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ACKNOWLEDGEMENTS

I gratefully acknowledge the invaluable help and assistance given to me by my three supervisors - Professor A.R. Kemp, Professor G.J. Krige and Professor R.V. Milford. I wish to thank the various persons who freely gave of their time as experts, or otherwise provided valuable data and insights. In alphabetical order these are - Brian Bruce, Jim Collins, Graham Cross, Dr de Clerq, Peder Firman, Mr Goldstein, Peter Jessop, the late Hennie Lemmer, Dr Lunt and Mr Napier. I also wish to acknowledge with gratitude all those persons whose advice and co-operation contributed to this dissertation. Chief amongst these is Stanley D. Kaplan who has greatly helped me. I also owe an intellectual debt to the various persons whose publications in this field have shown me the way to go - especially Professors D.I. Blockley and P.B. Checkland.

To Roseline and to Ife, but most of all to you my Father, my God. Thank you all for being so patient with me.

"My soul is escaped as a bird out of the snare of the fowler: the snare is broken, and we are escaped. Our help is in the name of the LORD, who made heaven and earth.

ABSTRACT

In this dissertation, the soft paradigm in the systems approach was applied to design errors to obtain a causation theory for design errors, thus providing a basis for design error prediction and control.

The theory is based on expert opinions about systemic 'human activity' factors, affecting design errors in a particular context. These opinions are modelled as cognitive maps and developed into a theory using the Grounded Theory method.

The predictive capacity of this theory is illustrated by a System Dynamics model, developed with the STELLA software. This model simulates the behaviour of factors in the theory to estimate relative likelihoods of design errors, for different human activity systems. Objective and subjective data is readily available for such factors, unlike when assessing errors directly.

The role of the theory in control is illustrated with Soft Systems Methodology models for one class of design errors. SSM prescribes activity logic in a system, for a given perspective. Hence, the models enable logical specification and assessment of error control schemes. The theory reveals relevant perspectives for control systems and guides the definition of activity logic, thus enhancing the SSM process.

DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering, in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Israel Oludotun ADEGOKE

15th day of March, 1996.

A THEORY OF HUMAN ERROR CAUSATION IN STRUCTURAL DESIGN: Error prediction & control via the soft systems approach

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A dissertation submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 1996

observed) level; the contextual (character of the local situation) level; and the conceptual (how a wider/local situation generates an error) level. A typical behavioural description might record an error as 'engineer error, in first floor slab'. A contextual description of the same error might add the information, 'fast track, design not checked'. The conceptual level would then go beyond this to include details of the principles e.g. information transfer problems (because of fast-tracking), aggravated by inadequate error detection procedures.

Error surveys, databanks and other statistic gathering exercises (reviewed in section 2.2 ahead), will typically classify errors behaviourally. The problem with behavioural classifications in structural design, is that they yield little useful information in themselves for error prediction and control. It is only when the context or local situation surrounding the error is known, that the behavioural description becomes meaningful. (This is the reasoning behind case-history style studies, which are contextual in character). Unfortunately, there is a large range of diversity in structures and in the design delivery process. This discourages the use of a contextual classification. It is difficult to specify all possible contextual situations beforehand, and be both exhaustive and non-ambiguous. Hence a conceptual level taxonomy appears more appropriate for this study.

From considerations about intention, Nowak & Carr (1985) divided human error into three fundamental classes based on the mechanism of occurrence. These are errors of concept[1], errors of execution and errors of intention. Errors of concept refer to unintentional departures from acceptable practice due to insufficient knowledge, (e.g. did not know which models were applicable). Errors of execution are unintentional departures from the conceptual model in the person's mind, (e.g. misread, forgot etc.) Errors of intention are intentional departures from what one believes to be accepted practice. Examples are sabotage, to save time or money etc.

[1]In this study, the word 'concept' is used to refer to several things - not only design concepts for example.

Neal Fitzsimons (1986) classified the causes of human error into three levels - personal, organizational and institutional. Personal causes relate directly to the individual and lie in the domain of psychology and the behavioural sciences. Organizational causes refer to the roles defined for various persons in an organisation, and the formal relationships between these roles. Institutional reasons for error relate to industry-wide practices and attitudes. Sir Alfred Pugsley also drew attention to the role of the wider environment in precipitating failure (via human error). Pugsley (1969) discussed the 'engineering climatology' surrounding structural failures. Hence, the political, financial, industrial, scientific and professional 'climates' surrounding a project have implications for error.

Ingles focuses on a single aspect of the error causation problem, without considering how this aspect interacts with others. A more holistic approach would have been desirable for a study of this sort. Fitzsimons and Pugsley's explanations are more holistic, but are not detailed. None of these explanations of error causes resulted from deliberate studies, and they are not exhaustive in their coverage. Perhaps this is why they don't appear to have contributed directly to error prediction and control efforts.

Besides these publications, some other authors have identified and listed factors that contributed to human error on various occasions. These are reviewed later in section 2.4.

2.1.2 A taxonomy of design errors

There is no universally accepted taxonomy of human error or of design error. Errors are often described in terms of various parameters related to cause and consequence - when, who, how, in which activity etc. Reason (1990) distinguishes three levels at which a classification of errors may be attempted: the behavioural (what was

CHAPTER TWO

LITERATURE REVIEW

In this chapter previous publications relevant to this study are reviewed. Using theories of cognitive processes as a basis, design errors are categorized into six distinct types. Previous attempts at modelling human error from the reliability and quality perspectives are described, and the soft systems approach is presented as an alternative perspective. The chapter ends with a discussion of basic principles in the systems approach and a description of how these have been applied in a few failure studies.

2.1 THE CLASSIFICATION OF DESIGN ERRORS

2.1.1 Previous work on error causation

There are few reports in the technical literature of previous attempts to propose a detailed explanation of how structural design errors occur. Ingles (1979) discussed the reasons for human error at the level of the individual, and divides them into physiological problems, psychological causes and philosophical factors. Physiological problems relate to the sensory organs and psychological relate to attitude, knowledge and temperament.

with reasonable care. *Acceptable* practice rather than *accepted* practice, is the guiding criterion.

Design errors can now be defined in terms of human error. For my purpose, **structural design errors are human errors during the design process - from the briefing of the structural designer(s) to the final handover of all structural drawings and schedules, including all clarifications and changes.**

1.6 THE LAYOUT OF THE OTHER CHAPTERS

Chapter two is the literature review. A taxonomy of design errors is presented, and the traditional approaches to error prediction and control mentioned in 1.1 are reviewed. Justification is given for the systems approach adopted here. In the final part of the chapter, the basic principles of the systems approach are described and a paradigm is elaborated for the rest of the study.

Chapter three describes the methodology in detail. Problems encountered in the elicitation of expert opinions are discussed at length, and reasons are given for the approach adopted. Each technique used in analysis is described, i.e. cognitive mapping, grounded theory, system dynamics and SSM. The chapter ends with a discussion of the merits of the chosen methodology.

Chapter four describes the design error theory I developed from expert data. The cognitive maps are presented in the context of the studied consulting firm, and then developed into a theory of how design errors occur. This is the main outcome of the study. Chapter five demonstrates how the theory can be used for error prediction and control, with illustrative error prediction and error control models. In chapter six I discuss the benefits and limitations of the theory and explain how it is to be interpreted. The results are summarized and the study concluded in chapter seven.

practice). His definition includes the second and third elements required for an adequate definition of human error, but lacks an explicit measure of performance.

Stewart and Melchers (1989) referred to human error as a departure from 'commonly accepted professional practice'. Though deficient in other respects, this definition introduces a useful idea - the judgement of a competent professional. This is a workable measure of performance, and as they point out, it is the measure used in law courts in most countries.

Psychology also contributes an additional and important aspect. Errors arise only in intentional behaviour (e.g. Reason 1990), i.e. the prior intention of the individual is itself a performance boundary. Hence, an error involves a deviation from prior intention.

It is now possible to propose a composite definition that incorporates the three fundamental elements. For this study, I define human error as **the departure of an individual (or group of individuals), both from his (or their) prior intention and from acceptable practice as judged by competent professionals.** The measures of performance are the individual's understanding of his/her intentions, and the judgement of his/her peers - competent professionals. The boundary defining error is the union of 'what was intended' with 'acceptable practice'.

In this definition human error may be large (gross) or small. It may be inadvertent or a deliberate risk. A mistake in the design process that does not compromise the performance of the structure (cost, structural response, aesthetics, maintainability, safety etc.), would not be an error. Though this might be a departure from intention, it would still be acceptable practice. Therefore an innovation would not be an error. Conversely, an act of sabotage would not be an error as it is not a departure from prior intention. Finally, a deficiency in the theory or in the state-of-the-art is not human error in this study, provided the individual has proceeded with due care. This is the legal viewpoint in most countries. An engineer who is acting within code provisions, yet is stretching the theory beyond previous boundaries, must proceed

In this study I have chosen the term 'human error'. This will refer to all errors that are a *direct* result of deviations from human intention. Random statistical errors are not included. For example, the removal of insignificant remaining errors in a numerical analysis may require excessive computation time, and so would be an error. However, it would also be an error to neglect significant remaining errors that could easily be removed. Both cases involve errors of judgement, which are not random in themselves. The term 'human error' here includes gross error if gross is taken to mean 'large' - referring to the size or the *effect* of the error.

In selecting a definition for human error a suitable starting point is a functional definition in the Systems & Control Encyclopaedia (19 which reads *"an event or count of events of a performance vector being outside some specified boundary."* This general definition suggests that the following elements are essential for a good definition. (1) A measure of performance, and (2) a specified boundary for proper performance. In addition the aspect of direct human intervention can be considered a third element.

Melchers et al. (1983), define a human error as *"an error of concept, of calculation, of design, of construction, or of maintenance which gives rise to a gross misunderstanding of how a structure will behave at some or all stages of its life, or how it would behave under hypothetical loads of different magnitudes."* The measure of performance here is the extent of understanding (or misunderstanding) of the structure's behaviour - presumably by the person committing the error. However, there is no explicit boundary of performance, though one is implied by the word 'gross'.

A widely accepted definition is given in Nowak (1992) who defined human error as. *"a manmade[1] departure from acceptable practice."* Nowak makes an important distinction between acceptable practice and accepted practice. The latter term would imply for example that innovations are errors (since these could differ from accepted

[1] The term 'man' refers to the human race, rather than to gender.

To illustrate how the theory could be used for error prediction, I modelled the systemic factors in the theory with a Systems Dynamics software called STELLA. The relationships in the theory were quantified using inductive choices[2]. A model was obtained that demonstrates how systemic changes may be simulated to generate changes in some index of error likelihood.

Finally, from the insights generated by the theory, I developed illustrative models of systems for the prevention and detection of design errors in conceptualising. This was accomplished using the Soft Systems Methodology (SSM). The models address the question of *what* is required in error control (not the *how* of individual techniques), thus providing a framework for system control.

1.5 A DEFINITION OF HUMAN ERROR

This study is concerned with errors in structural design. But what is human error? The term means different things to different people and the terminology is confused. Some authors refer to 'human error', others to 'gross error', and yet others to 'gross human error'. Melchers et al. (1983) pointed out that defective human behaviour is at the root of all errors; and gross bears the connotation of large, which is not necessarily what is meant. Madsen et al. (1986) distinguished between gross errors and random errors, describing random errors as purely statistical. Thus, the remaining errors after numerical analysis are an example of random errors. Madsen et al. then explained human error as the combination of gross and random errors. The difficulty with this is that their random errors are not altogether errors - in the sense that they are expected, accepted and catered for. Random errors are amenable to statistical treatment whereas other errors are not.

[2]Rather than parameter estimation as in classical statistics.

- To illustrate how this theory can be used for error prediction modelling from systemic considerations.
- To illustrate how this theory can lead to systematic specification of error control schemes.

1.4 THE METHODOLOGY EMPLOYED

To establish the impact of systemic factors on design errors I reviewed the literature on human error and structural failures. All the factors implicated in the literature as contributing to human error in previous incidents were identified. It was then possible to show the systemic nature of each factor.

To develop a theory of how design errors occur, interviews were conducted with four persons who work together as a design team in a firm of consulting engineers. The interviews provided expert opinions on how systemic factors lead to design errors in a particular setting - that of their own firm, and similar firms in their experience. A cognitive map of the opinions and experience of each person was developed during my interviews with him. These cognitive maps became the basis for a theory linking systemic factors to human error.

Using coding techniques from the Grounded Theory method, I identified key categories in the maps and isolated the concepts belonging to each category. It was then possible to differentiate the roles of concepts in a given group, as required in the grounded theory method. A taxonomy of design errors was established from a consideration of fundamental cognitive processes, and related to the theory[1].

[1] The theory developed is specific to the firm from which the experts were drawn, but it would be of relevance to other firms in areas where their characteristics coincide, and in the underlying principles

The systems approach seems to hold some promise as a means of tackling the prediction and control problems of human error. In this dissertation, I have applied the systems approach to human error to develop a theory of how design errors occur. At present, there are no reports in the technical literature of an existing theory of this sort. Yet it seems apparent to me that efforts at error prediction and control should rather be based on some clearly stated and coherent theory of error causation. The emphasis here is on design errors as these are marginally more frequent than construction errors (table 1.1).

1.2 THE PROBLEM

The central problem in this dissertation is the formulation of a theory of how human error is caused to occur in the structural design process. This theory must be systemic in perspective (i.e. based on a consideration of systems in the structural design process), and should definitely enhance the activities of design error prediction and control, beyond present approaches to these activities.

1.3 OBJECTIVES OF THE STUDY

To tackle this problem I adopted the following objectives.

- To show that systemic factors dominate the occurrence of design errors. This would imply that design errors are the result of systemic weaknesses, and so *should* be modelled in terms of systemic factors. It would not mean that *only* systemic factors affect design errors.
- To establish a theory of how systemic factors in a particular setting will initiate and affect the occurrence of design errors.

The importance of human error became conspicuous in the seventies. Since then various research and regulatory efforts have focused on this issue, and their efforts have been in two broad groups. The reliability-oriented group has emphasised modelling human error to allow error prediction, so that human error can be included in structural reliability calculations. A second management-oriented group emphasises the control of human error to ensure good quality structures.

Table 1.1 - Results from an analysis of 800 structural failures

		Percentage
MAIN CAUSES OF FAILURE	Human error	75
	Accepted risk	25
ACTIVITIES WHERE ERRORS OCCURRED	Planning & design	39
	Execution	37
	Planning, design & execution	19
	Use	5
ERRORS IN PLANNING AND DESIGN	Concept of structure	36
	Analysis and dimensioning	36
	Drawings, lists etc.	19
	Preparation for execution	9

Source: Adapted from Matousek (1977)

The study of human error is closely linked to the study of failures, so that these two styles of human error studies above have counterparts in failure studies. In recent years a new category of failure study has emerged. Researchers perceive structural failures as manifestations of a weakness in the institutional or/and organisational systems used on the project. They therefore adopt a holistic view in these systemic studies. Human activity is considered explicitly (human activity systems), and so organisational procedures and practices are included.

CHAPTER ONE

INTRODUCTION

1.1 PREAMBLE

The phrase human error loosely refers to deficient behaviour or decisions, by persons involved .. the planning, execution or use of a structure. As such, it has become a catchall description for all kinds of negligence, mistakes, and carelessness. This dissertation investigates a particular aspect of human error - errors in the design phase.

Human error has been identified as the single most important cause of modern-day structural failures. One study of 800 failures in Europe concluded that 75% of the failures (90% by cost), were due to human error. The other 25% were designated as 'accepted risks'. (Matousek, 1977). Of those failures due to human error, 39% were during planning and design. Table 1.1 on the next page, is a summary of Matousek's data. In the lower part, there is a breakdown of the errors during planning and design, into work tasks.

A more recent study of 500 case histories (Sowers, 1991), concluded that 73% of the studied failures were due to human shortcomings - ignorance of prevailing knowledge, or failure to use prevailing knowledge. A mere 27% were attributed to conditions beyond prevailing knowledge. Other published studies such as Walker (1981) and Fraczek (1979), are in conformity with the conclusions of Matousek and Sowers.

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evolving notions of quality. Initially, quality issues focused on the performance of the final product. Quality Control (QC) as it was known, employed statistical techniques to detect significant deviations in the end product, from the norm. A major drawback in this approach was the need to scrap already made defective products. (Eg. it is costly to allow errors to manifest as constructed defects before they are detected and corrected).

Quality Assurance (QA) shifts emphasis away from inspections to systematic procedures. Besides incorporating the techniques of QC this normally requires in addition, the establishment of a management system specifically to supervise quality implications at each step in the production process.

Total Quality Management (TQM) takes a broader view than the first two. In TQM, quality is defined as meeting the *expectations* of the customer, where the concept of the internal customer applies. That is, each stage in the production process becomes customer to the previous stage. In addition, TQM emphasises leadership above procedures. So there is the deliberate cultivation of a quality-consciousness in all cadres, through discussion and a continual improvement process.

2.3.2 Design error control in the quality paradigm

The models used in many consulting firms for error control, tend towards the QC and QA philosophies. At the institutional level, efforts have been made to prescribe a method of approach to design that will ensure high quality work. The best known of these is the International Organization for Standardization document, ISO 9001 (1994). This is a QA model for design/development, production, installation and servicing, and is applicable to a wide range of manufacturing activities. The ASCE Quality manual (ASCE, 1990) is an example of an institutional error control model (QA) that is specific to structural engineering.

Since statistical data is scarce, such a theory must be based on expert opinions. This cannot be developed in the frequentist probability paradigm, but requires an approach that is more suited to subjectivity.

2.3 PREVIOUS STUDIES OF ERROR AS A QUALITY ISSUE

2.3.1 Quality as a concept

Even when human error does not cause structural failure it could still lead to a reduction in quality. What constitutes acceptable quality is not easy to define. If quality is described as meeting the customer's expectations, that implies a different quality standard for a rural agricultural shed, than for say an urban corporation headquarters. Codes apply different factors of safety for differing structural types, but this is not quite the same thing. Different quality standards imply different levels of workmanship, checking, quality systems etc. In practice, professionals do tend to tailor their efforts to match a perceived level of client requirements (perhaps guided by their fees). However, this is rarely done systematically vis-a-vis quality. If a client's brief called for a design at a certain level of quality and the engineer provided a lower level, few professionals would deny that an error was made. This might not lead to structural failure, but would be a quality defect. Such defects typically manifest as cost and time overruns, structural and aesthetic defects, nagging maintenance problems and a dissatisfied client. Hence, a dull, unimaginative design could be structurally sound, and yet have defective quality.

The emphasis in the quality perspective of human error, has been the practical management of the error risk at the organisational level. The Quality concept has evolved over time, and various models for quality (error) control have appeared with to various causes may then be modelled as fuzzy sets. These are used to assess the proneness to failure.

There are two important contributions in Blockley's work that are of relevance here. It was the first attempt to account for organisational and institutional factors in an error prediction model. It was also one of the earliest attempts to formalize the use of engineering judgement.

The work on fuzzy models was then criticized on two counts. Ditlevsen (1980) pointed out inconsistencies in the algebra of fuzzy sets used by Blockley and went on to emphasize the lack of globally accepted rules in the then fledgling field of fuzzy logic. Ditlevsen (1983) also declared that it was neither necessary nor possible to combine a fuzzy measure of the probability of failure due to 'gross' errors (p_{gt}), with the theoretical probability of failure from random variations only (p_{th}).

The criticism of fuzzy algebra is no longer as valid now as it was then, as much progress has been made in that field. However, one abiding weakness of the fuzzy models lies in the fact that the choice of which climatological factors to use, is not systematic. Moreover, inter-relations between factors are ignored. The use of fuzzy algebra does provide a way to manipulate expert opinions, but it does not on its own provide a framework for a systematic and holistic consideration. Though useful, the sophisticated fuzzy logic is not essential to the elicitation and manipulation of expert opinions.

The most serious problem encountered in probabilistic error prediction is the lack of suitable statistical data from which to extrapolate. Researchers such as Stewart circumvented this by using expert judgements. However, the probabilistic models of Stewart, Melchers, Steinberg etc. still ignore causation. The older fuzzy models of Blockley and Brown incorporate causation indirectly from system-related issues, also from expert assessments. However, this is not done systematically. There is a need for a coherent theory of causation of errors, to enable a systematic approach to error prediction. For this theory to be coherent and valid it must be holistic and systemic.

2.2.3 Fuzzy models

The theory of fuzzy sets has been applied to the problem of predicting the probability of structural failure from human error. Leading contributors in this area are Professor Blockley at Bristol University, England and Professor Brown at the University of Washington in the United States.

Blockley built upon earlier work by Pugsley on the influence of the 'engineering climatology'. Pugsley (1969) suggested that structural failures are often the result of the financial, industrial, scientific, political and professional 'climates' surrounding a project. Pugsley (1973) then suggested that expert opinions be used to assess each factor, to obtain a prediction of the 'proneness to failure' for a structure. Blockley proceeded from the assumption that it would be more accurate for an expert to give such an assessment in linguistic terms (plain English phrases), than with single numerical values. A numerical value would be precise, but therefore less likely to be accurate: a linguistic assessment would be vague, involving a range. A linguistic assessment, say of the political climate as 'very poor', could then be replaced by a fuzzy set. Fuzzy logic could subsequently be used to manipulate the variables as required.

Blockley (1975) described the theory of fuzzy sets and how it could be applied to structural failure. In Blockley (1977), the method was applied to twenty three case histories of failures, to assess the 'inevitability' of each case. At that point, twenty-five variables were considered. The proneness to failure of each project was then calculated as the weighted average of the fuzzy sets, with each weight itself being a fuzzy set. In Blockley (1981), catastrophe theory techniques were incorporated to apply the method to ongoing projects

The work by Brown differs from Blockley's most significantly in the introduction of the 'surprise' concept. In Brown (1979), surprise is used as a dividing line between random variations which are expected and should cause no surprise, and errors which are unexpected and lead to surprise. Linguistic assessments of surprise at failure due where

P_{safe} = probability of a member design being judged safe,

Re = percentage resistance error,

f(z,v) = probability distribution function for the t distribution,

and v, z are constants.

Steinberg (1994) has also used undergraduate exam data to estimate failure probabilities.

In other models proposed by Stewart (Stewart, 1990,1993), typical design and construction tasks are divided into small micro-tasks that are then linked in an event tree. Experts are interviewed to obtain distributions of error frequencies/consequences for each micro-task. A distribution for the entire task is then obtained via Monte Carlo simulation. This was done for steel beam design, concrete beam design and concrete beam construction.

Within the third theme area, Nowak researched the use of sensitivity analyses in identifying consequential errors (see Nowak and Tabsh 1988).

The availability of raw data on error probabilities is a problem in all the models. The need for large quantities of data is due in part to the general nature of these models. The researchers try to describe all errors directly, without reference to error causative mechanisms or context. In the recent models based on expert opinion, the experts still provide error frequencies and probabilities directly, again without reference to causes and context.

In some cases, this may be because the researchers sought to enhance the validity of their models by involving large numbers of experts. Hence, their investigations were necessarily 'shallow' behavioural descriptions, rather than 'deep' contextual theories (see 2.1.2). Such investigations are more typical of the frequentist statistics school (where a probability is conceived as the frequency of occurrence of an event), than of the subjective (probability is a measure of belief) school. The use of expert opinions for probabilities should naturally be rooted in a subjective paradigm.

A basic difficulty in probabilistic models of error is the lack of suitable statistical data for estimating parameters. As explained above, the data gathering efforts such as databanks, have been largely unsuccessful. In the models above therefore, the modellers chose which factors were relevant, and then chose the suitable mathematical model, and also chose the parame   s. Everything was arbitrary - based on the intuition of that one individual.

A recent trend in probabilistic modelling, is rather to use several expert judgements for one or more of the three choices. Stewart and Melchers approached the problem of checking by trying to generate empirical data on error detection rates. (See Stewart and Melchers 1989, Melchers 1989). In their study, they obtained data on self-checks from examination scripts for undergraduates. They also conducted a survey of practising engineers, asking them to check typical design tasks. The experimental conditions bore little semblance to reality, but they proposed tentative models based on those results they obtained. They suggested a Type I extreme value distribution for self-checking, a modified t distribution for overview checking, and an S shaped learning curve for independent design checks. This last was informed oy the theory of learning in Educational Psychology. The models for independent and overview checks are presented as Equations 2 and 3 below.

$$\overline{P_{ind}}(t) = \frac{1}{1 + A\exp(-Bt^{\frac{1}{2}})} \qquad \textit{Eqn 2}$$

where P_{ind} is the average checking efficiency, and depends on checking time t in minutes. They obtained a good fit by setting the constants A and B to 376.4 and 1.436 respectively.

$$\overline{P_{safe}}(Re) = 1 + \frac{\delta}{2} + \int_{z}^{0} \delta f(z,v)dz \qquad Re < \bar{x} \qquad \textit{Eqn 3a}$$

$$\overline{P_{safe}}(Re) = 1 - \frac{\delta}{2} + \int_{0}^{z} \delta f(z,v)dz \qquad Re \geq \bar{x} \qquad \textit{Eqn 3b}$$

has not been very forthcoming and data paucity means statistics cannot be inferred. A second problem is that the data obtained is highly summarized, the classifications being behavioural.

2.2.2 Probabilistic modelling

The classical probabilistic models focus mostly on design errors, along the lines of three overlapping themes. The first theme is the prediction of error rates by considering the mechanism of occurrence. A second theme is the prediction of error reduction by checking. The third, which is linked to the first, is the estimating of a probability of failure, given the occurrence of an error.

From the first theme, early examples are found in Kupfer and Rackwitz (1980), and Nessim and Jordaan (1983). These both assumed design errors to be random events occurring at a given rate over a time interval. This led to a Poisson formulation for predicting error occurrence. In the second theme, Nowak and Lind (1986), describe a checking model by Nessim that uses Bayes' theorem: updating prior distributions for error, as errors are detected. Lind (1983) also proposed an error elimination model which assumes a uniform or normal distribution for initial error, and a detection probability expressed as a function of both inspection time and initial error magnitude.

$$P_E(t) = \left(1+\frac{t}{t_0}\right)^{-\frac{1}{2}} = (1+99t)^{-\frac{1}{2}} \qquad \textit{Eqn 1}$$

Equation 1 shows the final form of Lind's exponential model, where

$P_E(t)$ probability of error, and

t inspection time.

Lind chose $P_E(1)$ as equal to 0.1 so that a unit of inspection brings the error probability from 100% to 10%.

(5) Design errors predominate in areas requiring close attention to detail, e.g. connections and joints. Many of these are undetected until during usage when they become serviceability problems, sometimes leading to distress.

(6) Construction errors usually manifest or are detected in the construction phase. About half the undetected construction errors result in collapse or distress.

(7) Design errors are far more costly in terms of structure damage and equipment damage, but construction errors frequently lead to higher levels of fatality and injury.

(8) Relatively speaking, few user errors result in failure.

(9) Usually the errors could have been detected if someone had done something, just a little bit differently. They were not inevitable.

Efforts have been made in some countries to establish public data-banks on structural failure and related issues, which should obviously include human error. In the United States, there is the Architecture and Engineering Performance Information Centre (AEPIC), housed at the University of Baltimore. The U.K. has a similar initiative - the Construction Performance Centre located partly at UMIST and partly at the University of Strathclyde. Neither of these appears to have made any significant impact. A more successful venture, is the Système de Collecte d'informations sur les Desordres (Sycodes) in France, which is reported (CIB-W86 1992) to contain information on over 50,000 cases. There are also reports of data-banks in Finland, Belgium and the Netherlands. Kaplan (1987) described his own unsuccessful attempt to establish a failure data-bank here in South Africa.

Except for Sycodes, the public data-banks have not been successful. Their databases are small and superficial in detail. This is largely a consequence of their mode of operation. AEPIC for example, relies on voluntary information from design professionals about failures with which they are involved. For obvious reasons this

Failure surveys have also tended to generate data on errors, because of the high impact of errors on failures. Some notable failure surveys that contributed information on human error are published in Matousek (1979), Hauser (1979), Walker (1981) and Hadipriono (1985). The information from such surveys has also been of limited use in establishing detailed statistics; for much the same reasons as the ACI survey. A critical study of these authors reveals an additional complication. Their data cannot be compared easily, because of differences in terminology and taxonomy. They rarely state their assumptions and definitions clearly, and the criteria used in arriving at conclusions often appear subjective. However, these efforts have each contributed some insights into the roles of human error in structural failure. The following summary of such insights is from Matousek (1977), Fraczek (1979), Hauser (1979), Walker (1981), Hadipriono (1985), Fitzsimons (1986), Ellingwood (1987), Brown & Yin (1988) and Sowers(1991).

(1) Practically every completed project involves human errors, but not all these will contribute to failure. Moreover, the contribution to failure (structurally) of an error is not necessarily related to its visibility or 'magnitude'.

(2) Many of the errors that affect structural behaviour significantly will actually be built into the structure and lead to a problem before they are detected, i.e. many errors get through the checking process. There is a need to be cautious about this observation though. As Fraczek points out, the errors that were detected before construction are easily forgotten.

(3) A significant proportion of structural failures have been caused by human error in recent years, compared with failures due to overloading or to ignorance in the theory. Failures are often initiated by multiple errors.

(4) The design and construction phases roughly account for about the same total number of errors.

2.2 PREVIOUS STUDIES OF ERROR FROM A RELIABILITY PERSPECTIVE

Structural reliability is concerned with the prediction of failure ; .obabilities, i.e. the probability that a structure attains a limit state. This probability is known to be strongly affected by human error, and some researchers in this field have sought to investigate this effect. Their efforts may be put into three categories - data collection exercises, probabilistic models and fuzzy models. It will be shown here that the reliability approach to human error has been strongly statistical as is much of reliability theory. Little attention has been given to systemic error causes, or indeed to any sort of error causes. The statistical approach has been further hampered by a lack of statistical data.

2.2.1 Data collection exercises

Data collection exercises provide statistics for probabilistic modelling. Such exercises include error or failure surveys, and public and private failure data-banks. There is only one large scale survey of human errors reported in Structural Engineering literature to date. Fraczek (1979) reported a survey conducted by the American Concrete Institute on errors in concrete structures. The study covered Canada, the United States and Mexico, with most responses from Canada and a few from Mexico. Unfortunately, this survey was unable to establish detailed statistics. This was partly because of reported ambiguities in the phrasing of some questions. A more fundamental problem though was probably the additional cost of extending the questionnaire to include detailed questions: a cost associated first with a bulkier document, and secondly with a reduced percentage response. The lower the response, the greater the number of questionnaires that must be distributed.

an individual is solving problems from first principles. This type arises either because the individual's mental model of the problem is incomplete/inaccurate (lack of information), or else because of the bounded rationality phenomenon. This phrase 'bounded rationality' refers to the inability of man to focus simultaneously on all aspects of a normal-sized real-life problem. Rather, an individual selects what he/she considers important in the problem, and concentrates on these - a sort of sub-optimality. Further details of Reason's theory are given in Appendix A.

There are weaknesses in Nowak & Carr's classification from the perspective of this study. Not all 'errors of intention' qualify as errors by the definition adopted here. Moreover, one cannot establish a correspondence between their error categories and structural design tasks, as would be desirable. Reason's taxonomy is more suitable in this respect, with its natural division into planning and execution/storage phases. I have therefore chosen Reason's classes of cognition-generated errors as a basis for this taxonomy of structural design errors.

From a consideration of cognition in design activities, I have adopted the following categories for design errors.

(1) Knowledge-based mistakes in conceptualising (Type I).
(2) Rule-based mistakes in conceptualising (Type II).
(3) Rule-based mistakes in computation (Type III).
(4) Calculation [illegible] lapses (Type IV).
(5) Rule-based dra[illegible]g mistakes (Type V) &
(6) Draughting slips (Type VI).

The first two types of design error occur in conceptualising. They differ from the others in that they not sequential but mutually exclusive i.e., one is either using knowledge-based reasoning for structure characterization, or else he/she is using rule-based reasoning. The second two types belong to member-sizing activity, and the last two error types take place in draughting.

In the field of Psychology, Reason (1990) also proposed a classification of human error from a consideration of the underlying cognitive processes. Errors are divided into mistakes on one hand, and slips and lapses on the other. Mistakes are errors where the actions of an individual are carried out according to plan, but the plan is inadequate. Slips and lapses are errors in which the actions do not match the intentions of the individual. A slip differs from a lapse in that slips refer to obvious external actions, while lapses refer to failures of memory (intended actions that are forgotten) that do not necessarily manifest outwardly. Both slips and lapses take place either during the execution phase (when a planned activity is being executed), or in the storage phase (when the plan is stored in the memory before being executed). Both slips and lapses result from insufficient attention (or sometimes too much attention), during largely automatic 'skill-based tasks'. This is illustrated in Figure 2.1.

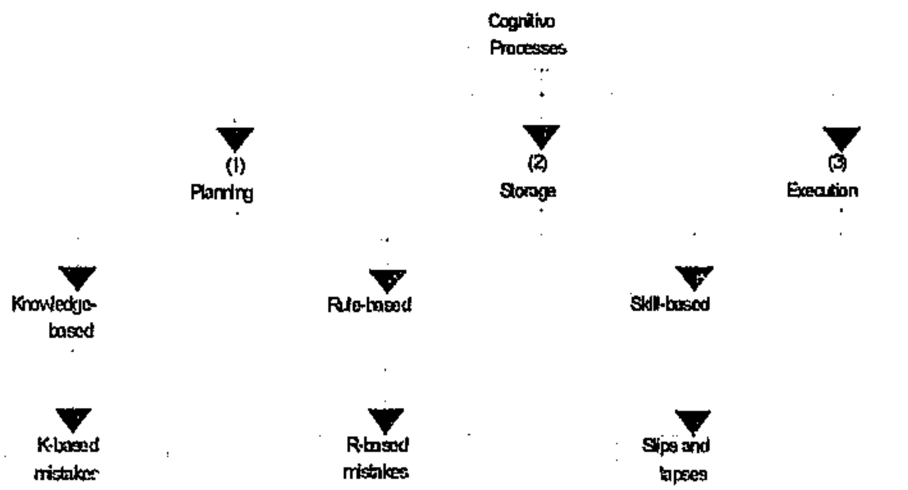

Figure 2.1 - Relationship between cognition and Reason's error categories

Mistakes take place in the planning phase itself and are of two types. Rule-based mistakes occur when an individual is trying to solve a problem, by applying known rules of the sort 'if <observed situation>, then <likely solution>'. The mistake could result from the use of a good rule applied to the wrong situation, or the use of a bad rule. The other type of mistake is the knowledge-based mistake, which occurs when

CHAPTER THREE

METHODOLOGY

This chapter gives the details of how the study was conducted. The first section is an overview of the steps followed to achieve the study objectives, and the techniques used for each step. In the second section, the various techniques used for data collection, theory development, error prediction modelling and error control modelling, are all described. Problems encountered in the collection of expert data are recounted in detail.

3.1 THE DESIGN OF THE STUDY: AN OVERVIEW

The main objective of this methodology is to enable the development of a causation theory for design errors. Methodologically, the first issue to be resolved is the level of detail required in the theory to be developed. This dictates the level(s) at which soft systems will be investigated in the study. In making this choice the following observations are relevant.

(1) Individual consulting practices can react faster to recommendations from this study, than say professional regulatory bodies. Error control schemes for example are traditionally implemented by individual firms, rather than being institutionally imposed.

Here in South Africa, Kaplan (1987) described a systemic study of data from a survey of timber roof failures, under the auspices of the National Timber Research Institute (NTRI). The survey involved a detailed study of some 47 roof failures from about 1964 to 1977, and was based on records kept by NTRI, as well as discussions with the failure investigators. The systemic study identified a causative factor in the wide-spread adoption of pre-fabricated timber trusses for roofs, which took place in South Africa in the early sixties. This was then linked to the roof failures of the seventies, and thus created a new understanding of industry practices. It later contributed to the decision to develop a local code of practice for timber.

More recently, Kaplan has applied systems methods to structural failure studies in the United States. Kaplan (1990) described a study he conducted for the Design Professionals Insurance Company, and the Structural Engineers Risk Management Council (SERMC) insurance program. The SERMC program maintains claim files on projects that led to large losses. Kaplan made a study of this data and derived a textual database, which was used to identify scenarios of common characteristics in the failures. This information was used to define loss prevention (error reduction and control) programs fo the structural engineering practices.

The methodology I have adopted in this dissertation is based on the soft systems paradigm. It borrows something from each of these previous failure studies, and builds on them. This methodology is presented in the next chapter.

soft analyst must continually remember that he/she defined the system for a particular purpose. The system is as suitable as it is relevant to the purpose.

(10) The definition of system boundaries becomes the analyst's way of separating between the given aspects of a situation (the environment), and those that may be manipulated in the analysis. Hence, the explicit questioning of 'givens' is standard for the soft paradigm.

2.5.2 Systemic studies of structural failure and human error

The literature reveals little evidence of systemic studies on human error. Pidgeon et al (1987) described a research program at Bristol using the systems approach, that is based on the initial work by Blockley. Their 'system characteristic model' approach relies on case studies of failures, to establish accident - cause sequences. Their goal is to establish a knowledge base of all possible safety hazards[5], to allow the systematic detection of 'incubating' hazards. Their case studies rely heavily on interviews of the various parties involved in a failure (Pidgeon et al. 1986; 1988). As such they have had to give attention to the difficulties associated with the analysis of expert opinions, and introduced the use of grounded theory (Pidgeon et al., 1991).

Dias (1994) too has applied systems thinking to case studies of structural failures, also basing his work on Blockley's. Dias considered a system for structural design that includes relevant principles in the theory of structures, the model assumptions, margins of safety and the underlying design philosophy. This system is known as the Calculation Procedural Model. Dias' examination of this system, identified weaknesses in the design philosophy that were at the root of the failures.

[5] A hazard here refers to 'a set of preconditions for failure, where failure relates to physical integrity and human safety'.

experience. One does not labour with soft systems to establish the 'real state of affairs', but rather the 'real experience' of the individuals. This implies that all viewpoints are legitimate - even 'hidden' agendas.

(2) In a given situation the individuals will hold certain perceptions in common. Hence, though there is no objective reality as such, there is an 'inter-subjective reality' which can be established.

(3) Given the vagueness of soft problems, it is wiser to think in terms of a problem situation (one in which there is unease), than of a problem. It would also be wiser to refer to problem mitigation and dissolving problem situations, rather than problem solution. Given the nature of soft situations, solutions that satisfy all the goals are unlikely. Problem dissolution refers to the fact that certain problems cease to be problems, because of changes in other areas.

(4) The political and social contexts of a problem situation are catered for explicitly.

(5) The nature of the investigator's own intervention and its effect in distorting the problem situation, must not be overlooked.

(6) Different perceptions of the problem situation must be catered for in analysis.

(7) The meanings to be attributed to data are things to be negotiated with problem participants, rather than imposed by the 'objective bystander' analyst.

(8) Accommodation of different perceptions is more important than consensus.

(9) The hard systems thinker refers to systems as though they really existed outside his imagination. (The everyday use of the word reinforces this impression, e.g. we are used to talking about 'the educational system'). The

readily admit to (it is often considered improper to take decisions for personal reasons). Nevertheless, these are of importance (Eden et al, 1983).

(4) The political and social context of the system will affect the information available to the person investigating it.

(5) Each individual in the system will react to the investigator's presence and recommendations. Such reactions depend partly on the social and political context, but may also depend on the individual's perception of the investigator's intervention. That is, the individual attributes meaning to the investigator's actions.

(6) The boundaries of what could constitute the system of interest and what should be the environment are often not obvious. (This may be the consequence of a lack of clear, unambiguous goals).

(7) In addition to all the above, soft problems have the usual characteristics of complexity that are common to problems in the systems approach.

The risk factors of table 2.1 in the previous section show that design errors are closely related to human activity. Hence, the design error problem is soft in nature, and we can expect to meet with most of these traits characterising soft problems in the study. These peculiar characteristics of soft problems have led to a different perception of problems, and the problem-solving process. In the analysis and specification of soft systems, a paradigm framework has evolved over the years (Checkland, 1981; Eden et al, 1983; Wilson, 1984; Checkland & Scholes, 1990). This may be summarized as follows.

(1) For soft systems *subjectivity is accepted as normal* - something to be handled in an adequate manner rather than avoided. Human relationships are tied to the perceptions of the individuals involved, and these may differ significantly. Hence, there is no 'objective reality' outside of what these individuals

goal. Such control is enabled by the fact of communication between the component parts of the system.

Since some properties are only emergent at particular levels of resolution, the control of system properties is linked to resolution levels. This means that control is also hierarchical, with different control units at different levels of resolution. For each controlling unit, the ranges of desirable behaviour are set by the controlling unit on the higher level. The fact that a system has a particular desired range for its state variables makes it exhibit teleonomic or goal-seeking behaviour i.e. the system behaves *as if* it existed to fulfil a particular purpose. For example, organisations exhibit adaptive behaviour as they respond to market forces, government policy etc. The study of adaptive behaviour in organisations (particularly the maintenance of dynamic equilibrium with the environment - homeostasis) is carried out in the field known as System Dynamics (Coyle, 1977; Flood & Carson, 1988).

Of particular relevance to this study is the class of systems known as 'soft' systems. These differ from 'hard' systems in that they tend to be ill-defined in terms of their boundaries and/or objectives (multiple and contradictory). Systems including human relationships are referred to as human activity systems. Such systems will always be ill-defined, as different people in relationship often perceive and interpret that relationship differently. The characteristic traits of soft problems, can be summarized as below.

(1) The system of interest will contain human elements, such that some aspects of the problem can only be expressed subjectively by the humans involved.

(2) The people in the system have different perceptions of their situation. One or more persons will have a sense of unease about the situation.

(3) The goals of many people in the system will be vague, and often contradictory. People have personal 'illegitimate' goals which they may not

2.5 THE SYSTEMS APPROACH

2.5.1 Systems thinking

A group of components or factors may be complexly inter-related, so that the behaviour of the individual components is dictated more by the 'manner of inter-rel. ionships', than by the peculiar characteristics of the component itself. The personal, organisational, institutional and climatological factors influencing design errors, form such a group as we found in the last section. In such cases, the group is best looked at holistically as a system.

There will be aspects of the behaviour of any given factor in the group that result from its innate potential, whereas there are also aspects that result from its position within the system linkages and inter-relationships. The latter aspects are said to be systemic. Systemic issues may dominate the responses of an entire system in cases where the inter-relationships are complex i.e. large numbers of inter-relations or/and very intricate inter-relations. Systems thinking is a manner of approach to such situations, which focuses on general trends rather than particular instances.

A system in this technical sense is an intellectual construct which an observer believes is relevant to the salient aspects of a problem. The observer chooses a portion of the real-world, such that the portions that are not chosen are those expected to have little or no effect on the problem. The boundaries of a system do not really have to conform to observable bounds in the real world. The observer who specifies the system, can specify the boundaries as desired.

The basic behavioural traits common to all systems are emergence, hierarchy, communication and control (Checkland, 1981). 'Well-defined' systems tend to be in hierarchies, such that certain properties are only distinct (emergent) at a particular level in the hierarchy. If a system is 'well-defined', it will exhibit the phenomenon of control - i.e. there will be a deliberate means of aiming the system towards a

Table 2.2(contd) - Relationship between design error risk factors, and typical systems adopted by various parties to the construction process

TYPICAL DESIGN PRACTICE SYSTEMS	Employee selection and training
	Design documentation
	Design checks and reviews
	Employee support du..ng design
	Design supervision and co-ordination
	Design responsibility allocation
	Feedback from users and sites

Each of the risk factors in table 2.1 could occur as a result of systemic weaknesses i.e. one could conceive of a notional 'human activity system', the operation of which would generate or eliminate the risk. This is illustrated by table 2.2 which suggests typical systems for some of the project organisation and institutional risks from table 2.1. I have also listed possible systems in the design practice, that would affect the personal and design practice organisation risks. The nomenclature in table 2.2 is drawn mainly from the ASCE 'Quality' manual. (ASCE, 1990).

The systems approach provides a means of tackling problems with complexly inter-related parts, in a holistic fashion. As the risk factors of table 2.1 are obviously inter-related, this alone would justify the use of the systems approach. Of greater importance however, is the fact that the systems approach includes a 'soft' paradigm which emphasizes human activity systems - thus catering for vagueness and human perception. The soft approach incorporates subjectivity and is more suited to handling expert opinions, than the classical reliability approach. The next section describes the essential features of the systems approach in general, and the soft systems paradigm in particular.

The risk factors of table 2.1 are mostly related to human interaction within the organizational settings of the structural design practice, the project team or the project climatology. Such human interactions may be conceived of as being dictated by 'human activity systems' that are stipulated and controlled by the design practice partners, the project managers and the professional regulatory bodies, respectively.

Table 2.2 - Relationship between design error risk factors, and typical systems adopted by various parties to the construction process

TYPICAL SYSTEMS THAT COULD AFFECT DESIGN ERRORS			
The client	**The architect & other consultants**	**Contractors & fabricators**	**Public, govt. & end users**
Designer selection	Design co-ordination	Submit shop details	Profession regulation
Project finance	Conflict resolution	Contractor design	Research funding
Share responsibility		Fabricator design	Educating owners
Setting goals			
RELEVANT RISK FACTORS			
Inadequate fees	Conflicts of interest	Details not submitted	Damage to neighbour
Poor communication	Architect error	Corrections neglected	Hazardous usage
Design time constraint	Hazardous project	Details missed on site	Unforeseen extension
Financial constraints		Low contractor ability	Inexperienced owners
Undefined usage-goal		New methods/material	Maintenance effect
Limited work scope			Political pressure
Fast track design			Code complexity
Fee bidding			New materials

Table 2.1 - Factors identified in literature as increasing the risk of design errors

Those related to individuals (personal)			
Lack of knowledge		Attitudes and ethics	
(1)	Designer out of depth experiencewise.	(8)	Slipshod work (carefree, untidiness).
(2)	Other engineer doing struct. engrs job.	(9)	Many design checks, thus careless
(3)	Unqualified person doing design task.	(10)	Postponing decisions on design aspect
(4)	Technical decision dictated by client.	(11)	Inadequate attention to detail.
(5)	Contractor ability can't match project.	(12)	Lack of professionalism or ethics.
(6)	Inexperienced users.	(13)	Low pay for design employees.
(7)	Poor training/pay of field inspectors.	(14)	Inadequate fee paid to design firm.
Those related to the organisation of the structural design practice			
Internal communication		Software related	
(15)	Discontinuity in design staff.	(20)	Program assumptions unknown.
(16)	Breaks in design process.	(21)	Analysis program unsuitable.
(17)	Model assumptions not understood.	(22)	Program not updated.
(18)	Inadequate instruction for detailers.		
(19)	Undetected errors in earlier tasks.		
Those related to the organisation of the project			
Contract administration		Communication problems	
(23)	Fee-bidding for designer selection.	(30)	Poor description of client expectation.
(24)	Fast-track contracts.	(31)	Undefined structural goals for usage.
(25)	Contractor/fabricator design.	(32)	Architect design errors or inadequacy.
(26)	Restricted scope of work for designer.	(33)	Shop drawings not corrected.
(27)	Nobody with clear overall authority.	(34)	Poor co-ordination of design firms.
(28)	Inadequate time for design.	(35)	Several design changes/site alterations
(29)	Interest conflicts between design firms		
Those related to institutionally-regulated practices			
Affecting the design process		Affecting project characteristics	
(36)	Traits of nearby structures unknown.	(40)	Production-style construction.
(37)	Unconventional designs	(41)	New materials/construction methods
(38)	Unknowns in design data.	(42)	Complexity of codes & specifications.
(39)	Deliberate departures from code, or design situation not covered by code.	(43)	Incompatibility of criteria for evaluating structural analysis.

2.4 THE NEED FOR SYSTEMIC CONSIDERATIONS

The problems described for error prediction in the reliability paradigm (section 2.2) and for error control in the quality paradigm (2.3), suggest that there is a need for an alternative approach to the study of design errors. The development of a theory of how errors are caused and occur, should be central to any such alternative.

Several publications have identified factors that increased the risk of human error, and possibly contributed to structural failure on different occasions. The following list of such factors relevant to design is compiled from Brown and Yin (1988), Fitzsimons (1986), Fraczek (1979), Hauser (1979), Walker (1981), ASCE (1990) and unpublished papers by S.D. Kaplan. The factors have been grouped loosely into eight categories in table 2.1, using Fitzsimons' classification of error causes (section 2.1.1) as a basis.

As we look through the factors in table 2.1 it is clear that most of these are not technical issues, but rather causative factors that affect the risk of error. These causative risk factors are ignored in most probabilistic models, and addressed only haphazardly in fuzzy models and error control schemes. It is also evident that these factors are not independent. For example, the performance of a design task by an unqualified person may be the result of fee-bidding. The interactions between factors will definitely be significant in some cases.

Most studies are content to simply list factors such as these. What is needed however, is a coherent theory detailing how these factors interact with one another and with design errors, and explaining the circumstances under which each factor or interaction becomes potent. This would enable us to assess the contribution(s) of individual error control measures in a holistic manner, and should lead to a means whereby predictive models can incorporate these fundamental error causes. The difficulty is that the relationships between some of these are vague and complex. Furthermore, human error involves humans, who are capricious and unpredictable.

Typically the techniques specified in error control models are managerial in nature - mostly qualitative, and are implemented in Quality Assurance schemes. Examples are fault and event trees, diagnostic trees, hazard and utilisation scenarios, control scenarios, morphological boxes, matrix charts, checklists, safety plans and control stops. Some of these techniques are described in JCSS (1981) and Schneider (1981). Event trees, scenarios etc. are attempts to systematize what people are already doing intuitively, hopefully to make them more effective. All of these techniques have been used in various fields of endeavour.

New techniques are being proposed or incorporated into error control models. Lutz et al (1990) have described their work on a PC based expert system for design checks. It allows a design reviewer to retrieve information on design review standards for different structural types and products. The Redicheck system (Nigro, 1988), is a technique for error detection, when co-ordinating drawings and specifications from different design disciplines. It emphasises a systematic comparison of salient points in drawings, following a checklist.

The error control scheme adopted in a given firm or on a particular project, will typically include several of the techniques above. In deciding which techniques to use firms develop their own models - guided by such philosophies as QA or TQM. Otherwise, they pattern their models on institutional ones such as ISO 9001 or the ASCE Quality manual. It is usually impracticable and undesirable to simply implement all known error control procedures, or all those in ISO 9001 for example. The suite of techniques chosen for a given project must be coherent, integrated and efficient. The techniques must also be relevant to the environment of the project and the firms involved, as well as being suited to the scale of the job and the time/cost. However, in QA, TQM or even ISO 9001, practitioners are given few guidelines on the relationship between technique and context. Hence, the problem here is one of how and when to choose techniques. These choices can only be made in a systematic manner where there is a theory of how errors occur, to guide the process.

categorisation extends beyond the idea of pigeon-holes into which to drop each fact, to include the relationships between categories and effects over time.

The coding was carried out in two streams. First, working from the cognitive maps towards the design error categories. Secondly, working from the design error categories back to the categories 'emerging' from the interviews and cognitive maps. (The design error categories themselves were in a constant state of flux, as they were refined often). This kind of approach to theory development is known as 'bootstrapping' - lifting oneself up by the bootstraps (see for example Strauss & Corbin, 1990).

There are three phases in the coding. These are usually sequential, but may involve iteration between phases. The phases are :

- Open Coding
- Axial Coding, and
- Selective Coding

Open coding is the process of tentatively identifying concepts within the data and establishing the degree of inter-relatedness between them. This is done by attaching conceptual labels to observed events, and grouping concepts provisionally around some phenomenon. For example, a person may mention "discussing aspects of a problematic design with my colleagues" (description) and I could record this as an example of "information exchange" (concept). In this study, a lot of the initial conceptualisation was carried out in consultation with the respondents, as part of the negotiative process of cognitive mapping. Moreover, the respondents actually specified the immediate and obvious relationships. This greatly simplified the open coding, which otherwise can be very demanding.

Axial coding. In this phase, each category is re-specified in terms of a paradigm model. This first requires the isolation of the central theme in the category. All other concepts can then be related to that theme as either causal conditions, contextual

Grounding theory in data

The Grounded Theory method was used in this study to develop the cognitive maps into a theory of causation for design errors (3.1.1).

The term 'grounded theory' was proposed by Glaser and Strauss (1967), to describe their technique for generating theory out of field data. (See also Strauss & Corbin, 1990). In the social sciences data often comes from unstructured interviews, field observations etc. In topics where there is little existing theory to make sense of data, it is possible for researchers to accidentally develop hypotheses which have no relationship to the facts. On the other hand, a theory is said to be grounded (in data) if it can be shown to have grown directly out of the observations. Such a theory will be characterised by "fit" (i.e faithfulness to observations in real-world), by understanding (it makes sense), and generality (accounts for a high degree of variety). Additionally, a grounded theory lead to the enhancement of control activities - monitoring, feedback etc. - in the studied situation (Strauss and Corbin, 1990).

The word 'theory' as used here requires amplification. A theory is a set of well argued ideas that offer a plausible explanation for a phenomenon. Theory differs from description in that theory explains events and behaviour in terms of concepts, and places the concepts in a relational framework. Description simply recounts the events. Moreover, in grounded theory concepts are arrived at from the interpretation of the data, but also provide feedback and direction for subsequent data collection - so that the data is collected in a systematic manner (Pidgeon et al, 1991). Hence, I was constantly isolating concepts and their relationships, concurrently with the interview process. Wherever concepts lacked clarity, or the respondent drew conclusions without examples, one would note this and question further.

The isolation of concepts and the development of their relational framework is referred to as a 'coding' process. Basically the coding procedures provide a systematic means for categorising otherwise overwhelming masses of data. In coding, The benefits of cognitive mapping are as follows:

- Each cognitive map is in essence, an explicit elucidation of the individual's personal theories on cause and effect, in the situation In short, a model of his experience.

- Problem content and structure are clearly stated. Inter-relationships are seen at a glance.

- It provides a vehicle for the researcher and each respondent to negotiate problem content and structure. They can also negotiate the meaning and relative impact to be attributed to each concept as a part of the problem.

These benefits are simple but powerful. When both parties can see the details of what has been said so far, it helps clarify thinking. Respondents can see where they have said enough and what needs expanding on. The researcher easily detects which areas have been neglected and which are elaborated, and this guides the discussions. The boundaries of the issue become obvious, and it is equally obvious when the respondent has gone outside them. Most importantly, it lends a transparency to the process which is otherwise lacking. Not only can any person see at a glance the information provided (and so ascertain the interview's impartial coverage), the expert respondent can also confirm that he/she has been properly understood. This last possibility is then an additional check on the veracity of the data.

Since the respondent is stating opinions (based on observations), there is no need to withhold embarrassing information. In fact, the visual display forces a discipline on the respondent in explaining his/her ideas. Most respondents will typically back up each link in the map with reference to particular projects, confident that the projects themselves are not included on the map. Finally, the map provides an assurance to the respondent that he/she has been understood, and many lengthy repetitions are thus avoided.

The cognitive map itself is simply a directed graph (di-graph): a network of elements joined with arrows. The elements are phrases describing ideas or concepts (figure 3.1). The map is drawn during unstructured interviews with the respondent, starting with some agreed label describing the problematic issue (design errors in this case). The consequences of the initial issue are explored by questions such as "why does this matter to you"? Similarly, the analyst may explore backwards to investigate the causes of a particular element, by asking questions such as "what reasons come to mind as explanations for this event?" The answers to the questions describe new concepts or lead to new arrows.

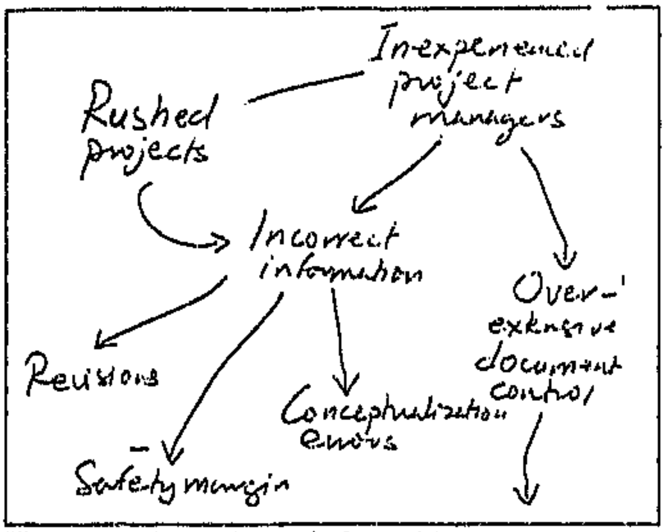

Figure 3.1 - Part of a typical cognitive map

The meaning(s) to be attributed to concepts are "negotiated" by drawing the respondent's attention to conflicting linkages, by constructing hypotheses for elaboration and by requiring him/her to define a term with psychological opposites. The analyst could also construct his/her own model, to merge with the respondent's in a joint session. This becomes a means of testing one's understanding.

The arrows in a cognitive map may carry minus signs. Arrows without signs are used for interactions where the preceding concept enhances the succeeding concept. Minus signs indicate the opposite. Simple lines are used instead of arrows, where concepts appear related, but there is no clear causal belief. These are called connotative links.

next sub-section (3.2.2). Cognitive mapping addresses all the concerns above and is set in the soft paradigm.

Once the details of the data collection were sorted out, a second attempt at expert interviews was initiated. These were the interviews which now form the raw data for this dissertation. I chose a new set of experts to avoid overtasking the patience of Dr de Clerq. Besides, I now needed several people from one firm with simple clear characteristics, and van Wyk & Louw would have been too large and complex. In chapter four (4.1), details are given about this final set of experts and the firm to which they belong, though names are withheld in the interest of confidentiality.

In this second and successful attempt, the data collection was carried out in two parts. In the first part, about twenty unstructured interviews were conducted with the experts over a period of 3 to 4 months. These yielded the primary data of opinions on factors causing design error and their inter-relationships, recorded as the cognitive maps (3.2.2). The second phase of data collection involved a second set of four or five interviews with two particular experts. The second set of interviews provided secondary quantitative information that was used to calibrate the illustrative error prediction model (see 3.1.2 and 5.1 ahead).

3.2.2 Elaborating relationships - Cognitive aps & Grounded theory

<u>The use of Cognitive maps</u>

Most of the information given by the respondents in the interviews was recorded as cognitive maps. The maps were drawn on the spot during interviews and were shown to respondents at intervals. Thus, the maps were both a data collection instrument, and the first step in analysis. A cognitive map is a visual model of a person's beliefs about relationships between concepts. The technique was developed at Bath University (Eden et al, 1983). The description below is a modified version.

than painting a complete picture. The interview process and methodology at that time, had no built-in checks for corroborating the testimony of the experts.

These difficulties led me to the conclusion that a completely unstructured approach should be used. That would prevent the experts being 'led' in particular directions. The difficulties also brought home the need for a new way of looking at the interview process, which was later provided by the soft system paradigm (2.5.1). Instead of dictating the meanings of key concepts to the experts, they chose their own terms. A shared understanding of what each term stood for would then be 'negotiated' with each expert. (The key phrase of 'human error' was the exception to this principle). To prevent people saying things 'for the record', 'raw' answers would not be printed and each person would only be given a chance to look through the conclusions. Each expert was to be informed of all these at the onset.

The soft paradigm emphasizes the context of expertise, and it had been clear that each expert spoke from his own perspective. I therefore decided to choose several experts from a single contextual background - which meant from the same firm in this case. This would also provide a means of double-checking, if it was suspected that someone was speaking 'for the record'.

In adopting completely unstructured interviews, it was realised that some of the problems encountered with semi-structured interviews would be present to a greater degree. It would be difficult to relate the issues, make sense of the ideas and generally analyse the answers. A means would also be required with which to assess the extent of each expert's knowledge, and whether or not the information given had fully exhausted those bounds. One option was the use of a Qualitative Data Analysis (QDA) software to analyse sentences for recurring themes, similarities etc. However, that process can be very tedious even with computer packages, and the software is not presently available in the university. Moreover, the experts had to have the assurance that their answers would not be published verbatim - for the reasons given above. An alternative was provided by Cognitive mapping which is discussed in the of information tended to be overwhelming. The lack of structure made it difficult to relate the ideas, or to make sense of the issues. The effort required in transcribing the tapes was also considerable (eight hours or so per hour of tape). After the first round of expert interviews, I decided the semi-structured answers would be too difficult to analyse.

At this point, I switched to a formal questionnaire with pre-defined answers from which the expert had to choose. Part of this questionnaire is presented in Appendix B. The data from this was easy to understand since answers from different experts would be directly comparable. However, the questions (and contact time) required for a detailed study were too involved, so that after four interviews we had only covered three risk factors in detail. At this point, it was clear that there were fundamental problems that had to be solved in the data collection process, and the interviews were terminated.

There were three major difficulties encountered in that initial attempt at expert interviews. First of all, the pre-defined topics (taken from the literature) tended to lead the experts in particular directions. The topics hindered them from giving free rein to their own inner opinions. When the change was made to the formal questionnaire, it was much worse. Secondly, there was a lot of confusion over concepts. I would mean one thing by a topic, and the expert would assume it meant something else. The expert too would sometimes perceive that he had been misunderstood, and would have to clarify himself. Eventually, the questionnaire had to include long passages defining key concepts. It also had to anticipate every possible situation with different questions, so that the answers would be comparable and exhaustive. All these led to an over-long questionnaire.

The third problem was the most serious. I realised that there would be no means of telling if an expert was simply speaking 'for the record'. In investigating an issue as sensitive as human error, there is a possibility that people [illegible] withhold information to give a good impression of themselves and their organisation, rather

3.2 DETAILS OF THE TECHNIQUES AND METHODS USED

3.2.1 The collection of data

The first data collected was a pilot study with a consulting engineer, Mr A.E. Goldstein. In four sessions of about an hour and a half each, I sought to establish the boundaries of what can be regarded as normal design practice in the South African context. At the end of the interviews, he had described the structural types common in South African practice, the procedures normally adhered to in practical design situations, roles assumed by various parties on construction projects, information and communication patterns and contract types used in South Africa. I followed up these interviews of Mr Goldstein, with a single interview of Mr Bruce of Murray & Roberts, to establish the contractor's normal practice in a similar way.

Before interviewing the chosen respondents, I interviewed Professor Krige and Dr Lunt at CSIR as "dry runs". Both the pilot studies and the dry runs were conducted as semi-structured interviews using only an interview guide - a list of topics to be discussed. This was satisfactory at that point, but later proved inadequate for actual respondent interviews.

The first attempt at expert interviews involved two respondents - Mr H. Lemmer of the South African Association of Consulting Engineers and Dr H. de Clerq of the consulting firm of Van Wyk & Louw. The interviews with Mr Lemmer were interrupted by a terminal illness after only two interviews. Those with Dr de Clerq continued over a three month period, before I terminated them to re-consider the data collection process.

The semi-structured interview had been adequate for the pilot studies, but it became apparent on the dry runs that each interview took too long. It was assumed at the time that this could be remedied by taping the interviews, but this was wrong. When the interviews with the experts commenced it was much worse, and the sheer amount

Hence, the model allows the calculation of an index of design error likelihood, whose value is dictated by the simulated events. This index is arbitrary but it is a measure of the relative likelihoods of error in different situations, within the bounds where the theory is applicable.

3.1.3 Using the theory for error control

To generate models from the error causation theory that allow the systematic specification of error control systems, I used the Soft Systems Methodology (SSM). SSM (described in 3.2.4 ahead) is an approach to system specification from the premise that if one can isolate a specific viewpoint of why a system exists, then one can determine what components of the system are logical, and their relationships. This is the issue at stake in the existing error control models. The proposed theory of design errors provide an understanding of the key mechanisms underlying occurrence and detection, in each design error category. An error control system can then be specified for any design error category, by assuming this system to exist for the purpose of aiding/hindering those mechanisms as desired. The process is demonstrated by the specification of an error prevention system and an error detection system - both for knowledge-based design errors in conceptualising (2.1.2).

3.1.2 Using the theory for error prediction

After the theory of design errors was completed, it was used to develop an illustrative model which predicts error likelihood by simulating the behaviour of factors in the theory. A System Dynamics simulation software - STELLA - proved to be suitable for this purpose. System Dynamics (section 3.2.3 ahead) is concerned with trends in system variables over time. By representing the likelihood of a design error as a system variable, the model simulates trends in the error likelihood in response to system changes.

The experts were unable to quantify error-related probabilities. However, they easily provided estimates for the behaviour of systemic factors in the theory. These estimates allowed the simulation of events in the firm over time, in a realistic manner. For example, they could estimate how often their firm has large projects, how long most of their projects are, how many times they have had to use contract draughtsmen etc. Of course, these were specific estimates for their own firm. However, they provided a means of calibrating the error prediction model, so that the occurrences of those estimated events can be simulated in a realistic manner.

For each factor and relationship in the theory, a mathematical expression was chosen to represent some notional measure of the variables involved. Mathematical expressions were chosen for their ability to reproduce the known characteristics (reference behaviour) of that relationship, as simply as possible. These relationships in the model were easier to model, than if one had tried to model error probabilities directly. Unlike error probabilities, these relationships are objectively well-known phenomena - at least in a qualitative way. For example 'breadth of experience' was measured on a notional scale of 1 to 10, with 5 representing 'average' conditions. It was then modelled as a slowly-increasing linear function of time[6].

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[6]Experience is known to grow as an S-curve (see for example Stewart & Melchers' model in 2.2.2), but over a relatively short span of time it would be approximately linear.

without necessarily citing occasions when this had occurred. The conclusions implied in such a statement would then be regarded as tentative until corroborated by other experts.

In effect, each respondent was drawing upon his personal experience. Since the four respondents who served as experts were selected from the same firm, their various experiences derived from a similar context. Of course no two persons have identical backgrounds in every respect. However, each of these persons had been associated with that consulting firm and had worked together for several years.

The information from the experts was obtained during a series of unstructured interviews with each individual. There were about 20 odd interviews in all, over a period of several months. In the course of each interview, the ideas and relationships outlined by the respondent were sketched out in cognitive maps. This provided a visual representation of the discussion, that both the respondent and I could see. The respondent could see from the sketches whether his statements had been understood. On the other hand I was repeatedly 'analysing' the information, using the maps to clarify the ideas. This is the negotiative process required in the soft paradigm (section 2.5.1).

Concurrently with the interviews, I was developing the emerging information into a theory, using the Grounded Theory methodology (see 3.2.2 ahead). In this process, the reminiscences and observations of the experts were stripped of their immediate contextual settings to identify ideas and concepts behind the observed phenomena, and the inter-relationships of these ideas. Where the experts drew conclusions of their own or inferred relationships between concepts, I would question the experts further to seek corroboration . Hence, the theory developed was 'grounded' in the data. The use of cognitive maps and Grounded Theory are described in section 3.2.2 ahead.

(2) Client organisations have the greatest capacity to determine the project organisation, but they also tend to be the least informed about advances in the construction sector.

From these considerations, this study focuses on organisation-level systems rather than broader institutional systems. Systems pertaining to the structural design practice are chosen. This is not to say that the institutional and climatological environment surrounding the design practice is ignored. The distinction is that the environment is considered to be only partially affected by my decisions.

A proper theory should emphasize conceptual explanations rather than behavioural or contextual descriptions (cf 2.1.2). Hence, detailed understanding of causation within a specific context is preferable to shallow understanding for a large number of contexts.

The secondary objective of the methodology, will be the demonstration of how the developed theory enhances error prediction and control.

3.1.1 Developing theory

In developing the theory the data of choice was expert opinions. This choice is in harmony with recent trends in modelling human error (2.2 and 2.3), and is necessitated by the lack of alternative data sources on a comparable scale. A case study of the error experiences of a design team in a consulting engineering firm, was undertaken. It was not a study of errors that necessarily led to failure, but rather of errors commonly encountered in everyday work. The respondents were not obliged to refer to particular incidents, though they often did. Such anecdotes were important in corroborating their conclusions, yet they were also encouraged to make general observations. For example, an expert could say, "errors in general arrangement drawings are copied to several other drawings, under such and such a circumstance", The study was originally intended to focus on a specific design team in the consultancy, *for a specific project*. It quickly became apparent though, that the composition of a specific team is not static. Projects tend to overlap in time, and different persons will be considering different aspects of any given project at any one time. It was more convenient to conceive of the design team in terms of persons who tend to work on a particular project type. The boundaries of the team defined in this way are fluid, but there are some persons who are constantly in the team, for given structural types.

4.1.2 The expert respondents

Four persons were interviewed during the study, who form the core of the team handling complex steel structures eg. mining headgears, containment structures etc. These four persons are identified here by their initials as CJ, JP, FP and NC.

CJ is a partner in the consulting firm. He has over 30 years of experience in structural steelwork design including periods with major mining houses. Educated at technical institutes in the UK, he has worked his way up through the ranks and is familiar with all the stages of the design process. As a partner he is responsible for getting work, client liaison and co-ordinating the others in the team. He bears the responsibility for design concepts and is considered to be particularly expert at competitive design.

FP is a senior design draughtsman who usually acts as section leader on the team. Though nominally a freelance draughtsman, he spends most of his time working for this consulting firm. He used to be a permanent member of staff before the consultancy reduced their staff. FP has had 33 years experience in draughting of steel structures - the last 16 of these have been with this firm. As a senior design draughtsman, he is required to work from design calculations to produce GA

These used to be permanent members of staff, but were let go when the firm ran into financial problems. Other draughtsmen and engineers are hired for specific contracts as required - usually on large projects or when there is a large volume of work.

The organisational structure adopted for most projects is illustrated in figure 4.1. A supervising partner is responsible for administering the contract and handles the liaison with the client and other design professionals. This partner is responsible for the overall concept of the structure (in consultation with other partners), but would assign the bulk of the "engineering" (calculations and member-sizing) to one or more design engineers. The drawing side is coordinated by a section leader who would be a senior design draughtsman. The section leader is responsible for the G.A drawings, and then co-ordinates the production of detail drawings by other draughtsmen. He/she may be assisted in either task by other ser ,aughtsmen, depending on the size of the project. The design engineer is perceived as rendering a service to the drawing office, and the section leader is said to 'run' the project.

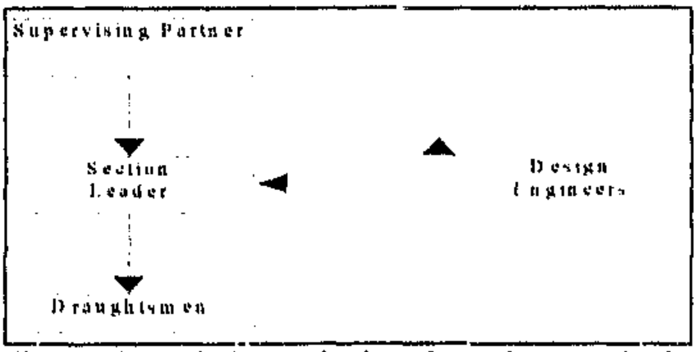

Figure 4.1 -Typical organisation of a design team in the studied consulting engineering firm

The atmosphere in the firm is largely informal. The professionals show respect for each other's judgement, and recognise each person's area of expertise. There is a culture of good quality work as the staff mainly appear to take pride in doing a good job. On the whole, this consulting firm enjoys a fairly good reputation in its areas of specialisation. This is underscored by the fact that many of its clientele are themselves knowledgeable professionals who would have high standards. In the competitive design market, surviving firms have to be innovative and economy-minded in approach, while retaining a reputation for good quality.

over time, with increased spending on infrastructure. The present atmosphere in construction (in 1996), is one of much uncertainty mixed with cautious optimism.

The firm of consulting engineers used for this study was formed in the sixties. In its present form it is a partnership of some five members, with a sixth retired member serving as an occasional consultant. The firm has been involved in civil engineering and project management activities in the past, and more recently in arbitration and legal matters. Nevertheless, their area of specialisation is the design of steel and concrete structures. The design team studied within the firm is the team that handles steel structures such as containment, mining and industrial structures.

On the steel design side, the consulting firm tends to offer a specialised service for a wide range of jobs. Their clients include construction firms who are tendering for projects on a design and construct basis. Such clients often require competitive designs which will enable them to secure the contract. The economic downswing of the last decade and a half has led to greater emphasis on low costs.

The services provided by the firm will typically involve one, two or three phases:

(1) The 'engineering' phase, which refers to conceptual design, layout and member analysis/design.

(2) The preparation of general arrangement (G.A) drawings.

(3) The detailed drawings.

They will either undertake all three phases or the first two phases, or only the engineering phase.

The firm retains a small nucleus of staff on a permanent basis - the five partners earlier mentioned, and two or three senior engineers. It had previously been a much larger firm, but like many other firms it experienced financial difficulties in the late eighties. The administrative side is handled by an administrative head who oversees two secretaries, a messenger and a tea lady. Besides this nucleus, there are three or four senior draughtsmen and senior engineers employed on a freelance basis, who have close relationships with the firm. Some actually do all their work for this firm.

CHAPTER FOUR

THE THEORY DEVELOPED IN THE STUDY

In this chapter, the methodology in sections 3.1.1 and 3.2.2 is applied to obtain expert opinions, from four persons in an engineering consulting firm. In the first section details are given about the firm, the experts and their background. In the second, the cognitive maps developed for each expert are presented and described. The process of identifying categories is traced, and finally the information is developed into a theory of design errors causation in the third section.

4.1 THE CONTEXT OF THE DATA COLLECTED

4.1.1 The consulting engineering firm

In the late eighties and early nineties, the South African economy has been depressed. This has taken its toll on construction work. Large projects have been relatively scarce and clients are much more cost conscious. The emphasis on low costs has led to tighter monetary budgets and time schedules. These trends are even more marked, when compared with the situation in the sixties and seventies. Then, construction was booming, firms grew rapidly, and good professionals were in demand. The various consulting firms have had to adjust to the times, each in their own different ways. Recently, the political changes have led to a perception of instability. Yet, it is hoped that these same changes will lead to economic growth

- Structuring of situations which could be messy, complex or inundated with information.
- Generating understanding of the perspectives of others.

The developers of SSM themselves refer to it as an enquiring system - a means to learn about a situation. Human activity systems do not really have optimal solutions (cf. section 2.5.1), since human relationships evolve with time. However, learning and the implementation of changes should ease problem situations. As relationships evolve and fresh problems appear, the previous learning provides a basis on which to apply the entire process again. A second effect of learning is that it brings about a change in our 'appreciative settings'. This last phrase refers to our readiness to notice particular aspects of a situation, and to accept certain aspects as more significant than others. Appreciative settings are conditioned into us by our previous experiences, and will in turn determine our new experiences.

In the di-graph representation, the elements of the conceptual model are short phrases describing the activities in the system. The elements are linked with arrows denoting the logic of activity flow. Checkland (1981) suggests that a model should have between five to twelve elements so the essential details can be easily grasped. These activities would all be at the same 'resolution level' i.e., the same degree of detail. Hence, a system including organisational factors, would not also include factors personal to one individual. If it is necessary to explore succeeding levels, each activity in this first system is easily turned into a new (sub) system by writing a root definition for it.

Of the four fundamental traits of proper systems, (section 2.4.1), it is evident that 'emergence' and 'hierarchy' are satisfied by root definitions and levels of resolution respectively. To satisfy the other two traits of communication and control, the conceptual model must always include control activities. Communication is assumed to be diffused through all activities. Checkland and Scholes (1990) suggested three types of criteria which the analyst could define within the model, for control purposes. These are criteria for measuring

(1) Efficiency - resources per unit output.
(2) Effectiveness - the long term aims of the system must be met.
(3) Efficacy - ensuring that the provided means (for the transformation) actually work.

To these may be added other criteria such as ethicality and elegance, depending on the type of system.

Mingers and Taylor (1992) discussed the benefits of SSM. From a survey of 137 persons, the following benefits were mentioned.

- Providing a structured approach for the study.
- Aiding clarity of thought.

- Identifying the necessary and sufficient elements (processes or activities) in that system, and the relationships between these elements.

The second and third steps are modelling activities. The second step leads to a 'root definition' of the system, while the third leads to a 'conceptual model'. A root definition is a verbal sentence defining what a notional system *must be*, if it exists for a specific reason or 'transformation process'. The transformation process is an expression of a particular 'weltanschauung' i.e. a view or perspective of the world held by a person or persons, which is relevant to the situation. Checkland (1981) proposed the mnemonic CATWOE to represent the essential ingredients of a proper (well-formed) root definition.

CATWOE stands for

Customers. The beneficiaries (or victims) of the system.

Actors. The people operating the system.

Transformation. The process which is central to the system's existence.

Weltanschauung. German for 'world-view' (perspective) from which the transformation is desirable.

Ownership. Those with power to implement or shut down the system.

Environmental constraints. The 'givens' in the situation.

The second modelling activity (the third step above) is the development of 'conceptual models'. A conceptual model is a di-graph representation of the *necessary* and *sufficient* activities making up the system. The analyst lists the minimum necessary activities that must be carried out in the system, for the system to be *what it is said to be* in the root definition. It is then possible to decide the logical connectivity between activities by considering information inflows and outflows. For each activity the questions are asked, 'what information is required as input for this activity' and 'which activities will produce that information as their own outputs?'

1990). In the more recent text, SSM is described as two streams of analysis: a logic-based stream, and a cultural stream of analysis.

The cultural stream is the analysis of the context of the studied situation. In section 4.1, a description is given of the consulting firm from which the experts were drawn. This is the context of their expertise.

In the logic-based stream of analysis, the analyst is seeking to determine which *structures* and *processes* in the system are actually logical, from relevant viewpoints Processes refer to the activities performed on such resources as information, capital, materials etc. Structure refers to the relationship (physical or abstract), between the various places where resources are stored or/and processed. For example, organisation trees and design checking 'systems' are structures, while design tasks are processes.

The emphasis of the logic-based stream is summed up by the question, '*what* activities are logical for a given viewpoint?' SSM helps one to specify the processes and structures required from a given perspective, and so leads to a judgement about existing processes and structures. What it does *not* do, is to specify a means or technique(s) for each activity i.e., the *how*.

In this study I have emphasised the logic-based analysis. The logic-based analysis was used to investigate the activities required for management of error risk, for some categories of design error. There were three steps in this approach. These are:

- Identifying views of the situation (the consulting firm and its operation), that are relevant to the study (of design errors). This is a 'cultural' aspect.

- Determining the nature of a human activity system that depicts each given viewpoint.

In most instances, the 'type of variation' was easy to assess since one was now dealing with elements with *qualitatively* well-known characteristics[7]. Typical values of course are only typical with respect to a given context. The values were selected to be typical for the particular consulting firm from which the experts were drawn. The experts were able to supply the required values easily in most instances (the secondary data described in 3.1).

In the simulation phase of STELLA, state variables such as stocks or levels (design errors in this case), are monitored to see their response to system changes over time.

3.2.4 Exploring system logic with SSM

As with error prediction (3.2.3), it was also necessary to demonstrate that the proposed theory of design error causation (produced via cognitive maps and the Grounded theory method - 3.2.2), will enhance the process of error control. For this purpose, illustrative models of error prevention and detection systems were developed. This was done using the Soft Systems Methodology.

The Soft Systems Methodology (SSM), is a means of exploring the logical implications of a particular perspective of some 'purposeful' human activity, while taking explicit cognisance of the activity's context. As such, it deals solely with human activity systems. SSM was developed by researchers at the University of Lancaster over the last 30 years (see Checkland, 1981 and Checkland & Scholes,

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[7] For example, it is qualitatively clear that 'time pressure' as a feeling, will depend on how much time is left for design (time left) and how much work is yet undone (outstanding work). Hence, I chose to model time pressure as a linear function of time left and outstanding work. The exact slope and abscissa are not critical to the model, since the object is to provide a comparison between error likelihoods in different situations. In modelling certain parts that deal directly with error behaviour, relationships were not 'qualitatively clear' since these were hitherto fuzzy in nature. However, the proposed theory now provided qualitative information on these.

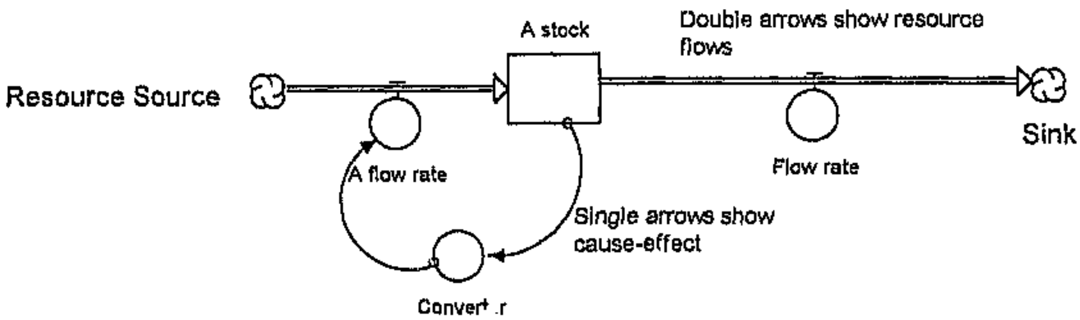

Figure 3.2 - Elements in a typical STELLA structure diagram

There are three steps to modelling in STELLA, and each of these are usually inductive when modelling soft systems i.e., modellers rely on subjective judgements. The first step is to lay out the various elements: representing each relevant variable with an element, and showing the relationships with arrows. (Large numbers of interconnections between elements are not easily implemented in STELLA. The modeller is therefore forced to select *basic* causative mechanisms and ignore more secondary relationships). The second step is to define the behaviour of each element as a mathematical form or 'model' e.g. linear, exponential etc. Thirdly, the values of the parameters for the mathematical form must be specified e.g. slope and abscissa for a linear model.

In this study, the theory I derived from the experts provided the basic causative mechanisms for the first step in modelling. The two other steps were subjective. In carrying out the two subjective steps, a reference behaviour was first defined for the element (High Performance Systems, 1994). Once a reference behaviour was established for an element, the mathematical model and its parameters could be chosen to reproduce the desired behaviour.

The phrase 'reference behaviour' indicates the *type of variation* expected (say over time for example), and also the *typical values* under 'average' or 'normal' conditions.

3.2.3 Predicting trends in error likelihoods - System dynamics & STELLA

After the proposed theory of design errors was developed via the Grounded theory method, it became necessary to demonstrate that the theory does enhance the prediction and control of error. An illustrative error prediction model was developed using STELLA - a System Dynamics software (see 3.1.2).

System Dynamics (Coyle, 1977), is about the study of adaptive behaviour in organisations i.e., how an organisational system maintains dynamic equilibrium with its environment. In soft and complex systems, the intricate and vague interactions make it difficult to determine the effect(s) of any one input or system change. System Dynamics is a technique that allows the prediction of the system's response over time, by modelling the causative factors and simulating their behaviour. STELLA (High Performance Systems, 1994), is a software package that enables one to carry out the modelling and simulation on a PC, and it is particularly useful for 'soft' systems.

Structure diagrams are the main graphical representation used in modern System Dynamics models. (See for example Cellier 1991, - chapter 11). The main elements in a structure diagram are system state variables called levels or stocks, and flow rates. Stocks are inventories of resources within the system, while flow rates model resource inflows and outflows. A third element type called an auxiliary or a converter is added to allow the carrying out of calculations, to hold values for variables, and to enhance clarity. Arrows are used to link the various elements according to prescribed rules, to demonstrate relationships.

In STELLA, double arrows represent resource flows, while single line arrows represent cause - effect relationships. The stocks are squares, flow rates are circles with spigot valves, and converters are simply circles. When a resource originates from outside the system, or ends up outside the system, then the sources and sinks are depicted with little clouds. These various elements are demonstrated in Figure 3.2 below.

conditions or intervening conditions. (Intervening or trigger conditions are those which are not necessarily present when the central phenomenon occurs; but when they are present, they alter the likelihood and outcome of the phenomenon). The selected categories of design error in section 2.1.2 emerged during this process, as the concepts were clustered round themes pertaining to the mechanisms of occurrence. This led me to seek an explanation in cognitive processes (Appendix A).

In the second phase of axial coding, the analyst seeks to identify mentioned action/interaction strategies to manage the phenomenon in the central theme (design errors), over time. For each action/interaction strategy, it is important to determine its goal or purpose, likelihood of success and consequences. The weakness of this technique in prescribing control actions, lies primarily in the fact that only actions *currently in use* can be considered. This allows one to assess current actions vis-a-vis the central concept, but does not help in a systematic development of new actions.

Selective coding is the third coding procedure. At this point, the core category is systematically related to all the other categories, in much the same manner as for concepts within a category, in open coding. At this point, a lot of emphasis is placed on validating each relationship from the data, and on identifying feasible patterns of action contexts. Selective coding ends when the theory can be laid out in narrative form or diagrammatic form. I really did not develop the aspect of action contexts (for the reason given in the last paragraph), preferring to use the SSM technique for this aspect.

The cognitive maps for the four experts were subjected to these coding procedures, to yield a theory of how design errors occur.

often take the form of slips (e.g. missing dimensions, slips of the pen etc.). However, there will also be mistakes which arise from the application of draughting rules (e.g. use of wrong convention for a weld).

From the above considerations, it was proposed in 2.1.2 to categorise design error into six types. These are:

(1) Knowledge-based mistakes in conceptualising (Type I).

(2) Rule-based mistakes in conceptualising (Type II).

(3) Rule-based mistakes in computation (Type III).

(4) Calculation slips and lapses (Type IV).

(5) Rule-based draughting mistakes (Type V) &

(6) Draughting slips (Type VI).

Table 4.2 - The occurrence of design error types in typical stages of a design project

DESIGN ERROR TYPES	TYPICAL STAGES IN A DESIGN PROJECT			
	Structure Conceptualisation	Member Design	Connection Design	General Arrangement & Detail dwg
K-B mistakes in conceptualising - type I	√	√	√	
R-B mistakes in conceptualising - type II	√	√	√	
Computation R-B mistakes - type III		√	√	
Calculation slips & lapses - type IV		√	√	
Draughting R-B mistakes - type V				√
Draughting slips & lapses - type VI				√

K-B - Knowledge-based; R-B - Rule-based.

Suppose a design project is divided into four stages: structure conceptualisation, member design, connection design (which could be done by draughtsmen), and different degree). The conceptual categories of this generic model are described in Appendix C.

4.3 A THEORY OF CAUSATION FOR EACH TYPE OF DESIGN ERROR

4.3.1 A further consideration of design error classification

It is convenient for this study, to divide the design of a structure into three types of work activity - conceptualising, selecting/calculating (of both member and connection dimensions), and draughting of general arrangement drawings and details. Responsibility for each type of activity is typically spread across different phases of the project, and may be handled by different persons.

Conceptualising or the appreciation and characterisation of structural behaviour, is carried out at three levels: for the entire structure; for individual members; and for each connection. Of the three cognitive processes of planning, storage and execution (see 2.1.2 and Appendix A), conceptualising involves only planning. As such, conceptualising may be either rule-based or knowledge-based. Therefore, errors in conceptualising will take either of the two mistake forms.

The selection and calculation of both member and connection sizes, will involve both planning and execution (2.1.2). Therefore, there will be slips[8] associated with these, as well as mistakes. Much of draughting is skill-based[9]. Hence, draughting errors will

[8]Henceforth, I will mention only 'slips' and this can be taken to refer to both 'slips' and 'lapses'.

[9]I distinguish between those 'design' tasks carried out by draughtsmen (e.g. member sizing from tables), and pure draughting.

Table 4.1 summarizes the relationship between the element groups in the cognitive maps and the seven conceptual categories. The conceptual categories are themselves divided into three types - those related to the 'environment' surrounding the design team; those related to the behaviour of individuals making up the team; and those relating directly to design errors.

Figure 4.10 shows how all the various conceptual categories are related to one another in a general manner.

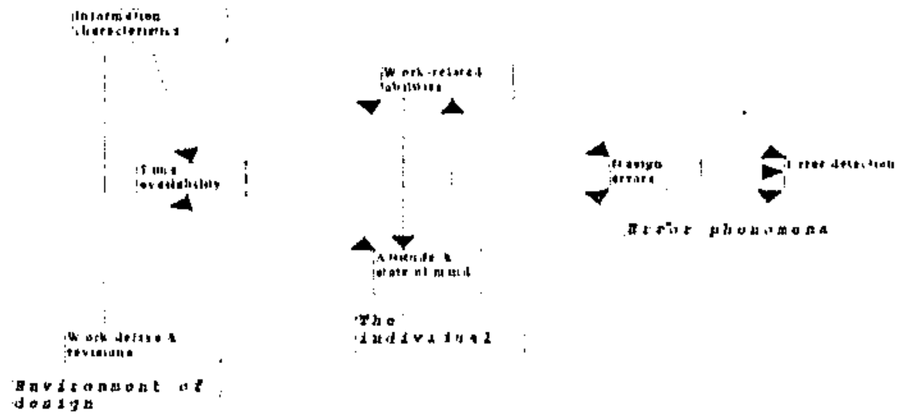

Figure 4.10 - Conceptual categorization of elements in the cognitive maps - a generic model

The conceptual categories and their relationships are outlined in figure 4.10. This can be regarded as a generic model of causality for design errors. This model suggests that design errors are to be viewed, as the result(s) of interacting 'weaknesses' in the abilities and states of mind of the individuals carrying out the design. Those weaknesses themselves are only present and are more potent or less potent, depending on the 'environment of design'. The environment of design is determined in turn by the wider project organisation, which is not included in the model. This model implies that the task of the consulting firm's leadership (vis-a-vis error), is to mediate the interface between the project and the individuals. (Project characteristics change from one project to another. Human behaviour is also dynamic, though to a

- The *characteristics of information* (input into the design process) e.g. wrong, late etc.
- The *availability of time* for structural design.
- The *effects of revisions*, corrections and other work delays e.g. due to low productivity or extensive document checks on some projects.
- The *work-related abilities* of members of the design team e.g. experience, understanding of the material, competence etc.
- Attitudes adopted by the members of the design team, and other concepts related to their *states of mind*.
- The various *design errors* themselves, and
- *Error detection*; mainly by checking - both formal and informal.

These conceptual labels are my choice of terms to describe the ideas which seem to be the common traits of various groups of elements. Appendix C describes the exact meaning of each label (as used here), and explains which ideas and concepts are included within each label and the boundaries of each conceptual category.

Table 4.1 - Relationship between the groups of elements in the cognitive maps and the conceptual categories

Cognitive maps	ENVIRONMENT OF DESIGN			INDIVIDUAL IN THE TEAM		ERROR PHENOMENA	
	Informatn Xteristics	**Time Available**	**Work delay & revisions**	**Work abilities**	**Attitude & mind state**	**Design errors**	**Error detection**
JP	Engr/ d'men communictn				Careless-ness	Faulty connectns	Design calc check
HP	Information needs	Production rate/ time	Design changes	Staffing & competence	Attitudes	Errors in drawings	Drawing checks
NC	Communi-cation	Time pressure		Material understand.		Error types I, IV & VI	Self-check
CJ	Incorrect information	Too little time	Revisions	Experience	Mental attitudes	All error types	

The last map in figure 4.8 is the one developed for CJ. This is the most elaborate, having 59 elements in 68 relationships. The main element groups are summarized in figure 4.9.

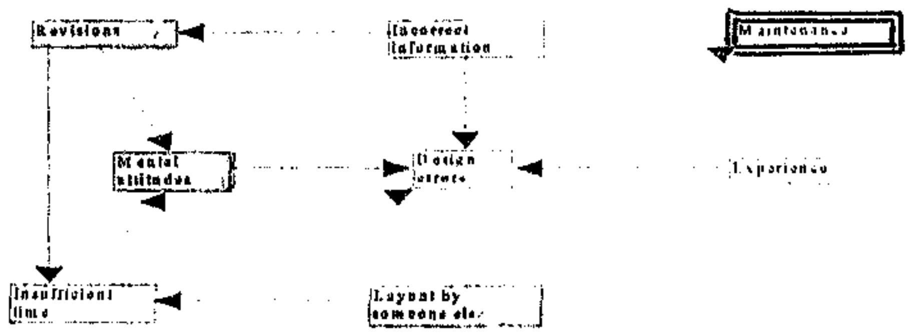

Figure 4.9 - The main groups of elements in CJ's map, and their relationships

4.2.2 A generic model of design error causation

The groups of elements in figures 4.3, 4.5, 4.6 and 4.9 reflect the first attempt at categorizing the various map elements. The open coding process of grounded theory (section 3.2.2) led to a simpler categorization of the map elements into seven classes. These new 'conceptual categories' evolved from the interview process as I tested my initial impressions on the experts. For example, further questioning revealed that the effect of maintenance (in figure 4.9) was not directly related to design error - at least not by the definition in section 1.5.

The seven conceptual categories that emerged from the open coding process were:

NC did not really develop the relationships between the groups in his map. This may reflect the fact that fewer interviews were held with him. The error types described in figure 4.7 are termed by NC as conceptualization, arithmetic errors and draughting/detailing errors. In the design error categories of 2.1.2, these correspond to type I knowledge-based conceptualization mistakes, type IV calculation slips and types V and VI draughting errors respectively.

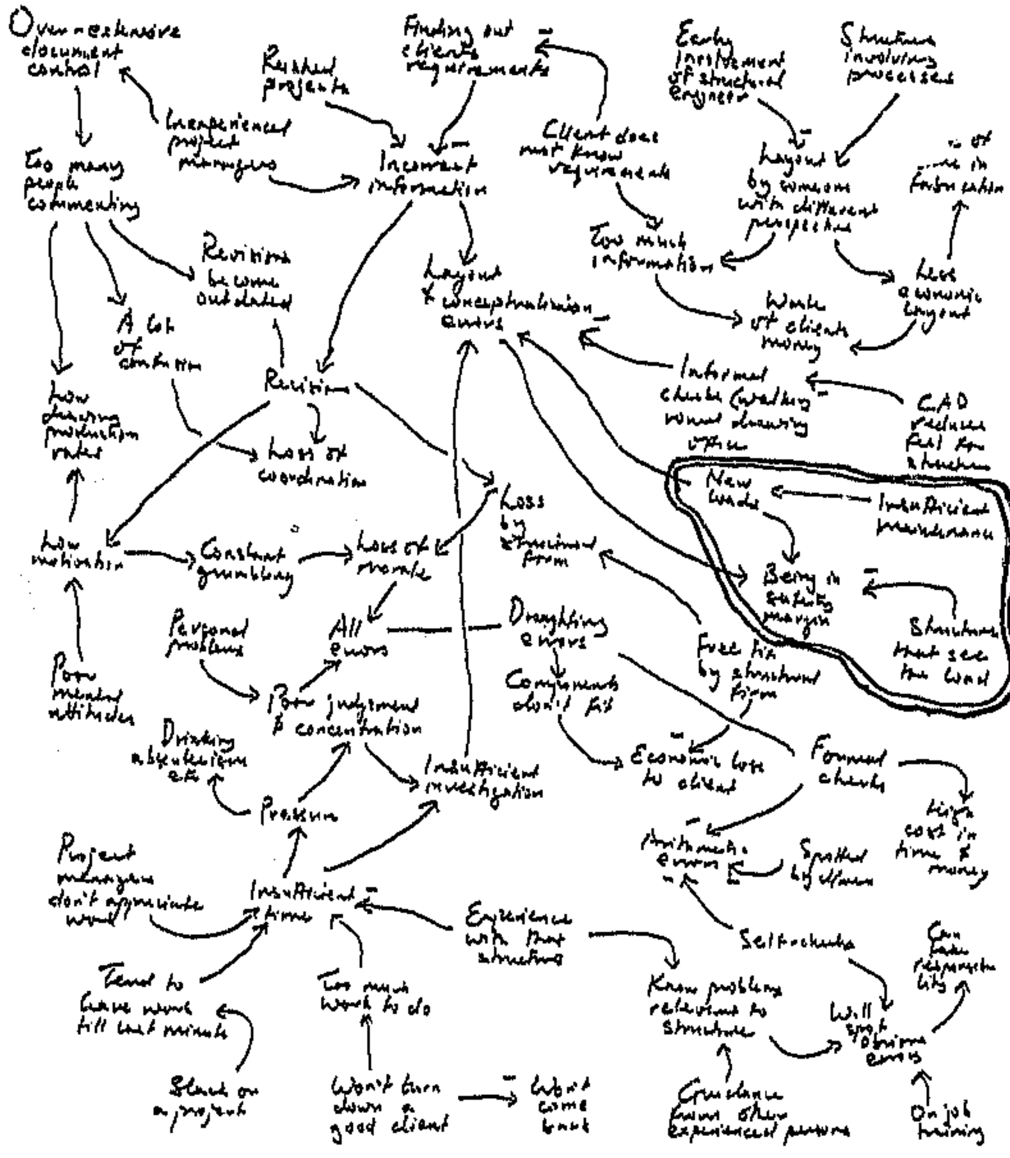

Figure 4.8 - The cognitive map developed for CJ

The cognitive map for NC (figure 4.7), has 46 elements in 54 relationships. He has had the longest experience of all the experts, and spent a considerable portion of his career in managing the design process. This shows in the clarity with which his ideas are presented. His description of self-checks of design calculations is a succinct example of this. I have divided the elements in his map into six groups in figure 4.6.

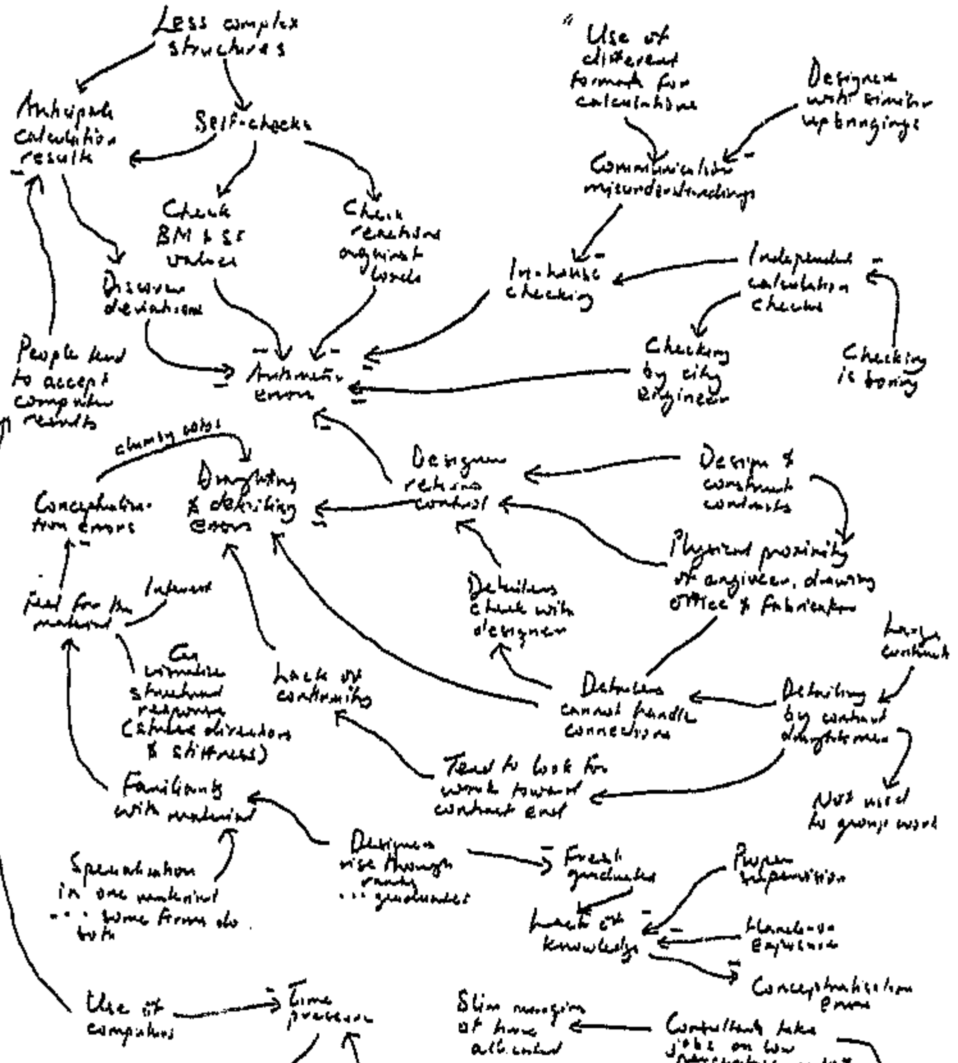

Figure 4.7 - The cognitive map developed for NC

The map for FP in figure 4.4 has some 42 elements in 53 relationships. The difference in perspective between FP and JP, is immediately evident. JP is a design engineer while FP is a senior design draughtsman, and their concerns are very different. In keeping with the organisational arrangement adopted in the firm, FP handles queries from clients. This leads to a greater awareness of the influence of external parties. The 'errors of design' in FP's map are the type V draughting mistakes in the proposed classification of errors (2.1.2), while 'errors of fit' refer to type VI draughting slips. The main groups of elements in figure 4.4 and their inter-relationships are summarized in figure 4.5.

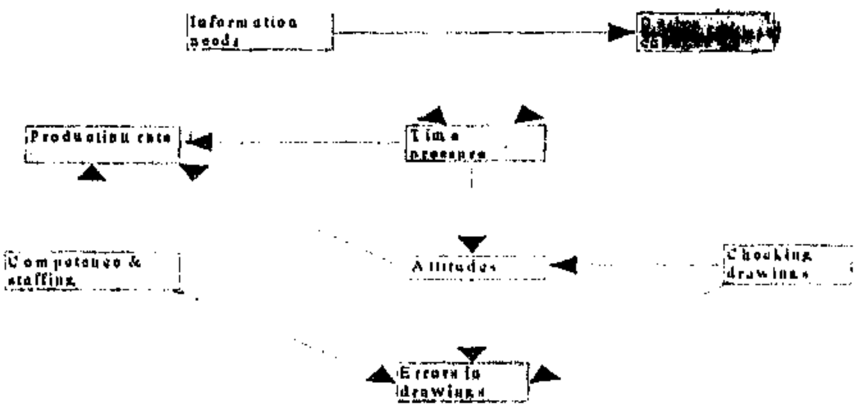

Figure 4.5 - The main topics in FP's map, and their relationships

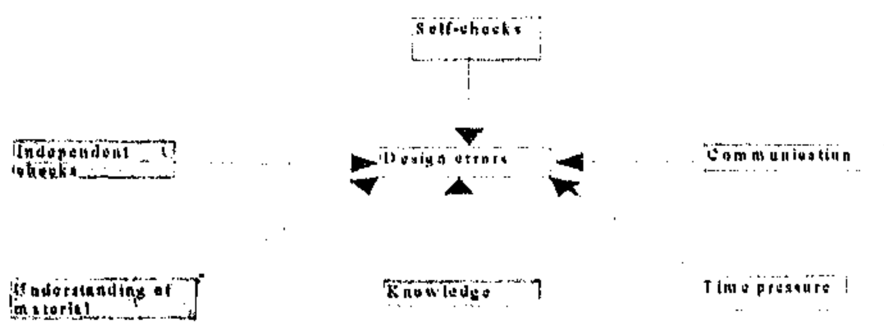

Figure 4.6 - The main groups of elements in NC's map, and their relationships

different nuances in meaning. In the later stages of analysis therefore, the map elements could be manipulated within conceptual categories with confidence. At this initial stage however, names were only changed in a few cases where I perceived two or more experts to be using similar words for dissimilar phenomena.

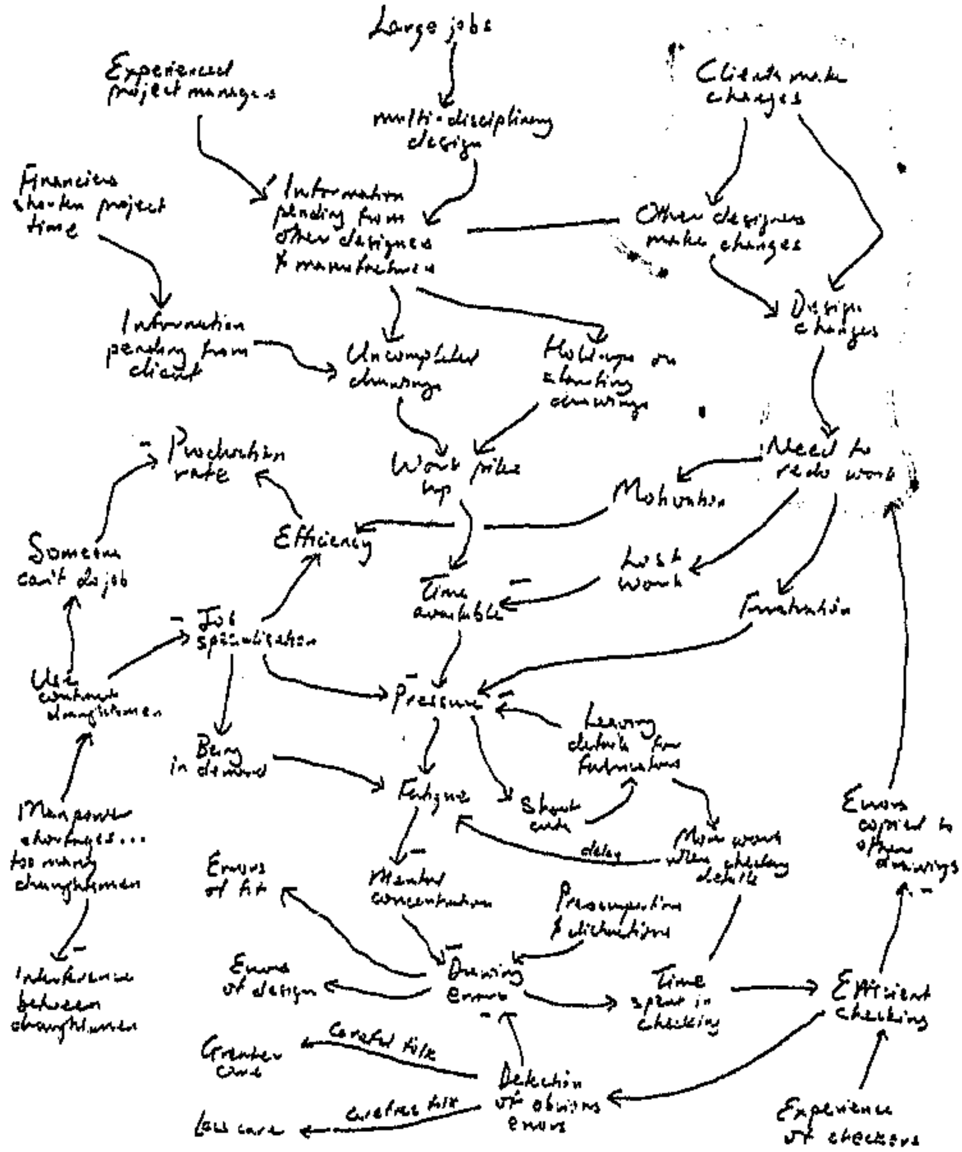

Figure 4.4 - The cognitive map developed for FP

groupings were either identified directly by the expert (round some key issue), or became obvious from the extent of attention given to an issue by an expert. The first tentative names given to the groups are as follows.

- Checking of design calculations.
- Communication between designers and draughtsmen.
- Faulty connections.
- Carelessness.

Figure 4.3 below summarizes the relationships between these groups, and so summarizes the map in figure 4.2. The group names in figure 4.3 are colour-coded to match the circles denoting groups in figure 4.2.

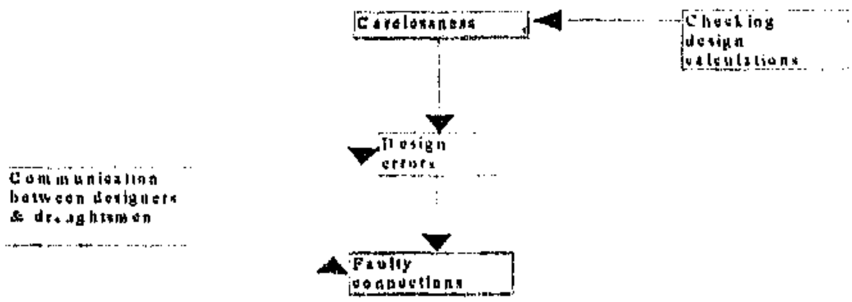

Figure 4.3 - The main groups of elements in JP's map, and their relationships

JP makes reference to three of the error types adopted in section 2.1.2 - computation slips and mistakes (grouped together), and rule-based mistakes of characterisation in the design of connections. These are error types III, IV and II respectively (2.1.2). Of course the proposed error categorisation was not fully developed till late in the study, and the names used in the maps do not fully reflect those distinctions. However, the context and the linked elements made it possible to distinguish which error type the expert had in mind, for each mention of error.

As much as possible, the names used in each map are the actual phraseology of the expert. As explained in 3.2.2, a meaning was 'negotiated' for each term in the interviews. This negotiation process made for very explicit understanding of the

4.2 DEVELOPING THEORY FROM EXPERT DATA

4.2.1 The cognitive maps

The cognitive maps for each of the four experts are presented in this sectio· As will be seen, the maps for different individuals differ in level of elaboration, complexity and emphasis. The maps here are cleaned up versions of the ones developed in the study, so as to enhance understanding. A comparison between the maps and table 2.1, shows that the experts collectively touched on most error risk factors in the literature - though sometimes doing so indirectly, or using a different term.

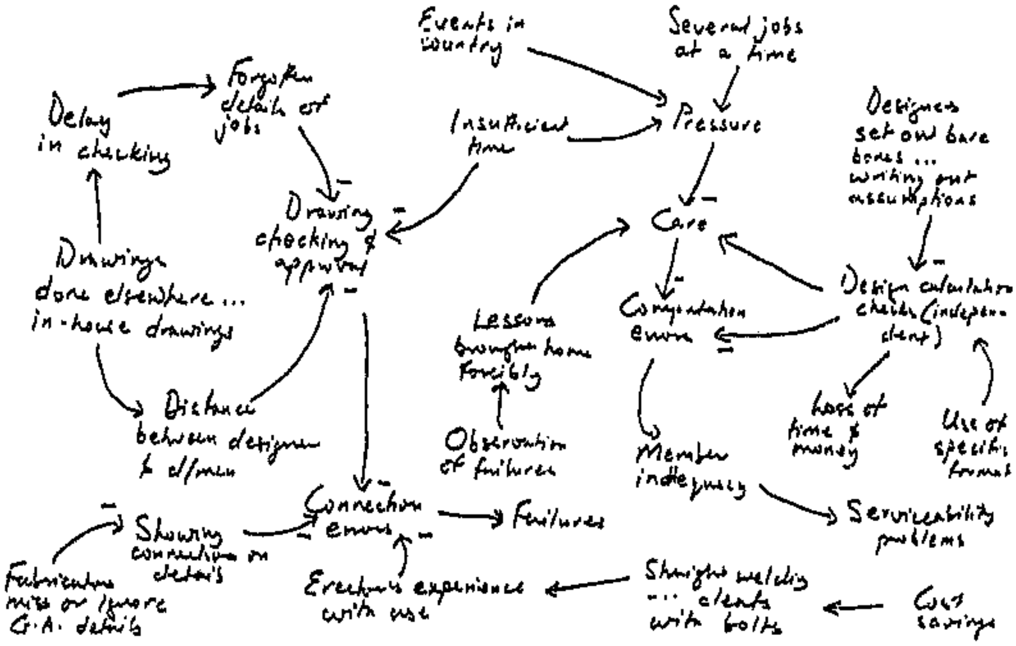

Figure 4.2 - The cognitive map developed for JP

The map for JP in figure 4.2 has the fewest elements, and so is the easiest to understand. There are 26 elements there, in 27 relationships. These may be grouped loosely into four main groups (shown with different colours in figure 4.2), though some elements are common to two or more groups. As explained in 3.2.2, these drawings, and then to check or approve shop details to ensure they are in accordance with his drawings. When he acts as a section leader (on larger projects), he takes on the additional responsibilities of co-ordinating other draughtsmen and answering queries from clients. He is regarded as an expert on draughting of silo designs.

NC is a freelance design engineer working for the consulting firm on a contract basis. Though only working there occasionally, he maintains a good relationship with the firm and is considered a member of their staff. NC retired from a position as chief design engineer with a large organisation in 1980, by which time he already had 38 years of experience in the industry. He also rose through the ranks - starting as a learner draughtsman - and holds technical qualifications. Besides freelance work as a private consultant and with this firm, he has been involved in drafting codes, manuals etc. with the Southern African Institute of Steel Construction (SAISC).

JP is an in-house design engineer with the consulting firm. He was educated at various technical institutes in the UK, and has had long experience in design.

The unstructured interviews with these experts yielded two forms of 'raw' data. The primary data (from about twenty unstructured interviews over a three to four month period - see 3.2.1) are the cognitive maps recording each expert's opinions and experience. Secondly, quantitative estimates of the likelihood of occurrence for some factors previously linked to design error causation, were a secondary type of data (3.2.1). This secondary information was obtained in later interviews (four or five) with CJ and FP after the theory of design errors was developed. Those quantitative estimates are specific to this consulting firm and would obviously differ for other firms. As such, I have used those estimates to calibrate the illustrative error prediction model (section 5.1 ahead), but the raw values are not presented. The cognitive maps are presented in the next section.

concepts and the member sizes must be communicated to the draughtsmen. Most draughting mistakes result from a poor communication of the concepts.

Type V errors are what FP refers to as 'errors of design'. These will normally affect connections, member sizes and leading dimensions. As such, type V errors have consequences for the integrity of the structure.

Error context and intervening conditions

There is no obvious context given for type V errors in the interviews. One intervening condition that is mentioned by almost all experts is the effect of physical distance between the design engineers and (some of) the draughtsmen. When some or all of the draughting is carried out at a different location from the conceptualization and calculations, opportunities for communication misunderstandings increase. As mentioned before (4.3.4), designers rarely state all their assumptions explicitly. Hence, the draughtsmen often check their understanding of the concepts in informal contacts. This is greatly facilitated by physical proximity.

A related condition is the situation where the designers and (some of) the draughtsmen, are not used to working with each other (FP & NC maps). This could be because they are from different organisations, or otherwise because the draughtsmen are only employed for a particular project - contract draughtsmen. Differences in symbols and terminology employed tend to increase the opportunities for misunderstandings. Personality clashes and a desire to avoid looking incompetent can aggravate such communication gaps. Hindrances to communication have been particularly problematic when draughtsmen design unusually loaded connections. Competitive design situations are more likely to lead to highly loaded connections and non-standard connections.

Contract draughtsmen may produce other opportunities for type V errors. Their skills are variable, often unknown quantities, and they require differing amounts of

Error context and intervening conditions

Calculation slips and lapses result from insufficient attention at critical points. There is no single contextual condition identified for this in the interviews. However, there are intervening conditions. One of these is a feeling of pressure due to time constraints, or to events in the wider society (map for JP).

Fatigue also tends to affect the likelihood of calculation slips and lapses, as with type III errors. In this case, the effect is evident even at low levels of fatigue and may not increase appreciably at higher levels.

As mentioned above, the use of sophisticated calculation aids will decrease the opportunities for type IV errors.

Action strategies

Calculation slips are easily detected by the same person committing the error, though this is affected by the complexity of the structure (see NC's map). Omissions are far less easily spotted, and are also not amenable to independent checks. Checkers will often go through a design sheet, and overlook the same thing the designer overlooked. The provision of memory aids such as checklists should help prevent lapses. Reminder messages can be posted at critical points in computer programs and design manuals, to help the self-detection of both slips and omissions.

4.3.6 Type V design errors - Draughting rule-based mistakes

Causative mechanisms

The rule-based portion of draughting has to do with recognising the nature of the structural design, and understanding how it is to be represented. The structural

4.3.5 Type IV design errors - Calculation slips and lapses

Causative mechanisms

Some of the work in analysis is simply the routine manipulation of numbers. Much of this number manipulation will be carried out in a semi-automatic fashion by most persons, as the process is familiar and the rules are mainly internalized. Analysis requires conscious concentration at other times, but this is relaxed during the routine manipulation of numbers. Hence, it is easier for one's attention to wander. This is all right if the person brings his/her attention back to the task at regular intervals to keep the task on track. However, if a necessary attention check is omitted, the task could go in an unintended direction. The tendency is to carry out some other familiar routine rather than the intended one, or to omit some aspect of the intended sequence. These slips and lapses are type IV errors.

Type IV errors therefore are the result of carelessness (insufficient attention) at required points (see the cognitive map for JP). They will manifest as slips of the pen and memory lapses during routine manipulation of numbers. Numbers may be transposed, decimal points shifted, reading (or writing) wrong figures from tables, or even applying the wrong mathematical operation. Mis-writing (or reading) formulae is also a common occurrence that belongs in this category. Such slips commonly lead to inadequate (or over-adequate) member sizes, as with type III errors. It is possible that an inadequate member size could lead in turn to partial or total collapse, but in most cases, serviceability problems are more common e.g. excessive sway or deflection. Perhaps this is because the need to standardize member sizes leads to large "reserves" in member strength for some members. Hence, failures are more common in structures such as silos where the effect of standardization is less pronounced. Besides, as mentioned in 4.3.4, major, significant errors in member size are probably obvious to designers, even with only a few years of related experience (see maps for JC & FP; and also NC on self-checks).

In type IV errors, the emphasis has shifted completely from 'abilities' in the generic model (section 4.2.2), to 'state of mind' factors.

for a long while. The more sophisticated the computation aid or programme, the less transparent its operations will be to the designer. Hence, the less likely that in-built errors will be detected. A related condition is the use of software or manuals with poorly written documentation, which encourages procedural type III errors.

High levels of fatigue will also affect the likelihood of type III errors. Such high fatigue levels result from long stretches of working without breaks under conditions of high pressure and/or low morale (see map for FP). Projects which everyone knows to be running at a loss, or on which the client is disliked or the deadlines are simply impossible, are strong candidates for low morale.

Action strategies

Computation mistakes are more easily detected than the first two error types. The ease of independent detection is affected by the fact that designers will rarely state all their assumptions explicitly (JP's map). Hence, the adoption of standard comprehensive formats for recording calculations makes independent error detection likelier.

Training can have a significant impact on computation mistakes, particularly with regards to software and computation aids. People come to understand the capabilities and limitations of their aids better.

The present industry requirement of a mentor ship period for newly-graduated engineers tends to be geared towards teaching them to avoid error types III and IV. As the calculations of these pupil engineers are checked, they learn to adopt systematic routines and develop an eye for obvious errors. Apparently, this system is dying out (see CJ's map). As a result of the leaner economic climate, consulting firm principals consider the time investment to be too high.

are a necessary part of both conceptualising and analysis. Hence, any tacit assumptions in the chosen analytical rules must match the assumptions in the conceptual models. When there is a mis-match between these two sets of assumptions, a type III error has occurred.

Like type II errors, type III errors are mistakes in pattern recognition (conceptual model assumptions), or remembering the correct solution (the appropriate analytical model). Common type III mistakes are the use of inappropriate formulae (or computer programs), incorrect application of an analytical procedure and the misinterpretation of analysis results. These errors will usually occur during the member design and connection design stages. Hence, the consequences of such errors will range from serviceability problems due to inadequate members, to failure of connections. (See the map for JP). Such errors can also result in member failures, but these are only likely with unusual or/and complicated structures. (On standard structures, large errors in member dimensions tend to be obvious - more so than errors in connection details).

Error context and intervening conditions

If the error stems from non-recognition of the critical assumptions in the conceptual model, the context is usually one of poor communication of the concepts. (This is brought out indirectly by NC in his reference to 'communication misunderstandings', when detecting type III errors). If the weakness is in the analytic procedure chosen, then the context is one of poor training or education vis-a-vis that structural type.

The use of computer programs, calculators, design manuals and other computation aids, are a common intervening condition for type III errors. The use of a computation aid tends to speed up and automate the computation process, reducing the likelihoods of calculation lapses and slips (type IV errors). As a second benefit it relieves the time pressures on the design engineer. Unfortunately, people tend to accept computation results at face value. If a program includes a bad rule or a mis-written formula (a type III error by the programmer), this could easily go undetected to untidy solutions. Obviously, process engineers are less likely to have experience in structural layout (small rule base), and also tend to interpret the structural goals only from a process perspective.

Action strategies

The prevention of type II errors is dependent on the provision of larger rule bases. This may require broad strategic decisions such as personnel selection/development policies, to cultivate broad experience. Career development planning is likely to be fruitful here. This would not be simply going for a single course or the occasional seminar. Rather, it requires a deliberate grooming of individuals over several years, to ensure wide exposure in certain project types.

The provision of rule bases may also be carried out at the tactical level, with external rule bases. Examples of external rule-bases are office design manuals, expert systems and records of how previous design concepts were arrived at and how they performed. (As mentioned before, firms rarely document the details of how and why concepts were arrived at. This is different from recording the concept itself in terms of form, load paths and assumptions made). A design code can also serve as a rule-base at a generalized level. Hence, the provision of design codes at a suitable level of specificity can be a strategy for error prevention at the institutional level. Presently, few codes or office manuals address the concepts in any detail.

4.3.4 Type III design errors - Rule-based mistakes in computation

Causative mechanisms

Once the design concept (or a part of it) is fixed, the designer applies analytical rules (formulae & procedures) to portions of the model, to estimate dimensions and confirm the suitability of preceding steps. Idealizations and simplifying assumptions

4.3.3 Type II design errors - Rule-based mistakes in conceptualising

Causative mechanisms

Rule-based conceptualisation is a model selection process. The individual is looking for cues in the structural problem to guide him/her as to which model fits best. In knowledge-based conceptualising the issue is problem comprehension; here the issue is pattern recognition. The conceptualiser recognises a familiar pattern in the information, and he/she remembers which structural model is applicable. Type II errors arise when the pattern that is taken to be important is the wrong one (similar to problem comprehension for type I errors), or when the model in the memory is wrong. In the first case a good rule is wrongly applied; in the other the rule is bad.

Error context and intervening conditions

Rules are available in the memory when the individual has seen several such structures, solved in various ways. Hence, the context of type II errors is the experience of the individual - both with a structural type and with the material of design. (The import of experience here is not length of years, but breadth of exposure relevant to the problem. The broader the relevant experience of the individual, the larger the rule-base). This is clearly brought out in NC's map where inexperience is referred to as 'lack of knowledge', and the material aspect is called 'a feel for the material'.

As mentioned before, problem recognition in type II errors is analogous to problem comprehension for type I errors. As with problem comprehension, problem recognition is affected by the characteristics of the information itself. Therefore wrong or missing information would have an intervening effect similar to that described for type I errors. CJ mentions a peculiar problem which he referred to as "too much information". On structures housing process operations, clients typically get the process engineers to design their aspects first. In some cases the process engineer could go ahead to stipulate the structural layout. This becomes problematic if the stipulated layout is clumsy, since the structural engineers are then constrained have to use knowledge-based reasoning, they are much likelier to make mistakes than with rule-based conceptualising. (Conceptualisers need to anticipate how their concepts will be implemented in successive stages, and this is best done by rule-based reasoning. Also see Appendix A).

Type I errors are difficult to detect (Appendix A). Detection by others is easier if that aspect is rule-based for the checker i.e., it is within his/her experience. Of course, with innovative structures this is very unlikely. It tends to be true that areas of weak or untidy conceptualization are easily identified. However, one can rarely show that these will critically affect the structure. Self-detection only takes place if the conceptualiser adopts a systematic problem solving approach which includes periodic checks. Since the work is knowledge-based and so is quite out of his/her experience, errors are not very visible. People can be taught to be systematic in their problem-solving approach, but this may be related to individual temperament.

Except for cases where the checker is considerably more experienced than the designer (larger rule base), independent checking of concepts is inefficient and time-consuming. If the checker is also adopting knowledge-based reasoning, he/she can only check to see if the processes followed in conceptualising were logical and systematic. Unfortunately, the thought processes of conceptualising are difficult to describe. Phenomena such as groupthink and tunnel vision[10] are actually far likelier with type I errors.

On the side of error prevention, a possible strategy is the management of information flows from other parties. (These other parties are not always clients or other designers. Connection conceptualising for example, may require information from colleagues in the design team). For example, a firm could allocate someone full-time to client liaison on 'information-risky' projects, such as fast-track jobs. Systematic problem-solving is a tactical means of error prevention.

---

[10]These phrases refer to situations of decision making where decision makers ignore seemingly obvious aspects of a problem, that would affect decisions taken. Tunnel vision is used for cases where an individual focuses on one aspect and so loses sight of others. Groupthink (coined by J. Janis) refers to situations of group decisions where peer influences make some members silent to avoid being different.

only erroneous if it differs from acceptable practice - given the quality of information available. This would not detract from the responsibility of the designer to proceed 'with reasonable care'; which reasonable care may involve seeking and checking information). The effects of judgement and correct information availability would overlap i.e. someone might emphasise non-critical aspects of the theory because of poor judgement, or because of wrong information, or both.

Pressures due to insufficient time for design also affect the likelihood of type I errors. (See this in CJ's map). There are two mechanisms involved. On one hand, such time pressures can lead to insufficient consideration of alternatives during conceptualising. This is likelier to manifest as clumsy or inefficient concepts, rather than outright unworkable ones. On the other hand, the feeling of pressure may affect the judgements of individuals to differing degrees.

A more subtle intervening condition is the occurrence of clumsy concepts at an earlier stage in the design. CJ recounted a case where he was called in to check a design by another firm. Some of the member concepts were extraordinarily convoluted and he sought to change them. It became apparent though, that the designer of the members had to resort to those unnecessarily complicated measures because the concept for the overall structure was quite untidy.

Action Strategies

The predictability of type I errors is very low. The experts could not put numbers to how often such errors occur or are likely to occur. However, it is clear that opportunities for knowledge-based mistakes will be relatively fewer than for other types. This is because conceptualising usually requires a relatively small proportion of design time, and much of the conceptualising will be rule-based (also see Appendix A). When conceptualising, individuals prefer to 'rule-match' - searching their minds for similarities to previous projects. People will only resort to knowledge-based reasoning when they have no choice. The opportunities for type I errors will be few, but the error/opportunity ratio will be very high. When people do directions, omitting loads or relevant limit states (not because one forgot but because their relevance was not appreciated), or even an unsuitable layout. An expert described a case he was involved with, where a well-respected UK firm proposed a restraint system which was a mechanism (and would not admit their error till it had been adjudicated by a professional body).

A related phenomenon, is the use of 'clumsy' concepts and details. These last are not errors in themselves, but can have consequences for other error types - notably computation mistakes.

In the generic model of figure 4.10, all design errors result from individual weaknesses in abilities or/and states of mind. Type I errors result from weaknesses in abilities - in this case, the ability to comprehend the essential details of a structural problem. This can be seen in the cognitive map for the expert NC (figure 4.4), where the phrase 'conceptualisation errors' refers to type I design errors. There was no evidence in any of the interviews linking such conceptualisation errors to 'state of mind' factors such as morale, carelessness etc.

Context and Intervening conditions

Ability to comprehend a problem will always be linked to the complexity of the problem. Hence, the context of type I errors is the complexity of the structure (or member) to be designed. The effect of complexity is variable, since individuals differ in their capacity to cope with complexity. Moreover, training and exposure (leading to good or poor judgement) will affect this capacity.

Sometimes, an individual's inability to grasp essential details from the information is because the information itself is deficient. In CJ's map (figure 4.5), he identifies wrong information and new unforeseen loads (e.g. unforeseen loads resulting from poor maintenance), as leading to layout and conceptualisation errors. Hence, the characteristics of the information given is an intervening condition that can affect the likelihood of type I errors. (There is a distinction to be drawn here. A concept is directions, omitting loads or relevant *limit states* (not because one forgot but because their relevance was not appreciated), or even an unsuitable layout. An expert described a case he was involved with, where a well-respected UK firm proposed a restraint system which was a mechanism (and would not admit their error till it had been adjudicated by a professional body).

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The seven conceptual categories of the generic model in figure 4.10 are not equally relevant to each of the six design error types. Each design error type had to be considered against the generic model, so that a specific theory of causation was evolved for each error type. In the axial coding process (section 3.2.2), the concepts and elements related to each error type were identified as either basic causative mechanisms, contextual phenomena or (outcome modifying) intervening actions. The resulting theory is presented in narrative form for each error type in turn, in the rest of this section.

4.3.2 Type I design errors - Knowledge-based errors in conceptualising

Causative mechanisms

Knowledge-based mistakes are generally due to the individual's inability to hold every facet of the problem, in his/her working memory at once. Type I errors take place during the conceptualising activity, when the individual is transforming real-world information into a relevant structural model. This could be for the entire structure, or less frequently for a part thereof such as a member or connection. (However, conceptualising of a member is likelier to be rule-based). For knowledge-based reasoning, the difficulty in the process lies not so much in the structural models (pinned joint, point loads etc.), but rather in distinguishing the relevant details and co-ordinating the implications, for all the given information. Hence, Type I errors are conceived here as mistakes in comprehending the structurally relevant aspects of a problem, from the input information presented to one.

Type I errors may manifest as poor load conceptualizations (e.g. point load represented as a distributed load), wrong assumptions about load paths and stress directly based on the generic model of section 4.2.2. The error prediction model is divided into four sectors as shown in figure 5.1. Three of these - the project time, budgeted work flows and information processing sectors - correspond roughly to the 'design environment' categories in the proposed generic model for design error in figure 4.10 (4.2.2). The fourth sector models the behaviour of the design error types.

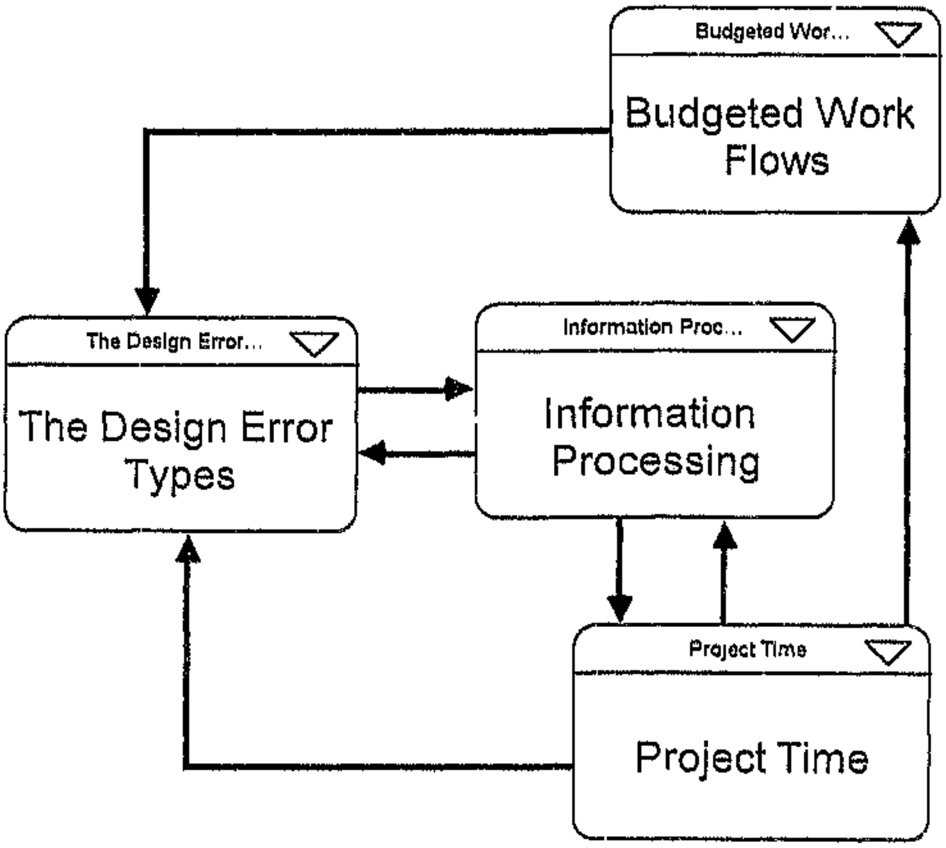


Figure 5.1 - The sectors in the error prediction model and their relationships

The second step in modelling was to specify the elements in each sector, and thirdly to specify the relationships between elements as mathematical equations. The objective in the three design environment sectors was to recreate (through simulation), what would count as normal events in the studied firm. In these three sectors the execution of several typical design projects are simulated over time, to

CHAPTER FIVE

ILLUSTRATIVE MODELS FROM THE THEORY

In chapter two, weaknesses in present error prediction and control methods were cited as reasons why a theory of design error causation is necessary (2.4). It was therefore necessary to demonstrate that the theory proposed in chapter four can be used for error prediction and control. This chapter presents some design error models developed in this study and illustrates the sort of process that can be used in applying them. The error prediction model developed is a System Dynamics model, implemented with the STELLA software (see 3.2.3). It enables a plausible representation of the relationships affecting design errors, and allows the effect of systemic changes to be simulated. This model is presented in the first section of the chapter. The error control models developed are SSM (3.2.4) representations of system logic, for defined viewpoints. They enable the assessment of existing systems with reasonable and cogent criteria, and enable 'optimal' system specification. These are presented in section 5.2.

5.1 AN ERROR PREDICTION MODEL FROM THE PROPOSED THEORY

5.1.1 An overview of the error prediction model

In developing the model there were three steps to carry out (see 3.1.2). First, the overall arrangement of the model had to be specified. This overall arrangement was on costs. And this is done without a thorough understanding of the emphasis and effect of each error control strategy. Competitive design is more common in such periods, with the attendant dangers of unusually loaded connections. Finally, the use of contract staff is more prevalent in times of economic pressure, and this is implicated in the causation of both draughting error types. There may be reduced professionalism amongst both draughtsmen and junior engineers, as design firms reduce salaries paid.

(9) From the standpoint of error prediction, it is clear that error likelihoods will have two components - the number of opportunities for an error; and the number of errors at each opportunity (error/opportunity ratio). The opportunities for each error type depend on the work task with which that error type is associated (see figure 4.11), and the content of each work task is easily estimated for a given project. The error /opportunity ratio is less easily estimated as it depends on the interplay of causative and intervening actions, for each error type (see figure 4.12). Opportunities for error will tend to increase from type I through to type VI; conversely, the error /opportunity ratio will tend to decrease from type I through to VI.

(10) Error prevention is not consciously practised at present. It is likely that systematic error prevention programs will lead to fewer incidences of error - at least for certain error types. However, looking at the error mechanisms for the different error types, it is unlikely that all errors can be wholly prevented. There will be a need for error detection as well, and error control procedures should seek to include both in a balanced manner.

concept). There is a need for further study on a means and format for recording the conceptualising process, which can be used on innovative projects.

(6) Failures from draughting errors are rarely catastrophic, but can be expensive. Calculation slips and computation mistakes can lead to collapse, but this will be rare. More often, the failures will be of the serviceability type. Conceptualisation errors of both types will be unpredictable in their results. These will probably lead to some of the more spectacular collapses. The issue is compounded by the fact that failures of innovative structures or structures going beyond the state of the art, tend to be highly publicised. Moreover, it is the larger firms that tend to handle such projects, and failures from conceptualisation errors cannot be waved off as 'inexperience'. Such failures have affected public confidence in the entire profession, in the past.

(7) A strategic means of preventing conceptualisation errors, is to assign only the most experienced persons in a firm to the conceptualising activities. Most firms are doing this already for overall structure concepts. (This is also the rationale behind the award of difficult projects to firms with proven track records). Connection conceptualising is far less obvious than member conceptualising and connection failures will often be more catastrophic, yet the former is often left to less experienced personnel than the latter. University curricula typically pay little attention to conceptualisation and to connections. Presently, more engineers are being trained in universities than before, and these will typically start halfway up the technical career ladder. Some of these will be senior engineers without having had sufficient understanding of concepts and connections.

(8) Economic difficulties lead to potentially risky periods in terms of design error. Firms will tend to diversify to ensure they have work, and so are more likely to take on work with whichthey are not familiar. Familiar error control strategies (e.g. independent calculation checks) are reduced in scale to save

4.4.2 Some conclusions drawn from the proposed theory

The following conclusions can be drawn in a general way from the proposed causation theory.

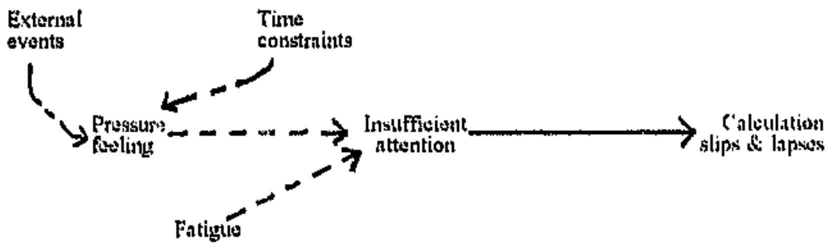
(1) All design errors result from interacting weaknesses in the abilities and states of mind of the individual(s) committing the error, in the design team (see 4.2.2).

(2) The key task of the leadership in a design firm (vis-a-vis error), may be view ' as the mediation of an interface between the design team members and the rest of the project. It is this 'mediation' (or error control) that determines how the project characteristics will (or will not) cause latent weaknesses in individuals, to lead to errors.

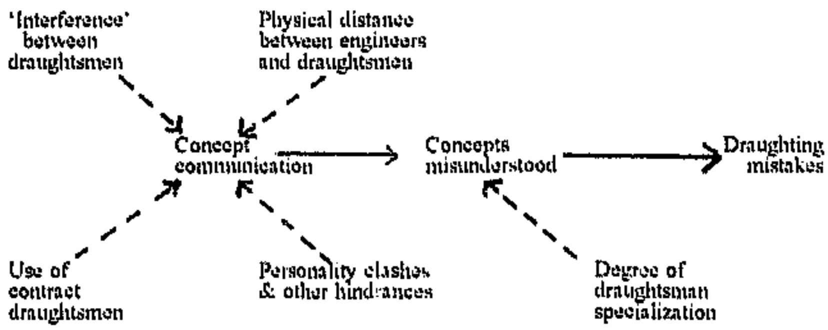
(3) The different error types require different approaches to error control. Error prevention is not consciously planned by design firm principals (perhaps because the causative mechanisms are not wholly understood), and the current emphasis is rather on detection via checking. Independent checks are adequate for error types IV, V and VI - calculation slips, draughting mistakes and draughting slips. They are less useful for type III errors (computation mistakes), except where computations are recorded in a specified format.

(4) The two conceptualising error types will be picked up by peer reviews, subject to the structural types being within the experience of the reviewers.

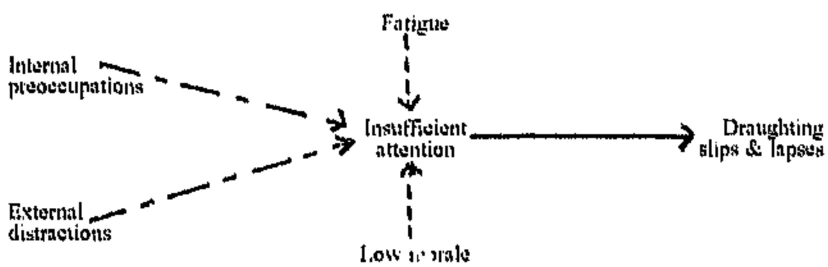
(5) Where the structural type is not within the reviewer's experience (innovative structures), conceptualisation errors are very difficult to detec· or prove. There is presently no accepted format for recording the thou ht processes in conceptualising, and in fact most conceptualisers do not record the process followed. They are mostly content to record only the end result (the resulting



(d) Causation of type IV errors - Calculation slips and lapses



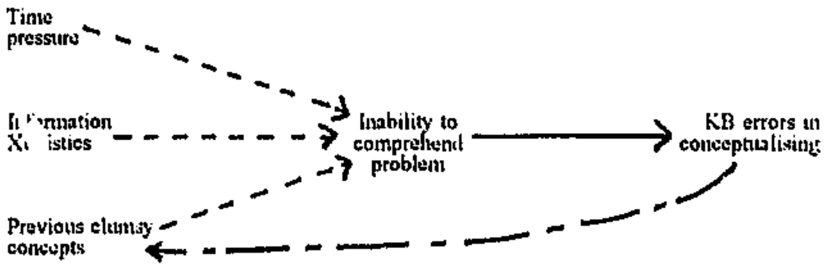
(e) Causation of type V errors - draughting mistakes



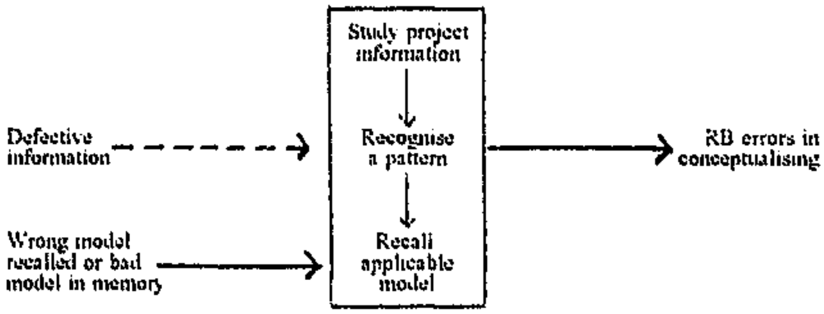
(f) Causation of type VI errors - draughting slips and lapses

Figure 4.12 (contd.) An illustration of the causation theory for each design error type

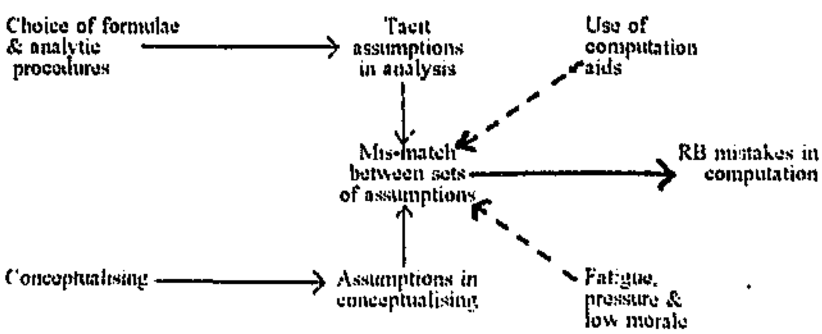
for each of the error types is summarized diagrammatically in figure 4.12. The full thick lines in figure 4.12 indicate basic causative mechanisms while dotted lines represent intervening actions. Thin full lines represent work task flows.



(a) Causation of type I errors - KB errors in conceptualising



(b) Causation of type II errors - RB errors in conceptualising



(c) Causation of type III errors - RB mistakes in computation

Figure 4.12 - An illustration of the causation theory for each design error type

4.4 IMPLICATIONS OF THIS CAUSATION THEORY

4.4.1 The main features of the proposed theory

The opportunities for each of the six design error types arise in distinct and different work activities. This is illustrated by figure 4.11 below which is an expanded version of table 4.2. The work flow shown in figure 4.11 refers to types of activity and not necessarily different people. Hence, one person could carry out the conceptualising of a connection, and then go on to analyse it and prepare the drawings.

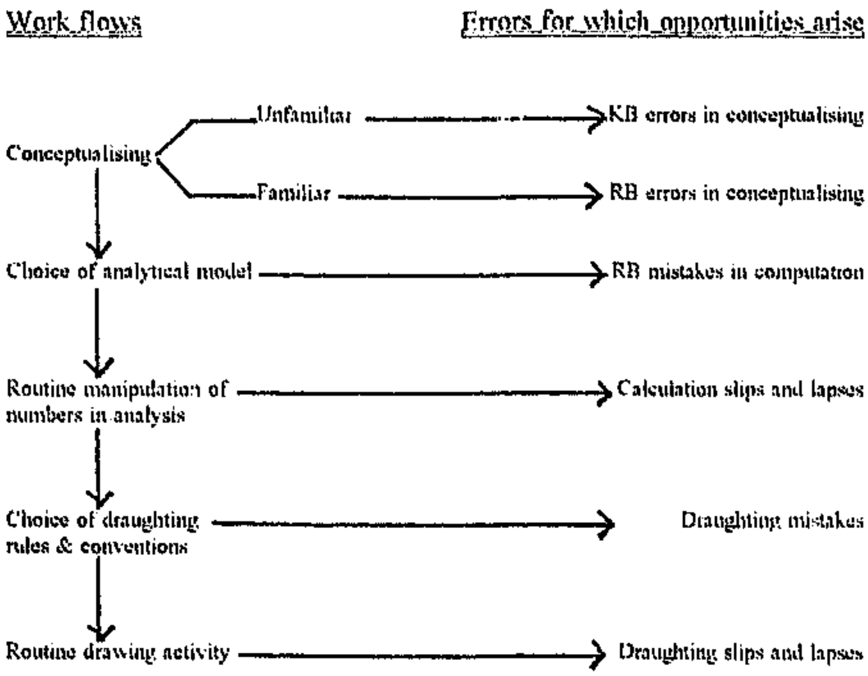


Figure 4.11 - An illustration of how error opportunities arise in work activities

Figure 4.11 has summarized the context for each error type i.e. how error opportunities arise. When an opportunity arises for some error type, the likelihood that the error will actually take place (error/opportunity ratio) will depend on the causative mechanisms and intervening actions. The theory of causative mechanisms

There is a particular problem of error-propagation in draughting. When an error (type V or VI), is made in a general arrangement drawing and it goes undetected for some time, it may be passed on to several other drawings (see FP's map). Depending on what the original error was, its effects could easily show up on twenty or more detail drawings.

Action strategies

One approach to preventing type VI errors is to remove distracting influences that could cause attentional capture. Hence, attention must be given to locating drawing offices away from distracting sights, sounds, smells etc. Yet there should be sufficient stimuli for the draughtsmen so that monotony and loss of attention (internal preoccupation) does not set in. Internal preoccupations are much more arbitrary - depending on the personal lives of the persons involved, but such preoccupations tend to be widespread during periods of social crisis or during national events. This may instruct the use of additional supervision during such periods.

Good supervision and personnel management are essential for high morale and well-motivated draughtsmen. The drawing office supervisors may not necessarily be the longest serving draughtsmen, or the most skilled, but should rather be chosen for supervisory skills. (However, professionals tend to respect skills and respond better to persons more skilled than themselves.) It would definitely be a worthwhile investment to train drawing office supervisors in supervisory skills.

draughtsmen are usually paid lower wages than engineers. A comparison with the classical motivation theories - Maslow, X & Y theories etc. - confirms that these are plausible reasons for motivational problems amongst draughtsmen[11].

Another explanation is that many projects tend to require more drawing hours than design (engineering) hours. Hence draughtsmen are more constantly under pressure, so that attitudinal problems become magnified. These generalizations do not negate the fact of individual personality. There are many draughtsmen who take pride in their work. However, there is definitely an impression created (FP & CJ), that dissatisfaction and discontent are likelier issues with draughtsmen, and tend to spread faster. Besides, these issues are more important for drawing than for the 'engineering' side, as it is easier to concentrate during conceptualising and analysis.

The use of contract draughtsmen was mentioned as being contributory to type V errors. There are other problems involved with using contract draughtsmen that are relevant here. Some of them are not used to working in groups (NC), and co-ordination problems arise. They may also leave projects before the end, leading to continuity problems. Others are sometimes unable to keep up their end of the work (FP), so that drawing production lags behind schedule. All these can contribute indirectly to the likelihood of type VI errors. Finally, contract draughtsmen may be more susceptible to the motivational problems discussed above, as they tend to have less loyalty to the firm.

The lack of suitable skills by draughtsmen will trigger both types V and VI errors, and this is not always the fault of the individuals. One respondent cited a case where a firm introduced CAD, and the principals thought they could save money by using school-leavers (matric level) to enter data. On the more general level, a less obvious (but potentially more dangerous) condition is that many firms have stopped training draughtsmen and engineers.

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[11]These two motivational 'theories' can also apply to junior engineers under certain circumstances. In some firms, junior engineers are restricted to certain types of members so that the work becomes routine and loses all creative challenge. They may also be poorly paid compared to senior colleagues, particularly in times of economic difficulty.

4.3.7 Type VI design errors - Draughting slips and lapses

Causative mechanisms

During those aspects of draughting that simply require the execution of well-known routines (drawing a line, looking up a table etc.), there is less need for constant concentration. Tasks may be carried out in an automatic manner. Of the three activity types in design - conceptualising, analysis and draughting, draughting has the largest component of such 'automatic' portions. If the draughtsman neglects to pay attention at a critical stage (an attentional check), the task could go awry and type VI errors result.

Typical type VI errors are the omission of details, transposing numbers and miscopying. These will manifest as wrong or missing dimensions, mis-alignments and lack of co-ordination between drawings. Where type VI errors are not picked up on time, the result is that structural components 'interfere' with one another and don't fit on site, leading to losses through delays and extra fabrication to rectify the situation (see maps for FP & CJ). Type VI errors will almost always manifest before the structure is completed, and rarely lead to collapse after completion.

Error context and intervening conditions

Something else occupying the attention (attentional capture) is the main context for draughting slips and lapses, causing the draughtsman to be less mentally alert and so omit an attentional check. These may result from internal preoccupations, or from external influences in the environment (see FP's map).

Intervening conditions that affect the mental alertness of the draughtsman are fatigue and morale. Motivational factors are apparently most significant for this class of errors (see FP's map). A possible explanation is that design engineers tend to work more on their own; the work is more creative and they take individual responsibility for their work. Draughting requires more of a team effort, and is less creative, hence individual draughtsmen are less easily fulfilled by the results of their work. Again, supervision. Some contract draughtsmen are not good at group work, yet they are mostly required on large projects where group work is essential.

Another intervening condition for draughting mistakes is the phenomenon of "interference" between draughtsmen on the same drawing. There is a maximum number of draughtsmen who can collaborate on any one drawing task, after which errors occur due to communication and co-ordination problems amongst them. This would typically be from 3 to 5 persons.

The degree to which a draughtsman is a specialist also appears to have an impact on how readily he/she commits type V errors (see FP's map). This probably reflects the tendency for a specialist to be more familiar with the draughting rules employed on a structural type and material. A specialist is also likelier to notice if the member or connection details are unusual.

Action strategies

The level of predictability of the design error types increases from very low levels for the first two types, to high levels for the last two. FP provided fairly definite estimates of errors expected for types V and VI, and their detection characteristics. When shop drawings are carried out within the premises of the consulting firm, type V errors 'hardly ever' occur. The number can increase significantly for drawings done elsewhere. In the studied consulting firm, all detail drawings done elsewhere are normally sent back for checking and approval. This checking is done by the section leader or the draughtsman responsible for the G.A. drawings, rather than the design engineers. FP described the error detection rate (type V) as 110 % i.e., the tendency is to detect even errors that are not there.

The obvious strategy for improving communication between designers and draughtsmen is to ensure physical proximity. At the institutional level, specific formats can be dictated for recording design concepts and calculations, and made mandatory for sensitive projects. This would probably increase the time (and cost) for design, but could lead to reduced safety costs for the entire industry.

Such simulations can be carried out to estimate changes in error likelihood from systemic changes. Say one wishes to compare the error likelihood indices for two possible systems - one currently in use, and another proposed. The simulation would then be carried out using values first for one system, and then the other. The error likelihoods obtained for each system, could be compared directly. Hence, the error prediction model enables estimates of the relative error likelihood (error/opportunity ratio) for two sets of systemic arrangements. Though the figures used to calibrate the model here were specific to the studied firm, one could easily change figures to suit other firms as needed. The intention here is mainly to demonstrate the process.

5.2 ERROR CONTROL MODELS FROM THE PROPOSED THEORY

In this section, models are presented that illustrate how the proposed theory of causation for design errors (section 4.3) can contribute to the task of error control. Since the aim is to illustrate the technique, models are developed for only one error type - KB errors in conceptualising (type I). As explained in 4.4, this error type has the greatest potential for spectacular and embarrassing failures.

The illustrative error control models are developed here using the Soft Systems Methodology (SSM). As described in section 3.2.4, SSM models are verbal-sentence representations of the logical activities in a human activity system. These activities are chosen as the logical consequences of adopting some relevant viewpoint, and are then connected in a di-graph to show their relationships. In this way, SSM prescribes the minimum details of activities and relationships in a human activity system, if that system exists to fulfil some relevant viewpoint. In this section, the methodology is applied to first the prevention and then the detection, of type I design errors.

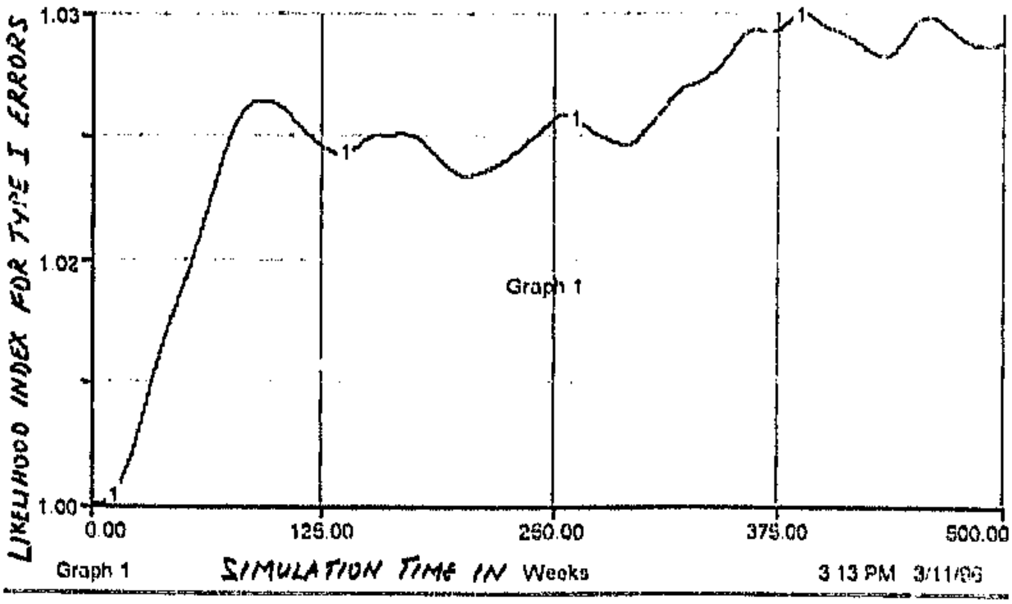

Figure 5.4 - Graph of type I error likelihood index over time, in a typical simulation run

Figure 5.4 is a graph of the likelihood index for type I errors over time in a simulation. In this simulation, all the various user-defined parameters have been set at default values or allowed to vary according to the pre-defined equations. Figure 5.4 demonstrates the typical form of the results of simulations. In the simulation for which this graph was obtained, all the systemic variables were set at their default values for the studied firm. In figure 5.4 therefore, a likelihood index of one refers to the likelihood of error under the present 'normal' or 'average' conditions in the studied firm. An index of 1.03 is an increase in error likelihood of 3% over the 'normal'. The variations occur due to everyday fluctuations in some of the variables. (These are modelled as default equations e.g. a normal distribution for structural complexity).

Time pressure was chosen to be a linear function of the difference between (outstanding) budgeted work and time left (to completion), normalized over budgeted work. (The budgeted work stock keeps an account of the work progress *as planned*, not as executed - see the budgeted work sector in Appendix D). Time pressure should grow with that difference (see section C.3). The equation parameters are chosen so that time pressure is zero when the time left is one and a half times the (outstanding) budgeted work. Conversely, time pressure is very high (ten) when the time left is only half of what is required for the outstanding work. A time pressure value of five would represent an 'average' pressure at which the work is going exactly according to schedule, (work left = time left).

The actual STELLA equation is:

Time_pressure = If [(Time_left <= 1) and (Budgeted_work > 1)] then 10 else [(10*(Budgeted_work - Time left)/Budgeted_work) + 5] *Eqn 14*

The first expression in square parentheses checks to see if there is less than a week left on the project. If the time left is less than a week then the pressure is very high (10), except if the outstanding budgeted work is also less than a week. When the time left is not less than a week the second expression in square parentheses applies. This is equivalent to the algebraic equation

$$\textit{Time pressure} = 10\left(\frac{B-T}{B}\right) + 5 \qquad \textit{Eqn 15}$$

where B is budgeted work and T is time left.

Finally, the likelihood index of type I errors is simply calculated as (1 - problem comprehension). When all the input variables are set to values of 5, this likelihood index is approximately one (1.005). The equation is given below.

Type_I_errors = Smth3((If (Time counter = 0) then 1.005 else(1 - Problem_comprehension)),50) *Eqn 16*

In equation 16 the Smth3 function of STELLA is used to smooth out rapid fluctuations in the likelihood index. Smth3 is a third order exponential smooth which is here performed over a 50 week period.

$$\textit{Problem comprehension} = 1.072(1 - e^{0.0022J(10\ S)}) \qquad \textit{Eqn 12}$$

Structural complexity (in the information processing sector - Appendix D) may be defined by the user on the simulation control panel, or a default value is used which is a normally distributed random variable - mean = 5; standard deviation = 1.67. This default assumes that most projects will have 'average' complexity (as defined by the user for his/her firm). The default standard deviation assigns a probability close to zero for complexities of zero and ten.

The correct information availability is also determined in the 'information processing' sector (Appendix D), and depends on the size of the project and the experience of the project managers (section C.5).

The judgement of the individual is conceived as a function of his/her innate ability (due to experience and training), and the time pressure on the individual (see 4.3.2). Innate ability must be the basic element here and it is modified by time. High pressure has the effect of lowering the judgement and this was assumed to be a linear effect. Thus, the STELLA equation (equation 13) was chosen so that extremely high pressure (ten) reduces the judgement to half the innate ability. At values less than average pressure (five), the judgement is unaffected[14].

Judgement = If (Time_pressure < 5) then Innate_ability else [Innate_ability* (1 - (Time_pressure/20))] *Eqn 13*

The innate ability of the individual to judge is measured on a scale of zero to ten (very poor to very good). It is determined in the type II error sub-sector as the average of the 'breadth of experience' and the 'quality of training'.

[14] Actually, some moderate level of pressure is required for peak performance (section C.2), so that at low pressure levels many individuals cannot give their best. However, there is some question as to whether this is true for judgement also. In any case, I found it more convenient to ignore any possible lowering of judgement at low pressure levels.

simplicity's sake, time effects are assumed to be dominant in generating pressure (cf. C.3 in Appendix C).

From section 4.3.2 problem comprehension is a function of structural complexity, judgement and the availability of correct information. (The effects of judgement and correct information availability overlap - 4.3.2 - and can be treated as being interchangeable i.e. only the one with the greatest effect need be considered). Problem comprehension was measured on a scale of zero to one, while each of the input variables were measured on scales of zero to ten.

A function was required to represent problem comprehension, such that comprehension is excellent (one) for low (zero) structure complexity and excellent (10) judgement (or information availability). Comprehension should also be low when complexity is very high (10) and judgement is very poor (zero). The relationship couldn't be linear as it didn't seem plausible. One would expect comprehension to still be high at average levels of complexity and judgement, and comprehension would only become low at fairly high levels of complexity and fairly low levels of judgement. For this reason, a negative exponential function was used to represent problem comprehension.

The exponential function was chosen so that problem comprehension is 0.75 when both complexity and judgement (or information availability) are 5; and is one when complexity is ten and judgement is zero. The STELLA equation is given below.

Problem_comprehension = 1.064*(1.05 - exp(0.0022*(10 - Structure_complexity)*(Min(Judgement, Correct_info_availability)))) *Eqn 11*

In equation 11, the min(a,b) function of STELLA always returns the value of the lower of the two variables in parentheses. Hence, the equation above would be written in simple algebra as equation 12 where J is the lower value of judgement and information availability; and S is structural complexity.

5.1.3 Details of the type I design error sub-sector

The three design environment sectors simulate the behaviour of projects and those factors in projects that affect design errors. As the values for such factors change, the various sub-sectors (six of them - corresponding to each error type) in the 'design error types' sector, calculate an error likelihood index[11] for each design error type. The reference behaviour (section 3.2.3) for each of the design error types was the same. The likelihood index of each design error may be expected to remain sensibly constant (or at least to fluctuate slightly about some mean) as long as there is no systemic change.

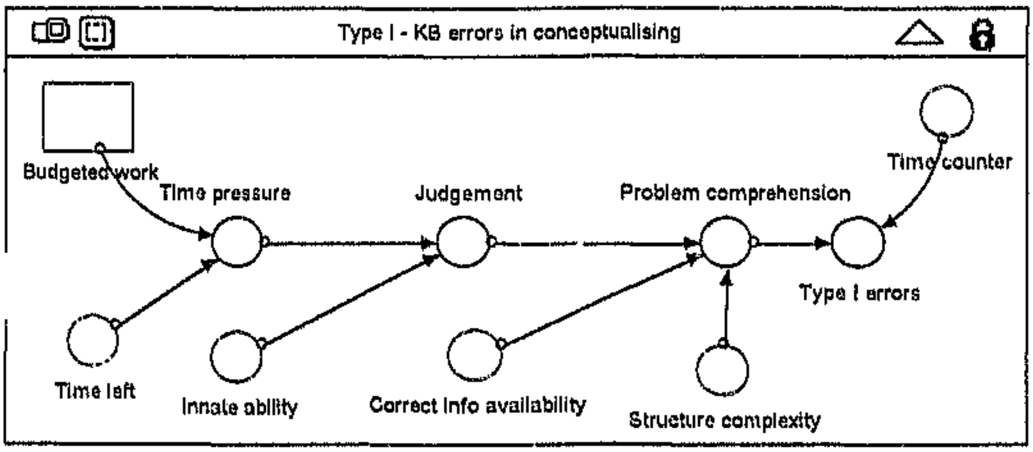

Figure 5.3 - Model elements in the 'Type I design errors' sector

Figure 5.3 shows the layout of the sub-sector for type I design errors - knowledge-based mistakes in conceptualising. From the theory of section 4.3.2, type I errors result primarily from inadequate problem comprehension. Also from the theory, the extent of problem comprehension is dictated by the complexity of the structure, the availability of correct information and the individual's ability to judge. The ability to judge in a given situation is then affected by the pressure on the individual. For

[11]This index measures the likelihood of design errors (error/opportunity ratio - see 4.4), with a different index for each error type. Since the parameters of the equations are only chosen, this cannot be said to be an absolute measure of the likelihood of design error. Values obtained for systems can only be interpreted relative to one another. 'Likelihood' is preferred to 'probability' in subjectivity-based probability.

random number, between the range determined by the first two numbers (a and b) in the function. (The third number is an optional seed that allows one to replicate the stream of random numbers).

The percentages quoted here are default values for the 'med job %' and 'small job %' converters. Thus, at the default values the first MONTECARLO function will return a zero at each dt for 80% of the time. When it does, the budgeted time will be a random number between one and six weeks. When it does not, the second MONTECARLO function is checked - and this returns a zero 98 % (80 + 18) of the time. If the second MONTECARLO function is zero the budgeted time is a random number between six and twenty-four, and so on.

Small_job_% = 80 *Eqn 8a*

Med_job_% = 18 *Eqn 8b*

These two equations are for the 'med job %' and 'small job %' converters which set the values for the montecarlo functions in the budgeted time converter. The default values are 80 and 18 respectively (leaving two percent for large projects), but these can be set to new values on the simulation 'control panel'.

Time_counter = COUNTER(0,(Project_Time + 0.2)) *Eqn 9*

In equation 9, the counter(a,b) function simply counts time units from the first part of the argument (a) to the second (b), and then resets to zero. In this way, the time counter converter was used to monitor how far the simulation of each project had advanced (elapsed time). The 0.2 factor added to project time was because the software was evaluating time counter a dt behind project time.

Time_left = If(Project_Time > Time_counter) then (Project_Time - Time_counter) else 0 *Eqn 10*

The time left converter (equation 10) monitored the time left to completion for each project by comparing project time with the time counter (elapsed time). Once the elapsed time became equal to the project time (adjusted for time losses), it would return a value of zero.

Time_losses = If (Time_counter = 0) then 0 else 0.5 * (Redoing_work + 1 - Real_work_rate) *Eqn 5*

Equation 5 is the equation for the time losses flow. When the converter time counter reads zero (at the start of a new project), there is no flow. Otherwise, there is a flow. In the second half of the equation '1 - real work rate' measures the deviation of the real work rate (rate of design production), from an average value of one (one week's work completed per week of elapsed time). The real work rate and the rate of redoing work (revisions), are determined in the information processing sector. When the revision rate is positive and the real work rate is less than one (low productivity), the time loss flow is the average of these two.

Reset_flow = If Time_counter = 0 then (-5 * (Budgeted_time - Project_Time)) else 0 *Eqn 6*

Whenever the time counter is zero (at the start of a new project), the reset flow obtains a new value for the (initial) budgeted time of a new project from the budgeted time converter, as shown in equation 6. In order to bring the project time stock to the same level as the budgeted time estimate, the reset flow calculates the difference and releases (or takes) that difference from the project time stock. Since the flow will only act for a dt (time counter will equal zero for only one dt), the flow must be multiplied by five - flow is in weeks /week (not per day).

Budgeted_time = [If MONTECARLO (Small_job_%) = 0 then (RANDOM (1,6,998))] else [(if MONTECARLO (Med_job_% + Small_job_%) = 0 then (RANDOM (6,24,996)) else (RANDOM (24,54,995)))] *Eqn 7*

As described in equation 7, the converter 'budgeted time' (for new projects) returns a random integer value between 1 to 6 weeks for 80% of the time. It will also return a value between 6 to 24 weeks 18% of the time and between 24 to 54 weeks 2% of the time. The MONTECARLO(a) function of STELLA draws randomly from a binomial distribution returning a value of zero for a given percentage of the time and a value of one otherwise. The percentage corresponds to the value of 'a' - the argument in brackets. The RANDOM(a,b,c) function returns a uniformly distributed yearly. These are typical numbers for the studied firm obtained from the secondary interviews with FP and CJ (see 3.1.2).

The project can gain or lose time through the flow 'time losses'. The 'time losses' flow is dictated by the efficiency of the team ('real work rate'), and the incidence of 'revisions' (see section C.3 in Appendix C, on availability of time). The converters 'time counter' (number of weeks spent) and 'time left' (number of weeks remaining to completion), are used to monitor the progress of the project from the project time stock. It is clear from section C.3 that these last two converters will determine the extent of pressure (from time constraints) upon individuals. Time pressure is causatory to types I and IV errors (sections 4.3.2 and 4.3.5), and is also related to other factors in the theory such as fatigue and morale (section C.2).

The actual equations used in the model are given below in the form in which they appear in the STELLA software. The equations in STELLA are written in what appears to be a proprietary brand of BASIC. Relationships between stocks and flows are interpreted by the software as difference equations, which are evaluated at intervals throughout each simulation. The iteration schemes available for these difference equations are Euler's method and Runge-Kutta's second and fourth order methods (High Performance Systems, 1994). I used the Euler iteration scheme throughout.

For the project time stock, the STELLA (difference) equation was:

Project_Time(t) = Project_Time(t - dt) + (Time_losses - Reset_flow) * dt *Eqn 4*

In equation 4 dt is the time interval between iterations (set to 0.2 of a five-day week - thus a day). The units in project time are in weeks. Time losses is a flow that adjusts the project time when time is lost or gained. Its units are weeks/week. The reset flow adjusts the stock at the start of each project to reflect the new (initial) budgeted time.

of time losses and gains, so as to know how much time is still required[12]. The layout of the elements in the project me sector is as given in figure 5.2.

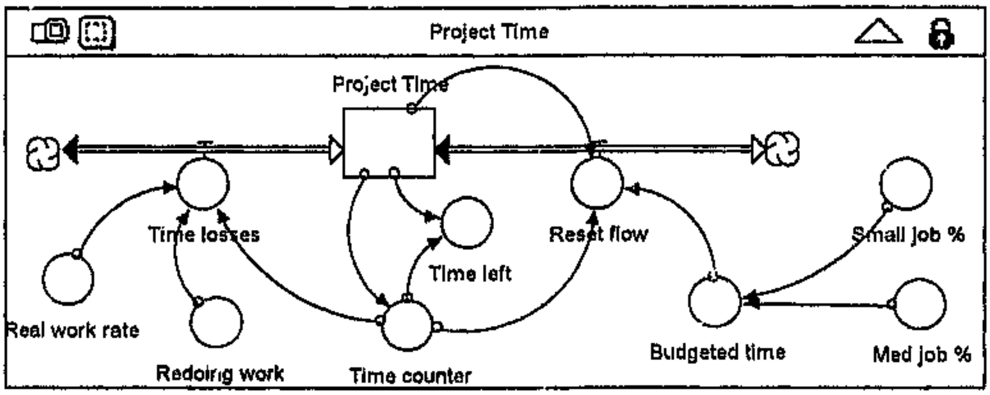

Figure 5.2 - Model elements in the 'Project time' sector

The central element in the project time sector is the stock 'project time' with two flows attached - 'reset flow' and 'time losses'. The time taken for each project is conceived as a variable resource. At the start of each project, the converter 'budgeted time' releases a number of time units (in weeks) into the stock 'project time' which behaves like a reservoir. Whenever time is lost (or gained), more time units flow into (or out of) this reservoir, thus increasing (or decreasing) the length of the project.

The initial budgeted time (released by the 'budgeted time' converter) is random, but will be large (24 - 54 weeks), medium (6 - 24 weeks), or small (1 - 6 weeks), for given percentages of the total time in a simulation. The percentages are user-specified in the converters 'small job %' and 'med job %', with defaults of 2% for large, 18% for medium and 80% for small. Thus, the default setting would lead to about 3 or 4 large contracts in a five-year simulation. It would also lead to about 7 to 9 medium sized contracts and anything from fifteen to twenty-five small projects

[12] In the budgeted work flow sector, the time budgeted for a project is converted into budgeted work (in manweeks). The sector also keeps track of how much time is left for the project, according to the original time budget. Information is input into design and processed at varying rates, within the information processing sector. These rates are real work rates (not budgeted work rates) which determine time losses and gains on the project. These sectors are described in greater detail in Appendix C.

During simulations, a 'control panel' is used to determine values for the various systemic factors so that one can explore different scenarios. The differences between likelihood indices for each scenario are then monitored on graph panels.

This model is specific to the studied firm. First because the theory (on which it is based) was derived for that firm, but more particularly, because the secondary data used in quantifying relationships is very specific to the studied firm.

In 5.1.2 the project time sector is presented as being representative of the design environment sectors. The other two design environment sectors are described in Appendix D. Most of the details for the design error types are also given in Appendix D, with only the sub-sector for type I (KB errors in conceptualising) being described here in section 5.1.3.

5.1.2 The 'Project time' sector

As described in section 3.2.3, the building blocks (elements) for System Dynamics models are (resource) flows, stocks (which are accumulating flows), and converters. These are represented as circles with spigots, squares and ordinary circles respectively. Double-line arrows are resource flows and single-line arrows are relationships. In the modelling, I have applied the principle of parsimony i.e each factor in the theory is described in terms of the fewest possible elements that allows me to reproduce its 'usual' behaviour. Hence, in modelling the design environment sectors, it is only those aspects that greatly influence one or more error types that have been included.

During simulations, the project time sector determines the time requirements for successive projects. It makes an initial budget for each project and then keeps track generate typical behaviour for the factors that affect design error (the causative mechanisms and intervening actions of 4.3).

The relationships modelled in the three environment sectors are based on the definitions given in Appendix C for the conceptual categories in the generic model. These relationships are objectively well-known in terms of their qualitative behaviour, and so it was easy to choose appropriate forms for mathematical representations. Hence, the rate at which information is input into the design process was modelled as an S-curve over time - a low rate of inflow initially; then much information comes later; then again it slows to a trickle towards the end of the project. (The slope of the S-curve was made a function of the experience of the project managers). The actual numbers used to calibrate the mathematical equations in the design environment sectors (abscissas, slopes etc.), were derived from the secondary data of quantitative estimates made by the experts (see 3.1.1 and 3.1.2).

The objective in the fourth sector on design error was to enable the calculation of an error likelihood index. This index is an arbitrary measure of the likelihood of each error type under a given situation. It enables a comparative assessment of error likelihoods across various alternative situations. The elements in the fourth sector were chosen to reproduce the theory proposed in section 4.3. The existence of the theory allows one to say that such and such an error type is more likely if such and such an event occurs; and less likely if it does not. Hence, it allows a *qualitative* understanding of relationships between factors in the theory - in a way similar to the 'well-known' relationships defined by Appendix C. Hence, one could propose mathematical relationships linking project phenomena (simulated in the other sectors), to error likelihood. The numbers for equations in this sector were mostly arbitrary. However, each error likelihood index was normalized over the value obtained when all design environment factors are set to the middle of their range. Thus, an index of one denotes an 'average' error likelihood. It was not felt that the indices (for the different error types) would be sensitive to the numbers chosen, since the emphasis is on comparison between situations.

Secondly, the explanations proffered in the theory from the experts' experiences, must be plausible. The theory must make sense in the light of whatever else we know about errors. Psychology provided an opportunity to define error categories from well-described behaviour patterns, and thus come to conclusions about mechanisms of design error causation. The mechanisms concluded have adequately matched the experiences of the selected experts. In the light of present-day psychological theories of cognition (Appendix A), those mechanisms are also quite plausible.

An important aspect of this theoretical development is the issue of context. The generic model of figure 4.10 is general in its presentation and application. It is not possible to state categorically that those elements will be so related in all circumstances or that these are the only elements in every situation. Nevertheless, one may say with some confidence that those elements will be applicable in a great deal of the design situations here in South Africa, and may be related in just this manner for the greater many. That generic model (section 4.2.2) is also independent of the error classification adopted in section 2.1.2.

When it comes to the details of the theory in section 4.3 however, that confident statement can no longer be made. The detailed theory of 4.3 is specific to the context from which those experts were drawn, which is why an entire section (4.1) is devoted to describing that context. To the extent that another design practice can identify with the characteristics and background of the firm described in 4.1, the theory of 4.3 will be applicable to them also. Secondly, the theory of 4.3 is tied to the design error classification of 2.1.2 and the conceptual categories described in Appendix C, since it is presented in those terms.

One consequence of regarding theory as a record of experiences is that the use of expert opinions, becomes perfectly logical (see also 6.3 ahead). There *is* however a problematic aspect to this. The theory is only relevant *now*. The experts have described what they have seen, not what is to come. The theory becomes suspect as soon as significantly large system changes are made, totally new measures are could be the result of poor training on the part of the draughtsman. Concept communication breakdowns are the most common reason for draughtsmen misunderstanding concepts. Such breakdowns are influenced by physical distance between draughtsmen and other members of the team; the use of contract draughtsmen; personality clashes and the level of specialisation of the draughtsman.

Type VI errors (4.3.7) are also caused by insufficient attention, but now in the routine drawing tasks. External distractions and internal preoccupations are contributory factors and motivational problems are considered important here.

The theory summarized above does not seek to establish some 'new' principles of how design errors occur. The design process has been refined over decades to what it is now, and the same principles have certainly been at work all along, differing only with the peculiarities of specific circumstances. What the theory does do, is to prescribe a coherent framework with which to fit together the various principles and so understand their inter-relationships. It is a record of our experiences in conceptual form. The intention is to foster greater insight into how errors occur in design, so that we can better see the implications of what we've been doing , and know why our procedures are successful or unsuccessful.

In proposing such a theory, I have adopted the position of the scientific philosopher Karl Popper. Theories are not p , they are only 'not falsified'. This is not *the* theory - some absolute statement of error behaviour; rather, it is to be considered a convenient framework which explains our experience in a plausible manner. Validation of such a theory is then dependent on the two words underlined in the last sentence. The theory must explain our experiences. If we observe a phenomenon that is totally inexplicable by this theory, then the theory is inadequate. Another way of saying this is that the theory must be *grounded* in the data (section 3.2.2). This is what I have sought to do. Within the given context of the experiences of the selected experts, the theory does match their experiences. I have sought to make my thought processes in generating the theory as transparent as possible. Hence my use of cognitive maps (3.2.2).

In section 4.3, the theory is elaborated in terms of the six design error types that were first proposed in section 2.1.2. The explanations proffered for each error type in section 4.3, were made in terms of the concepts and ideas in the conceptual categories of the generic model. The six design error types are:

- Type I - Knowledge-based mistakes in conceptualising.
- Type II- Rule-based mistakes in conceptualising.
- Type III - Rule-based mistakes in computation.
- Type IV - Calculation slips and lapses.
- Type V - Rule-based draughting mistakes &
- Type VI - Draughting slips.

It was found that type I errors (4.3.2) result primarily from the inability of an individual to comprehend the important aspects of a problem situation - because of the bounded rationality phenomenon (Appendix A). This is influenced by time pressures, wrong or missing information and the specification of clumsy concepts at an earlier stage.

Type II errors (4.3.3) result from breakdowns in the process of recalling models in the memory that are applicable to some present problem. This could be the effect of incorrect recognition of the problem character or because the model in the memory is actually bad.

Type III errors (4.3.4) are the result of mismatches between tacit assumptions in chosen methods of analysis (formulae and procedures), and assumptions in the conceptual models. The incidence of this error type is influenced by the use of computation aids and individual 'responses' such as fatigue, pressure and morale.

Type IV errors (4.3.5) result from insufficient attention (carelessness) during routine number manipulation. Fatigue and time pressures can influence these strongly.

Type V errors (4.3.6) are mostly caused by insufficient understanding of the concepts to be depicted during draughting, by the draughtsman. Sometimes though, these

CHAPTER SIX

DISCUSSION

In this chapter the results of the study are discussed in two sections - the theory proposed in chapter four (which is the main result of the study); and the models developed (in chapter five) to illustrate the use of the theory for prediction and control purposes. Some aspects of the methodology used to obtain these results are considered in the third and final section of the chapter.

6.1 A DISCUSSION OF THE THEORY

The theory developed in chapter four is the main result of this study and it is necessary to consider exactly what this theory is, and what it is not. In figure 4.10 (section 4.2.2), a generic model is presented for design errors in general. This generic model relates error phenomena to two conceptual categories (work-related abilities and attitudes/states of mind) associated with the individuals in a design team. It also relates error phenomena to three conceptual categories (time availability, work delays/revisions and information characteristics) associated with the environment of design. The meanings attributed to each conceptual category are explained in Appendix C.

individual members etc., to ensure faithfulness to the overall concept. There is some evidence that partners and senior engineers discuss concepts amongst themselves, but it is not clear that all aspects of any one concept are presented at such discussions. The supervising partner would probably discuss only those aspects he/she feels uncertain about. However, one might assume that totally new structural types and/or solutions would be discussed very extensively - *if the extent of departure from the usual is* recognized. In table 5.1, the 'procedures used' given for the firm are based on both the informal walks round the drawing office, and the discussions amongst partners.

The comments in table 5.1 are not an indictment of the studied consulting firm. In fact, the studied firm has a very good reputation in the industry for high error-free standards. What those comments do point to is that the systems in use for detecting type I errors are weak - first because they are informal and secondly because they are not systematic. The discussion in section 4.4 would suggest that this is probably similar to the situation in many other firms for type I errors.

In essence, we have a situation in which this firm has consistently avoided any major errors of the KB conceptualisation sort, but the details of how their various procedures etc. are contributing to this success are not clear to them. The firm cannot tell if there are areas of unnecessary waste or duplication in their formal and informal control schemes. More importantly, when changes are forced on them by clients, the economy or the climatology or even because of top-level personnel changes, the firm may find itself in the position of having to adjust human activity systems without knowing the exact effect or implications of each adjustment.

It should be borne in mind that opportunities for type I errors are relatively small compared with other error types (section 4.4). If a firm never does work of such a nature as to require extrapolation beyond their former boundaries, they might not need to consider type I error detection.

Table 5.1 - Judging the adequacy of type I error detection procedures in the studied consulting firm

THE ACTIVITY (Required 'what')	ACTIVITY OUTPUT	PROCEDURES USED (Observed 'how')	COMMENTS
(1) Select aspects of the problem, that are familiar, grouping them together.	Familiar patterns in input information, in commonly occurring groups.	Possibly done in informal 'brain-storming' sessions for overall concepts.	Weak. Informal procedures depend on the individual's discretion.
(2) Search for successful conceptualising solutions in past, for familiar aspects.	Identified concepts (and goals), used on past projects with 'similar' xteristics.	Searches of records of designs, during overall conceptualising.	This is not done as part of a checking process. The emphasis differs.
(3) Do concepts in the proposed solution, match those in the previous solutions?	A judgement as to whether present solution is similar to previous ones.	Mentally in self-checks; no evident procedure for some-one else to do this.	Self-checks are not always done. The same biases in knowledge- based reasoning (see Appendix A), that cause individuals to commit type I errors, make them unable to detect them.
(4) Check if aspects of the present problem invalidate the previous solutions.	A judgement as to whether concepts in past solution are still applicable.	Again only in self-checks.	
(5) Check if the steps in reaching each concept were carried out systematically.	A judgement as to the correctness of intervening steps to each goal.	Ditto.	Can't be done independently as conceptualizing steps not recorded.
(6) Classify the proposed concept as erroneous, error-free or unknown.	A knowledge of which concepts must be corrected, tested or accepted.	See paragraph des-cribing procedures in the studied consultancy, below.	Inadequate given the previous steps.

A consequence of this system is that the overall concept for the entire structure does not really get checked. This informal checking is being carried out for concepts on

5.2.3 Using an error control model for system specification - type I error detection

The activities defined for a human activity using SSM are subjective, and so are the viewpoints or world views modelled. What the theory does however, is to provide a basis for picking relevant viewpoints and activities in an informed manner. The subjective judgements are no longer based on simple intuition since the factors and mechanisms leading to error are now 'objectively' known in a qualitative fashion. The benefit of this lies in the fact that a firm can use this means (SSM) to specify the details of a human activity system say for error detection, and can be sure that the error control techniques chosen are consistent with an informed understanding of the issues, and are coherent. Additionally, a firm could use this means to study their existing systems and identify areas of weakness. This is done for type I error detection in the studied consulting firm, in this section.

In figure 5.6, the logical relationships between the activities are shown. These activities now provide a means for judging the adequacy of procedures in a structural design consultancy - see table 5.1.

In the studied consulting firm, there are two types of checking besides self-checks. Drawings are formally checked for types V and VI errors (see FP's map), and concepts and dimensions are checked informally. This informal checking consists of the supervising partner (or design engineer or senior draughtsman), walking round the drawing office looking at the emerging drawings - see CJ's map. Hopefully, the person walking round should spot any abnormalities. It is this latter procedure that would be expected to catch any type I KB errors in conceptualising. (Conceptualising during draughting is typically rule-based, and most errors in that phase would be type II errors).

The minimum and sufficient activities:

- Select those aspects of the problem that are familiar, and group them as they usually appear together.
- Search (the memory or other records) for successful conceptualising solutions in the past, corresponding to the groups of familiar aspects of the problem.
- Check if the (intermediate or final) goals in the proposed solution match the goals in the previous successful solution.
- (For cases where there is a match), check if there are aspects of the present problem that invalidate the previously successful solution scheme.
- (Where there are no invalidating aspects), check if the steps in reaching each goal were carried out systematically.
- Classify proposed concepts as erroneous, error-free or unknown.

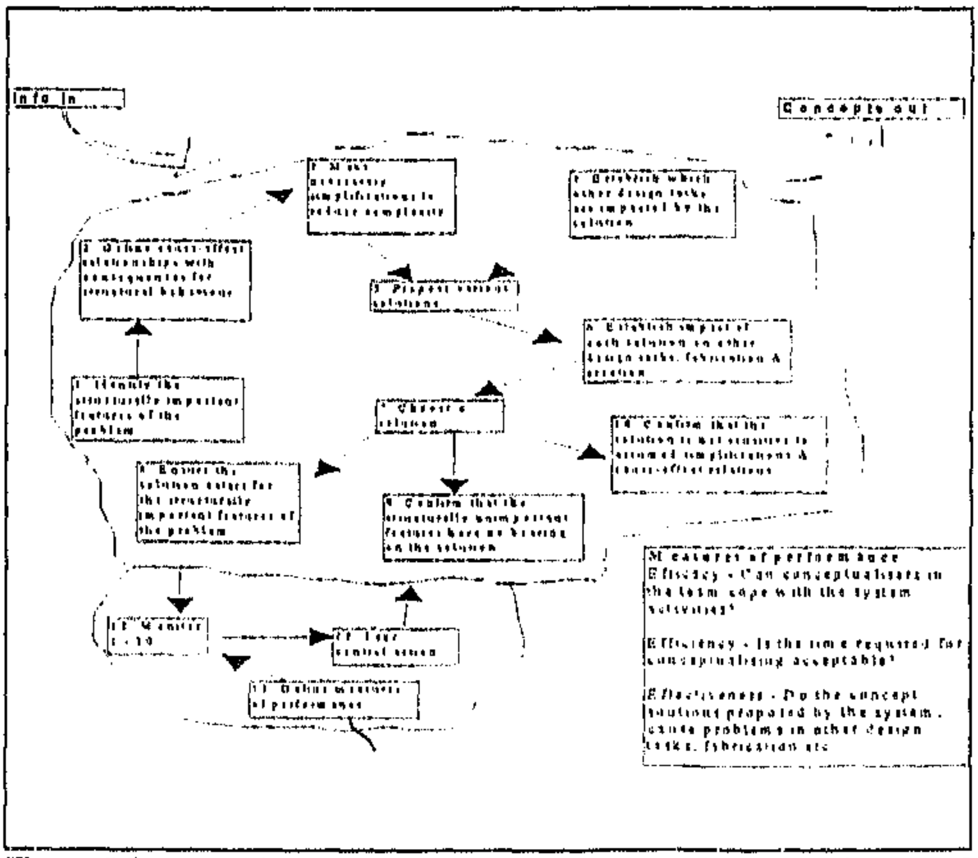

Figure 5.5 - An SSM conceptual model of a system for preventing type I errors

dependent either on one of two things. Either the checker is able to tell the form of a correct solution ahead (the goals), or he/she detects that the problem-solving has not been systematic (the means). (The second option is the only one used in self-checks of knowledge-based conceptualising). For the checker to know the right solution ahead, the problem must fall into the realm of his/her experience. Hence, for the checker, the problem is one of rule-based conceptualising even if it is only a loose or general rule.

One could adopt the weltanschauung (or viewpoint) that the independent detection of type I errors requires a pre-recognition of the correct form of the (final or intermediate) goals i.e. concepts proposed. This would obviously be relevant given the proposed design error theory. Then, the corresponding transformation for a system that fulfils this weltanschauung, will be as follows. "Correct concepts not recognised ⇒ correct concepts recognised". The details of this system are given below with the conceptual model in figure 5.6.

Root definition: A system owned by the partners of the firm and operated by the checkers of concepts, to cause the correct solution to a conceptualising problem to be recognised, and so detect type I errors; subject to constraints imposed by time and cost.

The elements in the definition:

Customers -	All persons whose tasks are affected by type I errors.
Actors -	The checkers of concepts.
Transformation -	Correct concepts not recognised ⇒ correct concepts recognised.
Weltanschauung -	Detection of type I errors requires pre-recognition of the correct concept solution.
Ownership -	Partners in the consulting firm.
Environment -	Constraints of time and cost.

activity). Such performance measures provide a basis for judging any selection of some particular techniques.

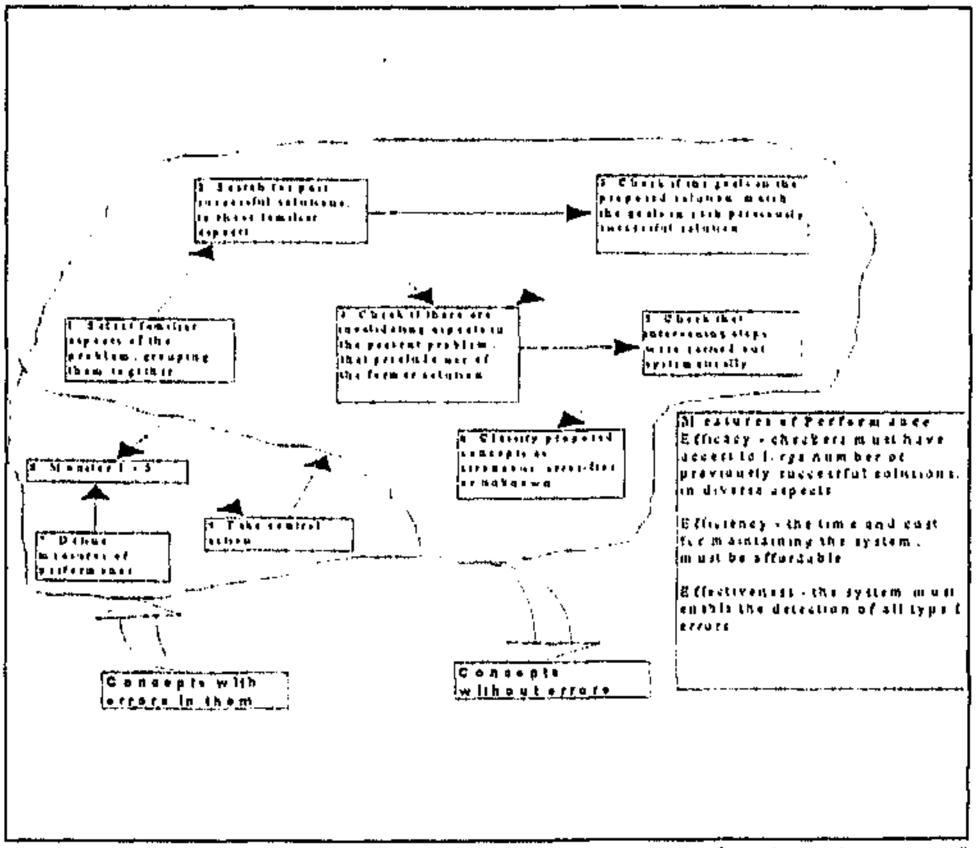

Figure 5.6 - An SSM conceptual model of a system for detecting type I errors

5.2.2 A system for the detection of Type I errors

There are two aspects to conceptualising (or planning in general): the specification of goals and sub-goals, and the specification of the means to achieve the goals. In section 4.3.2 and Appendix A, it is suggested that the detection of type I errors is

For the root definition above, the minimum necessary activities that must be included in this human activity system are as given below. Each of these emphasizes some verb that describes an action that must be carried out in the system.

- Identify those features of the problem that are structurally important.
- Define any cause-effect relationships (between aspects of the problem), that have consequences for structural behaviour.
- Make simplifications to reduce complexity as necessary.
- Establish which other design tasks will be impacted by the solution chosen.
- Propose various solutions (concepts).
- Establish the impact of each tentative solution on other design tasks, fabrication and erection.
- Choose a solution from alternatives.
- Ensure the solution caters for the structurally important features of the problem.
- Confirm that the 'structurally unimportant' features have no bearing on the solution.
- Confirm that the solution is not sensitive to assumed simplifications and assumed cause-effect relationships.

These activities are obtained from considerations of the mechanism for type I errors (section 4.3.2), and the general mechanisms for failure in knowledge-based reasoning (Appendix A). Besides these 'technical' activities, every 'viable' system will include the management activities required for proper system control. The conceptual model for this system is shown in figure 5.5.

The three control activities of defining measures, monitoring and taking action, are basic to all viable systems (for teleonomic behaviour - 3.2.4). Some suggested measures of performance (for control purposes) are in the box in the right-hand corner of figure 5.5. The model prescribes the activities to be carried out in the human activity system (though it says nothing about the specific techniques for each

5.2.1 A system for the prevention of type I errors

In developing the conceptual model of a system one must first determine a *root definition* for the system. This is a statement of what the system is to be. For the prevention of type I errors, a relevant viewpoint would be that 'type I errors result from poor comprehension of the problem, when conceptualising'. This of course is drawn from the proposed theory in section 4.3.2. For this stated viewpoint, one could adopt the following root definition of the type of system that would be required to prevent type I errors.

Root definition: "A human activity system controlled by the head of a design team (supervising partner) and operated by the various conceptualisers in the team. to cause conceptualisation problems to be adequately comprehended when they must be solved by knowledge-based reasoning, so that type I design errors do not occur".

Within this root definition it is possible to identify the following elements, which are required for a 'well-rounded' definition (see 3.2.4).

C - Customers or (direct) beneficiaries of the system: Other phases in the design process after the conceptualisation, and fabricators/erectors. This is implied by the phrase 'so type I design errors do not occur'.

A - Actors or operators of the system: The various conceptualisers in the team.

T - A transformation which is the heart of the system: The transformation here is 'problem poorly comprehended ⇒ problem well comprehended'.

W - The Weltanschauung or world view (viewpoint): Type I errors result from poor problem comprehension when conceptualising.

O - Ownership of the system: Those with power to close it down such as the supervising partner.

E - Environmental constraints: the 'givens' in the situation: The limits of working memory capacity for individuals, as implied in the reference to knowledge-based reasoning.

again inductive but there are sound management principles which must be adhered to in these choices. These principles as well as my design error theory, guide the process. SSM (3.2.4) is an inductive methodology with the same benefits mentioned for System Dynamics and STELLA above. Choices are transparent and repeatable and are made for a particular context (or perspective in this case).

6.3.3 Results not as expected

Besides the early data collection problems discussed in chapter three (3.2.1), there was a later unexpected difficulty in the data collection process. I found that the cognitive maps tended to become very complicated, and some of the experts had difficulty understanding them. This may be because engineers are not familiar with qualitative techniques. At any rate, I decided to play down the role of the maps. This meant a reduction in benefits since the visual aid to negotiation is an important aspect of cognitive maps (3.2.2).

Some experts were more informative than others - perhaps because of differences in fluency or in commitment to the study. Since each expert was chosen to represent a certain perspective, it has resulted in some parts of the theory being less developed than others.

In those relationships in the simulation model that required the union of two 'probabilities', I invariably assumed independence. This simplified the relationship to a straightforward sum. For example, the likelihood index for type II errors (Appendix D.3) was conceived as the union of the likelihoods of 'wrong structure recognition' and 'incorrect model selection'. In the model, this is simply represented as a sum.

inductive approach argues that it would be more rational to include all the information at our disposal instead of ignoring our experiences. However, the choice of model families and interpretation of results must be explicitly regarded as choices.

The question may be asked, "how do my intuitive choices differ from the subjective choices in the traditional probabilistic models of chapter two?" The answer is in the handling of subjectivity. First of all, the choice of the significant relationships is not arbitrarily mine alone, but the result of plural judgements by experts in that situation. I do not claim a domain of applicability for those judgements beyond situations similar to those described for my experts. The traditional models do not spell out the context of their expertise (which determined their choices), and so imply that their choices are relevant in all cases.

Secondly, in modelling each relationship, it is true that I chose both the mathematical model and its parameters myself. However, by explicitly acknowledging these aspects as choices, inductive approaches could be used (System Dynamics & STELLA - 3.2.3), that are developed for just such situations. The choice process has therefore been made transparent and repeatable - essential qualities for model 'validation'. The traditional models do not explicitly acknowledge that they made 'choices', and are formulated as though they seek to depict a 'reality' of error likelihood. But probabilities are really only a convenient mathematical abstraction - they lack external reality. It is therefore justifiable to *define* a 'probabilistic' measure for each of the error categories (in this case a likelihood index), as long as this is done in an internally consistent fashion. The choice process adopted is consistent across the variables, and the calculated error likelihoods may be seen as relative values consistent with those choices. The inductive error prediction model then, is simply a useful way of representing a situation to compare the error potential of various systems.

Finally, the SSM error control models are logic-based in the choice of system components and their relationships. It is not the formal theorems of mathematical logic being employed here, but the logic of good business practice. The process is probabilities, and also tend to remember recent events better, or events that made a striking impression at the time. The use of biased expert *opinions* (as distinct from expert '*recollection*', e.g. Stewart, 1993), may be justified on the following grounds. From the perspective of making engineering decisions, it is more important that data is internally consistent than that it accurately reflects external reality. It is also easier for most persons to accurately describe their *opinions* of how error occurs, than to numerically estimate probabilities of various events - unless they have received training in doing so (De Finetti, 1972 - Ch 3). I therefore gathered data on expert opinions of how errors occur, supplemented with expert recollections on well-known phenomena (not errors), such as how often the firm has large projects.

6.3.2 Subjective choices in the illustrative models

The error prediction model is based on inductive choices rather than deductive estimates. Deductive models start with a defined (probability) model, whose parameters are established from empirical data. The parameters are then manipulated using established axioms to obtain a probability of failure (or error). The result is taken to be a mathematical estimate of reality. Veneziano (1976) discussed this process in relation to structural safety and pointed out that deductive probabilistic models are based on unstated and arbitrary assumptions by the modeller, in his/her choice of a family of models (eg. Normal, Poisson, Binomial distributions). Moreover, the parameters for a given distribution are statistically variable when there is little empirical data available.

On the other hand, there is often a whole body of "intuitive" information (actually the sum of our past observations), which is ignored by the deductive modeller because it is subjective. This is not a problem in say electrical circuit theory, where the governing laws are well known and tightly defined. In structural safety and particularly human error, there are few laws - moreover empirical data is scarce. The

The chief argument against the use of expert opinions is that they are subjective. In response to this, the answer may be given that so is most of the structural design process. Subjective judgements and the use of engineering judgement have always played an important role in structural engineering (see Blockley, 1980 & Armitage, 1981). Despite the introduction of sophisticated reliability techniques in code-drafting, design codes are adjusted so that they produce design solutions that are intuitively satisfying, and in harmony with established practice. When this is not done, the drafters meet with resistance from experienced engineers. Besides all these, structural design and reliability deal with unique objects. In such circumstances the frequentist interpretation of probability is meaningless, and probabilities can only be understood as the exercise of a subjective judgement. Hence, subjective opinions are a feasible foundation for an error theory that seeks to enhance error prediction and control.

There *are* drawbacks to subjectivity and expert opinions. The opinion of a given expert may be considered as the summary of an unknown number of observations over a period of time. There are questions on bias in observation that can be raised. One of these is that no one person's experience can be expected to cover every possible case. A related issue is the fact that expert testimony will usually include "unspecified assumptions, background meanings and tacit knowledge" (Pidgeon et al, 1991). Hence the adoption of the soft paradigm (2.5.1), where we approach qualitative data with the explicit understanding that expertise is linked to its context, and an analyst must "negotiate" and interpret meanings with the expert(s). This is why the experts were taken from the same firm to ensure that their backgrounds are similar. In this way, the testimony of four experts from different stages in the design process, are all based on the same contextual setting. The results derived from their testimony will be directly applicable to firms with similar characteristics.

If an expert is asked to assess error probabilities from experience, or to count the number of times he/she has witnessed a given error phenomenon (as in Stewart, 1993 for example - reviewed in 2.2.2), there would still be biases present. It is well known that respondents tend to be conservative in their estimates of future

First of all, the involvement of practising professionals with various facets of the human error problem is practically an everyday occurrence. As such, professionals who have spent a considerable length of time in design situations will have observed many errors. If in addition to length of service, a professional acquires such status and reputation in his/her career as to be accounted an expert, then he/she is obviously doing something right. At some level - be it intuitive, subconscious or deliberate - the professional is managing the risk of error in an adequate manner. Such an individual has some knowledge of the human error problem, even if it is not consciously-held knowledge.

Secondly, as explained in 2.2.1 objective accounts of errors tend to be rather few. People are loath to admit to specific errors on specific projects for fear of litigation. Moreover, difficulties are experienced with summarizing error data into clear distinct categories in databanks. Added to this is the complication of establishing the details of human interaction on specific projects, in cases when the projects are completed and the details are forgotten. Project documents are better than technical reports in their conveyance of non-technical issues but these are rarely available to researchers without restrictions. What all this boils down to, is that expert opinions represent a rich repository of information on human error, which it would be difficult (if not impossible) to get elsewhere. Pragmatism alone dictates that this wealth of information be tapped. It can be seen in 2.2.2 that error prediction models have been moving in this direction.

Besides the reasons given above, the use of expert opinions meant that this study was not limited to failed projects. Errors that are seen to cause failures are only the 'tip of the iceberg' (e.g. Nowak & Carr, 1985). To focus on such would immediately limit us to a very small population, with an in-built bias towards more 'obvious' errors in 'spectacular' failures. When an investigation of errors on a failed project is based on expert testimony (or recollection), the data is more likely to be tainted as each person will seek to justify his/her role.

manifestations of the activity. For these reasons the comparison process was demonstrated with the error detection model.

In my detection model for type I errors, there is the implied assumption that conceptualisers will only go out of their experience in small extrapolations at a time. (It would be difficult to pre-recognise the goals in situations involving widespread departures from experience). While this assumption is not necessarily always true, it is at least in accordance with practice in most firms.
The comparison in section 5.2.3 shows that the detection procedures for type I errors in the studied consultancy, are largely informal. The emphasis seems to be on hiring experienced persons who can 'carry responsibility', and depend .n each person to avoid or self-detect, possible mistakes. This may be a response to the climatology of the last decade in which a decline in the economy has prompted firms to tighten up on expenditure. Independent error detection is perceived as expensive and unnecessary (except for drawings), in this firm. However, for projects that are complex, an informal approach to detecting type I errors is probably not the best choice.

6.3 A DISCUSSION OF CRUCIAL ASPECTS OF THE METHODOLOGY

6.3.1 The use of expert opinions in deriving theory

The primary source of data in developing the design error theory was expert opinions - the opinions of persons who could be reasonably considered experts in some aspect or the other of the structural design process. This choice was dictated by the following considerations.

of all, does *it* express a relevant viewpoint? If one happens to think a particular weltanschauung is cogent, then the model is useful. The second point is whether or not the listed activities are necessary and sufficient, and whether or not they are accurately related to one another. That is, are the activities logical?

In this study, the viewpoints relate directly to the topic of the dissertation, and so are relevant *from my perspective* (i.e. 'design error is worth investigating'). The viewpoints used in the two models derive directly from the theory of chapter four. If it is granted that the relationships described in that theory are plausible, then these viewpoints are relevant in a wide variety of cases, and are clearly relevant to the studied firm.

The other criterion is the logic - of the choice and arrangement of activities. The logic used for the activities in the models of 5.2 was based on the theory of chapter four and Reason's theory of cognitive processes in Appendix A. Reason's theory is representative of current thinking in Psychology on this issue.

In using the SSM models for error control, comparisons with existing systems are an important aspect. If some of the activities in the model lack counterparts in the real world (as in table 5.1), that would imply one of two things. Either the owners of the system do not perceive the viewpoint expressed in the SSM model as relevant, or they have not thought through the implications of the viewpoint. The latter is likelier to be the case when one is careful to model truly relevant viewpoints. This is particularly so, as there has been no systematic means of specifying required systems (before now) in error control situations.

I did not carry out a comparison for the error prevention model. In the studied firm, it appears error prevention has not been conscious consideration as such. Of course it is an underlying consideration in the existing procedures, but has probably never been explicitly considered in this manner. Type I error prevention in particular seems to have no defined procedures. If the activities in my model are carried out in the thought processes of individuals, in many instances there are no visible theory of section 4.3.2. The activities deemed to be logical for such a system were also suggested by 4.3.2 and Appendix A.

Similarly, the perspective modelled in the type I error detection model (5.2.2), was that 'the independent detection of a type I error requires a pre-recognition of the correct concept solution'. Again, this came from the theory of section 4.3.2. In section 5.2.3, it was illustrated how such models can be used to judge the performance of existing systems, by comparing the type I error detection model specified in 5.2.2 with existing systems in the studied consulting firm. It was concluded that the existing systems in the studied firm are weak due to their informal and unsystematic nature. Such weaknesses could manifest as larger error probabilities (type I) when forced changes occur in the firm. They could also manifest as inefficiencies and money lost. It should be noted however that opportunities for type I errors are much smaller than for other error types (see 4.4).

There is no such thing as the model for a given human activity situation, just as there is no one viewpoint that is the viewpoint in the situation. (It is sometimes necessary to cater for more than one viewpoint with multiple models, in order to better appreciate the interaction of activities.) For example, I modelled a system to prevent type I errors from the perspective of preventing poor problem comprehension. An alternative would have been to perceive type I errors as a problem of co-ordinating and managing information input, or as a case for avoiding knowledge-based reasoning altogether. The former would not be pragmatic since the consulting firm only influences information arrival indirectly. The latter would be unreasonable for some firms; say where there is a policy to go for innovative structures. Nevertheless, both viewpoints could be relevant under different circumstances.

It follows from the above that SSM conceptual models are not validated in the usual sense. The model simply expresses the logical implications of a certain perspective of the situation. It is therefore neither right nor wrong, in the usual sense of these words. There are two points to consider in assessing an SSM conceptual model. First linear function of time left and work left. Even though time pressure is abstract, this is clearly a good representation of its behaviour.

The actual equations relating the design environment to the design errors follow from the theory. The theory gives sufficient guidance as to the form of the equation, and the parameters are chosen arbitrarily to be plausible. This is allowable if it is borne in mind that the values obtained are only an 'index' of error likelihood, and not 'absolute' measures of likelihood. For example, I modelled type I errors as the direct result of 'lack of problem comprehension'. Once I obtained a likelihood for lack of problem comprehension, I had a likelihood index for type I errors.

In this model, I have emphasised the occurrence of errors throughout. Error detection is not included at all since the intention here was simply to illustrate the process. Error detection would obviously modify the behaviour of some variables since it can affect occurrence mechanisms. Perhaps that could be included in another study.

6.2.2 The SSM models

As described before (3.2.4), SSM is used to investigate the logical requirements of systems to fulfil some relevant viewpoint. The outcome is a model that specifies the activities that are required in a problem situation, to fulfil the mentioned viewpoint. Unlike the predictive model which tries to represent causative mechanisms accurately, the SSM models ignore causation and focus on control.

SSM was applied in 5.2 to the specification of human activity systems for the prevention and detection of type I errors. The prevention model specified (5.2.1) was a model of the following perspective - that 'type I errors result from poor comprehension' of a conceptualising problem. This perspective was suggested by the

The validity of this error prediction model is to be considered in two parts. Firstly, how valid are the causal interactions defined by the model? This is answered by the question, 'how valid is the theory', since the model derives directly from the theory. That is a very significant difference between this predictive model, and the ones reviewed in the literature (2.2). The relationships are not arbitrarily from one person's experiences alone, but from experts at different levels of design. Moreover, the context within which the theory is credible is clearly defined.

The second part of the validity issue may be phrased as follows. How valid are the mathematical relationships used to describe the causal interactions? I chose the relationships; how can those choices be justified over other alternatives? In all modelling the aim is to use simplified representations of reality. The simplifications are chosen so the model is amenable to the required manipulations, while retaining the ability to adequately reproduce the behaviour of some desired facet of the situation. I likewise chose my equations to reproduce a 'reference behaviour pattern' (3.2.3).

For the design environment sectors, I had to reproduce patterns of behaviour for project time, information input, work rates etc. However, this was much easier than if I had tried to stipulate behaviour patterns for design errors directly. That is because the behaviours of these externally observable factors *are common knowledge*, whereas error likelihood or probability only an abstract concept and is not externally observable. (Since there is no statistical data it cannot be inferred by normal statistical means)[15]. So for example, I modelled the planned progress of work (budgeted work - Appendix D.2) as a stock that 'dissipates' at exactly the same rate as simulation time i.e., for every week of simulation the project (as planned) advances by a week. Again it was straightforward to conceive time pressure as a

[15] In the error prediction models of section 2.1.2, modelers like Lind, Nowak and Melchers were trying to stipulate equations directly to reproduce 'the reality' of how error likelihoods occur. Yet, there are few measurements (statistics) of error likelihoods. In this study, I have stipulated equations of how information arrives, time passes etc. (These are better known phenomena and the experts could easily quantify most of these, e.g. number of large projects a year; extent of information that is typically available). The ways in which these factors lead to design errors are recognized in the proposed theory (4.3). *The occurrence of the factors could therefore be simulated and error likelihoods calculated.*

provided estimates of conditions in their own firm that were used to calibrate those sectors.

The fourth sector consisted of six sub-sectors corresponding to the six design error types. The theory of section 4.3 provided the details of elements in these sub-sectors and allowed the prescription of mathematical forms to describe the important relationships. The equations were calibrated to provide error likelihoods of one at average conditions (see 5.1.3).

When the error prediction model is used in a simulation, the design environment sectors simulate the normal inter-relationships of factors surrounding the design team, in the project and in the design firm. As these factors change, the design error sub-sectors will calculate the likelihood of each error type, and monitor changes in that likelihood for the entire simulation period (5.1.3).

The figures being obtained in the design error sub-sectors during simulations are to be interpreted as indices of error likelihood changing in response to systemic changes. The probabilistic interpretation suggested by the word likelihood results from the fact that some of the modelled relationships are of the 'intervening' sort. These are not directly causatory though they influence causation. The outcome of such an influence is not always definite. It is rather a 'probability' effect.

The values calculated for the likelihoods are not absolute probabilities. Hence, they are merely indices which can be interpreted relative to another likelihood obtained in a similar manner. The usefulness of such a model is in situations where comparisons are to be made between alternative systems. The model then provides an indication of which system is more likely to produce errors of a certain type, and by how much this is so. The use of such indices is common in situations where absolute probabilities are difficult to estimate. In structural reliability for example, the reliability index β is used to represent failure probabilities.

tried or a different engineering climatology evolves. When large changes occur, the theory is bound to prove inadequate in some respect sooner or later. It then becomes necessary to modify it to cater for those new experiences.

This last limitation does not imply that the theory is tied to the present state of knowledge in structural engineering. The underlying theme in this study has been that design errors result from systemic causes (rather than technical ones). For example, if it is discovered that the design methods for fatigue are inadequate, it would not affect the theory proposed in 4.3 significantly. This is true inasmuch as errors (as defined in 1.5), occur only within the boundaries of the 'state of the art'.

6.2 DISCUSSION OF MODELS DEVELOPED TO ILLUSTRATE USE OF THE PROPOSED THEORY

6.2.1 The error prediction model

An error prediction model was developed in 5.1 for the design environment and the six error types, to illustrate the use of the theory. The model was developed as a System Dynamics simulation model using the STELLA software (see 3.2.3).

There are four sectors in the model developed. Three of these (the project time, information processing and budgeted work sectors) correspond roughly to the design environment of the generic error model in 4.2.2. The various ideas modelled in these three sectors are therefore described in Appendix C. These are well-known phenomena; even though they are only known in a qualitative manner. Nevertheless, it was possible to prescribe mathematical forms for the relationships within those sectors from the well-known characteristics and Appendix C (5.1.2). The experts

(B) If no please explain the involvement you have had with the structural design process.

3. Please describe the stages in your career up to the present, including dates and the following information for each stage.

(A) The firm (B) The work they do (C) Number of employees

(D) Your job (E) Your involvement with structural design

(F) The types of projects, structures and materials you worked on personally (see attached list of structural types).

4. Please tell me the name of the last school you attended the qualification received.

5. Please explain any involvement you have with professional organisations and societies.

6. When was the last time you attended a training course? What was it called and who organised the course?

7. Please mention other courses you have attended - particularly those related to structural engineering.

SECTION II

This section seeks to establish the particular areas in which you have had intimate experience of the design process. This will allow us to concentrate on the areas you are most comfortable with and avoid less important topics.

The figure 2 (attached) is a list of activities that are directly related to the production and implementation of structural designs. These activities are referred to here as design tasks, and the questions in this section will be based on this list.

APPENDIX B

FORMAL QUESTIONNAIRE USED IN 1st SET OF INTERVIEWS

SECTION 1

The aim of this section is to establish general information about yourself and youı career background. These ba(kground details are often factors in understanding and analysing your answers.

If you have not been in your present job/position for up to six months, you should refer to the previous position in answering the questions related to your job.

Questions

1. Choose an answer from the following options that describes the organisation/firm you are working with presently.

   (A) Client firm | (B) Structural design consultants

   (C)Contractors | (D) Research institute

   (E) Project managers | (F) Other (explain).

2. Does your firm produce structural designs?

   (A) If yes then answer the following questions.

   (I) Are you directly involved with structural design?

   (ii) Please describe any other type of work your firm is involved with outside structural design.

   (iii) Estimate the number of employees in this firm and the number involved in structural design.

   (iv) Please describe the organisation of this firm e.g. the types of sections, departments, branches etc.

The opportunities for slips (and lapses) are greater than for any other error type, but the error/opportunity ratio tends to be low. At the other extreme there are fewer opportunities for knowledge-based mistakes than other error types, but the error/opportunity ratio is higher than any other. Rule-based mistakes are in between these two. Again, slips and lapses tend to be easily quantifiable, while mistakes are often very difficult to quantify.

Slips may be detected when an attentional check is made later, but there have to be cues to alert one to the earlier slip. In knowledge-based reasoning, mistakes are often detected by the results. Mistakes at the strategic level (the goal selected), are more difficult to detect than those at the tactical level (the means selected). Error detection is therefore easier where the correct solution is recognisable in advance.

Slips and lapses are detected far more easily than mistakes of both types. Slips are usually detected as the person sees a similarity to previous errors (direct error hypothesis - DEH). Rule-based mistakes are detected partly by DEH episodes and partly by error suspicion (ES) - 'something looks funny'. Knowledge-based mistakes are only picked up by standard checks - systematic checks of procedure.

(previously informative signs are preferred to rarer countersigns), and strong rules (frequently encountered rules are preferred).

Knowledge-based mistakes result from the bounded rationality phenomenon and they can take three forms: problems with judgement, problems with causality and problems with complexity. Judgemental problems arise from selective processing of task information when attention is paid to the wrong features. Psychologically salient problem aspects differ from the logically important, and may distract a person from considering the logical. Hence, persons will give undue importance to considerations such as loss of face in taking decisions. Causality problems arise from the tendency to oversimplify cause and effect.

There are several known biases that affect the individual in knowledge-based judgement. One of these is a tendency to overlook the significance of data that is not immediately present. Out of sight, out of mind. Others are the confirmation bias (the tendency to pick an interpretation swiftly and stick with it, even in the face of opposing evidence) and overconfidence. There can also be biased reviewing (the same mistakes are made during checking) and the halo effect (multiple orderings of an item are treated as though a single ordering). Causality is influenced by representativeness (perceptions of similarity between 'cause' and 'effect'). Complexity effects are made worse by delays in feedback, exponentially growing variables and events linked as nets rather than series.

Skill based slips and lapses occur during routine activity, usually as a result of insufficient attention to the task at hand. The attention has been "captured" by something else. Slips can also occur as the result of too much attention. Some cognitive tendencies associated with slips are habit intrusions (the actions continue along a familiar but incorrect routine because of inattention) and omissions after interruptions. 'Overattention' problems usually result from mistimed checks during a largely automatic sequence. The person comes alert with a start and says "now where was I"? He/she then concludes wrongly that the sequence is at a particular point.

If in the midst of knowledge-based reasoning a familiar pattern should emerge, the person will immediately fall back to rule-based reasoning.

Storage and execution

Once a plan is made, it is stored in the memory as a routine. It is this routine that is executed when the time comes for action. The recall of stored routines is largely automatic but requires attentional checks at intervals, the frequency of which depends on how well established the routine is for the individual.

Errors in the planning phase are referred to as mistakes. Mistakes are failures in the inferential processes in the selection of goals and the specification of means. Mistakes can then be subdivided into rule-based mistakes and knowledge-based mistakes. Errors in the skill-based phase (storage and execution) are known as slips or lapses. Slips are more easily observable as external unintended actions, but lapses tend to be covert omitted actions, sometimes evident only to the person who committed them. These error categories are illustrated in figure 2.1 (section 2.1.2).

Rule-based mistakes could result from a misapplication of good rules or the use of bad rules. The first is more common and refers to a rule which is fine in itself, but is being applied to the wrong situation. This happens when the person misinterprets his/her observations and other information. In real problems, the person solving is inundated with information much of which is irrelevant to the situation. He/she must screen out the 'noise' and search for cues (signs) as to which rule(s) to use, and cues (countersigns) as to which rule(s) to ignore. In any given situation, there will be cues for two or more contradictory rules "competing" for selection.

There are several features of cognition that affect the judgement of an individual in rule selection. One of these is conservatism - the tendency to select previously successful rules even in changed circumstances (particularly if he/she is coming across an exception to a previous rule for the first time). Others are informational overload (too much information), partially matched rules, deployment bias

APPENDIX A

THE EFFECT OF COGNITIVE PROCESSES ON ERROR

The theory of J.T. Reason (1990) linking human error to cogn tive processes, represents the present state of the art in the field of psychology. Cognitive (thought) processes are divided into three types - planning of activities, storage of the plan in memory, and execution of the activity. The planning is further divided into two parts. The first is rule-based reasoning for familiar problems (a rule of the sort "if <situation>, then <possible solution>" is called into play). Alternatively, knowledge-based reasoning is required for planning on unfamiliar problems.

Planning type I - Rule-based reasoning

Rules and plan routines are thought to be stored in schema or scripts which are hierarchical networks of "objects". Each schema may be "activated" once a match is made between some aspect of the problem situation, and the stored schema. The activation of a schema will also activate all the linked schema at lower levels in the hierarchy i.e other "aspects" that the person "associates" with the original rule.

Rule-matching requires conscious attention throughout. It is an extremely fast and efficient process - as the person scans his/her memory for any familiar aspect of the situation. People will always prefer this type of planning, and will only resort to the other type when no match is made with existing rules.

Planning type II - Knowledge based reasoning

For completely new problems the person must resort to knowledge-based reasoning, using the computational area of his/her consciousness called the working memory. The computational processes are powerful, but working memory is limited in its ability to hold information. Hence people can only deal with small portions of a problem space at once in knowledge-based reasoning. This often leads to sub-optimal solutions - a phenomenon known as bounded rationality. Knowledge-based reasoning requires conscious attention and the expenditure of large quantities of mental energy.

observable project and firm characteristics. In this way, an index of error likelihood may be calculated for an error type. The index will be arbitrary, but it will provide a measure of the relative likelihood of error under different circumstances.

The difficulty experienced in error control has been that error control schemes lack a means for coordinating the choice of control techniques, and there are conflicting viewpoints to consider. SSM provides a means for coordinating the choice of techniques (system specification) in a holistic manner, by focusing on one viewpoint at a time. To use SSM however, there must be sufficient understanding of the issues involved. This is provided here by the proposed design error theory.

7.3 RECOMMENDATIONS FOR FURTHER WORK

The theory and models developed here are specific to firms with similar characteristics to the one studied, though certain aspects have general applicability. There is a need to apply these methods further to firms with other characteristics. Other studies could also consider systems at different resolution levels (e.g. the entire project team) or in other phases of the construction process besides design.

because of the bounded rationality phenomenon (Appendix A). This is influenced by time pressures, wrong or missing information and the specification of clumsy concepts at an earlier stage.

Type II errors (4.3.3) result from breakdowns in the process of recalling models in the memory that are applicable to some present problem. This could be the effect of incorrect recognition of the problem character or because the model in the memory is actually bad.

Type III errors (4.3.4) are the result of mismatches between tacit assumptions in chosen methods of analysis (formulae and procedures), and assumptions in the conceptual models. The incidence of this error type is influenced by the use of computation aids and individual 'responses' such as fatigue, pressure and morale.

Type IV errors (4.3.5) result from insufficient attention (carelessness) during routine number manipulation. Fatigue and time pressures can influence these strongly.

Type V errors (4.3.6) are mostly caused by insufficient understanding of the concepts to be depicted during draughting, by the draughtsman. Sometimes though, these could be the result of poor training on the part of the draughtsman. Concept communication breakdowns are the most common reason for draughtsmen misunderstanding concepts. Such breakdowns are influenced by physical distance between draughtsmen and other members of the team; the use of contract draughtsmen; personality clashes and the level of specialisation of the draughtsman.

Type VI errors (4.3.7) are also caused by insufficient attention, but now in the routine drawing tasks. External distractions and internal preoccupations are contributory factors and motivational problems are considered important here.

This theory summarized above provides a qualitative understanding of factors related to error occurrence. Thus, one can use a qualitative simulation package such as STELLA to represent the error inter-relationships, relating them to the externally error detection system in the studied firm. These weaknesses are the result of the lack of a theory of error causation.

7.2 THE MAIN RESULTS FROM THE STUDY

Human error was defined in this study (1.5) as "the departure of an individual (or group of individuals), both from his (or their) prior intention and from acceptable practice as judged by competent professionals". Design error was then taken to be "all human errors in the design process - from the briefing of the structural team to the handover of all drawings and schedules; including clarifications and changes".

Design errors were categorized (2.1.2) into six types as follows:

Type I - Knowledge-based mistakes in conceptualisation,
Type II - Rule-based mistakes in conceptualisation,
Type III - Rule-based mistakes in computation,
Type IV - Calculation slips and lapses,
Type V - Draughting mistakes and
Type VI - Draughting slips and lapses.

All design errors result from an interplay of weaknesses in the work-related abilities of the individual, and weaknesses in his/her attitude or state of mind (section 4.2.2). The impact of these weaknesses is influenced by factors related to the environment of design - time availability, the effect of work delays/revisions and the characteristics of design information.

It was found that type I errors specifically (4.3.2) result primarily from the inability of an individual to comprehend the important aspects of a problem situation -

When the theory had been developed, it became necessary to show that such a theory will significantly enhance the processes of error prediction and control. This was done by developing models for error prediction and control for the studied consulting firm, in an illustrative manner (chapter five). The model proposed for error prediction was developed using STELLA, a System Dynamics simulation software (3.2.3). The model was based on the generic model of section 4.2.2 and included separate sectors for design errors and the environment of design (5.1.1). The relationships in the design environment sectors are qualitatively well-known phenomena (e.g. relationship between amount of work left and time pressure). Hence, these could be modelled easily as mathematical expressions which were calibrated to match usual experiences in the studied consulting firm (5.1.2). Two of the experts provided the additional quantitative information for calibrating the equations in additional interviews. Relationships in the design error sub-sectors were based on the theory of error causation (proposed in section 4.3).

The error prediction model allows the simulation of the occurrence of projects within the firm over a period of time. As projects are simulated in the design environment sectors, the design error sector calculates an error likelihood index for each design error type. This index is arbitrarily defined but is nevertheless a measure of the relative likelihood of error in a comparison between two or more possible situations.

The models developed to illustrate the use of the design error theory in error control were Soft Systems Methodology (SSM - section 3.2.4) conceptual models. SSM is a systematic means of expressing the logical implications of some relevant viewpoint, in a problem situation. By this means, one can specify the logic of activity occurrence and inter-relations in a human activity system that exists for a prescribed purpose or goal. To illustrate the method two models were developed - one for the prevention of type I design errors; and the other for the detection of type I design errors (5.2.1 and 5.2.2). The model for error detection was then used as a standard (via comparison) for judging type I error detection in the studied consulting firm (5.2.3). The comparison led to the identification of weaknesses in the present

It was necessary first of all to adopt a tight definition for human error in general and design errors in particular (section 1.5). Design errors were then categorized into six distinct types based on a consideration of cognitive processes (section 2.1.2). There were fundamental difficulties associated with the frequentist probability paradigm of classical statistics and the forms of data collection implied by that paradigm (section 3.2.1). Hence, the soft paradigm of the systems approach (section 2. 1) was adopted as a more feasible means of dealing with the issues involved in human error. For one thing, the systems approach promotes a holistic way of dealing with complexly related variables which has been lacking with current approaches to error prediction/control. More importantly, the soft paradigm introduces the idea of human activity systems, in which human perceptions and foibles are catered for and subjectivity is normal. Error of course, is intensely human in nature.

To actually develop the theory, the data used were the opinions of four persons who could reasonably be considered experts in various facets of the design process. These four persons constitute the core of the design team handling steel structures within a reputable consulting firm in Johannesburg. The experts described the factors causing design errors (and their inter-relationships) at the levels of the project and design firm, based on their experiences. This information was obtained during a series of unstructured interviews with each expert (section 3.2.1), and the information was recorded as cognitive maps (sections 3.2.2 and 4.2.1).

The elements of the cognitive maps w later broadened out into conceptual categories using the coding techniques Grounded Theory method (section 3.2.2). These conceptual categories were related to one another to form a generic model of causation for design errors (section 4.2.2). The details of those conceptual categories are given in Appendix C. At a later stage of the theory development the specific causative mechanisms for each design error type were isolated. These are described for each error type in section 4.3. That section is the core of the design error causation theory developed.

CHAPTER SEVEN

CONCLUSION

7.1 A SUMMARY OF THE STUDY

Traditional models for the prediction of errors are based on probabilistic estimates of error behaviour. Since there is little objective data available for these estimates, such models tend to be exercises in conjecture. The trend has been to replace direct observations with expert assessments. But expert assessments of error behaviour are bound to be weak, since error is not a phenomenon with well-known laws of behaviour (see 2.2).

Models for error control on the other hand are traditionally of the procedural (managerial) sort. They are typically derived from such philosophies as QA and TQM, and from institutional models such as ISO 9001 (see 2.3). However, none of these address the issues of how such models can be specified in a coherent and efficient manner.

It has seemed to me that the problems encountered in error prediction and control stem from the fact that error is a poorly understood concept, whose properties and behaviour are not clearly known. In this study therefore, I have set out to develop a theory of how errors occur (causation), for the specific case of design errors.

Correct_info_availability = If (Project_Time < 6) then (8.4 - 0.4*Project_Time) else (3/5 * PM_experience + 2) *Eqn D.5*

For small projects information is released relatively fast, as more of the details are often known before the contract is awarded (see C.5). The part of equation D.5 for small projects will be:

$$C = 8.4 - 0.4P \qquad \textit{Eqn D.6}$$

This is a linear relationship between correct info availability (C) and the length of the project (project time P). Otherwise, the rate at which information is available depends linearly on how experienced the project managers are. The correct information available index is calibrated so that very experienced managers will release 80% of the needed information within the first fifth of the budgeted design time, while very inexperienced managers will release 66% of the needed information in only half the design time. Very small projects (less than 3 weeks) have the same characteristics as for very experienced managers.

The percentage of work that must be redone (because of information changes), is determined by the 're-doing work' flow. The REWORK(a) function of STELLA simply causes a percentage of the original flow to be returned downstream. The percentage is equal to the argument.

Redoing_work = If (0 <= Project_Time <= 6) then (REWORK (5 * Change_index)) else (If (6 < Project_Time < 24) then (REWORK(7.5 * Change_index + 5)) else (REWORK (15* Change_index + 10))) *Eqn D.7*

In equation D.7 the rework percentages depend on the size of the project (thus mirroring the relationship between project size and revisions - C.4), and on a change index. This change index caters for the effect of structure complexity and project manager experience (or inexperience), which are also known to affect revision rates (see C.4). The change index is given as:

Change_index = (1 - (PM_experience/10)) + (Structure_complexity/10) *Eqn D.8*

Some of the already processed work will be returned to the stock 'known information' (via the flow 're-doing work'), to be re-processed. This caters for revisions and corrections. In this way, the rate at which information is processed is dependent on how much information is known (info input), the production rate of the team (real work rate) and the number of revisions (re-doing work) - see C.4 in Appendix C. The difference equations for the stocks are given as equations D.1 and D.2.

Received_Info(t) = Received_Info(t - dt) + (Info_input + Redoing_work - Real_work_rate) * dt *Eqn D.1*

Processed_info(t) = Processed_info(t - dt) + (Real_work_rate - Redoing_work - Info_output) * dt *Eqn D.2*

The rate of information input is determined by how much (correct) information is available. In turn the amount of available information is decided by the experience of the project managers (see C.5). The equation for info input is:

Info_input = (Project_Time/10)*([If (Received_Info > Project_Time) then 0] else [(Correct_info_availability * EXP(-Correct_info_availability * Time_counter / Project_Time))]) *Eqn D.3*

When the amount of information (work units) received becomes equal to the work required for a project of that length (project time - work units), no more information is input. This is the expression in the first set of square brackets. In standard notation, the second part of equation D.3 would be written as:

$$\textit{Info input rate} = \frac{P}{10}\left(Ce^{-\left(\frac{CT}{P}\right)}\right) \qquad \textit{Eqn D.4}$$

where P is the total project time; C stands for the correct information available index and T is the elapsed time (time counter) on the project. Hence, equation D.3 models information inflow as the slope of a negative exponential curve that flattens out to zero when the elapsed time on a project equals the total project time. The shape of the curve is determined by the availability of correct information index.

APPENDIX D

FURTHER DETAILS OF THE ILLUSTRATIVE ERROR PREDICTION MODEL

D.1 The 'Information processing' sector

The information processing sector is shown in figure D1. The main feature is a chain of resource flows including the two stocks 'received information' and 'processed information'. Information is input into the design process via the 'info input' flow and exits via the 'finished work' flow. Information is processed as work units flow from the first stock (received info), to the second (processed info).

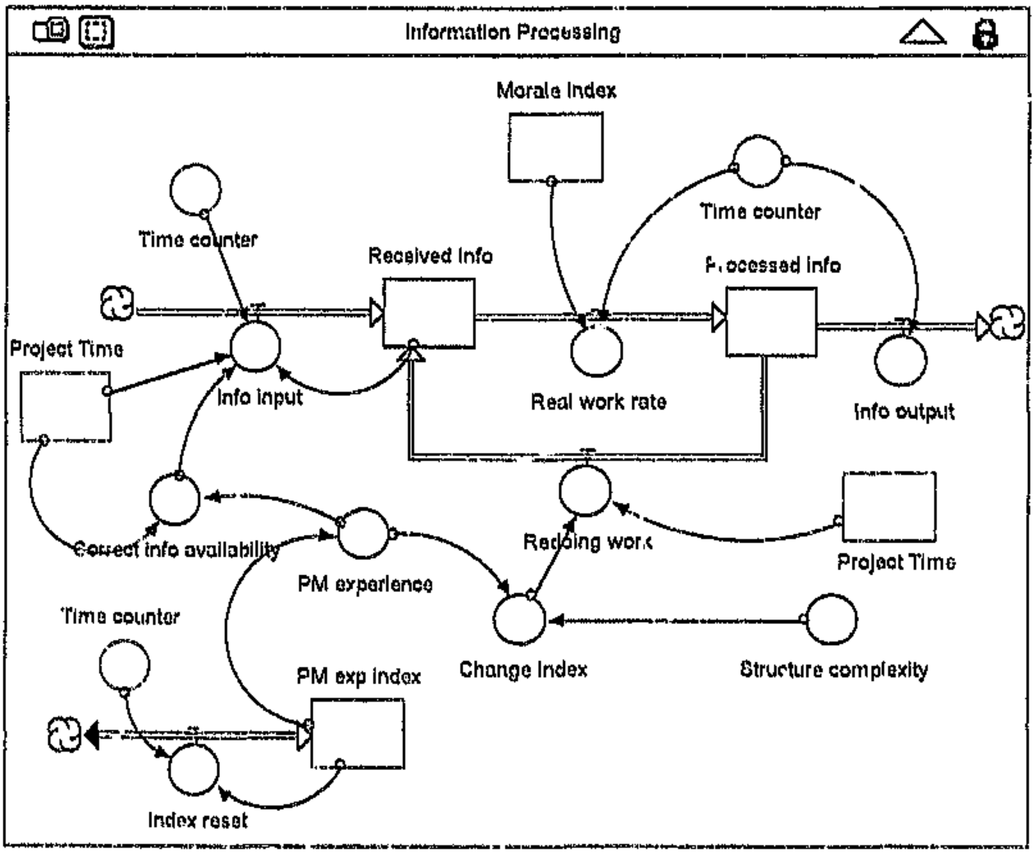

Figure D1 - Model elements in the 'Information processing' sector manager is an important factor in such situations (FP & CJ), particularly on medium to large projects.

Client liai- is enhanced by good relationships between persons in the design consultancy and the client firm. It is common to establish 'low-level' contacts in the project team, say between a structural draughtsman and an architectural draughtsman. However, this is sometimes problematic as informal exchanges are occasionally incorrect and are disputable.

Internal information flow within the design team can be hindered by physical distance between sections of the team, by personality clashes, or by breaks in the design process. This last influence refers to persons leaving the team during a contract. When contract personnel are used, differences in terminology will enhance the likelihood of misunderstandings.

C.4 Work delays and revisions

Delays (see FP), may arise because of pending information from other consultants, project managers or manufacturers. This is particularly problematic on larger projects involving multi-disciplinary design. The second source of delay is the need to re-do work due to corrections and revisions. Information delays are more common at the drawing stage than in design. (Once there is sufficient information to fix concepts, design calculations can usually proceed without additional information. If necessary, the design engineers can assume conservative figures and check these when more information is available).

Finally, a third source of delay lies in poor administration/supervision of the design team. I example, low drawing production rates can result because of 'interference' between uraughtsmen (work poorly apportioned), or because they are 'goofing off'. Both of these are sometimes associated with using contract draughtsmen.

Work delays are closely related to time losses (and so to time availability). A second effect is sometimes to influence the morale of the design team members.

The use of provisional details which can be corrected on site is often a feasible way of dealing with information delays. The use of standard equipment with known specifications, will also help in this respect.

C.5 Information characteristics

Information is required from the client and other consultants, to guide and focus the design effort. Sometimes, information is also required from other members of the structural design team or from the contractor. Problems arise when someone gives wrong information or the information required is not available Sometimes this is because a client does not yet know his/her requirements, or because final decisions on say machinery have not been made. The level of experience of the project physical exertion, financial constraints, getting on with others, personal problems etc. Up to a certain point, pressure stimulates greater concentration and more efficient performance. However, very high pressure can lead to loss of care. Design appears to be generally a high pressure activity, and many design personnel cope by using socially accepted drugs such as alcohol or cigarettes.

Individuals differ in their level of care - the time spent attending to details, and the extent of concentration for that time. The knowledge that they will be checked motivates some individuals to greater care, and others to less care.

C.3 The availability of time

Design time estimates are often fixed by extrapolating from similar jobs in the past. These are then adjusted for differences in complexity and the degree of repetitiveness of details. Sometimes though, there are no similar jobs to extrapolate from and estimates must be 'synthesized' from scratch.

Very often clients have their own deadlines and this can be the overriding constraint. The project manager may develop his/her program without consulting the design firm and may estimate the required time wrongly. This is often linked to the experience of the project managers with that type of structure. Other common constraints are the availability of qualified personnel, the number of jobs in hand etc.

Time constraints for design may be relieved by the use of contract draughtsmen and freelance designers, or by farming out drawing work to other jobbing firms. Some individuals will take 'short cuts' such as leaving details to be developed by the fabricators.

C.2 Attitude and state of mind

There are again four concepts in this category - again interrelated and overlapping. These are motivation or morale, fatigue, the feeling of pressure and the level of care. The definitions here are mostly derived from FP.

Motivation or morale has a long term component - overall job satisfaction. ('I like the job I'm doing and the roles it imposes upon me'). This is linked to a feeling of self-esteem and taking a pride in one's contribution. The latter attribute develops best, when the individual perceives the importance of his/her role and is made to feel like a valued member of the team (team spirit). When there are individuals in the team who are malcontents their grumbling tends to affect the others, and discontent spreads. Some individuals become unhappy because they believe they are not being treated fairly.

Morale also has a short term component - the interest of an individual in particular work tasks. Some engineers tend to take interest in the creative aspects of their jobs and neglect the administrative parts. Numerous revisions and work delays can lead to low morale on a particular project, especially if the revisions are on the same aspect. Projects that are running at a loss will also have the same effect on the team. The rate at which drawings are produced can be highly affected by the morale of the team.

Fatigue in this context, is an inability to concentrate mentally because of tiredness. This usually builds up over several weeks and months of long working hours (pressure), without breaks. Fatigue may lead to less care. Individuals with good track records or who specialise in an area, tend to be in demand. When there is much work, such individuals are fatigued faster.

The feeling of pressure is the result of being faced with challenging situations i.e., circumstances that call for performance beyond comfortable limits, yet not so difficult as to be obviously unattainable. (People are not challenged by totally unattainable goals, they just give up). Challenges arise from time constraints, the workforce. The workforce is shrinking as older engineers retire or emigrate because of the social changes. A related issue is that employers are picking and choosing since there is unemployment. It is easy to get information on the ability of an individual in the relatively small engineering community.

Competence is the general knowledge of principles governing the performance of a design task. It allows one to understand his/her limits and to know where to seek assistance. This seems to result from broad exposure to related structural types, and formal or informal education. Any firm will develop an area of work in which their personnel are competent. When they go out of those boundaries, they may lack both competence and material understanding. Yet, economic squeezes lead some firms to diversify structural types/materials as a means of ensuring work.

Material understanding or a 'feel' for the material, is an insight into how material-specific characteristics can influence structural response and performance. So for example, being able to visualize the stability of steel structures. Rising through the ranks and previous experience in fabrication or erection, may be contributory to this ability. NC mentions the trend in which more engineers are graduates with little practical exposure and implies that this prevents them from developing material understanding. The need for graduates has itself arisen from the fact that engineering analysis has become more complex and mathematical.

Innovation is the ability to extrapolate beyond normal boundaries imaginatively yet reasonably. It requires a touch of creativity. The trend in innovation has been towards cheaper, more efficient designs. Firms that acquire a reputation for this tend to build up a steady clientele.

The terms 'experience' and 'competence' as defined here result from the usage by CJ (and correspond to NC's 'knowledge'). The other two terms are largely patterned after NC.

APPENDIX C

CONCEPTS IN GENERIC MODEL OF DESIGN ERROR

In section 4.2.2, the data from the experts was divided into seven conceptual categories to form a generic model of causation for design errors (figure 4.10). In this appendix, the other conceptual categories in the model (besides the errors themselves), are explained. The purpose is to provide better understanding of what is meant ar . implied by the various term used to explain design error causation, in the theory of section 4.3. The categories are:

Those related to the individual.

- Work-related abilities.
- Attitude and state of mind.

Those related to the design environment.

- Availability of time.
- Work delays and revisions.
- Information characteristics.

C.1 Work-related abilities

There are four overlapping ideas within this category - experience, competence, material understanding and innovative ability. The meanings I negotiated for each of these are as follows.

Experience is the level of familiarity of an individual with a particular task on a given structural problem or configuration. It corresponds roughly to the length of time the individual has been involved with a particular structural type. FP and CJ both feel that fewer firms are training engineers and draughtsmen because the design consultancy market has become more competitive (more jobs on a design and build basis). This in turn is affecting the number of experienced and competent persons in

(B) About how many of each error type would you expect from a young engineer who had been working on this design task for a year?

(C) For a young engineer who has worked for a year, about how many of such errors would you expect him/her to discover himself/herself? About how many are likely to be discovered later in the design process? About how many would be discovered outside the design process e.g. by contractors ?

(D) What are the possible causes for each of these error types?

(E) In your opinion, what are the circumstances or methods that make it easier to discover each particular type of error? Please refer to possible situations in the design office and to the character of the project itself.

(8) What types of errors can take place in information, and from which sources are these likely? What are the likely consequences of errors in information?

Thank you for your time and your kind co-operation.

For this interview we will cover each of the following design tasks identified in section II, in turn.

(1) (2) (3) (4)

(5) (6)

Questions

(1) When was the longest continuous period you were ever involved with this design task? Where were you working at the time?

(2) Describe the types of structures you worked on at the time.

(3) Which of the following categories would best describe the total project cost for most of the projects you worked on at the time?
(A) Less than R100 000 (B) Between R2 million and R100 000
(C) Over R2 million.

(4) Mention the steps you would normally go through in carrying out this design task. Explain what happens at each step.

(5) What type of information would you normally require at each step in carrying out this design task? What would be the most likely source in each case?

(6) Describe the types of errors that could take place at each step in the design task. What are the likely consequences of these errors?

(7) For each of these error types mentioned above, please answer the following questions - relating the answers to the types of projects you worked on yourself. Put your answers in the provided table.
(A) About how many of each error type would you expect a young engineer to make on his/her first project?

Questions

1. Study the list of design tasks and indicate where any essential ones have been omitted. Mention these by name and describe each one briefly.

2. Look through the list of design tasks again and indicate those tasks you have had personal experience with, either because:
   - (A) you have done the task yourself,
   - (B) you have supervised others doing this task, or
   - (C) any other reason (explain).

   State whether it is A, B or C that applies in each case.

3. For each design task, how well can you give an opinion of the errors people make on that task? Choose your answers from the following options:

(A)	Very well	(B)	Well
(C)	Average	(D)	Weakly
(E)	Very weakly	(F)	Do not know.

4. For each design task, mention the stages in your career when this task was a normal part of your duties, or you regularly supervised others in the task, or you were involved in some other way (explain). Please include your present job tasks.

SECTION III

This section examines the design tasks you are most familiar with (from section II), in detail. The questions seek to obtain your assessments of the causes of error in each design task, and the types of errors that result.
Please bear in mind the definition of human error on the introduction sheet.

D.7 The 'Type VI design errors' sub-sector

Type VI errors result from insufficient concentration by the draughtsmen, (drawing concentration), and low morale. The concentration of draughtsmen is susceptible to environmental distractions, internal preoccupations and fatigue (4.3.7).

To model morale, I have focused on the short-term aspect of morale (section C.2), which would change for each project. This short-term morale is assumed random with a normal distribution - mean = 5; standard deviation = 1.67. Morale is represented as a stock, which is adjusted at the start of each project, using the morale reset flow (figure D8).

Internal preoccupation is randomly chosen to be absent 90% of the time. When it *is* present, it is assumed to be uniformly distributed between 0 and 10. Environmental distraction is user-specified with a default of 5. Drawing concentration is reduced by the greater of internal preoccupations and external distractions, and then modified further for fatigue as done for type IV errors. Type VI error likelihood is then a smoothed version of [20 minus the sum of morale and concentration].

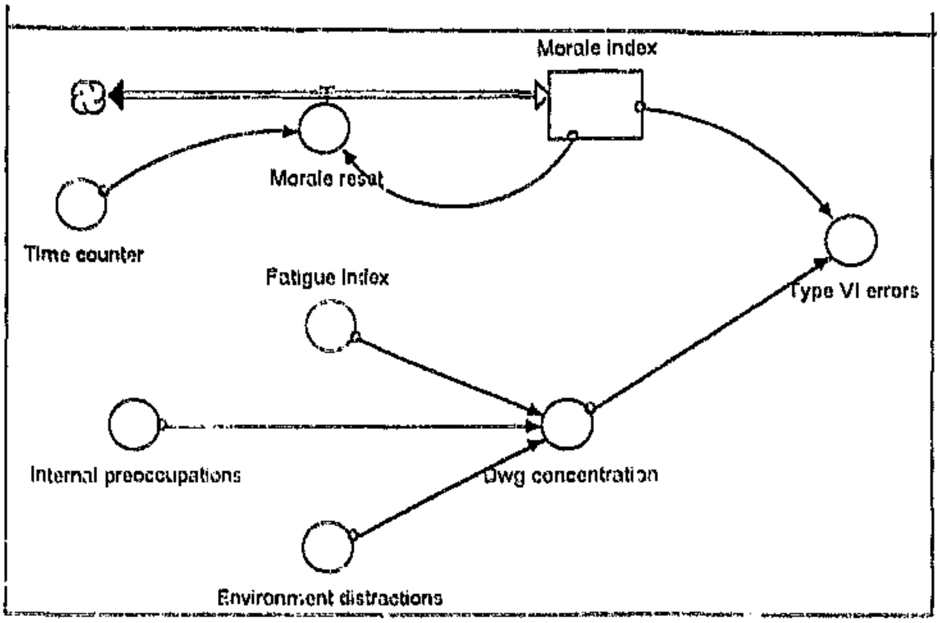

Figure D8 - Model elements in the 'Type VI design errors' sub-sector

D'men_:_Designer_relations = If ((Distance_effect = 1) and ('Outside'_d'men_effect = 1)) then (Concept_communication/2) else (if ((Distance_effect = 0) and ('Outside'_d'men_effect = 0)) then Concept_communication else (Concept_communication*0.75)) *Eq D.36*

Distance_effect = If ('Outside'_d'men_effect = 1) then MONTECARLO(30) else 0 *Eqn D.37*

[DOCUMENT: This variable will return a value of 1, (indicating that there is distance between the designers and the drawing office), for 30% of the time that outside draughtsmen are used].

Dwg_skills = If ('Outside'_d'men_effect = 1) then (Dwg_specialisation*0.8) else Dwg_specialisation *Eqn D.38*

Dwg_specialisation = 5 (default). *Eqn D.39*

Type_V_errors = Smth1((((10 - D'men_:_Designer_relations) + (10 - Dwg_skills))/20),50) *Eqn D.40*

'Outside'_d'men_effect = If (Project_Time < 24) then MONTECARLO(75) else MONTECARLO(10) *Eqn D.41*

[DOCUMENT: This variable measures the likelihood that 'outside' draughtsmen (e.g. a jobbing firm, the client's draughtsmen or contract draughtsmen), will be used for the bulk of the drawing].

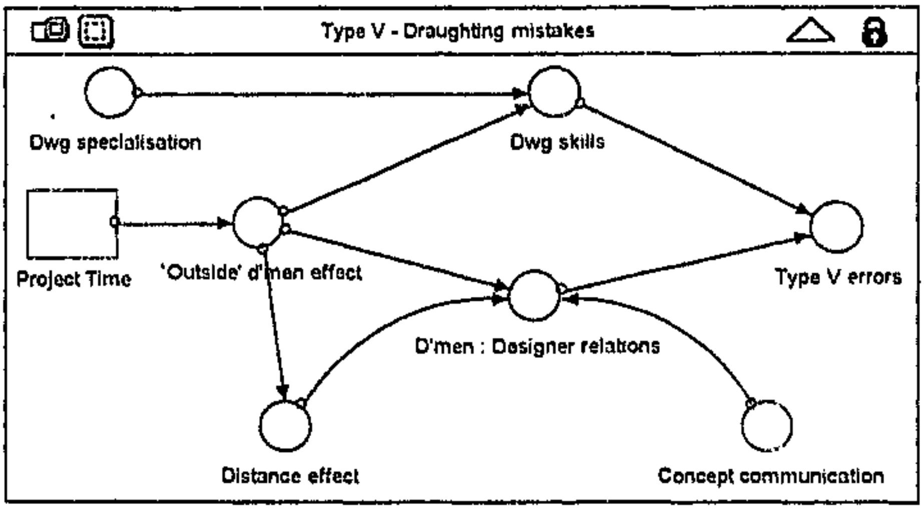

Figure D7 - Model elements in the Type V design errors' sub-sector

It is assumed that draughtsmen from outside the firm will typically be used on large projects. Hence, it is modelled to randomly occur 75% of the time on large projects, (over 24 weeks long), and only 10% of the time otherwise. Thus, the distance effect variable returns a value of one, for 30% of the times when outside draughtsmen are used.

Drawing specialisation is user-defined, with a default of five. Drawing skill is simply equal to the specialisation, save that when outside draughtsmen are used the skill is reduced by a multiplier[17] of 0.8. Similarly, the variable 'draughtsmen: designer relations', is essentially equal to the concept communication. However, if outside draughtsmen are used and there is no physical distance, the effectiveness of communication is reduced by a quarter. If there is also physical distance, it is reduced by half. Type V error likelihood is simply 20 minus the sum of drawing skills and draughtsmen: designer relations, (both 'skills' and 'relations', range from zero to ten). The result is then normalized over 20, and smoothed.

[17] The various multipliers *are* arbitrary, but they mirror the effects that are qualitatively known to be so, and the values are plausible. Since the error likelihood index being calculated is only a measure of *relative* differences, this is not critical to the use of the model

The function is chosen to be almost normal. This models the fact that people's minds tend to wander when there is no pressure, and they are at their best at medium pressure levels. However, when the pressure gets too high, their performance is again impaired. (See C.2 in Appendix C).

In the equation for type IV errors, the fatigue index is normalized over 1.5 (it has a maximum of about 1.3), and subtracted from one. This is then multiplied with concentration so that concentration is reduced by fatigue. The effect of calculation aids is then weighted by 0.3, and subtracted from the reduced concentration.

Calcn_aid_index = 5 *Eqn D.34*

Calculation_slips = Smth3((((Min(Fatigue_index, 1))*Concentration/10) + (3*(10 - Calcn_aid_index)/100)),50) *Eqn D.35*

Concentration = GRAPH(Time_pressure). See figure D6.

D.6 The 'Type V design errors' sub-sector

As shown in figure D7 type V errors are modelled as the result of two phenomena. The first is the relationship between the draughtsmen and designers, in which the most important effect is that of concept communication. Concept communication is however affected by physical distance between designers and draughtsmen, and by the use of draughtsmen from outside the firm (section 4.3.6). The other phenomenon is the level of drawing skills. This is again affected by the use of outside draughtsmen, who may need more supervision or may be unaccustomed to group work. The degree to which draughtsmen are specialists, is however the main effect.

D.5 The 'Type IV' design errors' sub-sector

The model elements for type IV design errors are shown in figure D5. Type IV errors result from lack of sufficient attention or concentration (4.3.5). Poor concentration is aggravated by fatigue - even at low levels, and may be triggered by time pressures. The use of sophisticated calculation aids will reduce the opportunities for type IV errors.

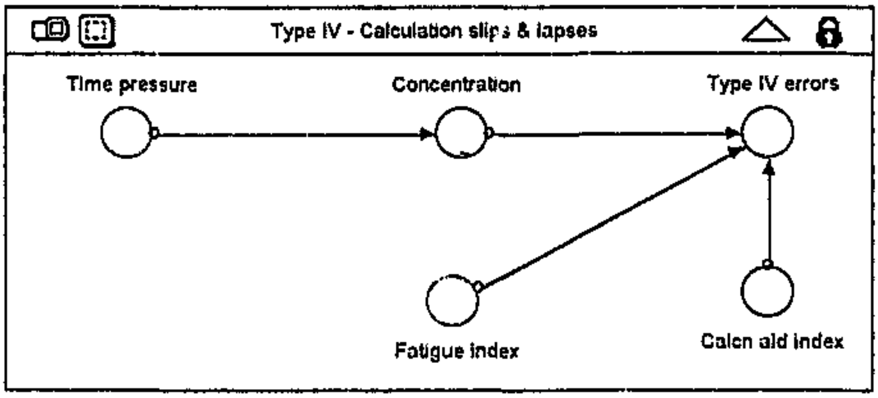

Figure D5 - Model elements in the 'Type IV' design errors' sub-sector

The calculation aid index is a user-defined variable that measures the sophistication of calculation aids. A very sophisticated computer program requiring little input from the user (e.g. some expert systems), would rate as 10. Conversely a slide rule could rate as 1. A simple PC-run structural analysis program would be say 5. The default value is 5.

Concentration is conceived as a graphical function of time pressure, depicted in figure D6.

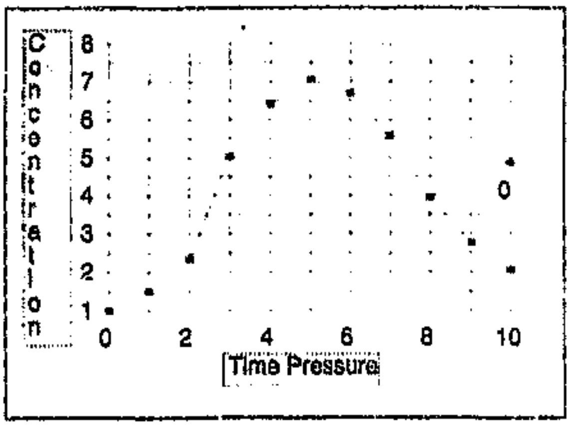

Figure D6 'Concentration' as a graphical function of 'Time pressure'

Accumulated_fatigue(t) = Accumulated_fatigue(t - dt) + (Busy_periods - Rest_periods) * dt *Eqn D.25*

Busy_periods = If (Time_pressure >= 5) then 1 else 0 *Eqn D.26*

Rest_periods = If (Time_pressure <= 0) then 4 else 0 *Eqn D.27*

Communicatn_system_index = NORMAL(5,1.67) (default) *Eqn D.28*

Concept_communication = (Communicatn_system_index + 10 - ((10 *DELAY(Type_I_errors, 2,0))))/2 *Eqn D.29*

Fatigue_index = Smth3(Accumulated_fatigue, 5)/11.6 *Eqn D.30*
[DOCUMENT: This index has been calibrated (after several simulations) so that 'high fatigue' values (> 1) are typically obtained about three times in 10 years. An index range of 0.4 - 1 will represent medium fatigue which may typically occur once a year].

Incorrect_computation_procedures = 1 - (Training_quality/10) *Eqn D.31*

Type_III_errors = Smth3(((Max(Fatigue_index, 1)) * (Wrong_model_assumptions + Incorrect_computation_procedures)),50) *Eqn D.32*
[DOCUMENT: Fatigue is assumed to have an effect on computation mistakes only at high levels (> 1). Otherwise computation mistakes are governed by the probabilities of unrealised model assumptions & unsuitable procedures/formulae].

Wrong_model_assumptions = 1 - ((Max(Experience_breadth, Concept_communication))/10) *Eqn D.33*

The effectiveness of concept communication to the design engineer, will depend on two things. Firstly, if the conceptualising was faulty, it might lead to clumsy concepts (4.3.2). These would not be completely unworkable (type I or II errors), but unnecessarily complicated. Clumsy concepts would hinder effective communication. Secondly, the systems adopted for communicating concepts would also influence the effectiveness of communication. The user scores the communication system index on a range of zero to ten (very bad to very good). The default is a normally distributed variable with a mean of five and standard deviation of 1.67. The likelihood of clumsy concepts is assumed to be highly correlated with the likelihood of type I errors, and so is represented by the type I errors of two weeks ago (using a delay function). Effectiveness of concept communication is then the sum of the communication system index, and 1 - type I error likelihood.

Wrong recognition of model assumptions is conceived as depending on the h [illegible] effective communication and experience breadth. Hence it is simply 1 - [the maximum of effective communication or experience breadth].

Incorrect computation procedures are a linear function of training quality.

Fatigue is modelled as a stock that accumulates when the team undergoes busy periods for long stretches, and depletes when things are relatively slow (see C.2 of Appendix C). Busy periods and rest periods are detected by monitoring the time pressure on the team. The rate at which fatigue is dissipated by rests is faster than the rate at which it accumulates under pressure (C.2). The amount of accumulated fatigue is measured by a fatigue index, which 'smooths' out rapid fluctuations, and normalizes the value over the high fatigue threshold. This threshold is arbitrarily chosen to occur about once every three years, at 'normal' conditions in the studied consulting firm.

Type III errors are then calculated as the sum of wrong model assumptions and incorrect procedures. However, when there is high fatigue that sum is multiplied by the fatigue index.

D.4 The 'Type III design errors' sub-sector

As described in section 4.3.4, type III errors result from wrong recognition of model assumptions, or incorrect selection of computation procedures. Recognition of model assumptions is assumed to depend on breadth of experience, (familiarity with many models), and effectiveness with which the concepts were communicated, (4.3.4). Incorrect selection of computation procedures depends on the training of an individual. The effects of both the type III error causes are made worse by high fatigue levels. Figure D-4 shows the various factors modelled to represent these relationships.

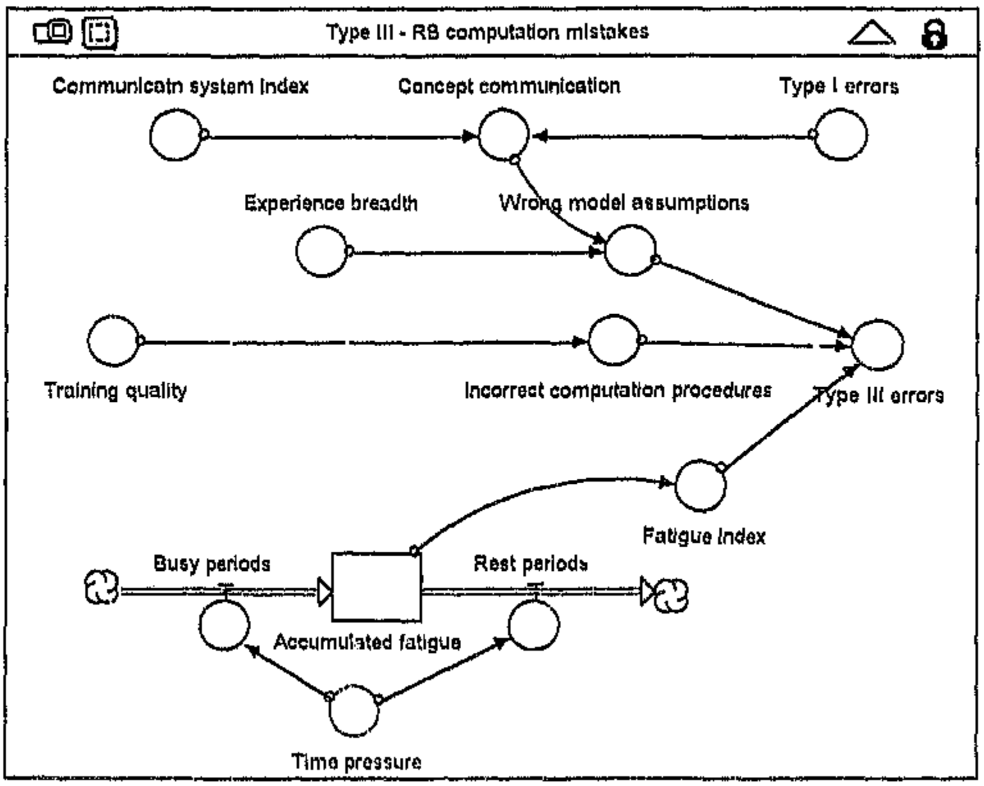

Figure D-4 - Model elements in the 'Type III design errors sub-sector and abscissa depending on the initial experience (at the start of a simulation). The initial experience is user-defined (range zero to ten), with a default of five - equation D.18. If the initial experience is at its default value, the experience breadth equation has an abscissa of 5 and a slope of 3/1000. Training quality is a user-defined constant with a default value of 5.

Correct model selection is conceived as the multiple of the breadth of experience and training quality (over 100), hence incorrect selection is one minus that multiple. This has a range of zero to one. Completely wrong structure recognition takes place when the correct information available is less than some threshold value. Otherwise, it is a linear function of time pressure with a slope of 0.1 and an abscissa of zero. The likelihood of type II errors is then the sum of likelihoods for incorrect model selection and wrong structure recognition, normalized for 'normal' conditions in the studied consultancy. The equations follow below.

Experience_breadth = ((Initial_experience*0.6*(1 + (TIME/1000))) + 2) *Eqn D.18*

Incorrect_model_selection = 1 - (Experience_brendth*Training_quality/100) *Eqn D.19*

Initial_experience = 5 (default). *Eqn D.20*

Innate_ability = (Experience_brendth + Training_quality)/2 *Eqn D.21*

Training_quality = 5 (default). *Eqn D.22*

Wrong_structure_recognition = If (Correct_info_availability <= 6) then (0.1*Time_pressure) else 0 *Eqn D.23*

Type_II_errors = (Incorrect_model_selection + Wrong_structure_recognition)/0.752 *Eqn D.24*

Estd_work_rate = If Time_counter = 0 then 1000 else 1 *Eqn D.17*

This outflow simply re·· ·es the budgeted work at a constant rate of a weeks work for every week of simulation. At the start of a new project, all outstanding work units are cleared.

D.3 The 'Type II design errors' sub-sector

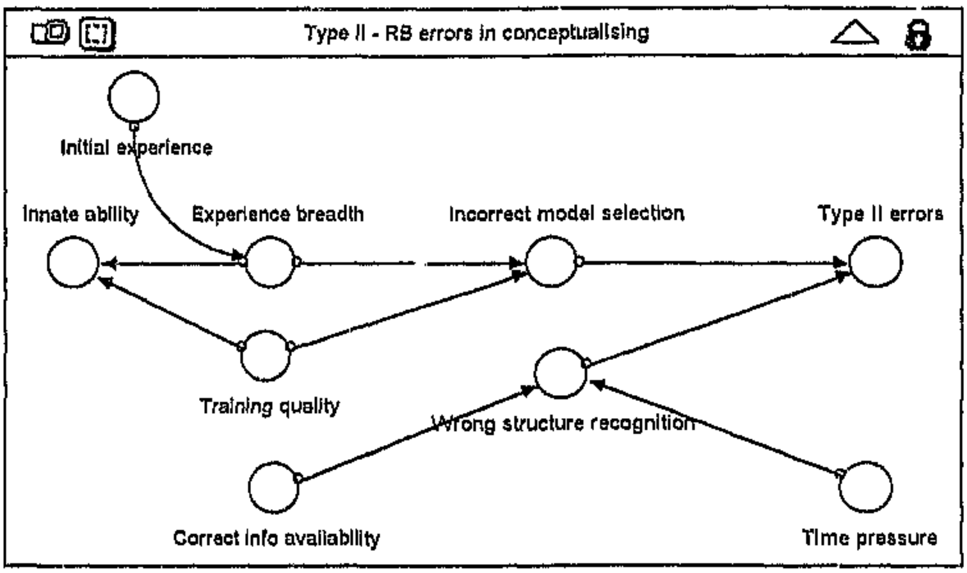

Figure D3 - Model elements in the 'Type II design errors' sub-sector

The incidence of type II design errors (in figure D3) is dictated by the likelihoods of recognising the structure correctly and selecting the right model (section 4.3.3 and figure 4.12b). The first likelihood is itself dependent on the availability of correct information (modified by time pressures), while the second depends on both breadth of experience and quality of training. The breadth of experience is a slowly increasing linear[16] function of (simulation) time measured in weeks, with the slope

[16] Experience is known to grow as an S-curve over time. For the relatively short simulation period, this may be approximated by a straight line.

D.2 The 'Budgeted work flow' sector

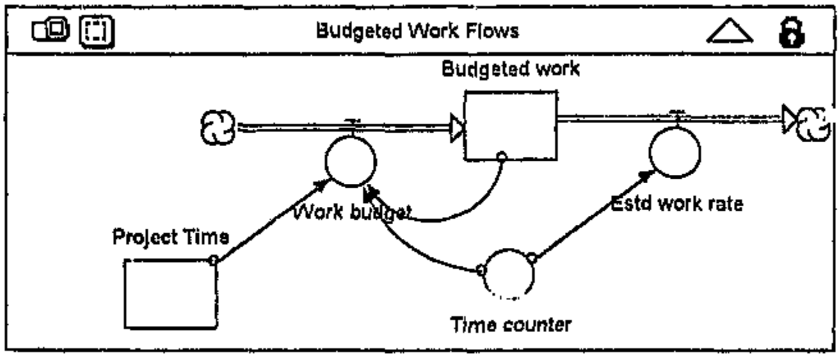

Figure D2 - Model elements in the 'Budgeted work flow' sector

The main element in the sector 'budgeted work flow' (figure D2), is the 'budgeted work' stock. At the start of every project (indicated by the converter 'time counter'), the flow 'work budget' releases work units to the stock. The work released is the number of working days corresponding to the budgeted project time (hence the presence of the 'project time' stock). Thereafter, the outflow 'estd work rate' will reduce the stock at a steady rate for each day in a simulation. In this manner, the stock 'budgeted work' keeps an account of the progress of the project *as planned*. The difference equation is:

Budgeted_work(t) = Budgeted_work(t - dt) + (Work_budget - Estd_work_rate) * dt *Eqn D.15*

The work budget inflow simply monitors the beginning of a new project (via time counter - elapsed time), and then releases work units corresponding to the (initial) project time. In equation D.16 project time is multiplied by 5 because the flow takes place in a single dt (0.2 weeks). The factor of one is added because the internal clock evaluates this a dt late and loses time.

Work_budget = if ((1 > Time_counter > 0) and (Budgeted_work = 0)) then (Project_Time * 5 + 1) else 0 *Eqn D.16*

It is the average of project manager inexperience (10 - experience), and structure complexity. It ranges from 0 to 2, being 2 for the combination of very inexperienced managers and a very complex structure.

Real_work_rate = If Time_counter = 0 then 100000 else (0.75 + (Morale_index/20)) *Eqn D.9*

The real work rate is a function of the morale of the team members (C.2). The large value corresponding to the beginning of each project (time counter = 0), is to allow all left over information units from the previous project to be cleared from the model. The morale index is set in the design error sector.

PM_experience = Min(PM_exp_index, 10) *Eqn D.10*

PM_exp_index(t) = PM_exp_index(t - dt) + (Index_reset) * dt *Eqn D.11*

Index_reset = If (Time_counter = 0) then (5*((NORMAL(7,2.33)) - PM_exp_index)) else 0 *Eqn D.12*

The experience of project managers may be prescribed by the user. Otherwise, it is determined via an index that is reset after each project. The default values generated by the index are normally distributed. Equations D.10 to D.12 show how this is done. Project manager experience is limited to 10 by the min function in equation D.10.

Info_output = If Time_counter = 0 then 100000 else 0 *Eqn D.13*

This flow is actually a dummy used to reset the model at the start of each project. Hence, it flows out all information units at the start of each project.

Structure_complexity = NORMAL(5,1.67) *Eqn D.14*

Structures are assumed to vary in complexity on a scale of 0 to 10, so that a complexity of 5 denotes the average for a firm. It may be user-defined; otherwise it is a normally distributed random number.

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Morale_index(t) = Morale_index(t - dt) + (Morale_reset) * dt. *Eqn D.42*

Morale_reset = If(Time_counter = 0) then (5*((NORMAL(5,1.67)) - Morale_index)) else 0 *Eqn D.43*

Dwg_concentration = (Max(Environment_distractions, Internal_preoccupations)) * (Min(Fatigue_index, 1)) *Eqn D.44*

Dwg_slips = Smth1(((Morale_index + Dwg_concentration)/20),50) *Eqn D.45*

Environment_distractions = 5 (default). *Eqn D.46*

Internal_preoccupations = SWITCH(0.1,(RANDOM(0,1))) * RANDOM(0,10) *Eqn D.47*

[DOCUMENT: Internal preoccupation will be zero for 90% of the time. When it is present, it is assumed random with a uniform distribution between 0 & 10].