courses and guest lectures at universities and technikons;
- hands-on workshops to train people in the use of new technologies (e.g. the rehabilitation manual workshop for the DoT);
- demonstration projects and construction of trial sections (e.g. the N3 trials to evaluate modified binders and the LIC sections constructed for HVS testing at Cullinan);
- pilot projects such as the LIC project at Phutaditjaba in the Free State province); and
- technology transfer projects such as the CalAPT project, which involved the transfer of knowledge and expertise in the use and application of HVS technology from CSIR Transportek to the University of California at Berkeley and the California Department of Transportation, and the Transportation Research Board workshop on South African pavement engineering technology held in Washington DC, USA, in January 1999.

Implementation was very successful, especially where the funder of the project was directly involved. It was generally found that those projects in which the implementation of the results was planned right at the outset, involving the funder and users of the technology, were the most successful. This was in line with the new approach to managing R&D described in Chapter 6.

7.3.7 Education and training

Education and training activities at CSIR Transportek usually related to two categories:

- internal education and training of CSIR staff, and
- training and education of people external to the organisation.

The former relates to the provision of bursaries to undergraduate students, as mentioned in Section 7.3.3 above, as well as to post-graduate students who usually worked on research projects for thesis work in conjunction with the educational institution. This facilitated the dissemination of the latest project results to universities and the addition of this information to curricula.

Education and training of people external to the organisation took place mainly through:

- courses that were presented regularly (e.g. the Road Infrastructure Course);
- seminars and workshops;
- guest lecturers from Transportek to local and international universities (e.g. Dr Morris de Beer acting as a visiting professor at the University of New South Wales in Australia); and
- management of and participation in formal post-graduate courses at universities (e.g. the post-graduate course for Transport Managers at the Rand Afrikaans University in Johannesburg).

A number of professionals currently practising in the public and private sectors, as well as lecturing at universities, spent some time at CSIR Transportek conducting research and post-graduate studies. Often young professionals spent a period of less than five years working at CSIR Transportek and studying at one of the local universities and then moved on to careers in the transport sector. This not only ensured the transfer of technology to the private sector, but also facilitated the implementation of future technologies in the industry.

From the above indicates that the education and training link in the holistic approach to R&D management in CSIR Transportek was well developed and was successful.

7.3.8 Impact measurement

Evaluation of the impact of R&D at CSIR Transportek in terms of the system discussed in Chapter 6 was aimed only at the organisational level, i.e. the focus was on the benefits to CSIR Transportek itself (and later on the CSIR Built Environment Unit). Implementation of the system for measuring research effectiveness described in Chapter 6 is underway.

7.3.9 General discussion

It has been shown above that most elements of the new approach to the management of R&D were implemented successfully at CSIR Transportek. However, measuring the impact and research effectiveness was lacking. Nevertheless, the programme was very successful as was indicated by a fact-finding visit from a group of professionals from the United States transportation industry co-ordinated by the Federal Highway Association in 1997.[310] In their report these professionals commented on the quality of road building technology in South Africa and recommended that several of these technologies be transferred to the USA. They also recommended that the approach to R&D management discussed in Chapter 6 be adopted in the USA. A final favourable comment was made on the value of the role of CSIR Transportek in filling the gap between academic research (at universities and technikons) and the industry. They also suggested that the founding of a similar body in the USA should be investigated.

7.4 Managing joint CSIR/ Sabita/ DoT projects

From the discussion in the sections above it can be seen that the holistic approach to R&D becomes more powerful and indeed more effective if applied to all the ongoing R&D programmes in a particular field. This has the following advantages:

- the sharing of visions and strategies between industry, road authorities and the developers of technology;
- the co-ordination of R&D programmes in order to minimise duplication and to allow cross-fertilisation of ideas and technologies;
- improved planning of a balanced overall portfolio of R&D projects; and
- joint implementation actions such as seminars, workshops and pilot projects, thus minimising the cost of these events.

CSIR Transportek facilitated the joint planning of the R&D programmes of Sabita, the South African Road Authorities through the South African DoT and the Road Materials Committee (RMC), and the CSIR Transportek Parliamentary Grant programme related to the road building industry. The needs-determination processes and technology trees discussed above were used as input to the project plans.

Figure 7.6 above and Figures E.12 to E.25 in Appendix G show the positions of the project ideas on the technology trees. In a group process (or 'think tank') using the ARP Board meeting as a vehicle, these trees were then used to assess the inter-relationship between projects, to suggest co-ordination between organisations and to ensure that the maximum benefit would be obtained from the various programmes. The balance in the technology trees was assessed by visually observing the number of projects positioned at each level and their relative size and cost (vertical balance) in order to assess the balance between basic work (long term) and applied work or key solution development (medium to short term). Similarly, the horizontal balance was assessed in order to ensure that the level of investment in each focus area was in line with the strategic planning process. The balance between R&D projects and implementation projects could also be addressed. The portfolio of R&D projects could then be adjusted accordingly.

PG projects were usually aimed at the 'roots' (lower levels) of the technology tree; DoT projects were generally aimed at the higher levels, and private sector projects were usually directed at delivering key solutions. However, the use of technology trees allowed significant synergy to be achieved between the efforts of all the parties involved. This also allowed researchers to ensure the relevance of the PG projects in relation to needs in industry and to ensure that they supported other research efforts (thus not becoming 'ivory tower' research).

Examples of the co-ordination described above were:

- The development of the three-dimensional stress sensor shown low on the technology tree in Figure 7.6 (PG project RE2), the basic SIM system (PG project RE14) and the link to the assessment of tyre pressure distributions for Gautrans (project EX2), and the implementation of a stress-in-motion system for the DoT at Montsole (project EX1).
- The planning of the HMA project discussed in Section 7.5.
- The development of the HVS database system (PG project RE1) to support the Gautrans HVS project (project EX7), the CalAPT project (project EX8) and the Finland, CRREL and WES HVS projects (projects EX10, EX11 and EX12) as shown in Figure 7.8.

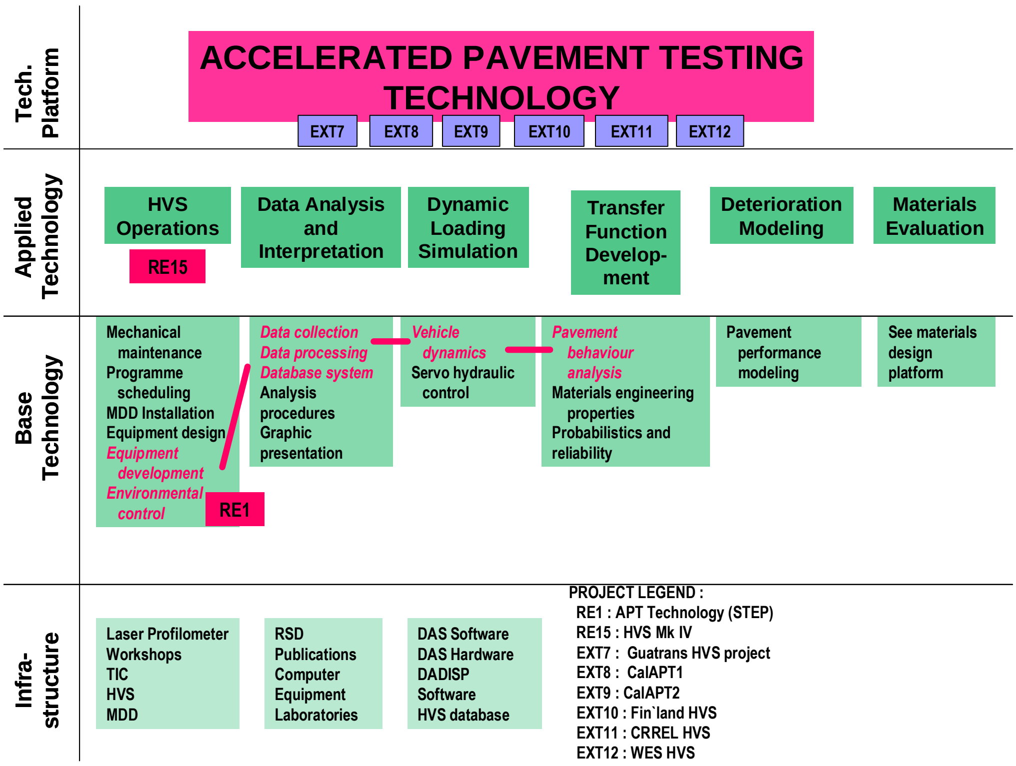


Figure 7.8: The CSIR accelerated pavement testing technology tree showing Parliamentary Grant projects (red) and contract R&D projects (blue)

Levers in the technology tree

The technology tree concept can also be used during strategic planning to decide where to invest in basic developments for long-term results. Maximum effect of investment can be achieved through identifying the 'levers' in the technology tree that would lead to the multiplication of the effect of the investment. This process was used in investing in the enhancement of basic technologies for Accelerated Pavement Testing (APT) technology through a facilitated workshop approach with a group of selected professionals. The identified 'levers' were:

- procedures for simulating and controlling environmental factors such as temperature and moisture;
- the development of a user-friendly database system which would allow the use of historic data to enhance the outputs from current and future work;
- the simulation of the dynamic effects of moving truck loads;
- advanced pavement behavioural analysis; and
- advanced pavement performance modelling.

The position of these levers in the technology tree is shown in Figure 7.9. It can be seen that all the levers were situated at the base technology level, i.e. low down in the technology tree. It is important to realise that if only direct user needs had been taken into account, these projects would not have been rated as a high priority. However, they were extremely important in supporting the development of the applied technologies necessary to enhance the technology platform to the level where it could deliver the required key solutions. The above factors were then prioritised and projects were planned to address them. The projects were selectively funded in order to achieve the maximum benefit for the investment.

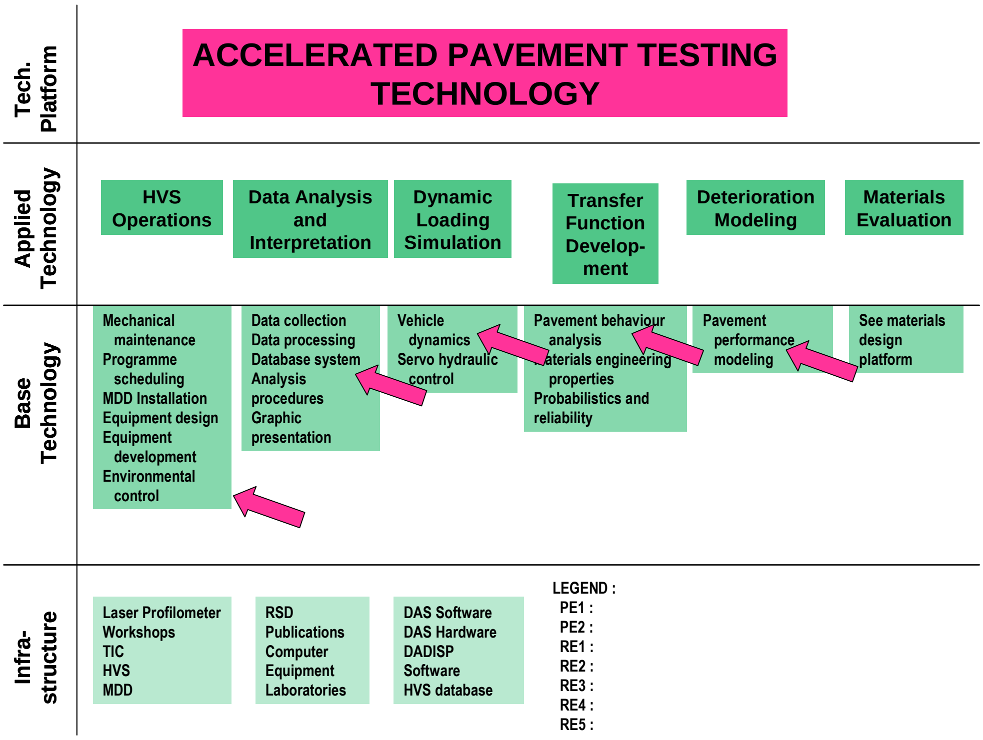


Figure 7.9: Levers in the CSIR accelerated pavement testing technology tree

7.5 Implementation of the models and tools in the South African Hot-Mix Asphalt Design project

7.5.1 Introduction and background

The holistic approach to R&D management presented in Chapter 6 and discussed above can also be used at the project level if the significance of the project warrants it. The development of a new South African Hot-Mix Asphalt Design method is discussed as an example of such a project planning exercise.

In the early 1990s, the need for a new Hot-Mix Asphalt (HMA) design method was identified by the DoT, Sabita and the CSIR. This led, *inter alia*, to a feasibility study into the development of analytical mix design procedures for HMA[311] conducted by CSIR Transportek for the DoT in 1993 and to a state-of-the-art review of mix design procedures based on spatial composition conducted by CSIR Transportek for Sabita in 1995.[312]

The need for a new, improved HMA design method was reinforced by the BMLC at its meeting in November 1996. Some basic thinking on the topic was then done by CSIR Transportek and the DoT, and in 1997 three parties (the DoT, Sabita and CSIR Transportek) agreed to co-fund work on a comprehensive HMA programme. An HMA Steering Committee was formed by the funders to provide strategic direction to the project. In December 1997, the DoT appointed a Project Management Group (PMG) for the HMA project which was a joint venture between CSIR Transportek, VKE (a consulting engineering firm) and the University of Pretoria. The first task of the PMG was to develop a draft business plan for the HMA project to be presented to the HMA Steering Committee. The fact that it was envisaged to be a relatively expensive, multi-year project prompted the decision to use the holistic R&D management approach to plan and control the execution of the project.

Problem statement

The problem statement (or needs description) for the HMA project given in the HMA business plan indicated that there had been relatively few changes in mix design technology over the past 20 years. However, there had been significant technological changes in the fields of road building materials and construction in this period, particularly related to developments in modified binder technology and the use of special gradings such as Stone Mastic Asphalt (SMA). In addition, traffic loads, traffic volumes and tyre contact stresses had increased and changed in nature. It was therefore natural to conclude that the growing incidence of premature failures (e.g. rutting, cracking, ravelling and skid resistance deficiencies) experienced at the time bore witness to the fact that the approach to HMA design then was no longer sufficient. The deficiencies in HMA design could conveniently be grouped as follows:

- *Traffic-related issues*: The South African HMA design method used at the time had been developed for lower tyre pressures, lighter axle loads and fewer load repetitions than the traffic experienced at the time.
- *HMA design issues*: The method used at the time did not cater for a wide array of mix types and binder types. It was quasi-performance-related and was predominantly based on empirical parameters developed decades previously. Road user requirements and environmental considerations were not fully integrated into the mix selection process.

Durability and ageing were not addressed, and one design approach was used for all situations.

- *Material issues*: There had been changes in crushing methods and there was increased use of modified binders.
- *Pavement design issues*: There was little synergy between structural design and HMA mix design with a lack of reliable performance data.
- *Constructability / workability issues*: There was a tendency to reduce layer thicknesses and to specify coarser mixes. Laboratory procedures did not reflect field practice.

Project objective

The ultimate aim of the project was to develop a new Hot-Mix Asphalt design method that would be based on relevant engineering properties of asphalt, that could be used to conduct performance-related design of asphalt mixes and that would be integrated with pavement structural design. The envisaged scope of the project embraced the following aspects:

- paver-laid hot-mix asphalt, thin surfacings and base course layers;
- all mix types (gap-graded asphalt, continuously graded asphalt, Stone Mastic Asphalt (SMA) and open-graded asphalt);
- all conventional and modified binders used in South Africa; and
- mix design for both new roads and rehabilitation projects.

The scope of the project, however, excluded mixes manufactured with emulsions, cut-back bitumens, foamed bitumens or tars.

In addition to the development of a mix design method, the scope of the project included the linking of the method with structural design and performance predictions. International experience was to be incorporated into the project and special emphasis would be placed on construction aspects, as well as on the issues of reliability of design outputs and ease of implementation.

Expected benefits

The HMA business plan estimated that the benefits from the project would be substantial. If the total annual production of hot-mix asphalt in South Africa of approximately 2,5 million tons at a cost of approximately R375 million was considered, and savings of between 5 and 10% due to the impact of the project were to be effected, then savings of between R18 million and R38 million could be effected annually. The business plan estimated the cost of development and implementation at more than R6 million over a five-year period. This implied a significant potential return on investment and full project cost recovery in a very short period of time.

Expected deliverables

The following were listed in the HMA business plan as expected deliverables:

- Various levels of mix design that could be used appropriately, depending on the level of design reliability required for a specific project.
- New, revised or re-assessed test methods, test criteria and specifications for the components used in asphalt mixes, including methods of assessing durability.
- Methods for preparation and conditioning of laboratory asphalt samples that simulate construction practices.
- A method of optimising the spatial composition of asphalt mixes, including simple models to predict engineering properties from spatial parameters.
- Test methods to determine the relevant engineering properties of asphalt mixes that could be linked to durability and performance, taking into consideration the level of design reliability required (i.e. the level of mix design within the HMA design method).
- Guidelines on construction aspects to be considered in asphalt mix design and guidelines on field testing for quality control.
- Recommendations for capturing constructability data and for monitoring long-term pavement performance for input into HMA design.
- Guidelines for situational analysis (environment, road geometrics, traffic, pavement support, availability and cost-effectiveness of available mix components) and for choice of analytical parameters (stress, strain) to be used together with mix engineering properties and transfer functions to provide input to first- and second-order structural design and to predict pavement performance.

In addition to the above, the PMG would manage the overall approach to be adopted and provide recommendations for implementation and future revisions. The following additional deliverables were envisaged from this process:

- a review of international HMA design methods, with the emphasis on approach and implementation;
- a comprehensive plan for the R&D process to deliver the desired outputs, taking cognisance of the ‘bigger picture’ and all parameters affecting the mix design method (to be adjusted as progress was made);
- exception, progress and financial reports;
- recommendations for the establishment of a user-friendly database which would provide information and guidelines to designers on the behaviour and performance of different mixes and binder types under a range of operating conditions, as well as procedures which could be used to enhance this information;
- suggested delivery systems for implementing the new mix design method; and
- recommended procedures for future enhancement and refinement of the HMA design system.

In the process of planning the project, some of the principles discussed in Chapter 6 were applied as illustrated in the sections below.

7.5.2 Strategic considerations

Strategic planning played a significant role in the development of the HMA project plan and some of the activities are discussed below in relation to the guidelines given in Chapter 6.

Vision statement

The following vision statement was defined:

> *To develop a new southern African hot-mix asphalt design method which will be integrated with pavement design, construction and expected performance and which will yield superior designs and concomitant savings based on the best available technologies (developed locally or imported) and on sound practice, and which can be implemented readily.*

Management structures

Due to the importance of the successful implementation of the HMA project and therefore the importance of obtaining early 'buy-in' from all stakeholders, it was decided to create a steering committee for the project with the following functions:

- to provide general direction for the project;
- to appoint contractors to conduct the work; and
- to assess progress and outputs.

The South African DoT decided to fund the PMG activities. The PMG consisted of representatives from CSIR Transportek, VKE (a consulting engineering firm) and the University of Pretoria. The functions of the PMG were to:

- submit projects (defined in terms of objectives, scope and deliverables) and a list of potential contractors (selected on the basis of skill and expertise) to the Steering Committee for approval;
- assess the technical merit of proposals submitted by researchers (if applicable) and make recommendations to the Steering Committee;
- schedule projects, conduct technical management and manage deadlines;
- integrate the project outputs and combine them into a final set of deliverables; and
- make proposals in respect of implementation (with special emphasis on the delivery systems necessary to facilitate implementation), education and training activities and future impact assessment.

Approach

In order to ensure that a holistic approach was followed in the project planning, a 'top-down' approach to the elements of the project was followed. As depicted in Figure 7.10, this process started with a definition of the desirable final outcome of an improved HMA design process, namely the improved performance of asphalt pavements, including safety, comfort of the road user and noise attenuation. Subsequently, four main elements in the asphalt pavement design process were defined. These were:

- structural design and performance of asphalt pavements;

- functional design and performance of asphalt pavements;
- quality issues; and
- environmental aspects such as traffic, climate, ageing of asphalt, etc.

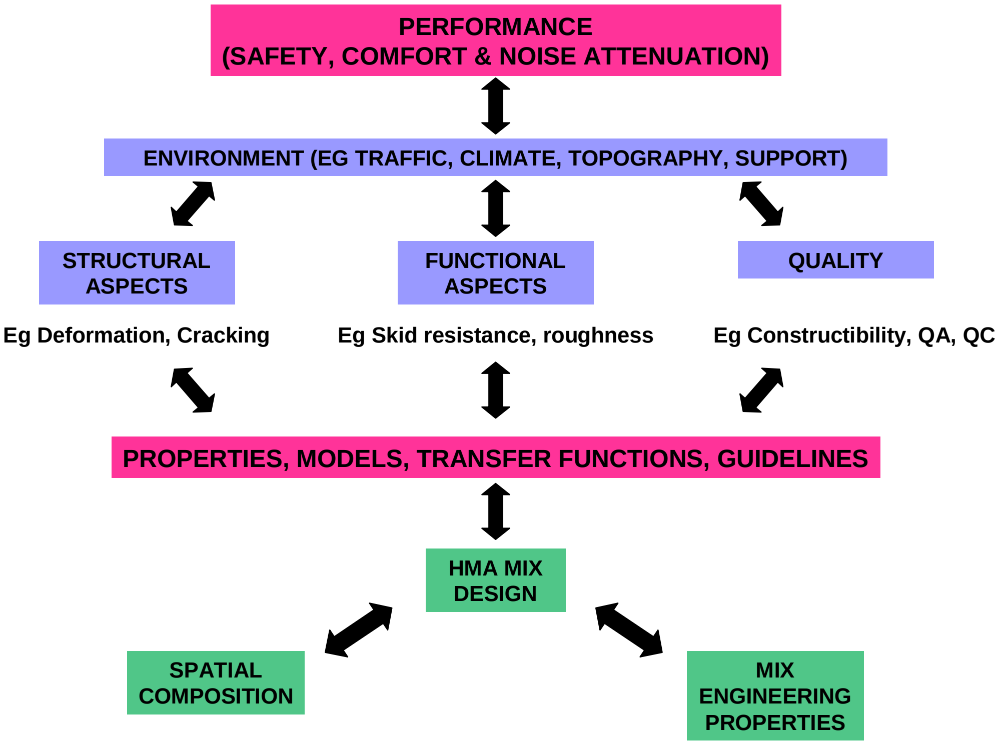


Figure 7.10: Schematic diagram of the HMA project development process

The results from the first three elements above are transformed by the environmental effects element in order to provide parameters for performance prediction. The four main elements are linked to the actual mix design process through engineering properties, models, transfer functions and guidelines.

This approach called for the assessment of the actual requirements regarding engineering properties and models for the structural design and performance prediction of asphalt pavements. This was radically different from the usual approach to the development of asphalt design methods by materials-focused engineers, which emanated from laboratory testing of materials. As an example, the top-down approach would determine the current and future properties required for structural design of asphalt pavements (e.g. strain-at-break, bending stiffness or compressive stiffness), then determine the required transfer functions and models, and only then focus on laboratory test methods and criteria.

Apart from the planning process, the diagram in Figure 7.10 also depicts the interactive process to be followed during integrated materials and structural design. As an example, the structural design engineers would run a first-order design, using assumed values for the asphalt layer properties. The results and requirements (e.g. stiffness and thickness of the layer or fatigue life required) would then be used by the materials design team to design the optimum mix. In a second-order analysis, the structural design engineer could then modify the structure (e.g. layer thickness or strength of the supporting layers) in order to achieve the required result. However, in this second-order design process realistic and achievable material properties and characteristics were used, thus optimising the design.

Project planning process

The project planning process was approached in a holistic manner, initially taking a broad view of the goals and expected deliverables, and then providing focus in the most critical areas. After the broad definition of the scope of work and dominant issues had been agreed on, the following Technical Focus Areas (TFAs) were defined:

- TFA1: Components of asphalt mixes
- TFA2: Spatial composition of asphalt mixes and laboratory processes
- TFA3: Performance-related properties of asphalt materials
- TFA4: Construction issues
- TFA5: Structural design requirements.

For each of the TFAs, a TFA leader was appointed with the task of:

- convening a core group of experts and an advisory group for the TFA;
- consulting with the TFA core group in order to define the scope of work to be conducted in the TFA, identify the gaps in existing knowledge and propose potential project areas for work to be conducted;
- informing the Advisory Group of developments within the TFA, and encouraging feedback;

- providing input into the development of the strategy and business plan for the project;
- defining projects in terms of objectives, scope and deliverables, and assisting the PMG to identify potential contractors who might tender for such projects (and who could submit detailed proposals for achieving such objectives); and
- assisting the PMG with the co-ordination of projects and with compilation of the outputs into products that could be easily integrated into the final deliverable.

Needs determination

Apart from the strategic process for defining the need for and contents of the project, a review of all needs identified by various processes and/or organisations was conducted. The result is given in Appendix O (see companion document). The problem statements and project ideas were categorised into the Technical Focus Areas in order to allow for proper project definition.

7.5.3 Use of technology trees to develop a project portfolio

The technology trees developed for the HMA project are shown in Figures 7.11 and 7.12. Using the strategic inputs, the definition of the TFAs, as well as the project ideas listed in Appendix O, a project portfolio was defined in an interactive planning process in the PMG. The projects were:

TFA1: Components

- TFA1/A/1: Qualitative assessment of the influence of (super) fines on binder rheology and durability, and procedures for establishing the selective sorption potential of aggregate on long-term performance.
- TFA1/A/2: Synthesis of test procedures for the assessment of the durability (ageing and loss in flexibility) of bituminous binders and qualitative assessment of the effects of ageing on binder stiffness.
- TFA1/B/3: Re-assessment of relevant test methods and of specifications for mix components, and compilation of new test procedures and specifications for mix preparation, compaction and characterisation (as proposed by TFA2 and TFA3)

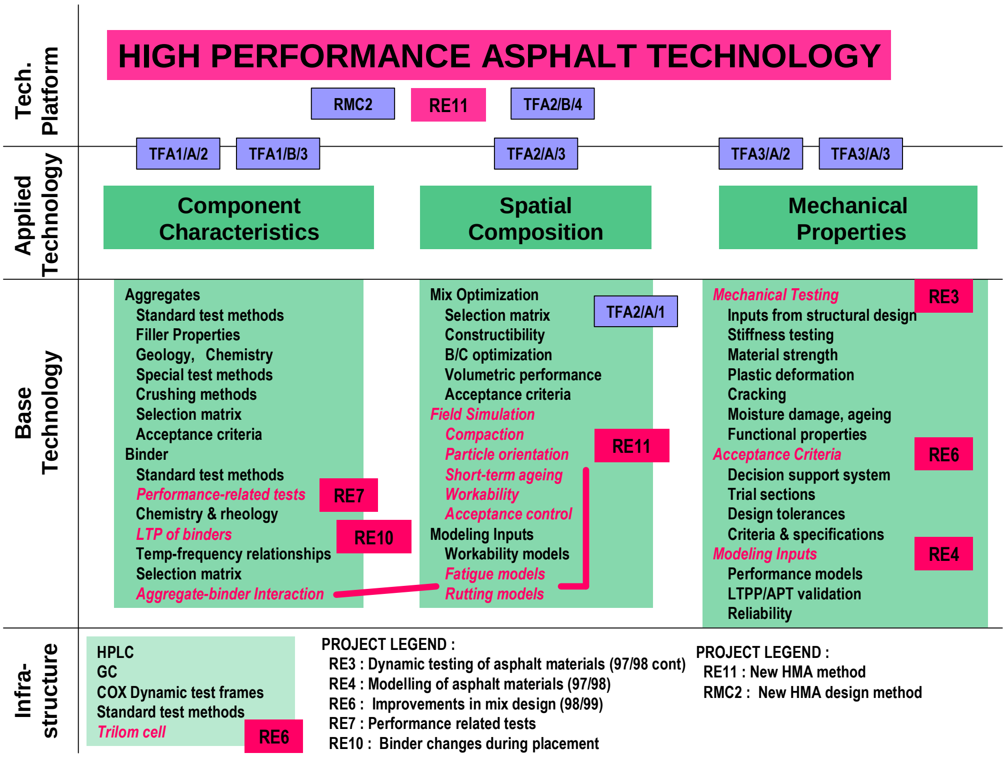


Figure 7.11: The CSIR high-performance asphalt technology tree showing Parliamentary Grant projects (red) and contract R&D projects (blue)

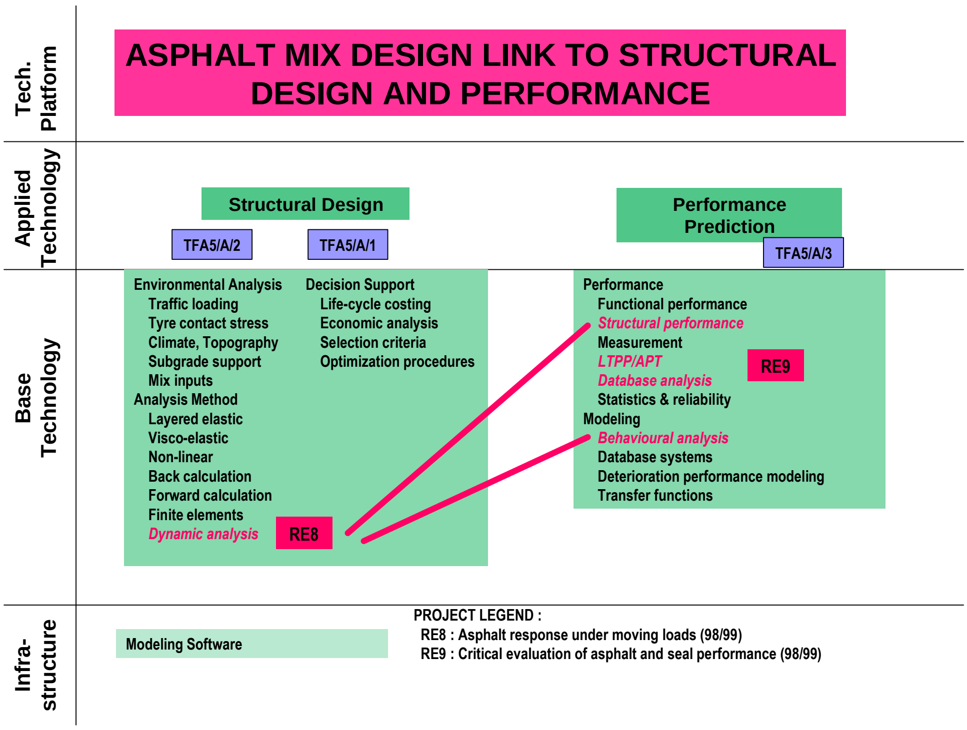


Figure 7.12: The CSIR asphalt mix design link to the structural design technology, showing Parliamentary Grant projects (red) and contract R&D projects (blue)

TFA2: Spatial composition and laboratory processes

- TFA2/A/1: Conceptualisation of spatial composition.
- TFA2/A/2: Synthesis and validation of laboratory procedures for the simulation of construction processes in the laboratory.
- TFA2/A/3: Development of volumetric/spatial design procedures and the establishment of criteria, taking cognisance of environmental effects (traffic, climate, etc.), constructability, design reliability and performance requirements.
- TFA2/B/4: Development of a mix selection matrix.

TFA3: Performance-related properties

- TFA3/A/1: Synthesis of test procedures which can be employed to assess the resistance of HMA to permanent deformation and cracking.
- TFA3/A/2: Development of procedures for the prediction of permanent deformation of HMA.
- TFA3/A/3: Refinement of procedures and development of constitutive models for the characterisation of the resistance of HMA to fatigue and reflective cracking, taking cognisance of ageing effects with time.

TFA4: Construction

- TFA4/A/1: Investigation and synthesis of constructability/workability problems experienced in the field.
- TFA4/B/2: Construction of trial sections for HMA project.

TFA5: Structural design and performance

- TFA5/A/1: Identification of the most appropriate mathematical modelling procedures and identification of required input parameters for mechanistic modelling.
- TFA5/A/2: Situational analysis and sensitivity analysis, taking into consideration environmental influences and traffic loading.
- TFA5/A/3: Review of available performance data and recommendations.
- TFA5/B/4: Development of plastic deformation and fatigue transfer functions, and their incorporation into a mechanistic design system.

Project descriptions for the above are given in Appendix P (see companion document). The positions of the above projects on the relevant technology trees are shown in Figures 7.11 and 7.12. The project priorities were determined by assessing their position in the technology tree and their importance in achieving the end goals of the project. A and B priorities are indicated in the project numbers. In addition, a project planning process using the Critical Path Method (CPM) was used to identify the sequence for conducting the projects.

7.5.4 Implementation actions

The business plan for the HMA project stated that the PMG would be responsible for making proposals in respect of implementation, with special emphasis on the delivery systems necessary to facilitate implementation and on the provision of practical final solutions. The proposals would include recommendations for:

- Delivery systems:
  - reports, articles and codes of practice;
  - purchasing cost of new equipment and associated training;
  - information technology such as the Internet and CD-ROM technology; and
  - seminars and workshops.
- Demonstration projects in conjunction with industry and the road authorities.
- Events, such as BMLC and the 1999 Conference on Asphalt Pavements in Southern Africa (CAPSA '99).

7.5.5 Education and training

Education and training activities would also be planned and co-ordinated by the PMG and would make use of the following organisations:

- Society for Asphalt Technology (SAT);
- Sabita Chair at the University of Stellenbosch;
- other universities; and
- technikons.

Since 2000, subsequent to the completion of the project, CSIR staff members have been invited as guest lecturers in asphalt technology at the University of Pretoria and the University of Stellenbosch.

7.5.6 General discussion

The planning process for the HMA project successfully used some of the principles of the R&D management approach described in Chapter 6., However, the following aspects could have been improved:

- a clearer link between the prioritisation of projects and strategic and technical inputs, or the technology trees;
- more detailed planning for the implementation of the project; and
- the development of an impact measurement plan using the tool described in Chapter 6.

7.6 Application of the model and tools in the CSIR Built Environment Unit

The models and tools discussed above were also applied in the CSIR Built Environment Unit which was formed during the CSIR's 'Beyond 60' restructuring process in 2005.[313] The CSIR Built Environment Unit was formed from the previous CSIR Transportek Division, the CSIR Boutek Division and the Coastal Engineering Group from the previous CSIR Environmentek Division. Transportek had a research-focused culture and Boutek, in general, a consulting services culture. The fusion of the two cultures and the balancing of research activities with activities aimed at problem solving for government was a major challenge. Furthermore, the Science, Engineering and Technology (SET) base in the ex-Boutek part of the new Unit was significantly depleted. The model and tools described in Chapter 6 were used to assist in the restructuring and subsequent R&D planning of the new Built Environment Unit in the following way:

- The development of technology trees to identify the areas that were high in the tree, delivering mainly consultancy services and thus earmarked to be moved to the CSIR Knowledge Services Unit.
- The use of technology trees to determine the Science, Engineering and Technology base that was required in some areas to redirect the efforts towards new knowledge generation and research.

- A renewed focus on strategic planning and R&D strategy based on the understanding of the process of R&D as a cybernetic system.
- The use of the model as a basis for developing detailed Competency Area plans, which included an environmental and market analysis, the market's need for solutions, the rationale for and the description of the required SET base, and therefore the research agenda.
- The setting up of a Research Advisory Panel for the Built Environment Unit consisting of academics, practitioners and government officials.
- The continuation of the activities of the Pavement Research Advisory Committee (PRAC).
- An internal SET committee to assist with strategic planning and the formulation of research agenda.
- The development and initial implementation of the Research Effectiveness measurement system as described in Chapter 6.
- The development of a suite of flagship research projects that are innovative, will receive dedicated funding over a three- to five-year period, are aimed at building the SET base and will yield significant SET outputs in terms of patents, technology demonstrators, publications and PhD degrees.
- The planning of larger, more significant projects with critical mass, thus yielding an average project size in excess of R800 000 per annum, which is significantly higher than in the past.
- The implementation of the greater concept of a holistic approach and a systems approach to the management of R&D activities and programmes.

The model and tools were successfully used to restructure and set up the new Built Environment Unit. The processes followed were also endorsed by the Research Advisory Panel of the Built Environment Unit[314].

The Infrastructure Engineering Competency Area of the Built Environment Unit is a combination of road engineering, port and coastal engineering, and structural engineering. In the Road Engineering group, particular emphasis is placed on stakeholder interaction and participation in the R&D process through the Pavement Research Advisory Committee (PRAC)[315]. This committee serves as a steering group to guide all research related to pavement materials, pavement design and accelerated pavement testing (HVS testing).

The Pavement Research Advisory Committee (PRAC)

The PRAC was structured and designed in 2004 under the auspices of the South African National Roads Agency (SANRAL) using some of the results from this work. The following organisations and companies are members of the PRAC:

- the Cement and Concrete Institute (C&CI);
- the Aggregate and Sand Producers' Association of South Africa (ASPASA);
- Vela VKE – a consulting engineering firm;
- Jeffares and Green – a consulting engineering firm;
- the Southern African Bitumen Association (Sabita)
- the Asphalt Academy;
- the South African National Roads Agency (SANRAL);
- the national Department of Transport (DoT);
- the Provincial Government of KwaZulu-Natal;
- the Provincial Government of the Western Cape;
- the Provincial Government of Gauteng;
- the University of Stellenbosch;
- the University of Pretoria;
- the Technical University of Tshwane; and
- the CSIR Built Environment Unit.

The PRAC has the following objectives:

- to provide advice on R&D needs and priorities;
- to assist with technology foresight studies;
- to advise on the development of strategic plans and research portfolio plans for the research programme;
- to assist with project portfolio analysis;
- to assist in the review of outcomes and objectives; and
- to assist in assessing the impact of R&D activities.

In essence, therefore, the PRAC provides a platform for a holistic approach to defining the road infrastructure R&D agenda and to evaluating the outputs. The first document released by the PRAC dealt with road pavement research needs for South Africa[316].

As indicated above, the new approach, model and tools have been used in the research activities of all the Competency Areas (groups) in the Built Environment Unit (BE Unit) which encompasses a number of diverse fields. These include:

- planning support systems (including access planning, design of sustainable human settlements, geographic information systems, sustainability science, etc.);
- infrastructure engineering (including pavement engineering and materials, port design and design of structures);
- construction (including conventional and labour-intensive construction and construction materials);
- architectural science (including a focus on schools and hospitals, as well as the design of sustainable buildings);
- infrastructure operations (including passenger and freight transport, network asset management and intelligent transport systems);
- logistics and quantitative modelling (including logistics analysis, modelling of built environment problems and complexity theory); and
- rural infrastructure and services (including rural access, transport, sanitation, water and energy supply).

The use of the strategic-level model described in Chapter 8 has been augmented with a number of management processes. These are depicted as a system outside the management model in Figure 7.13.

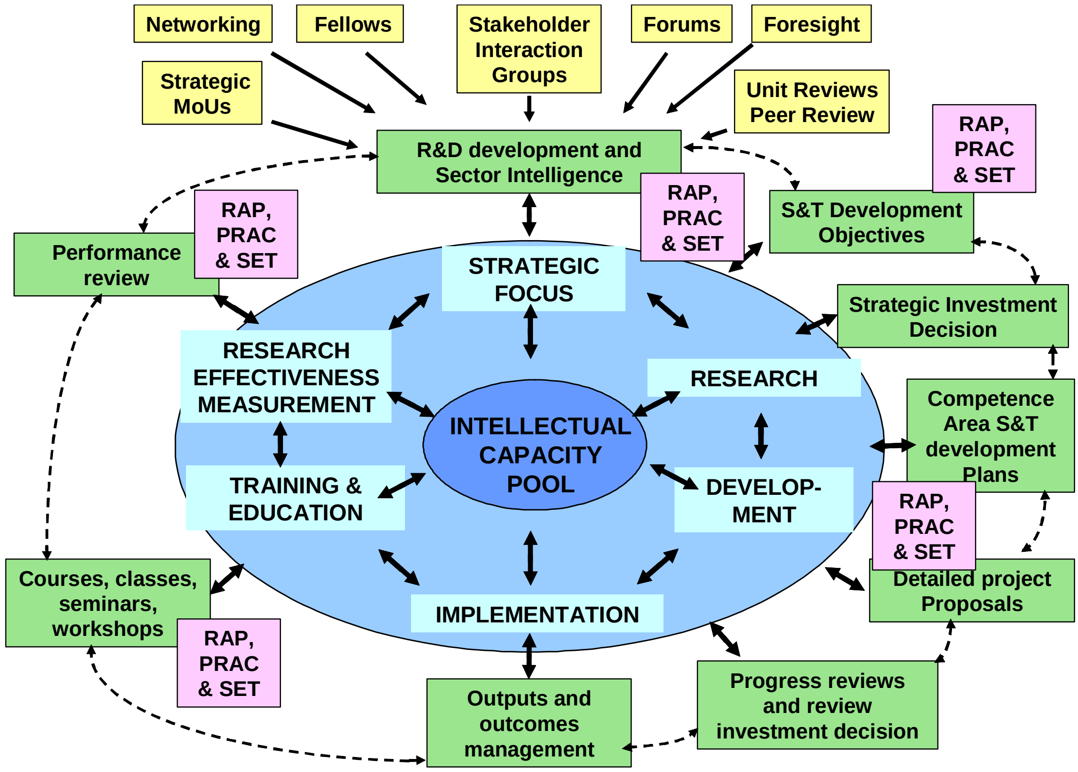


Figure 7.13: Implementation of the new model in the CSIR Built Environment Unit

The outer system is shown in green and with dotted arrows. As described in previous chapters, the system boundary of the strategic model can now be drawn wider to include the management process elements. The management process elements include the following:

- The accumulation of industry sector intelligence through a number of activities, including:
  - networking with peers at local and international level;
  - the activities of four BE Unit fellows (external members and own staff) who interact regularly at an international level;
  - strategic Memoranda of Understanding with research partners such as the Department of Transport, the Department of Housing, the Department of Public Works, local universities and international universities (e.g. the University of California at Davis);

    - stakeholder interaction groups such as the Road Pavements Forum and the HVS International Alliance (which includes all sectors of the road building industry);
    - technology foresight studies such as those described above; and
    - international peer review of projects every three years.
- The definition of Science, Engineering and Technology (SET) development objectives and SET focus areas based on the strategic planning process of the BE Unit.
- The strategic-level investment decision to allocate resources to the SET focus areas, as described in Section 7.3.5.
- The development of detailed SET research and development plans at the Competency Area level which are submitted and presented to the Research Advisory Panel (RAP) for approval. (These plans include the use of technology trees as discussed in Chapter 8 to indicate the state of the SET base, the rationale of the specific focus of the research agenda and the link of the SET base to key solutions and needs in the industry.)
- The development of detailed project proposals based on the Unit and Competency Area strategic plans.
- Progress reviews in each Competency Area twice a year to evaluate the progress and strategic direction of the research activity (internal presentations to the Strategic Research Manager, as well as presentations to the RAP) and reallocation of resources if required.
- The management of the outcomes from the research process which include patenting, commercialisation of technology demonstrators (see Chapter 6), technology transfer projects and electronic knowledge dissemination through an Internet portal (managed by the Strategic Research Manager and assisted by a BE Unit Outcomes Manager).
- The presentation of training courses, classes at tertiary education institutions, seminars and workshops to disseminate research results.
- Performance review of the outputs of the research process by the Strategic Research Manager, the SET Committee and the RAP based on the following aspects:
    - evaluation of the quality and innovativeness of the research project;

  - evaluation of the quality of the project management process, presentation and clarity of the final deliverable;
  - evaluation of the relevance of the output to the BE Unit strategy and national priorities; and
  - evaluation of the potential value of the outcomes of the research.
- Finally, evaluation of the performance of the BE Unit against its Key Performance Indicators (KPIs) and targets set by the CSIR Executive (as given in the BE Unit Strategy and Operations Plan[317]). These KPIs include the evaluation of the R&D outputs as described in Table 6.1.

The roles of the RAP, the SET committee and the PRAC (in the case of the road infrastructure research activities) are also shown in Figure 7.13. The above management process is an interactive, cybernetic system that encapsulates the conceptual, strategic-level model. In essence the process is therefore a system within a system. The inner core of this greater system is the intellectual capacity pool, the middle level of the system is the strategic R&D process and the outer level is the operational process of the management of R&D activity, including elements of the business management of the BE Unit. The system as a whole has elements of a cybernetic system which include feedback loops, two-way information flow, a 'sensor' to measure performance and an element of self-correction (the investment decision process is influenced by the performance measurement processes).

The above process is complicated as can be noted from the number of elements that need to be managed in parallel, their interaction and the diversity of the research programme.

7.7 Concluding remarks and critical appraisal

The model and techniques described in Chapter 6 have been successfully implemented in practice, both in the private and public sectors, as well as in the management of the Parliamentary Grant programme at CSIR Transportek and the new CSIR Built Environment Unit. The model is radically different from the conventional linear models that had been designed for the development of products intended for the consumer market. The success of the model in terms of facilitating successful implementation of new technologies is demonstrated by the above examples.

Although implementation of the model (as described in this chapter) is not yet perfect, it is expected that the process will improve with time as organisations learn. Some of the lessons learnt in the process up to now include:

- It is essential to involve people, both technical and managerial, from all parts of the industry in the R&D management process and to view them as being part of the pool of intellectual capacity in order to obtain early 'buy in' into the process and thus enhance implementation.
- The use of the model has forced organisations to place more emphasis on R&D strategy during their business strategy planning sessions, thus improving the research and technology strategy and its link with business strategy.
- The effort and cost associated with the implementation of new technologies and the transfer of technology to the industry should not be underestimated and these costs should be budgeted for upfront.
- Technical forums such as the Bituminous Materials Liaison Committee (BMLC, which was later transformed into the Road Pavements Forum) and the Research Advisory Panels play an essential role in involving practitioners in needs determination, sharing of results and providing general direction (thus instilling a feeling of ownership of the process and results).
- The role of a central, primary research organisation such as the CSIR in ensuring the focus of the programme, developing critical mass in research capability and developing links with other research organisations and educational institutions is invaluable.
- Longer-term planning (multi-year project planning) and dedicated funding are essential to allow creativity and innovation and to counter fragmentation of the programme into a host of small projects.
- The use of technology trees has not only improved the project portfolio planning process, but also allowed the R&D management team to explain to senior management the process of investment, the business and technical reasons for investing in specific technologies (sometimes low on the technology tree and therefore otherwise difficult to motivate), as well

as how key solutions will be developed cost-effectively through enhancing the quality of the defined technology platforms.

- The use of technology trees has also improved the rational discussion of individual thrusts or project ideas as part of the larger whole and thus negated the usual behaviour of every researcher pushing his own pet topic – behaviour that can have an adverse effect on funders and users of new technology.
- The use of the strategic model has forced researchers to think 'in reverse' in order to define clearly the end product and its implementation and technology transfer to industry before significant amounts of money are spent on basic research.

However, the following aspects of implementing the R&D management approach discussed here should, in particular, still receive attention:

- Implementation planning at the time of project initiation should be improved to define clearly the nature of the end product as this will influence the R&D approach and also as there is a need to plan and budget for implementation activities and the commercialisation of research outcomes.
- Use of Information Technology (IT) as a delivery system for transferring technology to industry and users should be improved.
- Although the basic framework and indicators for the measurement of research effectiveness have been developed, the process still needs to be fully implemented and an events and outcomes database should be created.
- The equivalent rand value indicators for the measurement of Research Effectiveness can be improved through a Delphi process and through consulting with a broader base of stakeholders.
- A process should be developed to analyse the indicator trends to provide input into technology and business strategy development, thus completing the full circle of the holistic R&D management process.
- The Human Resources development plans (multi-year strategies) and links with educational institutions should be improved to enhance the development of the intellectual capacity pool.

8 ASSESSMENT OF THE SUCCESS OF THE IMPLEMENTATION OF THE MODEL

8.1 Introduction

The South African government clearly stated its intention to increase research activity in South Africa in the National Research and Development Strategy[3]. This was again emphasised by President Thabo Mbeki in his State of the Nation Address in February 2007 as one of the critical actions to build the South Africa of the future: *"to increase spending on scientific research and development."* The most recent State of the Nation Address by President Jacob Zuma (June 2009)[318] indicated that infrastructure development, the Expanded Public Works Programme (EPWP) and poverty alleviation remain very high on the agenda.

Research and development have been important to the government since South Africa became fully democratic in 1994. The relevance of the model and tools developed here will therefore be reviewed in the light of a number of government policies and plans over the period since 1994. In view of the focus on R&D as an enabler for a prosperous South Africa, it is imperative that R&D expenditure be optimally utilised and the delivery from the programme be maximised. The question now remains whether the work done in this study has indeed had a positive effect on the R&D programmes in the road infrastructure sector of South Africa.

In this chapter the model is therefore assessed critically from the following perspectives:

- its relevance to South Africa in view of major government strategic initiatives such as the Reconstruction and Development Programme (RDP)[319], the Growth, Employment and Redistribution (GEAR) strategy[320], the Accelerated and Shared Growth Initiative of South Africa (AsgiSA)[321] and the South African Science and Technology White Paper[322];
- how well the model addresses the set of summarised tenets that are defined in Chapter 6; and
- the performance trends of the road infrastructure R&D programme over the past number of years as measured against the criteria defined in

Section 6.4.4 (including publications, post-graduate degrees awarded and growth in contract R&D work).

The purpose of this chapter is not to assess either the validity of the government initiatives or their successes and failures, but rather to assess the relevance of the new approach, model and tools in the light of the stated objectives of these initiatives. There are criticisms of some of the aspects of these policies, e.g. the RDP and GEAR[323]. Nevertheless, they still remain government ***policy*** irrespective of differing opinions on their validity and the success of their implementation. Where relevant, some indications have been given of the potential contribution of the new model and approach to address some of these criticisms.

8.2 Assessment of the new R&D management approach against the objectives of the Reconstruction and Development Programme (RDP)

8.2.1 General

The Reconstruction and Development Programme (RDP)[319] developed by the African National Congress (ANC) prior to elections in 1994 served as a general strategy for transforming South Africa. It specifically focused on (Section 1.4.1 of the RDP):

- meeting the basic needs of the people of South Africa;
- the development of human resources;
- the building of the economy;
- democratising the state and society; and
- implementation of the RDP.

At a general level, the R&D management model addresses the imperatives of the RDP in the following ways:

- In view of the RDP's objective of meeting the basic needs of people within budgetary constraints, both the prioritisation of projects and the optimisation of value for investment are essential. The model developed here facilitates both the prioritisation of projects on the basis of their strategic linkages, and the optimisation of the use of funding.

- The RDP focused on human resource development which is reflected in the model by the central focus on the intellectual capacity pool and the fact that education and training are essential elements in the model.
- The RDP emphasised the importance of building the economy which, apart from the fact that R&D essentially stimulates economic growth (see Chapter 1), is also reflected in the model by the focus on enhancing competitiveness through the optimisation of the investment decision and the stimulation of innovation.
- The RDP focused on participation of stakeholders and the identification of stakeholder needs, which is reflected in the strategy and needs determination elements of the model.
- The RDP emphasised the importance of implementation, which is reflected in the model by the focus on planning for implementation and technology transfer, the focus on delivery systems and the measurement of effectiveness and impact.

In addition to the above general comments, specific relevant aspects of the RDP are discussed below in relation to the model developed in this study.

8.2.2 The importance of human resource development

The RDP sees human resource development as central to its success and generally emphasises training and ‘getting information and knowledge to the people’. Higher education is also regarded as important: “*The higher education system represents a major resource for national development and contributes to the world-wide advance of knowledge”* (Section 3.3.13 of the RDP).

As discussed in Chapter 6, the R&D management model concentrates on human resource development through:

- a fundamental focus on the central pool of intellectual capacity;
- specific emphasis on education and training;
- emphasis on the transfer of technology to industry and users and communities through appropriate delivery systems and technology transfer processes;

- the monitoring of human resource development in the research effectiveness measurement system through measurement of:
    - o the number of post-graduate qualifications;
    - o the number of trained practitioners in industry; and
    - o the number of professional registrations.

8.2.3 The importance of science and technology

The RDP places significant emphasis on science and technology: *"Technology policy is a key component in both industrial strategy and high-quality social and economic infrastructure. It is critical for raising productivity in both small and large-scale enterprise."* - Section 4.4.8.1.

It furthermore states that a science and technology policy should pursue the following broad objectives (Section 4.4.8.2):

- developing a supportive environment for innovation;
- reversing the decline in resources for formal science and technology efforts in both the private and public sectors;
- enabling appropriate sectors of the economy to compete internationally;
- ensuring that scientific advances translate more effectively into technological applications, including in the small and micro sector and in rural development; and
- humanising technology to minimise its adverse effects on working conditions and employment.

The importance of innovation, a holistic approach, linkages and foresight are also indicated:
"Technology policy must support inter-firm linkages that facilitate innovation. In research and development, the democratic government should support pre-competitive collaboration between local firms and public-domain efforts combining enterprises and scientific institutes." - Section 4.4.8.3.

"The democratic government must develop programmes to make university-based science more responsive to the needs of the majority of our people and for basic infrastructure, goods and service. Scientific research should link up with

technological advance in industry, commerce and services and in small and micro production. In particular, there must be research into appropriate and sustainable technologies for the rural areas." - Section 4.4.8.7.

"The democratic government must develop extensive institutional support and enhance government capacities to ensure successful research foresight. Because science and technology play a crucial role in the RDP, a strong co-ordinating agency in government must maintain on-going consultation with key stakeholders." - Section 4.4.8.9.

The R&D management model addresses the above issues as follows:

- the essence of the model is a holistic, systems approach that emphasises interactivity between the elements and linkages between all players;
- it strives to create a supportive environment for innovation;
- it enhances the competitiveness of the roads industry so that it can compete with international firms through the development of cutting-edge technology while optimising the benefit achieved from investment;
- the systems approach ensures that basic R&D is translated into implementable key solutions which are transferred to the industry through appropriate delivery systems, and it measures the efficacy of the process through the research effectiveness measurement system;
- the implementation of the model has demonstrated the co-ordination of public sector (Department of Transport) and private sector (Sabita) R&D efforts with those of the CSIR through the use of technology trees;
- the needs determination process in the model ensures that real needs are addressed in R&D programmes and that stakeholders are appropriately involved at the outset; and
- the needs determination process combines stakeholder insights with reviews of technology trends in order to determine the appropriate R&D agenda (the focus areas).

8.3 Assessment of the new R&D management approach against the objectives of the GEAR strategy and AsgiSA

8.3.1 Focus areas of GEAR and AsgiSA

The Growth, Employment and Redistribution (GEAR)[320] strategy was published by the Ministry of Finance in 1996. This was followed by the Accelerated Shared Growth Initiative for South Africa (AsgiSA) in 2006[324, 321]. GEAR essentially aims at the implementation of the economic guidelines spelled out in the RDP. GEAR aims at:

- a competitive, fast-growing economy which creates sufficient jobs for all work seekers;
- redistribution of income and opportunities in favour of the poor;
- a society in which sound health, education and other services are available to all; and
- an environment in which homes are secure and places of work are productive.

The core objective of AsgiSA is to halve poverty and unemployment by 2014. AsgiSA deals with a strategy focused on:

- macro-economic issues;
- infrastructure programmes;
- sector investment strategies (or industrial strategies);
- skills and education initiatives;
- second economy interventions; and
- public administration issues.

Although GEAR is a strategy for general economic reform, it mentions the following issues pertinent to this discussion:

- acceleration of growth, particularly in the non-gold export sector (this implies a need for improved transport systems);
- an increase in infrastructural development and service delivery making intensive use of labour-based techniques (this includes the provision of road infrastructure);

- a competitive platform for a powerful expansion of the tradable goods sector (once again implying that improved transport systems will be necessary);
- gradual relaxation of exchange controls (this implies increased international competition);
- "*it is Government's conviction that we have to mobilise all our energy in a new burst of economic activity*" (implying that a significant effort in R&D will be required);
- the creation of public-private partnerships in transport and telecommunications;
- an expansionary public infrastructure investment programme to provide more adequate and efficient economic infrastructure services in support of industrial and regional development and to address major backlogs in the provision of municipal and rural services;
- industrial innovation support programmes will be enhanced - this includes the incentive provided in terms of the Special Programme for Industrial Innovation (SPII), as well as the matching grants under the Technology and Human Resources for Industry Programme (THRIP) designed to strengthen the relationship between educational institutions and industry;
- investment in social and economic infrastructure will play an important role in increasing labour and business productivity, thus achieving higher growth rates;
- public infrastructure needs include, among others, roads, railways, airports, harbours and pipelines; and
- progress in all these areas adds to the quality of life in communities, while simultaneously building productive economic capacity.

8.3.2 Discussion

The discussion in the previous sections indicate that the GEAR strategy focuses on stimulating economic growth and recognises that infrastructure development is essential for achieving this. Specific emphasis is placed on job creation, particularly by using labour-intensive methods for the creation of infrastructure. In addition, the emphasis on accelerated growth in exports indirectly stresses the importance of transport. This is underscored by the AsgiSA strategy, which places importance specifically on poverty reduction, the second economy and infrastructure development.

However, as Bell[325] reports, opinions are divided as to whether GEAR is a reversal of the RDP or a way of taking RDP aims into the international macro-economic arena. Opinions are also divided on the exact differences between GEAR and AsgiSA. Suffice it to say that both GEAR and AsgiSA are premised on *"the concept that growth equals job creation equals wealth redistribution"*. Piasecki's[326] is of the opinion that the failure of conventional development paradigms globally to lift the majority out of poverty can be ascribed to an over-emphasis on economic growth and a simplistic view that all that is needed for growth are technology, foreign capital and efficient institutions.

The importance of R&D to support the required growth in the manufacturing of tradable goods is emphasised in initiatives such as SPII and THRIP (funding programmes by the Department of Trade and Industry) which are aimed at stimulating innovation. Many of the principles incorporated into the R&D management model developed in this study (e.g. co-operation between public and private sector, focus on human resource development) are therefore reflected in the GEAR strategy.

However, no mention is made of a concerted effort to co-ordinate R&D to ensure maximum return on investment. Programmes such as SPII and THRIP would be more effective if managed as part of a holistic, systems approach.

South Africa is not alone in the developing world in its quest to balance the imperatives of engaging with a globalised economy to create a climate for attracting international trade and investment with the imperatives of attending to domestic issues such as employment creation and increased social spending. Such a balance necessitates trade-offs.

According to the Isandla Institute[327], GEAR was successful in the early to mid-2000s in reducing inflation and the budget deficit, but this has been at the cost of employment creation and social spending. This has created the need for a 'shared growth strategy' as embodied in AsgiSA.

It is in the effective management of the necessary trade-offs of a growth strategy that models such as the one developed in this study are useful. This model, with its focus on the development of human capacity and the use of technological solutions to create employment, makes a significant contribution towards this goal. However, it is in the adoption of a systems approach that the model has the greatest potential to support the objectives of a holistic development strategy in South Africa that goes beyond purely economic principles.

8.4 Evaluation of the model in terms of South Africa's S&T policy

8.4.1 The South African Science and Technology White Paper and the DST's Ten-Year Plan

The White Paper on Science and Technology[322] stressed the importance of R&D in the global context, especially now that political changes have placed South Africa in the global arena, thus exposing the country to international competition and to the pressures and challenges of rapid change in the global environment. It is essential to strike a balance between being competitive in the global arena and addressing local needs. This policy document was followed up by the National R&D Strategy[3] and the Department of Science and Technology's (DST) Ten-Year Plan published in 2007[328].

Some of the global trends mentioned in the White Paper that will affect planning and resource allocation in South Africa are:

- the knowledge-based transformation of many of the world's societies resulting from the increased flow of information made possible by new communication technologies;
- the competitive pressures on the South African economy as it becomes exposed to global market forces;
- increased co-ordination of innovation policies and strategies in response to the complex challenges generated by global social and economic changes; and
- a problem solving, multi-disciplinary, partnership approach to innovation.

This, and the discussion in Chapter 6, indicate that the R&D management model takes into account the main trends discussed in the White Paper. In particular, the model focuses on knowledge generation rather than on hard product development. In addition, it emphasises the need for the road construction sector to become more competitive in the face of increasing international competition. These aspects are reflected in the new model through:

- the holistic approach, which combines the efforts of a number of organisations to enhance delivery from research and development;
- the focus on developing key solutions to critical problems and issues facing the industry;
- the focus on implementation through suitable delivery systems; and
- the forming of partnerships that strengthen the science and technology base.

The important aspects of the National R&D Strategy[3] that pertain to transport were discussed in Chapter 1. The DST's Ten-Year Plan[328] focuses on a knowledge-based economy with the following main supporting elements:

- innovation;
- economic and institutional infrastructure;
- information infrastructure, and
- education.

The plan mentions six grand challenge areas:

- the farmer to pharma value chain to strengthen the bio-economy;
- space science and technology;
- energy security;
- global-change science with a focus on climate change; and
- human and social dynamics.

Although the grand challenges do not directly mention infrastructure or transport, the following are important aspects of this plan:

- the development of specific technology platforms to focus the research effort;
- the importance of technology transfer to industry; and
- the importance of SET human capital development.

These aspects are dealt with in detail in the model and tools discussed in Chapter 6.

8.4.2 Requirements underlying South Africa's Science and Technology Policy

South Africa's Science and Technology policy is based on the following broad themes:

- promoting competitiveness and employment creation;
- enhancing the quality of life;
- developing human resources;
- environmental sustainability; and
- promoting an information society.

These themes are aimed at achieving the aforementioned balance between addressing local needs and competitiveness while enhancing human capital. In particular, the S&T White Paper emphasises the importance of co-operation between government and the private sector in the development of new technology.

The R&D management model addresses the above issues in the following way:

- it has a dominant focus on human resource development (the intellectual capacity pool) and it recognises that education is a vital element;
- it provides a balance in the R&D portfolio through the use of the needs determination process and technology trees, thus allowing the required balance of competitiveness versus quality of life issues; and
- it recognises the importance of developing appropriate delivery systems including Information Technology-related platforms.

8.4.3 The National System for Innovation (NSI)

According to the S&T White Paper[322], a National System for Innovation (NSI) comprises a set of functioning institutions, organisations and policies that interact constructively in the pursuit of a common set of social and economic goals and objectives. The functions of the NSI are:

- policy formulation and resource allocation at the national level;
- regulatory policy making;
- performance-level financing of innovation-related activities;
- performance of innovation-related activities;
- human resource development and capacity building; and
- the provision of research infrastructure.

The NSI indicates that the sciences, engineering and technology should acquire a new status in South Africa. Technological change is one of the primary sources of economic growth, and therefore the S&T policy should recognise the need for the successful management of research and technological development, in particular management of the main agents of technological change: innovation and technology diffusion.

The R&D management model addresses the main elements of the NSI in the following way:

- the holistic approach of the model and the use of tools such as technology trees stimulate co-operation between organisations that fund technology development and organisations that carry out technology development;
- the systems approach ensures that inventions become innovations (i.e. that they end up in the market place) and that the process is based on a sound strategy, is controlled and monitored, and also provides a feedback loop to R&D strategy;
- the notions of thrust management, portfolio management and the investment decision process of the model assist in the optimisation of funding allocation and ensure that maximum benefit is derived from a portfolio of investments;
- the research effectiveness measurement system ensures that the performance of innovation activities is monitored and provides basic information for future investment decision processes;
- the human resource development issue is addressed by the development and maintenance of the intellectual capacity pool and the fact that education and training are main elements of the model; and

- the use of technology trees ensures that relevant investments in research infrastructure are made.

The above discussion indicates that the model is well aligned with South Africa's S&T policy.

8.5 Assessment of the new model and tools in view of the tenets for the development of a new model

The characteristics of the new model and tools were analysed in terms of the summary tenets developed in Chapters 2, 3 and 5. This analysis is shown in Table 8.1. The table indicates the summary tenets, the characteristics of the models and tools that address these tenets as well as an ordinal rating[329] of how well the model and tools address each of the tenets (albeit subjectively).

As can be seen from Table 8.1, the model and tools addressed the majority of the tenets in an excellent way. However, the following can still be improved:

- A greater focus on the integration of the natural sciences and social sciences is needed to ensure that key solutions are delivered which are not only technologically excellent, but also address the broader needs and preferences of the communities and stakeholders that they are intended for.
- Standard portfolio balance diagrams and tools such as those described by Roussel[81] can be used to complement the balancing of projects in technology trees.
- The use of technology trees to assess manpower balance and skills gaps can be improved.
- More formal policies relating to creativity can be developed at the organisational level, including special reward systems.
- The research effectiveness measurement tool should be broadly implemented and a benchmark study done through a retrospective analysis of the past performance of research programmes relating to the road infrastructure industry.

Table 8.1: Assessment of the degree to which the new model and tools satisfy the summary tenets developed

Summary Tenet	Characteristics of the model and tools	Rating
1 A holistic approach should be integral to the model The model should take account of the broader environment of the research programme, which includes the needs of stakeholders and communities. Interaction with all role-players is essential and their R&D efforts should be co-ordinated. The full innovation chain including the eventual impact of the programme should also be part of the model.	The model takes account of the relevant aspects in its immediate environment, including technology trends, organisation strategy, research partners, educational processes and the economy. Stakeholder needs are catered for by the needs determination process and interaction with structures external to the model such as research advisory panels and stakeholder forums. The final model presented in Figure 7.13 includes a 'system within a system', indicating that the strategic management model interacts with a secondary system (in its environment) consisting of the elements that form the broader management process. The research effectiveness and impact of the process is measured by a 'sensor' which feeds information back to the process itself. The use of technology trees and management structures such as the PRAC allows the holistic management of a number of research programmes to avoid duplication and to seek synergy.	Excellent
2 The model should be based on a systems approach The model should take into account the principles of systems thinking, cybernetics and complexity theory with a specific emphasis on non-linear thinking to address the development of new engineering methodology and knowledge as opposed to the development of hard products for the consumer market; the interaction between the elements of the system and their interdependency; feedback loops that allow control, self-reference and self-organisation;	The model is circular (depicting circular causality), with elements that are interlinked and interdependent. The process of management does not follow a prescribed path but can follow a number of paths through the model. The model is a complex system with elements of cybernetics inherent in its operation. The research effectiveness element acts as a 'sensor' which measures the effectiveness of the system. The research effectiveness element provides feedback to the system through a number of loops and causes corrective action. The collection of performance data introduces an element of self-reference and self-correction. The model operates in a non-linear fashion and is complex; however, some degree of reduction is achieved through the viewing	Excellent

Summary Tenet	Characteristics of the model and tools	Rating
circular causality which means that the system can impact on itself; the fact that small changes can cause large effects elsewhere in the system, and some degree of informed reduction to deal with the breadth of the problem.	of the technology focus areas in separate technology trees that show the link between the S&T base and the key solutions which are in turn linked to stakeholder needs.	
3 Elements or levels of the model should be integrated to enhance the value and quality of the outcome from the research process The multi-disciplinary nature of the research and development process in the road infrastructure industry requires that these disciplines be integrated to yield enhanced outcomes. The integration of basic pockets of expertise to deliver higher-order key solutions that will provide long-term impact should be emphasised.	The technology tree tool includes the notion of a technology platform, the main function of which is to integrate a variety of multi-disciplinary capabilities. This leads to the development of higher-order key solutions that are of a multi-disciplinary nature and thus enhance the quality and applicability of the research outcomes. Some aspects of integration of the natural sciences and social sciences can be improved.	Good
4 The manpower pool should be central to the model The effectiveness of any R&D programme depends to a large degree on the quality of the researchers and practitioners involved in the process. The quality of the manpower pool should therefore be integral to the model and the research programme should be linked to future manpower development through education activities.	The manpower pool is central to the model and plays a key role in all the activities of the model. Technology trees can be used to plot manpower capability both in terms of number and quality or experience. This allows a critical assessment of the manpower capability in a specific focus area. The research effectiveness measurement system monitors the development of new qualifications as well as the number of industry members trained as part of the activities of the programme.	Excellent

Summary Tenet	Characteristics of the model and tools	Rating
5 Strategic planning must be a core element of the model The strategic planning and vision for both the road industry as well as the research organisation must form an integral part of the model. The model must also allow for a body (e.g. a steering committee) which provides strategic direction to the programme.	Strategic planning and associated activities such as stakeholder interaction are incorporated in the model. The needs determination process ensures effective assessment of stakeholder needs. Informed strategic direction comes from interaction with steering committees (e.g. the Research Advisory Panel and Pavement Research Advisory Committee) as well as from technology foresight studies and internal technical think tanks such as the Science, Engineering and Technology Committee at the strategic level and 'virtual skunk works' sessions at the project level.	Excellent
6 The research and development programme must be balanced Balance implies that there should be a strategic view of the balance between solving short-term problems and building new technology and knowledge platforms in the long term. As such there should be a balance between 'market pull' and 'technology push'.	The technology tree tool is used to assess the balance of the portfolio at the focus area or 'thrust' level. The vertical balance of the portfolio (high vs. low in the technology tree) is assessed to ensure a balance between immediate problem solving and longer-term strategic R&D. Horizontal balance in the tree gives an indication of the balance in the application of available funding. The investment decision process assists with balancing funding and resources at the strategic level. The use of standard portfolio balance diagrams and tools such as those described by Roussel can, however, be improved.	Good
7 Core competencies and platforms should be integral to the model The concept of core competencies and technology platforms should form an integral part of the model to ensure that long-term R&D capability is developed, that critical mass in terms of human resources is developed and that stakeholder needs are addressed effectively.	The model focuses on core competencies through the technology strategy planning at Competency Area level (as described in Section 7.6). The technology platform is a key concept in the technology tree tool. The technology tree tool can be used to assess the quality of the S&T base and its associated manpower capability, although this aspect has not been fully implemented. Stakeholder needs are clearly linked to key solutions and to the research capabilities through the technology tree tool.	Good

Summary Tenet	Characteristics of the model and tools	Rating
8 The model must stimulate creativity and invention It is important to allow enough room for researchers to be inventive to ensure that new knowledge generation is effective.	The model caters for stimulation of creativity and invention through the recognition of technology push as an important driver in the system. The model also allows for different management approaches between research projects and development projects. Virtual skunk works sessions are used to assist the stimulation of creativity. Some aspects of the 'lead users' concept are utilised through the rich interaction with users and stakeholders. More formal policies relating to creativity can be developed at the organisational level, including special reward systems.	Good
9 The model should counter the effects of fragmentation The model should stimulate the formulation of larger, multi-year and multidisciplinary projects that will ensure increased return of value for the investment made.	The holistic systems approach has had a significant effect on the research agenda in the road infrastructure field. In particular, there is now one national research agenda supported by a number of stakeholder organisations participating in the Pavement Research Advisory Committee. Research projects are now of significant value with critical mass in terms of resources, which thus negates the negative effects of the fragmentation of the research agenda in the past.	Excellent
10 Research effectiveness measurement The model must allow the measurement of the effectiveness of the R&D programme as well as its impact.	The model contains a specific tool for the measurement of research effectiveness and impact. However, this tool has not been implemented fully and in the long term a research performance database needs to be developed.	Good for the model, weak for its implement-ation
11 Stakeholder interaction and technology transfer are essential The involvement of stakeholders and communities in the planning as well as the technology transfer stages of the process is essential to ensure that stakeholder needs	The model includes stakeholder interaction as an important part of the strategic management element. The needs determination process tool is used to ensure effective participation of stakeholders. This is further enhanced by the activities of the research advisory panels and other steering committees. Broad communication of outputs takes place through stakeholder forums such as the Road	Excellent

Summary Tenet	Characteristics of the model and tools	Rating
are addressed and that implementation is facilitated. This is particularly important where new solutions are implemented that will affect the daily lives of people in communities. Information and Communications Technology (ICT) should be used optimally to ensure effective technology transfer.	Pavements Forum. General information sharing takes place though publication, conferences and the use of websites (e.g. www.csirkms.co.za)	
12 The model and tools should allow effective internal and external communication including the motivation of long-term funding It is important that the model should allow researchers to communicate effectively about research activities across the boundaries of a number of disciplines. The programme of work should also be linked to the stakeholders' needs to ensure that they understand the need for, and the objectives of, the R&D programme.	The technology tree tool is used to describe the SET base, to analyse gaps in the SET base, to define new SET focus areas and to promote discussion among researchers on the integration of capabilities to deliver higher-order key solutions. The technology trees are also used to discuss the links between research projects and research infrastructure investment and the needs of stakeholders. These diagrams have been widely shared with practitioners at forums such as the Road Pavements Forum. The model and tools have to some extent been used to motivate longer-term research funding.	Excellent

8.6 Indicative assessment of the impact of the new model on the performance of the road research programme at the CSIR

As indicated in Chapter 6, it is difficult to assess the positive impact of the implementation of the new approach because of the complexity of the process. However, some quantification of the success of implementation can be derived by assessing trends in research outputs and outcomes before (before 1996) and after the implementation of the new model and tools. The factors used in this analysis were selected from the research effectiveness measures developed in Chapter 6 and are also in line with work done by Walwyn[292]. The factors are:

- the number of academic publications (book chapters, journal articles and papers published in the proceedings of peer-reviewed conferences);
- post-graduate degrees awarded;
- the number of national guidelines and design manuals delivered;
- the average size of research projects (using 2005 Rand as a base); and
- growth in contract R&D funding in the CSIR for the road infrastructure sector.

Two criteria were added specifically for this analysis:

- the number of national guidelines, which is an indication of the value of the research and the breadth of its implementation and use (a factor rated as important by the Research Advisory Panel of the CSIR BE Unit); and
- the average project size, which is an indication of the degree to which the fragmentation process described in Chapter 3 has been reversed and has therefore led to the improvement of the critical mass in the research project portfolio.

The performance of the roads-related research programme in CSIR Transportek between 1989 and 2004 as well as the roads-related research programme in the new CSIR BE Unit from 2005 to 2007 (based on the above criteria) is discussed in the following sections.

8.6.1 Academic publications

The Department of Education defines recognised research output as[330]:

- journals, referring to peer-reviewed periodical publications devoted to disseminating original research and new developments within specific disciplines, sub-disciplines or fields of study that are officially approved;
- books or book chapters, referring to peer-reviewed, non-periodical scholarly or research publications disseminating original research on developments within specific disciplines, sub-disciplines or fields of study; and
- proceedings, referring to a published record of a peer-reviewed conference, congress, symposium or other meeting, the purpose of which is to disseminate original research and new developments within specific disciplines, sub-disciplines or fields of study, and that are published with an ISBN number.

To calculate the subsidy at academic institutions, journal articles receive one equivalent unit, conference papers one half of a unit and books between one and five units depending on the length of the contribution (generally one equivalent unit is given for every 60 pages).

The publication equivalents from the road infrastructure research programme at the CSIR over the period 1989 to 2007 were calculated using the criteria above. The data reported were compiled from the publication records of the CSIR Transportek Division and the CSIR BE Unit. The data are shown in Figure 8.1. The output in terms of academic publications from the road research group at the CSIR was significantly higher after 1995 than in the period immediately before. The data show a cyclical trend due to the fact that major conferences in the road engineering field are generally held every four years. However, Figure 8.1 indicates that the equivalent units of publication increased from about four per annum to more than double that. In some years (e.g. 1999 and 2004) significant numbers of conference papers were published. After 1996 the group also started publishing in peer-reviewed journals.

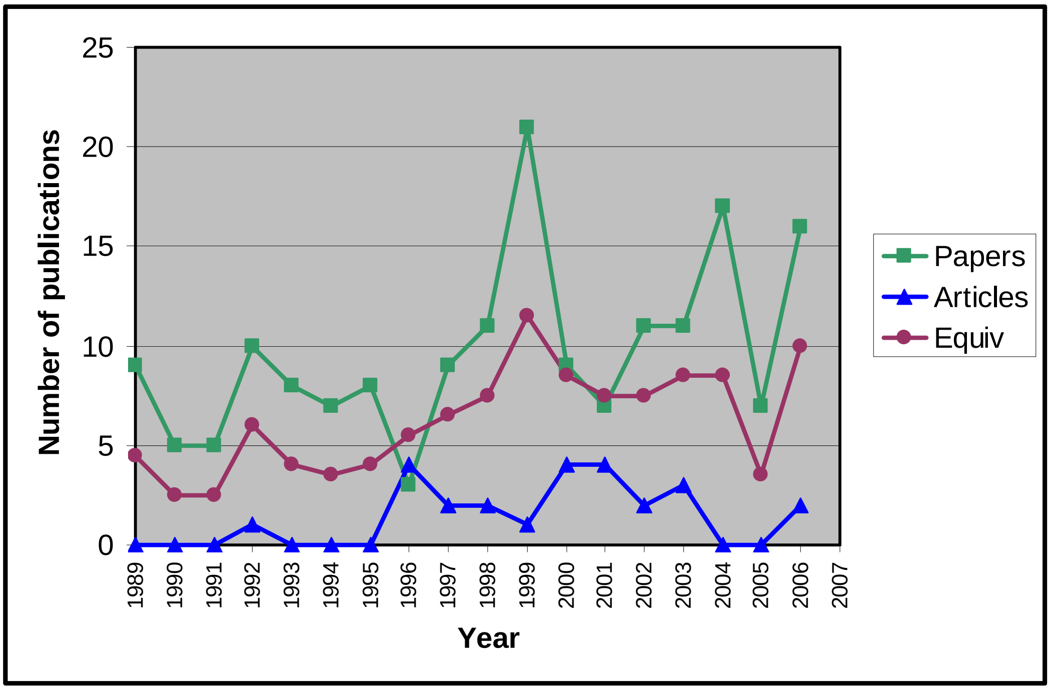


Figure 8.1: Trends in roads-related academic publications in CSIR Transportek from 1993 to 2006

Although the data are difficult to interpret due to their cyclical nature, it appears that there was an increased emphasis on publication – probably owing to the change in the research process but also owing to the fact that research of a more basic nature was conducted after 1996.

8.6.2 Post-graduate degrees awarded

The research effectiveness measures developed in Chapter 6 incorporate post-graduate qualifications as an indication of the quality of new knowledge generation taking place in a research programme. Table 8.2 shows an analysis of the Masters' and Doctoral degrees awarded to staff members at CSIR Transportek in the eight years prior to the implementation of the new approach and models discussed in this thesis, as well as during the nine years immediately thereafter. It was assumed that the dissertations and theses completed up to 1996 belonged to the previous era (before implementation of the new model), because it takes some time to complete a dissertation or thesis. In the years prior to the introduction of the new approach (up to 1996), 1.5 post-graduate degrees were awarded per annum and in the years after there were 1.64 post-graduate degrees per annum. This indicates that there was no significant increase. However, in the period immediately after the implementation of the new approach (1997 to 2003), the average was 2.43. This indicator is therefore neutral in terms of the effect of the new model and tools.

The data also show that the number of dissertations and theses completed in the period 2002 to 2005 dropped to only two. This is indicative of the commercial focus of the CSIR prior to the Beyond 60 strategic change discussed in Chapter 3. It is also indicates the dwindling number of engineering students in South Africa at the time.

Table 8.2: Trend in post-gradate qualifications before and after the introduction of the new approach and model

Year	MSc	PhD	TOTAL
1989	1	1	2
1990	1	1	2
1991		1	1
1992	3	1	4
1993			
1994	1		1
1995	2		2
1996			
Total	8	4	12
Total per annum			1.50
1997	3		3
1998	2		2
1999	2		2
2000	3		3
2001	1	4	5
2002	1		1
2003	1		1
2004			
2005			
2006			
2007	1		1
Total	12	4	18
Total per annum			1.64

8.6.3 National guidelines and design manuals

As discussed in the previous chapters, a significant part of the research effort in the road infrastructure sector is aimed at the development of new knowledge and methodology. An effective way of transferring such new knowledge is through the production of design guidelines to be used by practitioners, government officials, other researchers and students. South Africa has a history of producing high-quality manuals and design guidelines such as the Technical Recommendations for Highways (TRH) series and the Technical Methods for Highways (TMH) series. These manuals are widely used locally and have also been used in some other countries such as Australia, and to a limited extent in some states in the USA. These manuals are usually the end result of many years of research and are released under the auspices of a national committee (e.g. the Highway Materials Committee) or an organisation such as Sabita. The production of these manuals can therefore be seen as one of the indicators of a successful research programme.

The status of these manuals was analysed, as was the trend in the timing of their release over the period 1988 to 2007. Each new manual was given a full point and each upgrade of a manual half point. The data are given in Table 8.3. The data indicate the following:

- there was a significant drop in the completion and upgrading of manuals by the National Department of Transport after 1995, which indicates the fragmentation of the national transport research programme;
- the total number of manuals developed by the road engineering programme increased from 12.5 in the period 1988 to 1995 to 48.5 from 1996 to 2007 – this represents a significant increase;
- the total expenditure on research in the Sabita programme was R18.71 million (in 2008 Rand) and the number of manuals completed was 21.5;
- the total expenditure on roads-related research in the RDAC programme was R139.34 million (in 2008 Rand) and the number of manuals completed was 12.5; and
- the average cost of research per manual completed in the Sabita programme was R0.87 million (in 2008 Rand) as opposed to the average cost of research of R11.14 million (in 2008 Rand) in the RDAC programme.

The above numbers indicate more than a three-fold increase in the number of manuals after 1995.

Table 8.3: Number of manuals completed

Date	DoT post-RDAC	Sabita	Other	TOTAL
1988	1			1
1989				0
1990	1			1
1991	0.5			0.5
1992	1	3		4
1993	1	2		3
1994	2			2
1995		1		1
TOTAL	6.5	6	0	12.5
Per Annum				1.56
1996	1.5	1		2.5
1997		2	2	4
1998	1.5	3.5	1	6
1999		1		1
2000		1	1	2
2001			4	4
2002	2	1	4	7
2003		1	5	6
2004			4	4
2005		3	1	4
2006		2	2	4
2007	1		3	4
TOTAL	6	15.5	27	48.5
Per annum				4.04
Funding (2005 Rand)	R139.34 m	R18,71 m		
Rand/manual	R11.14 m	R0.87 m		

The figures also indicate that the Sabita programme delivered relatively more manuals per research Rand than the RDAC programme (or alternatively the cost of research per manual delivered was more than ten times less). Although these figures could have been influenced by other factors as well, indications are that in the post-1995 period more manuals were completed and that the Sabita programme was comparatively well managed in terms of cost effectiveness.

8.6.4 Average project size

In Chapter 3 the characteristics of six research programmes were discussed. It was shown that particularly in the RDAC programme and the CSIR Transportek Parliamentary Grant (PG) programme the projects became smaller and less focused. Therefore the research programmes became fragmented to such an extent that the RDAC programme collapsed. This fragmentation was one of the main reasons why the programmes did not deliver to expectations. By contrast, the funding in the Steering Committee era prior to 1988 and in the Gautrans programme was much more constant, and the average project size was much greater. It was also indicated in Chapter 3 that these two programmes performed significantly better than the others. These trends are shown in Figure 8.2.

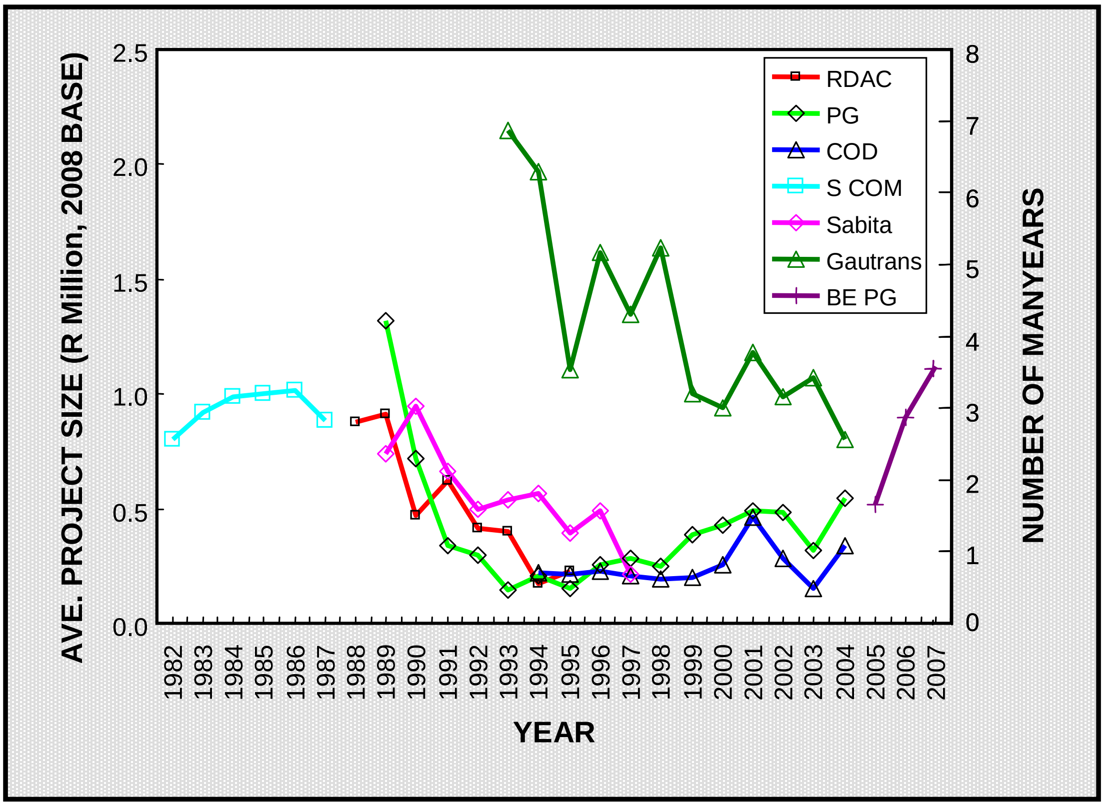


Figure 8.2: Increase in average project size in the Parliamentary Grant programme

In the period 1995 to 1996, the new approach discussed in this thesis was implemented on a trial basis in the CSIR Transportek Parliamentary Grant programme (particularly the roads-related research programme). Figure 8.2 indicates that after the initial implementation, the average project size increased gradually. Subsequently, during the Beyond 60 restructuring of the CSIR in 2005, the approach was also implemented in the CSIR BE Unit. In this Unit the average project size in the PG programme increased to more than R800 000 in the 2006/2007 financial year, and more than R1 million in 2007/2008. For the first time since the late 1980s, the average project size in the CSIR BE Unit will exceed that during the highly successful Steering Committee era.

The above data are indicative of the fact that the fragmentation of the PG research programme in the CSIR Transportek Division and the CSIR BE Unit has effectively been reversed. This means *inter alia* that on average three staff members will work on the average project, thus allowing more effective mentoring and strategic human capital development.

8.6.5 Growth in contract R&D funding

Growth in contract R&D can be seen as one of the indicators of the performance of an R&D organisation[331, 292] and is therefore an indication of the success of the programme as recognised by research funders. The contract R&D income in the roads-related programme in the CSIR Transportek Division has grown significantly since 1996 (see Figure 8.3). Financial data prior to 1995 were unfortunately not accessible in the CSIR system. Figure 8.3 shows the following:

- the contract R&D income from 1993 to 2007 (actual figures are given and not corrected for inflation);
- an ‘inflation line’ which is the value of contract R&D in 1993 increased at the official actual inflation figures per annum; and
- a linear regression line of contract R&D versus the year.

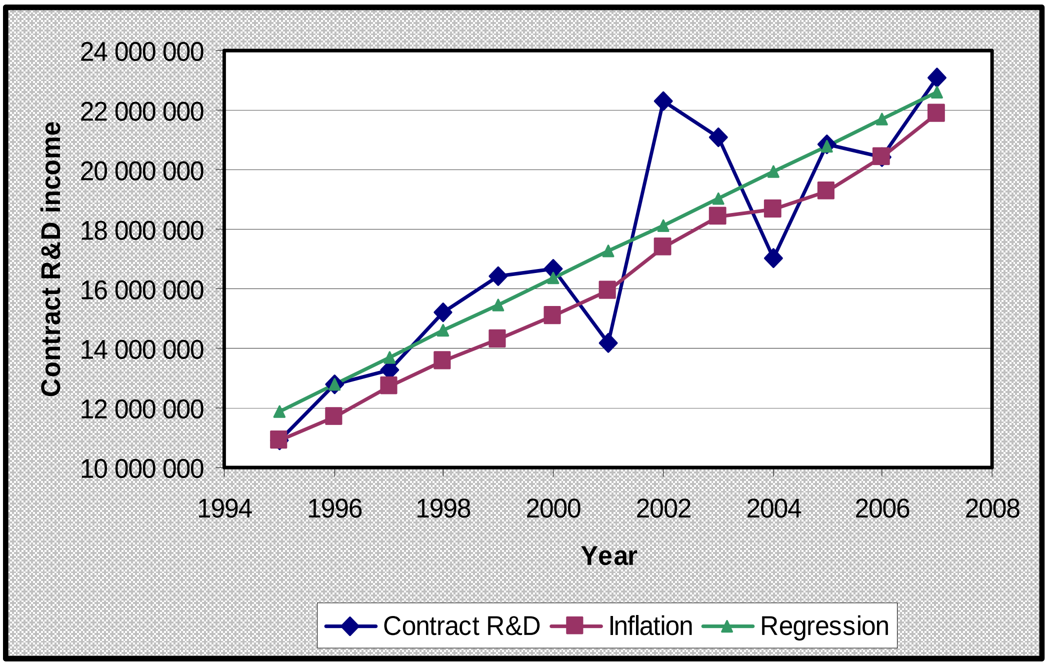


Figure 8.3: Roads-related contract R&D income in CSIR Transportek from 1993 to 2007

Figure 8.3 indicates that from 1995 to 2000 there was a steady increase in roads-related contract R&D income. In 2001 there was a sharp decline due to a minor restructuring process in roads-related research programmes and management[332]. In 2002 there was a sharp increase owing to the income derived from the sale of a Heavy Vehicle Simulator which was a once-off event[332]. In 2004 there was once again a sharp decline in income due to the fact that a number of senior researchers resigned to take up positions in the private sector. This is in line with the trend of decreasing numbers of civil engineers available in the South African industry and therefore increased marketability of such individuals[30].

The regression line in Figure 8.3 indicates that the contract R&D income over the period generally remained above the inflation rate in spite of the two extraordinary low years discussed above. The average growth over the period was 6.93% higher than the inflation rate which indicates an excellent performance in terms of this measure.

8.6.6 Research effectiveness calculation

The output data from the roads-related R&D programme was used to calculate a 'research effectiveness' value using some of the indicators listed in Table 6.2 for which data were readily available. The weighting factors shown in Table 6.2 (which are the result of inputs from the SET committee and evaluation and endorsement by the RAP committee) were used. The formula used was as follows:

RE_n = [(500,000 x PE_n) + (600 000 x $Masters_n$) + (1 500 000 x PhD_n) + (3 500 000 x $Manuals_n$) + (0.15 * $CR\&D_n$)] / R_n

Where:

RE_n	=	Research effectiveness per researcher in year n
PE_n	=	Publication equivalents in year n
$Masters_n$	=	Number of Masters' degrees in year n
PhD_n	=	Number of PhDs in year n
$Manuals_n$	=	Equivalent number of manuals in year n
$CR\&D_n$	=	Rand value of contract R&D projects in year n
R_n	=	Number of researchers in year n.

In this calculation the following assumptions were made:

- the perceived value calculation of the various factors as endorsed by the Research Advisory Panel of the CSIR BE Unit were used as relative weights for this calculation (see Chapter 6);
- new manuals were counted as a full point and upgrades of manuals as a half point;
- contract R&D data prior to 1994 were not available and it was assumed that during the period 1989 to 1993 the contract R&D grew by 5% per annum; and
- the number of researchers in 1989 and 1990 was not available in the CSIR database, so the same number (39) as in the previous year was assumed.

Table 8.4 shows the calculation of research effectiveness per annum.

Table 8.4: Result of the research effectiveness calculation for the roads-related R&D programme from 1989 to 2007

Year	Publica-tion Eq.	No of Masters’	No of PhDs	Eq. no of manuals	Contract R&D	Number of Res’s	Equivalent value per researcher
1989	4	1	1	0	8 144 383	39	136 453
1990	2	1	1	1	8 551 602	39	202 122
1991	3.5	0	1	0.5	8 979 182	39	162 740
1992	4	3	1	4	9 428 141	40	517 856
1993	4	0	0	3	9 899 548	33	423 786
1994	3.5	1	0	2	10 394 526	31	351 909
1995	4	2	0	1	10 914 252	30	277 905
1996	5.5	0	0	2.5	12 793 626	28	479 252
1997	6.5	3	0	4	13 265 877	35	601 139
1998	7.5	2	0	6	15 208 944	34	830 334
1999	11.5	2	0	1	16 408 342	32	403 477
2000	8.5	3	0	2	16 683 877	29	536 296
2001	7.5	1	4	4	14 179 859	27	980 629
2002	7.5	1	0	7	22 307 535	25	1 287 845
2003	8.5	1	0	6	21 116 431	23	1 261 629
2004	8.5	0	0	4	17 008 710	23	904 405
2005	4	0	0	4	20 840 244	17	1 125 061
2006	10	0	0	4	20 419 713	18	1 225 720
2007	12	0	1	4	23 116 716	15	1 664 500

The data are presented graphically in Figure 8.4. It can be seen that the median value of research effectiveness per researcher before the model was implemented is R277 905 and after implementation R942 517 – thus a more than three-fold increase. The same trend can be noted for the mean values. The equivalent values per researcher before and after 1996 were analysed by comparing the medians of the scores of the two groups of respondents using the Mann-Whitney U Test. This non-parametric test was preferred to the T-test for comparison, as the sample size was relatively small and therefore the normality assumption required for the T-test could potentially be violated. The results of the Mann-Whitney U Test, using SPSS version 16.0 are shown in Table 8.5 below.

Table 8.5: Results of Mann-Whitney U Test: before and after implementation of new R&D management model and tools

Mann-Whitney U Test	3
Wilcoxon W	31
Z	-3.296
Asymp. Sig. (2-tailed)	0.001
Exact Sig. [2*(1-tailed Sig.)]	.000a
a. Not corrected for ties	
b. Grouping Variable: BefAft	

The p-value of less than 0.05 indicates with a high confidence level that the two medians are statistically different.

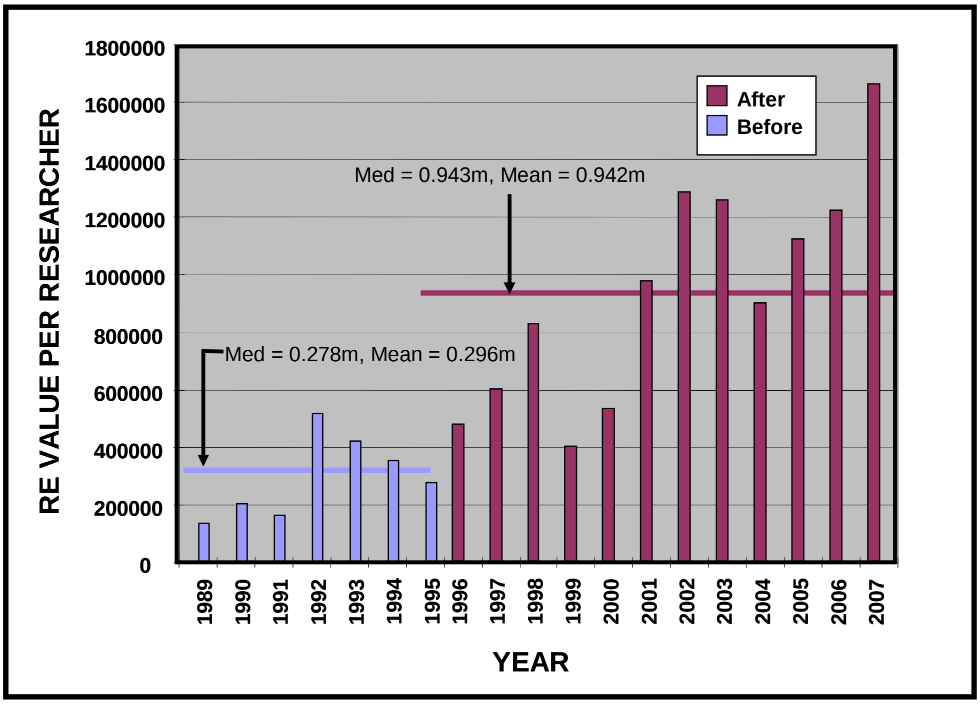


Figure 8.4: Research effectiveness values per researcher before and after implementation of the new model and tools

The above analysis is indicative only and is intended to support the qualitative analysis discussed in this chapter. The main limitation is the low number of data points; however, in conjunction with the qualitative analysis in this chapter, it provides significant support for the thesis statement in Chapter 1.

8.7 'Before' and 'after implementation' analysis of survey results

In addition to the above analysis, the data obtained from the survey discussed in Chapter 5 were analysed for the 'before' and 'after' implementation cases. The 'before' group consisted of respondents outside of the CSIR BE Unit who had not been exposed extensively to the new model and tools developed for this thesis. The 'after' group consisted of respondents from the CSIR BE Unit as well as the manager of the Gautrans R&D programme who had been exposed extensively to the model and tools during the implementation activities discussed in Chapter 7. As described in Chapter 5, the budget per researcher and budget per project values were normalised with the Purchasing Power Parity indicator. The non-parametric Mann-Whitney U Test was again used to compare the above cases due the small sample size. The analysis included only the 'extent of use' scores, the 'extent of use of tools' scores, the descriptive values relating to the budget per researcher and the number of researchers per project. The results (from SPSS version 16.0) are shown in Table 8.6 below.

The factors, characteristics and tools are highlighted in yellow in Table 8.6 where there is a significant difference both in terms of the difference in the median values and the statistical significance ($p < 0.05$).. The results indicate the following:

- the median value of the budget per researcher of the 'after' group was double that of the 'before' group;
- the median value of the budget per project of the 'after' group was four times that of the 'before' group;
- the median value of the researcher per project was significantly higher in the 'after' group;
- the median value for the total score of 'extent of use' and the extent to which tools were used is significantly higher (25% to 50%) in the 'after' group; and
- the characteristics and tools that were used more by the 'after' group include technology transfer activity, use of systems approaches, use of a formal investment decision, scenario planning, foresight studies, needs determination and technology trees.

Table 8.6: Before and after implementation comparison of survey results

	Before						After						Difference	Mann-Whitney U test	
Variables	N	Mean	Std. Dev.	Median	Min	Max	N	Mean	Std. Dev.	Median	Min	Max	Med. Diff	Mann-Whitney U	Asymp. Sig. (2-tailed)
Bud/Res	29	250 740	180 072	266 667	1 473	700 000	11	566 031	170 279	589 136	327 298	853 821	322 470	33.5	0.000
Bud/Proj	31	406 115	484 872	200 000	1 052	1 963 788	11	876 776	285 734	981 894	441 852	1 309 192	781 894	44	0.000
Res/Proj	30	1.36	1.05	1	0	5	11	1.57	0.42	1.42	1	2.5	0.42	95.5	0.040
TotalScE	34	39.62	7.90	39	25	58	11	50.09	5.74	49	41	59	10	53.5	0.000
TotTools	34	14.15	3.77	13	7	25	11	19.00	2.83	20	15	24	7	50.5	0.000
StratPlanE	34	3.94	0.95	4	2	5	11	4.36	0.81	5	3	5	1	140.5	0.194
Long/SE	34	3.35	0.98	4	2	5	11	3.82	0.40	4	3	4	0	137.5	0.152
PortfolE	34	2.06	1.25	1.5	1	5	11	2.36	0.81	3	1	3	2	148.5	0.284
TechTr.E	34	2.62	0.95	2	1	5	11	3.64	0.92	4	2	5	2	84.5	0.004
ImpactE	34	2.00	0.85	2	1	5	11	2.46	0.82	2	1	4	0	126.5	0.082
SystemE	34	2.38	1.21	2	1	5	11	3.36	0.81	4	2	4	2	94.5	0.012
InvesDecE	34	2.97	1.31	3	1	5	11	4.00	0.77	4	3	5	1	103.5	0.023
HumResE	34	3.24	1.16	3	1	5	11	3.91	0.83	4	3	5	1	125.5	0.093
ProjManE	34	3.09	1.36	3	1	5	11	3.18	1.25	3	2	5	0	180.5	0.859
Scenario	34	2.15	0.82	2	1	4	11	3.09	1.14	3	1	5	1	95.5	0.011
Foresight	34	2.21	1.01	2	1	5	11	3.27	1.01	4	1	4	2	81.5	0.003
Needs	34	3.24	0.99	3	1	5	11	4.18	0.98	5	3	5	2	98	0.013
RoadMap	34	2.15	1.13	2	1	5	11	1.27	0.47	1	1	2	-1	96.5	0.011
TechTrees	34	1.44	0.61	1	1	3	11	4.27	0.65	4	3	5	3	1	0.000
CausalMap	34	1.56	0.70	1	1	3	11	1.64	0.92	1	1	4	0	185	0.953
Other	34	1.41	0.89	1	1	5	11	1.27	0.65	1	1	3	0	176.5	0.703

The result of the 'before' versus 'after' implementation analysis supports the findings of the qualitative and quantitative analysis conducted earlier in this chapter and provides further support for the thesis statement formulated in Chapter 1.

8.8 Conclusion

The qualitative analyses and discussions in this chapter indicate the following about the new approach, model and tools for management of R&D developed in this study:

- they are aligned with the objectives of major government growth strategies and imperatives in South Africa;
- they address the tenets that were developed in the first part of this thesis very well;
- their implementation in the CSIR Transportek PG programme and the CSIR BE Unit PG programme had significant benefits in terms of:
    - an increase in academic publications
    - an increase in the completion of associated national design guidelines
    - a significant increase in the average project size in real terms
    - a significant growth in associated contract R&D income;
- their implementation in the Sabita research programme led to significant outputs, including a number of manuals developed at an associated research cost of an order less than that of the RDAC programme;
- the calculation of the research effectiveness values per researcher indicated that there was significant evidence that the implementation of the new model and tools led to the trebling of the research output;
- in the 'after' group budgets per researcher and per project as well as researchers per project were significantly higher than in the 'before' group, thus emphasising again the importance of focus rather than fragmentation in the R&D portfolio as discussed in Chapter 3; and
- the analysis of the 'before' and 'after' cases in the survey discussed in Chapter 5 indicated that the 'after' group, which had been exposed to the model and tools developed for this thesis, had implemented a number of

the desired R&D management characteristics and tools at a much higher level than the 'before' group.

The above analysis provides significant support for the thesis statement formulated in Chapter 1:

The development and implementation of a systems-based conceptual management model and decision-support tools in a road engineering research programme will lead to an increase in research effectiveness in terms of number of outputs and long-term growth in the R&D programme.

9 IMPLEMENTATION PROTOCOL FOR MANAGING R&D IN ROAD ENGINEERING

9.1 Context

The development and implementation of a conceptual model and supporting tools for the management of R&D programmes have been discussed in the previous chapters. The purpose of this chapter is to discuss the development of a simple protocol for the implementation of the conceptual model and the technology tree tool in a road engineering-related R&D programme. The other tools discussed previously are relatively less complicated and it is not deemed necessary to develop a protocol for their use. The two protocols developed were then also used to analyse the challenges in the Labour-Intensive Construction (LIC) field (also sometimes termed Employment-Intensive Construction). The applicability of the protocols to the LIC field is demonstrated and a set of three technology trees for the LIC field is developed. Finally, recommendations are made for the implementation of some of the principles to enhance the output and outcomes from the LIC programme in South Africa.

9.2 R&D management implementation protocol at strategic level

The R&D management implementation protocol depicts the use of the conceptual model (the 'wheel model') discussed in Chapter 6 in three consecutive cycles of an R&D programme. The rationale for the three-cycle approach is that the model represents a complex system process that is self-learning, self-correcting and self-balancing. Thus, in practice, the model needs to be applied repetitively in consecutive cycles to achieve the maximum benefit. The protocol depicts the use of the model in three consecutive cycles which, in practice, could amount to three fiscal years of funding of the programme.

The main focus of the application of the conceptual model in the three cycles is:

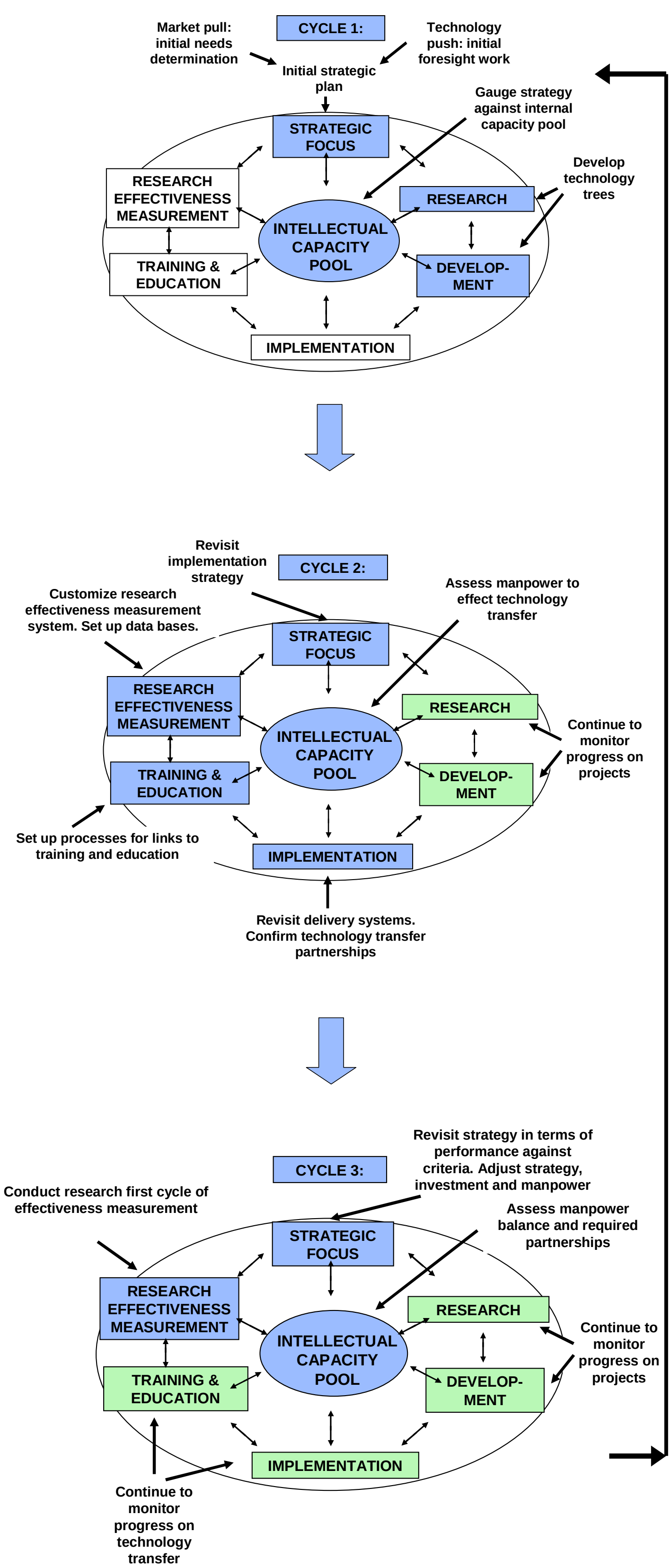
- **Cycle 1:** initial strategic planning (taking cognisance of the mandate and culture of the organisation), setting up the R&D programme and management systems, defining initial R&D needs and developing an initial R&D project portfolio (mainly short-term projects to yield 'quick wins').

- **Cycle 2:** taking cognisance of the learning of Cycle 1 and the early results of a technology foresight process to adjust the strategic direction and enhance the content of the R&D programme accordingly.
- **Cycle 3:** conducting a Research Effectiveness Measurement process to assess the early success of the programme, taking cognisance of the final results of the technology foresight programme and adjusting the strategy and R&D project portfolio for the next three-cycle period.

The emphasis on the use of the conceptual strategic level model in the three cycles and brief descriptions of these cycles are given in Figure 9.1. Blue blocks indicate elements of the model that are particularly important in the specific cycle, and green blocks indicate activities that continue from the previous cycle. It is important to note that after the three-cycle period, the process is repeated to ensure that learning from the previous three cycles is incorporated in the future of the R&D programme. The detail activities and tasks for each cycle are shown in the full description of the protocol in Table 9.1. This table indicates the stage of the R&D process as depicted in the conceptual model in Figure 6.3, the activity in each stage, the section in this thesis where the activity is described in detail, and the detailed tasks relating to that activity in each of the three cycles.

The protocol addresses the detailed tasks required for each of the strategic elements in the conceptual model as they progress through the three cycles. In Cycles 2 and 3 the learning and results from the activities in the previous cycles are important inputs for the optimisation of the process in the next cycle.

One of the findings from the survey and analysis conducted in Chapter 5 was that the R&D process in universities is different from that in contract R&D organisations or ‘government laboratories’. Universities seem to be more internally focused and their R&D activities are managed on a project rather than a portfolio basis, taking less cognisance of the potential return-on-investment of R&D activity. Universities usually also have a different funding mechanism than a contract R&D organisation with different monitoring and control mechanisms. These differences should be taken into account when using the protocols described here; particularly during the strategic planning phase.



Brief description Cycle 1

- Focus on initial strategic planning, and setting up the programme. Define strategic objectives.
- Set up Research Advisory Panel (RAP). Conduct basic strategic thinking with research team and RAP.
- Conduct Needs Determination process. Initiate Technology Foresight Study.
- Draw technology trees (see protocol below).
- Assess manpower capability against strategic objectives.
- Using technology trees, define immediate gaps in knowledge, technology and manpower capability.
- Develop a plan for knowledge and technology partnerships if required.
- Initiate obvious R&D projects based on assessment of balance in technology trees and immediate needs (to ensure quick wins).

Brief description Cycle 2

- Focus on setting up technology transfer elements, while continuing to monitor progress on initial projects.
- Revisit technology transfer strategy with emphasis on delivery systems.
- Assess manpower capability in terms of capability to conduct technology transfer, including patenting and commercialisation activities.
- Set up required systems to ensure effective training and educational impact.
- Using the RAP define research effectiveness (RE) measurement criteria.
- Set up RE system including data recording processes and data base management systems.
- Complete technology foresight and revisit R&D portfolio – adjust as required based on assessment of current and future needs, own manpower capability, balance in R&D portfolio and potential partnerships.

Brief description Cycle 3

- Focus on setting up RE measurement system and revisiting strategy.
- Continue to monitor and manage R&D projects and technology transfer activities.
- Conduct retrospective RE measurement analysis to determine performance against RE criteria defined in Cycle 2.
- Analyse performance of R&D personnel in terms of delivery and technology transfer.
- Assess applicability of R&D project portfolio, and adjust as required.
- Revisit overall R&D strategy in terms of strategic objectives and required output.

Figure 9.1: Overview of R&D management implementation protocol

Table 9.1: Detailed R&D implementation protocol in three cycles

STAGE	ACTIVITY	SECTION[xiv]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
STRATEGY	1 Set up the programme		Develop the initial strategic objectives in conjunction with the Research Advisory Panel (RAP). The RAP should consist of a small group (max. 10) of stakeholders and experts in the field of research. Prepare initial resource requirements (manpower and budgets). Obtain approval from RAP.	None.	None.
	2 Needs determination	6.4.1; 7.2.4	Conduct a needs determination process to define initial short- and medium-term R&D needs.	Review needs determination annually through interactions with RAP and stakeholder forum.	Review needs determination annually through interactions with RAP and stakeholder forum.
	3 Technology Foresight	7.6	Initiate a project to conduct a technology foresight study.	Continue with technology foresight process. Implement early results by adding value to the strategic portfolio development process.	Complete technology foresight process. Ensure implementation into strategic definition of R&D focus areas.

[xiv] The section in this thesis where this activity is discussed in more detail

STAGE	ACTIVITY	SECTION[xiv]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
	4 Develop a strategic plan	2.4; 6.3 7.2.2; 7.3.2; 7.5.2	Prepare an initial strategic plan with basic purpose statement, objectives and resource planning. Take cognisance of the principles in the strategic-level conceptual model in Section 6.3.	Review strategic plan to incorporate additional needs determination information and early results from technology foresight process.	Review strategic plan to incorporate additional needs determination information and final results from technology foresight process.
R&D PORTFOLIO	5 Develop technology trees	6.4.2; 7.2.5; 7.3.4; 7.5.3	Use the protocol given below to develop technology trees based on the strategic focus, the available resources and the input from the strategic planning activity.	Review technology trees and incorporate new information from needs determination process and early technology foresight results.	Review technology trees with information from final foresight process results. Conduct a strategic gap analysis to identify new important applied technology areas and base technology areas for investment – thus building the SET base.
	6 Develop project portfolio	6.4.1; 6.4.2; 7.4	Develop an initial R&D project portfolio based on the needs identified.	Revise the project portfolio annually based on the technology tree analysis, needs determination process and foresight work.	Revise the project portfolio annually based on the technology tree analysis, needs determination process and foresight work.
	7 Investment decision	6.5	Prioritise the R&D projects according to selected criteria that describe the strategic intent and based on the available financial and human resources.	Revise the criteria based on the revision of the strategic plan. Reassess project portfolio.	Revise the criteria based on the revision of the strategic plan. Reassess project portfolio.

STAGE	ACTIVITY	SECTION[xiv]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
INTELLECTUAL CAPACITY POOL	8 Use the technology trees to assess the balance of and gaps in the R&D personnel	6.4.2	Plot the R&D personnel coded according their level of expertise, assess gaps in terms of required project work and determine potential partnerships to fill the gaps.	Review the balance of R&D personnel in the technology trees based on the revised strategy and focus areas.	Review the balance of R&D personnel in the technology trees based on the revised strategy and focus areas.
	9 Human resource management	See note[xv]	Develop career plans, mentoring plans and performance criteria in terms of R&D output for all R&D personnel.	Continue with performance management and mentoring processes. Revise criteria according to revised strategy.	Continue with performance management and mentoring processes. Revise criteria according to revised strategy.
	10 Strategic partnerships	See note[xv]	Identify potential strategic partnerships to fill knowledge gaps and initiate discussions.	Set up strategic R&D partnerships to address the manpower gaps.	Continue with strategic partnership management.
TECHNO LOGY	11 Implemen-tation plan	6.3	Develop initial implementation plan as part of strategic plan.	Review implementation plan based on results of first cycle R&D outputs and strategic partnership discussions.	Review implementation plan based on results of second cycle R&D outputs and strategic partnership discussions.

[xv] These aspects, although important for the R&D management process, are not central to this thesis and are therefore not discussed in detail here

STAGE	ACTIVITY	SECTION[xiv]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
	12 Delivery systems	6.4.3	Set up potential delivery systems as part of initial strategic plan.	Revise delivery systems based on outputs from first cycle.	Revise delivery systems based on Research Effectiveness (RE) assessment.
	13 Technology transfer partners	6.4.3	None.	Identify potential technology transfer partners based on the nature of the first year's outputs.	Finalise technology partnership arrangements and contracts.
	13 Stakeholders' forum	7.2.4	Set up a stakeholders' forum for discussion with industry of outputs, technology transfer opportunities and secondary needs determination.	Use stakeholders' forum to discuss early results from the R&D programme.	Use stakeholders' forum to discuss outputs as well as future opportunities.
EDUCATION	14 Education links	6.3.1	Determine the required educational links to ensure that information intended for public consumption is transferred to students at an early stage.	Continue to manage educational links.	Continue to manage educational links.
	15 Training activities	6.3.1	Develop partnerships for training of professionals in the use of new methodology and knowledge.	Continue to manage training programmes.	Continue to manage training programmes.

STAGE	ACTIVITY	SECTION[xiv]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
RESEARCH EFFECTIVENESS	16 Set up research effectiveness measurement (RE) system	6.4.4	None.	Define criteria for RE in conjunction with RAP and stakeholders. Design the RE system and associated data base.	Revise criteria for RE measurement.
	17 Record project-level RE information	6.4.4	None.	Record inputs, outputs and outcomes for each project at the end of every cycle.	Record inputs, outputs and outcomes for each project at the end of every cycle.
	18 Conduct retrospective RE analysis	6.4.4	None.	None.	Conduct an RE analysis to determine the performance of the R&D process against the criteria. If possible, conduct a retrospective analysis of historic information on indicators (e.g. publications) to develop a trend over time and to set a 'before' benchmark that can be used for future analyses of the effect of a new R&D management process.

STAGE	ACTIVITY	SECTION[xiv]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
CLOSING THE LOOP	19 Strategic-level management model	6.3	Review the elements of the strategic plan and process to ensure that the principles of a systems approach are incor-porated. Place particular emphasis on non-linearity, including 'thinking in reverse' by assessing the desired outcome and impact as well as the envisaged delivery system prior to finalising the R&D plan at the project level.	Review the elements of the strategic plan and process to ensure that the principles of a systems approach are incor-porated. Place particular emphasis on non-linearity, including 'thinking in reverse' by assessing the desired outcome and impact as well as the envisaged delivery system prior to finalising the R&D plan at the project level.	Review the elements of the strategic plan and process to ensure that the principles of a systems approach are incor-porated. Place particular emphasis on non-linearity, including 'thinking in reverse' by assessing the desired outcome and impact as well as the envisaged delivery system prior to finalising the R&D plan at the project level.
	20 Revisit strategic plan	6.3	Close the loop in the initial strategic plan to ensure that the information in the above steps is incorporated into the strategic plan for the R&D Unit.	Close the loop in the initial strategic plan to ensure that the information in the above steps is incorporated into the strategic plan for the R&D Unit.	Close the loop in the initial strategic plan to ensure that the information in the above steps is incorporated into the strategic plan for the R&D Unit.

The following aspects should specifically be taken into consideration in the use of the strategic-level protocol to set up an R&D programme:

Strategy phase:

- Consult as widely as possible initially and then focus the strategic planning activity through consultations with an advisory panel or work group.
- The panel should include a number of 'lead users' who apply outputs from the R&D programme and provide feedback on their successes and failures and also provide ideas for future innovation.
- Balance the inputs from the stakeholders (mainly short-term focus) with strategic input from a technology foresight study.
- Focus the strategy on the strong points of the R&D organisation and partner (in an 'open innovation' mode – see Section 2.6.3) where the R&D organisation lacks in expertise.
- Ensure regular feedback to and interaction with the advisory panel to ensure stakeholder buy-in and to take cognisance of strategic changes in the environment in which the R&D organisation operates.
- Ensure that the appropriate organisational structure and operational framework is in place.

R&D portfolio development:

- Use the inputs from the strategic planning phase and the technology tree tool to ensure a balance between short-term quick wins and longer-term strategic R&D activity.
- Balance the R&D portfolio taking the mandate and strategic objectives of the R&D organisation into account.
- Use the portfolio management tools (technology tree as well as tools described by Roussell[81] – see Chapter 2) to ensure a sustainable R&D programme.
- Ensure the use of relevant investment decision criteria based on the strategic objectives of the R&D organisation.

Intellectual capacity pool:

- Human resource management issues such as performance measurement of staff should take the strategic objectives of the organisation into account.

- Strategic partnerships should focus on organisations that could supplement the capabilities where the R&D organisation is weak or lacking in the appropriate human resources.
- Ensure that stakeholders and partners are part of and participate in the activities of the intellectual capacity pool in the conceptual model.

Technology transfer:

- Technology transfer activities can be costly and the strategic planning process should ensure that adequate funding is made available for these activities to ensure optimum impact from the R&D programme.
- Technology transfer projects should be planned separately and their progress monitored closely to ensure effective transfer.

Education:

- Education and ongoing training is very important in R&D activities that deliver mainly new methodologies to ensure that students are exposed to these outputs at an early stage.
- Professionals should be exposed to new outputs regularly to ensure their effective use in practice.

Research effectiveness:

- The purpose of research effectiveness (RE) measurement should be to provide the information for the improvement of the strategic management process and the R&D investment decision as well as to indicate the benefits of the programme to stakeholders.
- The RE measurement criteria should be tailor made for the R&D organisation, taking its strategic objectives into account and should be endorsed by the stakeholders through the advisory panel.

Closing the loop:

- Continuity in the R&D management process is important to ensure that learning is not lost.

9.3 Technology tree protocol

As discussed in Chapter 6, the technology tree tool (see schematic in Figure 9.2) can be used for the following:

- to obtain a holistic visualisation of the process to develop key solutions and/or products that will address the defined needs;

- to focus the planning process on those elements of the technology tree that need attention and then identify projects to address those elements;
- it is a powerful tool to assist with the prioritisation of projects based on their position in the tree and not merely on 'importance ratings' by stakeholders that would provide mainly a short-term focus;
- it is a tool to balance the R&D portfolio in two ways: shorter-term deliverables high in the technology tree vs. longer-term strategic investments lower in the technology tree, and balanced investment in each of the technology focus areas;
- definition of gaps in knowledge that should be addressed;
- to assess the quality of the science base by assessing the quality of the individual capabilities and the base technologies;
- to assess the quality of the HR pool in terms of their skills balance (also senior vs. junior staff) in relation to the elements in the technology tree;
- to indicate how base and applied technologies can be integrated to provide the platform for developing appropriate key solutions; and
- to provide a clear indication of the link between the needs, key solutions and the required SET base to develop them.

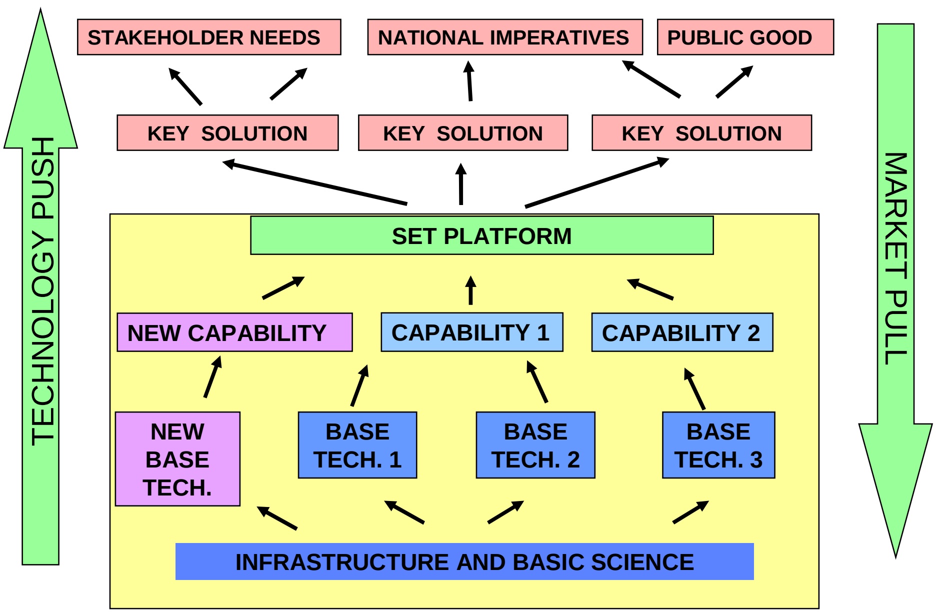


Figure 9.2: Schematic of a technology tree

A protocol for the development and use of technology trees is shown in Table 9.2.

Table 9.2: Protocol for developing and using technology trees

STAGE	ACTIVITY	SECTION [xvi]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
DRAWING A TECHNOLOGY TREE	1 Define key solutions	6.4.2	Use focus areas and needs defined by the Needs Determination process to develop a set of potential key solutions required. Link the key solutions to the needs.	Review the definition of key solutions based on the early results from the technology foresight study. Add some medium- to long-term solutions as required.	Use the RAP, the input from the previous cycles' needs determination processes as well as the final results of the technology foresight study to determine a new set of required key solutions for the next three-cycle period.
	2 Define applied technologies	6.4.2; 7.2.4; 7.2.5; 7.3.4	Define the required applied technologies to be integrated to allow the development of the required key solutions.	Review the definition of the applied technologies that would be required to develop the key solutions.	Use the results of the foresight study as well as the results of and the learning during the R&D process in the previous two cycles (including the gap analysis) to determine radically new applied technologies that need to be developed.

[xvi] The section in this thesis where this activity is discussed in more detail

STAGE	ACTIVITY	SECTION [xvi]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
	3 Define the platforms	6.4.2; 7.2.4; 7.2.5; 7.3.4	Group the capabilities and key solutions logically together to form the SET platforms required in the R&D programme. Assess the integrative skills required to manage the function of the platform successfully.	Review the definition of the portfolio of platforms based on the learning in Cycle 1.	Review the definition of the portfolio of platforms and assess the potential for new platforms based on the learning in the previous cycles as well as the results of the technology foresight study and needs determination processes.
	4 Link the applied technologies	6.4.2; 7.2.4; 7.2.5; 7.3.4	Link the applied technologies to the key solutions and identify omissions.	Link the applied technologies to the key solutions and identify omissions.	Link the applied technologies to the key solutions and identify omissions.
	5 Define the base technologies and R&D infrastructure	6.4.2; 7.2.4; 7.2.5; 7.3.4	Define the base technologies and R&D infrastructure required to develop and support the applied technologies. Complete the technology tree diagram (usually one platform per tree).	Review the required base technologies and R&D infrastructure.	Review the required base technologies and R&D infrastructure. Emphasis should be placed on new base technologies and infrastructure required if there are changes in the platforms and applied capabilities.

STAGE	ACTIVITY	SECTION [xvi]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
R&D PROJECT PORTFOLIO	6 Plot potential projects on the trees	7.4 7.5 7.6	Plot the initial project portfolio on the technology trees in terms of their horizontal and vertical position. Plot horizontally next to the applied technology, base technology, etc. the elements in the tree where they belong. Plot vertically in terms of whether they are basic or applied technology projects or projects to directly enhance the platform or develop key solutions. Include the project size in monetary terms.	Add new potential R&D projects to the trees (in addition to those funded in Cycle 1) with emphasis on the results of the gap analysis.	Add new potential R&D projects to the trees (in addition to those funded in Cycle 1) with emphasis on the results of the gap analysis as well as the required future capabilities and key solutions determined by the foresight study and needs determination processes.
	7 Link the projects	7.4 7.5 7.6	Link the projects to the key solution that they support to show the relevance of the project in the technology tree.	Link the projects to the key solution that they support to show the relevance of the project in the technology tree.	Link the projects to the key solution that they support to show the relevance of the project in the technology tree.
	8 Prioritise the projects	6.5	Prioritise the R&D projects based on their logical position in the technology tree (some projects need to precede others logically) as well as based on the investment criteria that describe the strategic intent.	Prioritise the R&D projects based on their logical position in the technology tree (some projects need to precede others logically) as well as based on the investment criteria that describe the new strategic intent.	Prioritise the R&D projects based on their logical position in the technology tree (some projects need to precede others logically) as well as based on the investment criteria that describe the new strategic intent.

STAGE	ACTIVITY	SECTION xvi	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
BALACING THE RESOURCES (PROJECT COST AND MANPOWER)	9 Analyse vertical balance in trees	7.3.4; 7.4; 7.5	Assess the vertical balance (top vs. bottom) in the technology trees by calculating the required resources at each level. Assess the short-term investment (high in the technology tree) as opposed to the long-term investment (low in the technology tree) and evaluate the situation in terms of the strategic objectives. Adjust the portfolio. At this stage the portfolio is likely to contain more short-term projects based on the immediate needs.	Revisit the vertical balance in the technology trees. The portfolio is now likely to have some medium- to long-term projects added.	Revisit the vertical balance in the technology trees. The portfolio should now contain a significant number of long-term projects that address the overall strategy of the R&D programme.
	10 Analyse horizontal balance in trees	7.3.4; 7.4; 7.5	Assess the horizontal balance (left vs. right) in the portfolio of trees by calculating the required resources for each platform. Assess the horizontal balance in each tree by calculating the resources required from right to left in the tree, giving an indication of planned focus in parts of the tree. Adjust the portfolio as required to fit the strategic objectives.	Review the horizontal balance in the technology trees.	Review the horizontal balance in the technology trees. Adjust the portfolio as required to fit the new strategic objectives.

STAGE	ACTIVITY	SECTION [xvi]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
GAP ANALYS	11 Project analysis	7.3.4; 7.4; 7.5	Use the RAP and research personnel to analyse the technology trees to assess obvious gaps in knowledge that need to be addressed in the future.	Review the composition of the technology trees, projects and gap analysis with the RAP.	Review the composition of the technology trees, projects and gap analysis with the RAP.
	12 Manpower analysis	7.3.4; 7.4; 7.5	Use the RAP and research personnel to analyse potential gaps in the manpower (both in the research unit and with current partners) to determine a strategy for appointing staff or establishing additional partnerships.	Review the manpower analysis with the RAP.	Review the manpower analysis with the RAP.
FINAL PROJECT	13 Develop a potential project list	7.3.4; 7.4; 7.5	Based on the needs determination process and the analysis of the balance in the technology trees, determine a potential project list that addresses the strategic objectives of the research programme.	Review the potential project list based on the learning of the first cycle, early results from technology foresight and the needs determination processes.	Review the potential project list based on the learning of the first two cycles, final results from the technology foresight and the needs determination processes.

STAGE	ACTIVITY	SECTION [xvi]	TASKS IN CYCLE 1	TASKS IN CYCLE 2	TASKS IN CYCLE 3
	14 Final resourcing and funding allocation	7.3.5	Use the RAP to rate each of the projects in terms of the investment decision criteria, to discuss the balance in the technology trees and to make a final decision on the resource allocation.	Use the RAP to rate each of the projects in terms of the investment decision criteria, to discuss the balance in the technology trees and to make a final decision on the resource allocation.	Use the RAP to rate each of the projects in terms of the investment decision criteria, to discuss the balance in the technology trees and to make a final decision on the resource allocation.

To obtain full benefit from technology trees the following should be considered:

- Develop a set of technology platforms that will address the needs and focus areas defined from the strategic planning process described above.
- For each technology platform develop a separate technology tree to facilitate the analysis of the elements in the trees and the visualisation process.
- Develop the basic structure of the technology tree and plot the desired deliverables at each level of the tree in a column next to the tree. This allows the definition of key solutions high in the technology tree as well as less complicated deliverables from lower levels of the tree.
- Use the technology trees interactively in each of the cycles to build on each other as the understanding of the focus areas among the R&D team improves.
- Develop the technology trees in an interactive process with the R&D team and present them to the Research Advisory Panel for comment.
- Use the technology trees to explain to stakeholders and funders of R&D why certain projects low in the technology tree are essential to improve the final key solutions developed by showing the linkages between the key solutions and the lower parts of the technology tree.

9.4 Application of protocols to the LIC field in South Africa

9.4.1 LIC in South Africa

South Africa has historically had a high unemployment rate - Statistics South Africa reported an unemployment rate of 25.5% as of September 2006. McCutcheon *et al.*[333] estimated the cost of unemployment to be in the order of 6% to 9% of GDP. One way of increasing employment is through Labour-Intensive Construction (LIC) which is defined as[334]:

> *Labour-intensive construction is the economically efficient employment of as great a proportion of labour as is technically feasible, throughout the construction process including the production of materials, to produce as high a standard of construction as demanded by the specification, the result being the generation of a significant increase in employment opportunities per unit of expenditure by comparison with conventional*

capital-intensive construction, without compromising cost, time and/or quality.

In the ground-breaking work in South Africa in the 1990s, the term 'Labour-Intensive Construction' was used. However, McCutcheon[335] stated that this placed too much focus on the labourer and not on the broader issue that includes appropriate policy, suitability of project, quality and efficiency, organisation and training, management, etc. However, although EIC (Employment-Intensive Construction) is a more holistic term that encompasses issues pertaining to labour and the labourer as well as those mentioned above, LIC is used in this thesis as it is the terminology recognised in all legislation.

McCutcheon[335] stated that LIC would be more feasible in industries that are 'product centred' (e.g. civil construction including road building) rather than 'process centred' (e.g. mass manufacturing of consumer products). Furthermore, LIC aims to increase employment opportunities by at least 300% to 600% per unit of expenditure as was demonstrated by experience in Kenya, Botswana, Lesotho, Malawi and Ghana. These experiences also indicated that it is indeed possible to construct good-quality, low-cost, low-volume rural roads with labour-intensive methods. McCutcheon[336] also listed the main factors for the success of LIC projects as appropriate: policy, project selection, design/specification, training at all levels, and the linking of payment to production through output-based remuneration.

Labour-Intensive Construction in South Africa came to the fore with the establishment of the South African National Public Works Programme (NPWP) in 1994 as an outcome of the ANC's Reconstruction and Development Programme (RDP). Its main objective was to reduce unemployment using LIC methods for the construction of physical assets. In addition, individual training and community capacity building were set as objectives[337]. The NPWP contained two strategic thrusts:

- a programme to re-orient public expenditure on infrastructure and transform the institutional capacity of the functions of all spheres of government to ensure larger-scale job creation, skills development and capacity building; and

- a Community-Based Public Works Programme (CBPWP) to ensure short-term funding to a variety of government and non-government organisations provided they meet the criteria consistent with the NPWP.

McCutcheon *et al.*[337] state that the NPWP failed to meet its objectives on a larger scale and made very little perceptible impact on the nature of public expenditure on infrastructure. The factors influencing this outcome pertain mainly to policy and institutional factors as well as to training and implementation of projects.

In 1996 the Labour Commission Report[338] stated the following about the CBPWP:

> *The commission cannot recommend an increased commitment to the CBPWP until credible monitoring and evaluation information from the CBPWP convincingly shows that the CBPWP is creating jobs and skills by delivering infrastructure through processes that are both community-driven and cost-effective.*

In 2003 the South African Government announced the Expanded Public Works Programme (EPWP), the aims of which were much the same as the NPWP, but it was expanded into areas other than infrastructure. In 2003 the Department of Public Works published a business plan for the EPWP[339]. The main goal of the EPWP was:

> *To alleviate unemployment for a minimum of one million people in South Africa of which at least 40% will be women, 30% youth and 2% disabled between 2004 and 2009.*

9.4.2 Challenges relating to LIC in South Africa

McCutcheon *et al.*[337] summarised the remaining challenges for the EPWP as follows:

- Generation of productive employment opportunities:
    - o the differentiation between jobs and employment opportunities go hand-in-hand with public expectations of the EPWP and this requires a significant communications investment;

- the EPWP should be evaluated against the magnitude of the investment of R3 billion as measured against South Africa’s GDP of more than R1 400 billion;
- normal construction practice would employ 11 000 people for an investment of R3 billion and this can therefore not be seen as the panacea for creating one million jobs;

- Lack of a programme approach:
  - although the EPWP is called a programme, there is no long-term plan consisting of a stream of linked construction projects;
- Legislation:
  - uncertainty in the interpretation of who has the responsibility for employment creation, the client or the contractor;
- Institutional capacity:
  - lack of institutional capacity at provincial and municipal level, particularly organisation, administration and technical capacity;
  - lack of a proactive approach to provide assistance where there is a lack of capacity in authorities;
- Time scale for implementation:
  - the demand to implement 100% of the planned R3 billion from the first year of the programme as apposed to a phased approach is unrealistic;
- Training:
  - although some progress has been made with training, there remains some confusion about the different types of training required, for example for management as opposed to training for labour;
  - training for labour is sometimes focused only on life skills;
  - there is some confusion about the payment of labourers while in training;
  - there is some doubt about the efficacy of the Construction Education and Training Authority (CETA) in terms of monitoring the quality of accredited training companies;
- Implementation of projects:
  - lack of prior identification of the suitability of the intended project for LIC;

    - lack of a pre-feasibility study to determine the availability of people able and willing to work in the area of the intended project;
    - lack of assessment of both technical and socio-economic factors in the pre-feasibility study;
    - in tendering for LIC projects it seems that contractors build at least a 30% increase into the tender price;
- Lack of mainstreaming of LIC practice:
    - there seems to be a lack of willingness among engineers and contractors to adopt LIC processes or to avail themselves of the existing knowledge in the field, such as 'team balancing' approaches;
- Lack of standard designs:
    - a manual with standard LIC pavement designs is required to provide cost-effectiveness, to aid consistency and assist consultants in managing their risk;
- Lack of adherence to government policy:
    - this is to some extent exacerbated by the three levels of government and the lack of institutional capacity at certain levels;
    - this is also aggravated by a lack of sufficient monitoring and evaluation to ensure compliance with the Act (Basic Condition of Employment Act);
- Continuity of funding:
    - in practice there has been no continuity of funding from the Medium Term Expenditure Framework (MTEF) process.

The Best Practice Manual[340] developed for the Gauteng Department of Roads and Public Works (Gautrans) lists a number of success factors for LIC. These include:

- a sound understanding of the principles of LIC in government;
- appropriate project selection as part of long-term programmes and not on an ad hoc basis;
- a sound assessment of the technical and economic feasibility at project level;
- consideration of technical, institutional, organisational, managerial and socio-economic aspects;

- significant institutional capacity is required;
- training should be extensive and targeted at various categories of workers;
- long-term financial commitment; and
- good coordination between authorities and all stakeholders.

Although LIC has been used successfully in a number of projects in South Africa, the Best Practice Manual also lists a number of failure factors for LIC projects:

- too many ill-defined objectives that could not be independently and verifiably measured and confusion between short-term relief objectives and long-term developmental objectives;
- inappropriate institutional structures responsible for implementation;
- ‘add-on’ funding as opposed to the formal procedures normally followed for the provision of public infrastructure, leading to fragmentation;
- ad hoc projects linked neither to a programme of construction nor to training;
- inappropriate definition of the scope of labour intensity;
- inadequate planning with, in particular, unrealistically short lead-in times between project conception and initiation of construction;
- inadequate and inappropriate contract documentation;
- lack of appropriate legislation (in particular employment legislation) to allow the principles of labour-intensive construction to be used;
- little national, provincial and local institutional capacity-building along with a lack of communication between the various levels and agencies of government;
- the expenditure on development failed to reach the target group (the poor) to the extent envisaged;
- individual skills were not improved. Training, where present, was not particularly appropriate or focused and has not shown itself to be carried through into post-project employment;
- individual commitment to the long-term success of the project was lacking: it was seen as a short-term source of income for the community; and

- internal planning, recording, reporting, monitoring, control and evaluation were severely lacking and any independent evaluation was noticeable by its absence.

9.4.3 Applying the principles of the R&D programme implementation protocol to the LIC field

These challenges and important aspects were summarised and then analysed using the detailed R&D programme implementation protocol given in Table 9.1. The result is shown in Table 9.3 below. This table indicates the stages of the R&D programme implementation protocol; the challenges/issues currently pertaining to the LIC field; and recommendations for implementation into a holistically-managed R&D and innovation programme in LIC. The analysis is based on lessons learnt from the implementation of the new R&D management model and tools – see Chapter 7. The emphasis in the analysis is placed on possible interventions that could maximise the return from the LIC innovation programme and yield the maximum impact.

Table 9.3: Use of R&D protocol developed in this thesis to assess the LIC focus area

STA-GE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
STRATEGY	1 Set up the programme	The LIC programme was set up in 1994, so no set-up is currently required	
	2 Needs determination	Lack of a programme approach, institutional capacity and understanding of LIC. Lack of mainstreaming of LIC practice. Lack of continuity of funding. Although the EPWP is called a programme , there is no long-term plan consisting of a stream of linked construction projects.	A participative needs determination process at a national LIC forum would prevent fragmentation of activity into small ad hoc projects and would yield the required focus areas coherently planned to fit into a more holistic approach. These focus areas should include technical as well as socio-economic aspects. Participation of managers from authorities and the private sector will create the awareness and understanding of LIC principles and benefits in these organisations, thus facilitating implementation. The Rural Development Agency currently being discussed could also play an important facilitation role.
	3 Technology Foresight	Lack of a programme approach that balances short-term objectives with longer-term needs.	One of the elements of a programme approach should be to build the required technology and knowledge platforms that will enable the process now and in the future. A technology foresight study that focuses on new directions in construction materials, processes and methods will facilitate this development. A Research Advisory Panel should be formed from key stakeholders and practitioners to provide strategic direction and to monitor R&D and innovation projects.

STA-GE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
	4 Develop a strategic plan	A business plan was developed for the EPWP, however some problems remain: confusion about short-term relief vs. long-term strategic achievement, the types of projects to be addressed and the envisaged benefits. The enormity of the task of creating one million employment opportunities in five years still remains a problem. Too many ill-defined objectives.	The existing business plan should be reviewed to assess its comprehensiveness in terms of a strategic approach that should incorporate all the aspects discussed here. The LIC forum can be used to determine the strategic focus, obtain buy-in from authorities and the private sector and to define the required action plan. A critical element is to ensure the integration of skills to combine hard technology skills with social science skills, thus ensuring that key solutions developed will have the desired social acceptability and impact. The strategic plan should be presented to and discussed with the RAP.
R&D PORTFOLIO	5 Develop technology trees	Lack of a programme approach, lack of standard designs.	This aspect is discussed in Table 9.4 below.
	6 Develop project portfolio	Lack of a programme approach, and lack of standard designs, proper selection of implementation projects, feasibility studies.	The project portfolio should be linked to the strategic objectives as well as the needs identified. These should be of a multi-disciplinary nature to address both technical and socio-economic issues. Projects should include those aimed at developing new solutions, pilot projects and full-scale LIC projects. Technology trees can be used to indicate the link between the needs, the focus areas, the required key solutions, the required technologies and the projects.
	7 Investment decision		This issue has not been raised in the documentation reviewed, but it pertains to the value derived from the investments made. The effectiveness measurement system should incorporate aspects of funding spent on LIC projects in order to facilitate the calculation of a 'return on investment' indicator.

STA-GE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
INTELLECTUAL CAPACITY POOL	8 Use the technology trees to assess the balance of and gaps in the R&D personnel		The technology tree tool can be used to assess both the quantity and the quality of the manpower available for the development of the required key solutions (in the broader sense and should include non-technical aspects).
	9 Human resource management	Institutional capacity still lacking, understanding in private sector not mainstreamed.	The national LIC forum will provide a platform for the sharing of knowledge with authorities as well as the private sector to facilitate the implementation of LIC techniques.
	10 Strategic partnerships	Institutional capacity still lacking, understanding in private sector not mainstreamed.	The relationship between authorities and the private sector should be a win-win situation, which means that for long-term viability the private sector will need an incentive (other than legislation) to become involved in LIC.
TECHNOLOGY TRANSFER	11 Implementation plan	Time scale for implementation.	The strategic plan discussed above should also take cognisance of implementation activities and their time scales.
	12 Delivery systems	Legislation and regulation have been much improved but are still not sufficient (to allow the principles of Labour-Intensive Construction to be used)	The delivery systems to enable LIC mainstreaming should be analysed and planned. Apart from appropriate legislation and regulation, aspects such as awareness (through the LIC forum and training), incentives for private sector and key solutions (such as a guideline with standard designs) should be investigated.

STA-GE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
	13 Technology transfer partners	Lack of co-operation between authorities and implementers, lack of adherence to government policy.	The relationship between authorities and the private sector should be a win-win situation, which means that for long-term viability the private sector will need an incentive (other than legislation) to become involved in LIC.
	14 Stakeholders' forum	Lack of communication with all stakeholders, little national, provincial and local institutional capacity-building, along with a lack of communication between the various levels and agencies of government.	A national LIC forum will provide a platform for the sharing of knowledge with authorities as well as the private sector to facilitate the implementation of LIC techniques.
EDUCATION	15 Education links		Training of new professionals in LIC at tertiary education institutions should be incorporated into curricula.
	16 Training activities	Training targeted at various levels of labour and management.	Current training activities should be continued and refined to ensure that the requirements are met.
RESEARCH EFFECTIVEN ESS	17 Set up research effectiveness measurement (RE) system	Generation of productive employment opportunities, lack of impact (the expenditure on development failed to reach the target group (the poor) to the extent envisaged).	A system to measure the effectiveness of the LIC programme should be developed. This should include anecdotal, qualitative information as well as quantitative information in the form of indicators monitored over time to assess trends.

STA-GE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
	18 Record project level RE information	Internal planning, recording, reporting, monitoring, control and evaluation were severely lacking.	The LIC forum can be used to validate the information collected; the indicators used and the results of the measurement shared.
	19 Conduct retrospective RE analysis		The current work to assess the success of LIC projects should be continued, but should take cognisance of the principles of retrospective effectiveness assessment and relevant indicators.
CLOSING THE LOOP	20 Strategic level management model		A national steering committee should be put into place to direct the process of mainstreaming LIC and to monitor the progress of the process.
	21 Review strategic plan		The strategic plan should be reviewed regularly (at least annually) to ensure that learning from the process is captured and implemented.

9.4.4 Drivers in the conceptual R&D management model

Similar to the implementation of the conceptual model in the Sabita programme (see Section 7.2.3 – Figure 7.1), the following 'levers' in the conceptual model were identified (see Figure 9.3):

- national-level strategic planning;
- political will and influence;
- integration over a number of knowledge fields;
- institutional capacity;
- legislation, regulation and incentives;
- training programmes; and
- outcomes assessment system and results.

These are discussed in more detail below.

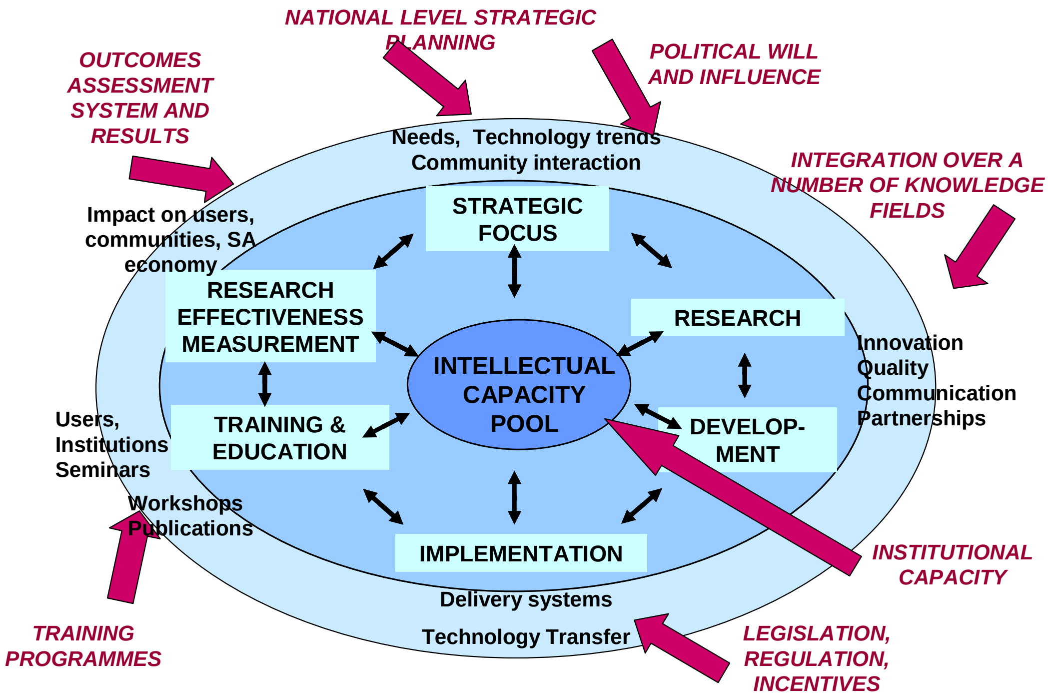


Figure 9.3: Levers in the application of the conceptual model for the LIC field

Driver 1: National-level strategic planning

The creation of an LIC forum consisting of stakeholders, authorities, the private sector, researchers and academia will assist in the reviewing of the existing business plan for the EPWP to ensure that:

- a comprehensive strategy is in place, including aspects pertaining to strategic objectives, short- and long-term objectives and project activities;
- partnerships are developed to yield the desired effect;
- cognisance is taken of the inputs from the LIC forum to ensure general buy-in; and
- a system for assessing the outcome of the programme is designed and implemented.

Driver 2: Political will and influence

The success of a national-level job creation programme such as the EPWP is dependent on long-term funding and commitment from government. This goes hand-in-hand with the enforcement of legislation regarding LIC projects and activity. The new ANC government elected in 2009 placed renewed emphasis on these aspects as can be seen from the State of the Nation Address by President Jacob Zuma delivered in June 2009[318]. This driver is therefore very important and the timing is opportune for a renewed focus on LIC.

Driver 3: Multi-disciplinary integration

A number of disciplines such as road engineering, construction methods, economics and social sciences need to be integrated to ensure that the key solutions developed are of the right quality and take cognisance of technological, institutional and social (community) aspects. This multi-disciplinary approach will ensure that implementation projects have maximum benefit and impact.

Driver 4: Institutional capacity

The perceived lack of institutional capacity could also be exacerbated by a lack of communication with and understanding among officials about the principles and benefits of LIC. Correcting both the institutional capacity as well as the communication processes is one of the major drivers in the process.

Driver 5: Legislation, regulation and incentives

Some modifications and improvements have been made to legislation and regulation, but some problems remain and legislation is not always enforced. The legislatory actions should be balanced with an incentive for the private sector to create a win-win situation. In the energy field, for example, a number of feed-in tariffs have been recently announced to stimulate the generation of power from renewable sources[341]. Government also allows the private sector a 150% tax rebate for R&D. A similar incentive would certainly also increase the use of LIC. Hattingh *et al.*[342] also proposed the introduction of penalty or bonus schemes with reference to the LIC component achieved.

Driver 6: Training programmes

There has been significant focus on training of both labour as well as management in the LIC programmes in South Africa[343]. Training needs to be kept up and this aspect remains an important driver. A longer-term intervention that may need to be considered is the incorporation of LIC as a compulsory subject in engineering and technical courses at tertiary institutions. The LIC forum can be used to disseminate new information as well as success stories to the professional community.

Driver 7: Outcomes assessment system

There is a significant need to collect information on the successes of the LIC programme and to analyse it to convince politicians and practitioners alike of its benefits and value. The information can also be used to improve the decision making in the LIC programme in terms of priorities and focus. In Section 6.4.4 of this thesis the development of a research effectiveness measurement system was discussed. The system focuses on input, output, outcome and impact. Some of these principles can be used to develop an outcomes measurement system for the LIC field which focuses on those achievements in the immediate implementation arena without having to wait for long-term impact assessment. This is one of the key success factors of the LIC programme.

9.4.5 Applying the principles of the technology tree protocol to LIC

These challenges and important aspects were also analysed in terms of the technology tree protocol given in Table 9.2. The result is shown in Table 9.4 below. This table indicates the stages of the technology tree protocol, the challenges/issues currently pertaining to the LIC field, and recommendations for implementation to use the technology tree tool.

Table 9.4: Application of the technology tree protocol to LIC

STAGE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
DRAWING A TECHNOLOGY TREE	1 Define key solutions 2 Define applied technologies 3 Define the platforms 4 Link the applied technologies 5 Define the base technologies and R&D infrastructure	Lack of a programme approach that balances short-term needs with long-term objectives, institutional capacity and understanding of LIC. Lack of mainstreaming of LIC practice. Lack of continuity of funding. Although the EPWP is called a programme, there is no long-term plan consisting of a stream of linked construction projects. Lack of some key solutions such as standard designs.	Use the inputs from the needs determination process in the LIC forum to define the focus areas and required key solutions (technical, institutional, training, etc.) to achieve the objectives. Define the technology and knowledge platforms required to put the key solutions in place. Plan the detailed technical and non-technical knowledge base in terms of applied technologies and required R&D infrastructure (if any). Link the applied technologies to the key solutions to determine the priority technology development projects.
R&D PROJECT PORTFOLIO	6 Plot potential projects on the trees 7 Link the projects 8 Prioritise the projects	Lack of a programme approach that shows a series of technology development projects linked to a series of implementation projects that would ensure maximum impact based on sound technical principles. Balance required between short-term activities and longer-term strategic projects. A link is required between the high-level issues and the detailed projects to assist with communication to stakeholders and authorities.	Plot all R&D, innovation and implementation projects on the technology trees to assess potential linkages and synergies between them.

STAGE	ACTIVITY	LIC ISSUES AND SUCCESS FACTORS	PROPOSED ACTIONS BASED ON THE R&D MANAGEMENT PROTOCOL
BALACING THE RESOURCES	9 Analyse vertical balance in trees 10 Analyse horizontal balance in trees	Need to balance the short-term activities with the longer-term strategic projects to assist with planning of funding and communication to stakeholders and authorities.	Investigate the balance in the technology trees by assessing the vertical balance (shorter-term implementation projects vs. longer-term strategic projects) as well as the horizontal balance (how well the projects address each of the strategic focus areas).
GAP ANALYS	11 Project analysis	Need to determine the gaps in R&D, innovation and implementation projects required to form a holistic programme approach.	Conduct a gap analysis by analysing the inputs from the LIC forum, the current and future projects as well as the existing applied technologies and capabilities in the tree. Identify areas where gaps exist that could be addressed through focused projects.
	12 Manpower analysis	Need to assess the existing and required manpower in R&D, authorities and practitioners to deliver the required results.	Analyse the available manpower versus the required manpower to assess areas where high-level skills need to be developed.
FINAL PROJECT PRIORITISATION	13 Develop a potential project list 14 Final resourcing and funding allocation	Need for a holistic strategic plan that details the strategic objectives, measurement system and the required technological, training and manpower needs.	Identify strategic interventions (projects) that will address the needs, key solutions required as well as the gaps in the technology tree. Prepare proposals and interact with stakeholders and authorities to obtain funding for the strategic interventions.

The staff members of the Centre for Employment Creation at the University of the Witwatersrand (Wits) were consulted in an interactive workshop to develop the basic technology trees that can be used for the R&D management and planning of Key Solution development. These trees are built on three platforms:

- Process technology (policy, social issues, implementation aspects, management aspects)
- Construction and maintenance technology
- Structures and materials technology.

A number of Key Solutions that should be developed were defined, and these are shown in Figure 9.4. An important aspect of these technology platforms is that they should be used in an integrative manner to deliver the required Key Solutions. This means that the applied technologies and base technologies from more than one platform should be integrated to ensure that the Key Solutions take cognisance of, and are developed from, a multi-disciplinary skills base, thus ensuring, for example, that solutions are socially acceptable to communities. Figure 9.4 indicates that many of the Key Solutions are linked to more than one platform.

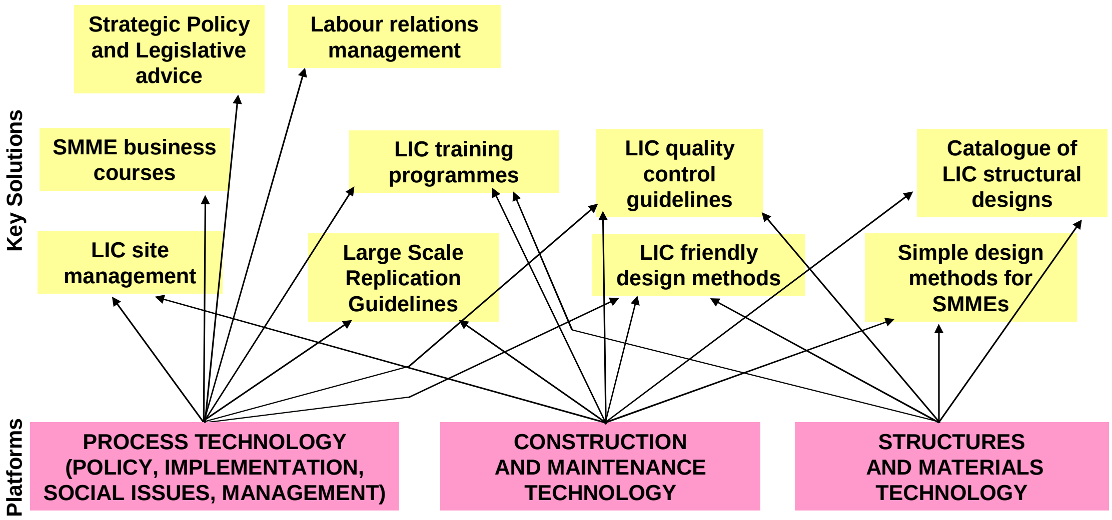


Figure 9.4: LIC technology platforms and Key Solutions

The detailed levels of the technology trees containing these platforms were also developed with the Wits team and these are shown in Figures 9.5 to 9.7 below.

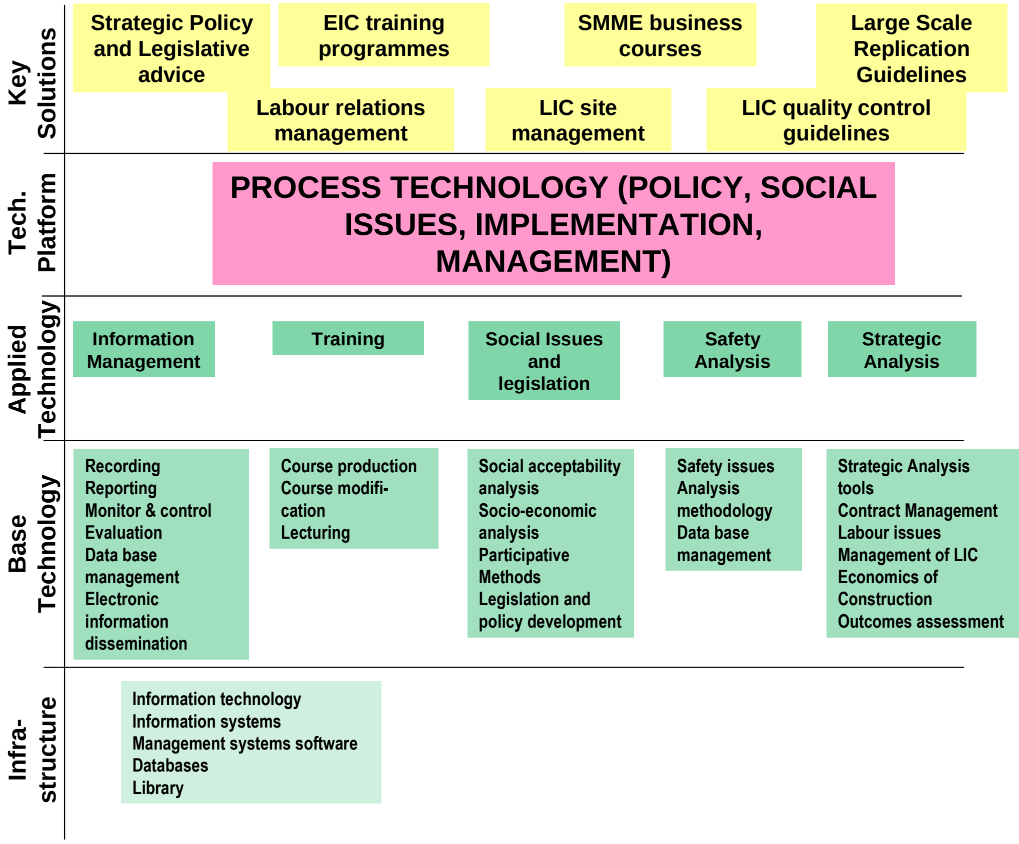


Figure 9.5: The LIC Process technology tree

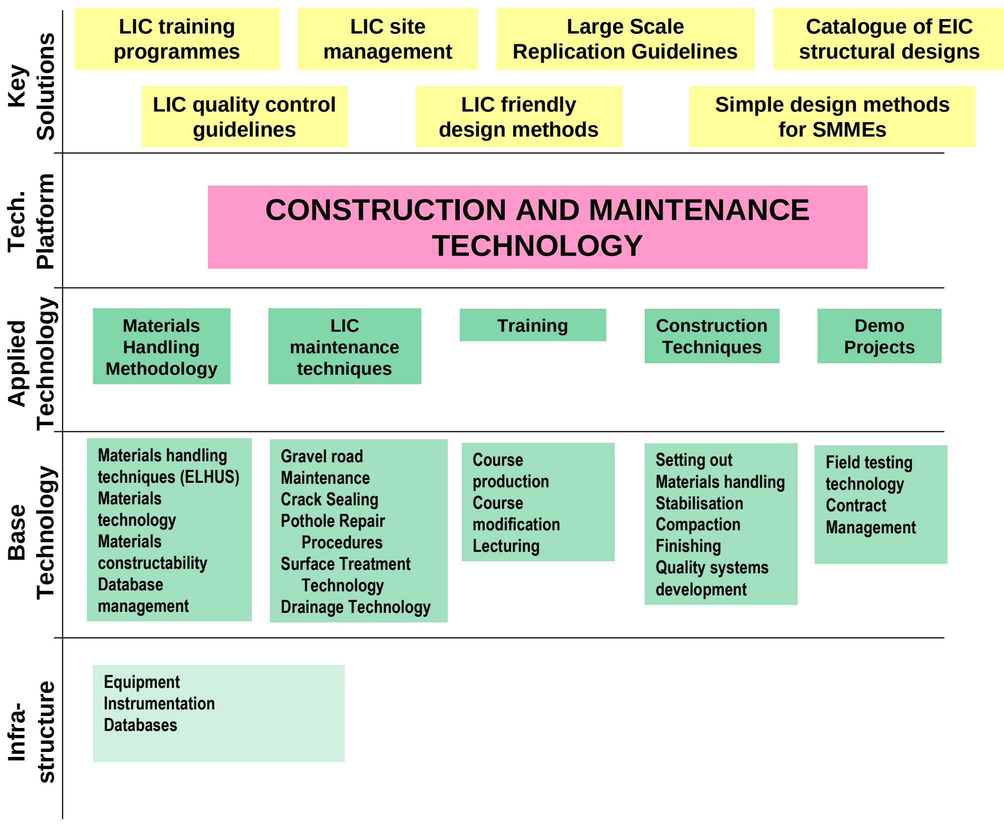


Figure 9.6: The LIC Construction and Maintenance technology tree

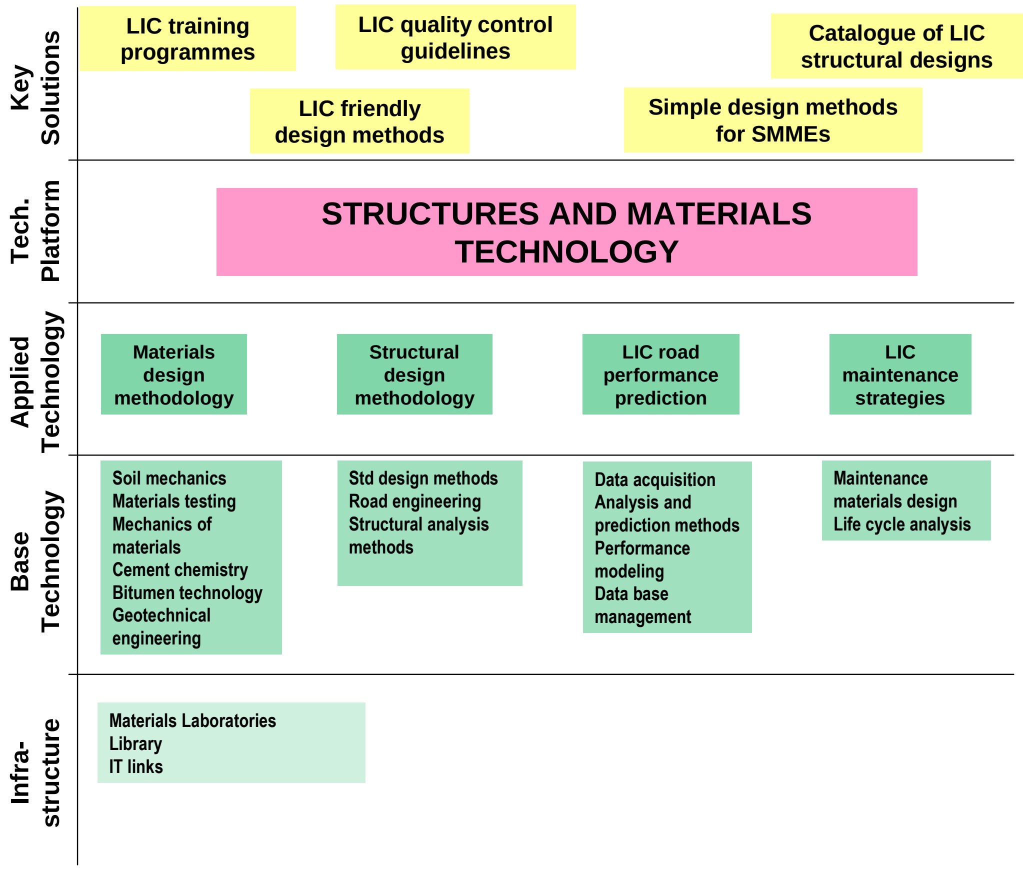


Figure 9.7: The LIC Structures and Materials technology tree

The Process technology tree in Figure 9.5 specifically contains elements pertaining to Social Issues, Legislation and Strategic Analysis to ensure that multidisciplinary approaches are taken into consideration in the development of the Key Solutions. This is of particular importance when Key Solutions are developed that will impact directly on communities. The social acceptability of these Key Solutions is vital to the sustainability of the LIC programme.

After the needs determination processes described above have been completed, these basic technology trees should be used to plot the projects (R&D and implementation) as well as the required manpower (researchers, trainers and implementers) linking the implementation projects to Key Solutions and in turn linking the Key Solutions to required R&D projects positioned in the technology tree. The completed technology trees should then also be used to conduct gap analyses to determine technology development and human resources needs.

9.4.6 Recommendations for application of the R&D management and technology tree protocols in the LIC field

It is recommended that the following aspects and interventions, highlighted by the analysis above, should be implemented in the LIC programme:

- An LIC forum should be created where stakeholders, authorities, the private sector, academia and researchers can discuss needs, problems, new developments and success stories.
- The LIC forum should be based on the principles of the highly successful Road Pavements Forum (RPF), should meet biannually and may even be attached to the RPF.
- The LIC forum should be used to:
  - obtain buy-in from all stakeholders
  - conduct needs determination processes (see Section 6.4.1)
  - formulate focus areas
  - develop the delivery systems (see Section 6.4.3) that will make the programme successful
  - initiate the mainstreaming of LIC practice.
- The technology trees developed for the LIC field should be reviewed to ensure that they incorporate a number of disciplines (road engineering, construction methods, economics, social sciences) and that they are integrated to deliver key solutions that are appropriate and acceptable to communities.
- The technology trees should be used to:
  - develop an understanding of the needs, key solutions and underlying knowledge and technologies as well as their linkages
  - communicate the 'holistic picture' and rationale for selecting and conducting projects to stakeholders and funders
  - balance the activities and prioritise R&D projects as well as implementation projects
  - identify gaps in knowledge or new key solutions required (e.g. catalogue of standard designs)
  - analyse the required manpower.
- The potential to change legislation to provide effective incentives to private sector for using labour intensive methods should be investigated.

- An outcomes assessment system should be developed and trends of indicators produced that can be used to:
    - improve the internal strategic decision processes on focus areas and implementation projects
    - provide strategic information to stakeholders and funders about the successes of the programme;
- The current EPWP business plan should be reviewed to ensure that new elements and strategies are added, including:
    - a technology foresight study
    - an outcomes assessment system
    - incentives for practitioners.
- In the use of the conceptual model the aspect of 'reverse thinking' (see Section 6.3) should be applied so that the envisaged outcome and impact and the required delivery systems and training programmes are clearly understood as part of the project planning phase and before new key solutions are developed.

Whereas some of these recommendations may already be partially or fully implemented, it is the full holistic approach that will yield the maximum return. The LIC field is a complex system and even small changes can have large effects (see Section 2.3.3).

9.5 Concluding remarks

The protocols discussed in this chapter are intended as a guide to implementing the new R&D model and tools which are based on a complex systems approach. The model and tools therefore have to be used iteratively over a number of cycles to allow some of the important characteristics of a complex system (e.g. self-learning, self-correcting and self-balancing) to emerge. It is important to use the principles developed for this thesis, but they must be adjusted to bring them in line with the specific mandate, culture and mode of operation of the R&D organisation concerned or the knowledge field where they are applied. This has been demonstrated by analysing the LIC field in terms of the two protocols and by making recommendations for the application of the principles of the protocols to enhance the output and outcome from the LIC programme.

10 CONCLUSIONS, CONTRIBUTION AND WAY AHEAD

10.1 Introduction

The first section of this chapter summarises the work done in this study and highlights the findings of the work. Section 10.3 reflects on the relevance of the methodology used and the relation of this work to previous work conducted in this field. Section 10.4 discusses the specific contribution of this work. The last section draws some conclusions and makes recommendations for further work.

> *"I have walked that long road to freedom. I have tried not to falter; I have made missteps along the way. But I have discovered the secret that after climbing a great hill, one only finds that there are many more hills to climb. I have taken a moment here to rest, to steal a view of the glorious vista that surrounds me to look back on the distance I have come. But I can rest only for a moment for with freedom come responsibilities, and I dare not linger, for my long walk is not ended yet." - Nelson Mandela*

10.2 Summary of work conducted and main findings

10.2.1 Definition of the problem

This study aimed to address the problem of R&D management in the road engineering field. It was particularly motivated by the under-performance of past R&D programmes in spite of the importance of SET and R&D in a developing country. The main problems experienced with R&D management in this field in the past were the fragmentation of the R&D programmes due to simplistic linear management models and the use of open tenders to allocate research funding (see Chapters 1 and 4). In addition, it was shown in Chapter 2 that the R&D process is a complex system which includes a number of organisations that are in themselves complex systems, and therefore a simplistic linear management model is unlikely to yield the desired results.

The analyses done in Chapters 2 and 3 also indicate that traditional R&D and innovation management models were developed for hard product development and are linear in nature, following the steps of idea, research, development, engineering, manufacturing and marketing. It was also shown that more than

72% of case studies in a typical technology management handbook and series of journal articles dealt with hard product development and most of the remainder dealt with software development – none dealt with R&D in infrastructure or transport. Thus traditional R&D management models do not take cognisance of the complexity of the process to develop the new knowledge, engineering methodology, know-how, expertise and capacity building required in the road engineering field (see Chapter 6).

This study defined five research questions which are reflected on below as well as the following thesis statement:

> ***The development and implementation of a systems-based conceptual management model and supporting decision tools in a road engineering research programme will lead to an increase in research effectiveness in terms of number of outputs and long-term growth in the R&D programme.***

10.2.2 Research approach and objectives

This study followed a developmental research approach supported by a case study approach. The classical steps of problem analysis, solution development and evaluation of the implementation of the solution were followed (see Chapter 4). The study used a mixed research method combining qualitative analysis with some quantification to support the arguments. The data used for the work were compiled from literature reviews, case studies, a survey of local and international R&D managers, personal interviews, interactive workshops, project reports, internal CSIR publications and the CSIR's and Navplan's financial systems.

The main objectives of the study were to:

- quantify the problems experienced in past research programmes;
- develop a set of principles and tenets that could guide the development of an improved R&D management model and supporting tools;
- develop a new R&D model and supporting tools based on complexity theory and a cybernetic systems approach;
- implement the new model and tools in a number of R&D programmes and record the lessons learnt from this activity;

- evaluate the effect of the implementation of the new R&D management model on the outputs from the road engineering research programme in the CSIR;
- present a set of protocols, based on the work conducted for this thesis, that can be used to set up and manage an R&D programme; and
- evaluate the applicability of the protocols in the Labour-Intensive Construction field and make recommendations for the enhancement of the LIC programme in South Africa.

10.2.3 Main findings

The following are the main findings of this study:

- Classical technology management and R&D management models were developed for hard product development and do not take cognisance of the complex systems nature of the R&D process in road engineering, which is aimed at developing new engineering methodology and solutions (see Chapters 2 and 6).
- The R&D process in road engineering displays many of the characteristics of a complex (cybernetic) system, and the organisations participating in this process are also complex systems. Therefore simplistic linear models of R&D management are unlikely to yield the required performance.
- Past R&D programmes in road engineering display some of the typical characteristics of a complex system, particularly the effect of a relatively small change (implementation of low-cost tendering process), which had a very large, unforeseen effect (fragmentation and demise of the programme) – see Chapter 3.
- It was possible to conduct qualitative research using the literature, case studies of research programmes and large projects, quantitative analysis of some of the characteristics of past research programmes, interviews and interactive workshops to develop a set of twelve tenets that were used to develop a new conceptual model for managing R&D in the road engineering field (see Chapter 6).
- The desired characteristics of an R&D programme defined from these analyses were evaluated through a survey of the opinions of 45 local and

international R&D managers operating in a number of research fields. Particular findings from this survey were:

  - although only a few of the defined characteristics are currently used by R&D managers, they were all rated as important;
  - in terms of the 'gap' between importance and extent of use of the characteristics, the following were the most important: formal technology transfer projects; the formal assessment of impact and the use of integrated, system-based approaches in R&D management;
  - project size and the number of researchers per project were important factors in terms of R&D performance.

- The results from the survey confirmed the findings of the qualitative and quantitative analyses conducted in Chapters 2 and 3.
- In addition to the above, the work done also led to the development of three supporting decision tools for needs determination, portfolio management using technology trees and research effectiveness measurement.
- It was found that the use of a formal needs determination process ensures that research programmes are relevant and have buy-in from a range of stakeholders.
- Technology trees can be used very effectively to depict the content of a research focus area around a technology platform and to show the link between the SET base and the key solutions required.
- Technology trees can also be used as a portfolio management tool to assess the relative importance of projects as well as the balance in the project portfolio.
- An indication of research effectiveness can be obtained by measuring specific indicators of research output, outcome and impact over time and conducting trend analysis on the data.
- The conceptual model and decision-support tools were implemented in three research programmes and one large research project, and were found to improve the understanding of researchers and stakeholders of the holistic, bigger picture, and to enhance the output from these programmes.

- There was significant qualitative and quantitative evidence that the implementation of the new conceptual model and tools was an important contributor to a three-fold increase in the research output after such implementation (see Chapter 8), thus supporting the ***thesis statement***.
- The two protocols developed for the implementation of the conceptual R&D management model and the technology tree tool were used to assess the challenges in the Labour-Intensive Construction (LIC) field.
- A number of recommendations were made (based on the implementation protocols) to enhance the LIC programme in South Africa. The most important were:
    - the creation of an LIC forum for discussing needs, problems, new developments and success stories relating to LIC;
    - a set of three technology trees were developed that can be used to balance the project portfolio, communicate the project portfolio to stakeholders and to identify gaps in knowledge and resource needs;
    - the possibility of changing legislation to provide effective incentives to the private sector for using labour-intensive methods should be investigated;
    - an outcomes assessment system for the LIC area should be developed;
    - the current EPWP business plan should be reviewed to ensure that new elements and strategies are added, for example a technology foresight study, an outcomes assessment system and incentives for practitioners, and
    - in the use of the conceptual model the aspect of 'reverse thinking' should be applied so that the envisaged outcome and impact, the required delivery systems and training programmes are clearly understood as part of the project planning phase before new key solutions are developed.

10.3 Discussion of results

This study has created a new paradigm for managing R&D in the South African road building industry. The focus was shifted from short-term investigations to a holistic, systemic approach to R&D. The new conceptual model and decision tools form a suite that has been successfully used at strategic programme as well as at project level. Although developed for road engineering, the R&D management suite has also been used successfully in related fields such as integrated planning and transport research.

10.3.1 Reflection on research approach

The combination of the developmental research approach with case studies provided a sound method for the development of the new R&D management suite. Research instruments such as the interactive workshops were important for compiling the required information for the study as well as for obtaining early buy-in from the stakeholder grouping where the final model was implemented. The survey was instrumental in confirming the findings from the qualitative analysis. The study employed a mixed model using both qualitative and quantitative analyses. It was found that the quantitative data strongly supported the qualitative argument.

10.3.2 Reflection on comparison with other published research

This study produced novel results in comparison with the results of classical technology management and R&D management literature which focus mainly on the managing of hard product development and ICT-based products. The application of a complex, cybernetic systems approach to managing R&D in road engineering is novel in South Africa and, as far as could be determined, also in general. The development and use of the technology tree as a portfolio management tool and the 'perceived equivalent value' approach to determine research effectiveness are also novel.

10.3.3 Reflection on implementation of the model in CSIR Transportek and the CSIR Built Environment Unit

The model was implemented in all the research programmes in CSIR Transportek. The early work was conducted in the road engineering field, but has also subsequently been implemented successfully in the Transport Programme and the Traffic Management Programme. Due to the early adoption of the process in the road engineering field, the progress in this field was more advanced than in the other areas.

During the restructuring process of the CSIR in 2005 and 2006, the model and tools were used to assist with the strategic planning of the new Built Environment Unit. Technology trees were applied extensively to describe the SET base and how this links with the required key solutions and stakeholder needs in all the new Competence Areas (previously Programmes) in the process of generating the research agenda of the Unit. The process of implementing technology trees worked well and yielded significant results. In particular, there has been a significant increase in R&D outputs as was discussed in Chapter 8. A significant amount of work was also conducted to develop the operational management processes that enable the new process to work. These are shown in Figure 8.13, which is the final version of the conceptual model based on a complex, cybernetic systems approach.

The following aspects of implementation could still be improved:

- implementation of the research effectiveness measurement system and the development of associated database structures and analysis software; and
- although aspects of the model and techniques have been applied in a number of Units of the CSIR, the uniformity of the application of the approach throughout the CSIR could be improved.

10.3.4 Reflection on implementation of the model in transport authorities and the private sector

As discussed in Chapter 7, the R&D management approach was implemented in the road infrastructure field in conjunction with Sabita and Gautrans. The use of the model ensured the buy-in of a number of stakeholders, and technology trees were developed which show a number of client projects and CSIR Parliamentary Grant projects. However, the following aspects still need attention:

- There is no single structure (e.g. a committee) which focuses on a holistic approach to the development of new knowledge and engineering expertise in the transport sector (although the PRAC committee discussed in Section 7.7 fulfils this role in the road-related research programme).

- The formation of a number of agencies such as the South African National Roads Agency (SANRAL) and the Road Traffic Management Corporation (RTMC), although important in the execution of the DoT's strategy, could counter efforts to reduce fragmentation of the R&D programme.
- The issue of dedicated funding for an R&D programme should be investigated under the auspices of the National Department of Transport.
- Special delivery systems for implementation aimed specifically at transport authorities need to be developed.
- The model should be implemented by all transport authorities.

CSIR Transportek used a number of steering committees (including the Pavement Research Advisory Committee mentioned above), and the CSIR Built Environment Unit is currently interacting with four new research advisory panels. This will go some way towards addressing the above issues. Although the model can still be improved and extended, its implementation has had some success.

10.4 Reflection on answers to the research questions

The research questions posed in Chapter 4 are reviewed briefly below to assess to what extent they have been answered.

Question 1: To what extent are currently used technology management practices and models applicable to the management of R&D in the road engineering field?

During this study, no existing technology management practices and models could be found that are applicable to the management of R&D in the road engineering field. This was mainly because road engineering R&D focuses on the development of new engineering methodology and not on hard products for the consumer market. Existing models were found to be linear in nature and do not address the complex and iterative process of effectively developing new engineering methodologies.

Question 2: What are the critical success factors for an effective R&D management model in the road engineering field?

This question was answered through the analysis of technology management principles in the literature, the success and failure factors of several past research programmes, the success factors of a selection of major research projects, the survey conducted among local and international R&D managers and interactions and discussions with stakeholders and practitioners in industry. From this information twelve tenets were developed (see Chapter 6) that describe the critical success factors for a new management model.

Question 3: What are the critical principles and required elements of a systems approach to such a model?

These principles were summarised in the twelve tenets for a new approach as given in Chapter 6. The specific aspects of a systems approach emphasised in the new model included circular causality; interlinked and interdependent elements; feedback loops; a sensor which monitors performance and provides feedback for self-correction; emerging behaviour; and non-linearity. The process of research and development does not follow a prescribed path but can follow a number of paths through the model. The model is a complex system with elements of cybernetics inherent in its operation. However, some degree of reduction is achieved when the technology focus areas are viewed in separate technology trees, and this shows the link between the S&T base and the key solutions, which are in turn linked to stakeholder needs.

Question 4: What are the appropriate tools required for managing complex, multi-disciplinary research programmes in the road engineering field?

This study developed the following frameworks and tools:

- a conceptual model for managing R&D in the road infrastructure field;
- a needs determination process and tools to assist strategic planning and the setting of the research agenda;
- the use of technology trees to develop an understanding of the SET base and how basic technologies and capabilities are linked to key solutions and stakeholder needs. The trees were also used to assess the balance of the research portfolio;
- a research effectiveness measurement system which includes elements of impact assessment; and

- frameworks for more effective technology transfer and the linking of the research programme to educational processes.

Question 5: If a new approach and management model are implemented, what effect will they have?

This study defined a number of parameters to assess the effectiveness of the implementation of the new approach and model:

- the number of academic publications (book chapters, journal articles and papers in peer-reviewed conferences);
- post-graduate degrees awarded;
- the number of national guidelines and design manuals delivered;
- the average size of research projects (using 2008 Rand as a base); and
- growth in contract R&D funding of the road infrastructure sector in the CSIR.

The analysis in Chapter 8 showed that the new approach and model had a significant impact on the research programmes where they had been implemented. Quantitative analysis of research outputs over an 18-year period indicated a possible three-fold increase in research effectiveness per researcher after implementation of the model and tools.

The 'before' and 'after' analyses of survey responses indicated a significant difference in the extent to which the desired characteristics had been used by R&D managers who had not been exposed to the model and tools and those who had used them.

10.5 Contribution of this work

The implementation of the systems-based approach to R&D management developed in this work has led to a three-fold increase in the research effectiveness per researcher (see Chapter 6). In particular, this work contributed the following to the knowledge base of R&D management:

- the motivation and basis for a paradigm shift in road engineering R&D management away from simplistic, linear models aimed at short-term investigations to a holistic, systemic approach (see Section 6.2.1);

- the development of an understanding of the drivers and characteristics that will ensure a successful R&D programme as well as the factors causing unwanted behaviour (see Chapter 3);
- the analysis of the responses of 45 local and international R&D managers regarding the extent to which they use the identified characteristics as well as their importance (see Chapter 5);
- the development of twelve tenets for constructing a new R&D management model and tools for the road engineering sector (see Section 6.2);
- the development of a conceptual model for the management of R&D in the road-building industry in South Africa that takes cognisance of complexity theory and cybernetics (see Section 6.3);
- the development of a process for needs determination that focuses on top-down strategic input, bottom-up technical input from industry professionals, interactions with end-users as well as foresight studies (see Section 6.4.1);
- the development of the technology tree approach to managing the balance of a portfolio of research projects that are linked to customer needs and strategic objectives (technology pull) and also allows for structured invention (technology push) – see Section 6.4.2;
- the development of an investment-decision approach for the allocation of research funding at portfolio level (see Section 6.4.1);
- the development of a research effectiveness measurement system that includes impact assessment based on perceived-value equivalents (see Section 6.4.4);
- the development of indicators for the measurement of research outputs, outcomes and impact in road engineering (see Section 6.4.4);
- the implementation of these systems and tools in the Sabita research programme as well as the CSIR Transportek's Parliamentary Grant research programme and the identification of positive and negative aspects of this implementation process (see Chapter 7);
- protocols for the implementation of a systems-based R&D management process and the technology tree tool (see Chapter 9); and

- recommendations for the enhancement of the Labour-Intensive Construction field in South Africa based on the implementation of the above protocols in this field (see Chapter 9).

10.6 Recommendations and concluding remarks

10.6.1 Recommendations for policy implementation

This work has highlighted the importance of a systems-based approach to managing complex R&D processes. The conceptual model and decision-support tools developed in this study have been implemented successfully and there is significant evidence that this implementation has had a number of benefits and has increased the output of the road engineering R&D programme in the CSIR by a factor of three. Road engineering and transport infrastructure engineering R&D continue to be of major importance to South Africa, and in the light thereof, the following general recommendations are made:

- transport and transport infrastructure should be established as a theme in the National R&D Strategy;
- transport foresight studies should be conducted that will assist in finalising the national research agenda;
- a comprehensive national transport R&D strategy and agenda should be developed, prioritised and funded;
- a national forum for transport R&D co-ordination should be created to ensure synergy between government departments and between government and the private sector in terms of developing and managing the R&D portfolio for South Africa;
- partnerships between government and the private sector should be established to ensure that the full innovation chain from invention to commercial application is addressed, particularly in the current scenario where the infrastructure sector is growing rapidly;
- improved processes for R&D procurement need to be put in place to ensure that there is a holistic, non-fragmented effort to address R&D in the infrastructure sector;
- the establishment of mechanisms for funding transport R&D and for the allocation of such funding to research teams that is not based on an open tendering process and lowest-cost assessment of R&D projects; and

- a centre of excellence in transport and transport infrastructure research should be considered to ensure that critical mass in the diverse fields discussed above can be developed.

10.6.2 Proposed further work

Future improvements to the model and techniques and their implementation should focus on the following aspects:

- the development of an understanding of resources by plotting human resources and facilities on technology trees and rating their quality, thereby identifying strengths and areas for potential improvement;
- the improvement of the investment-decision process to incorporate the appropriate strategic decision factors for the broader transport sector and to implement it on a detailed project level;
- the improvement of the research effectiveness measurement system through additional analysis to improve the perceived equivalent value indicators;
- the development of an appropriate database and data analysis software to support the research effectiveness measurement process;
- the implementation of a link between the trends in the research effectiveness measurement process and strategic planning;
- the enhancement of the technology trees developed for the LIC field and their use to define gaps in knowledge and human resources in LIC; and
- the implementation of the recommendations made in Chapter 9 to enhance the LIC programme in South Africa.

10.6.3 Concluding remarks

This work describes the development and implementation of a new systems-based R&D management model and decision-support tools for the road engineering sector. The model and tools have also been implemented in some areas of the broader transport and built environment fields. This activity has had a significant effect on the quality of the R&D process and its outputs. The implementation of the new approach to R&D management in new research programmes should benefit the identification of new research themes and the quality and quantity of research outputs. It should enhance technology transfer from research and it should enhance education and training programmes.

Future monitoring of the research effectiveness indicators will allow the assessment of the true value of such implementation. The process of developing the model and techniques has been relatively long and arduous, but the benefits observed to date have made the investment worthwhile.

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