FORMING A GENERAL SYSTEM DYNAMICS TRANSITION METHOD BETWEEN SYSTEM ARCHETYPES AND SIMULATIONS

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DEDICATION

Dedicated to my colleague, leader, motivator, legendary friend, and beloved brother Naledi Memela. You continue to inspire me. Until we meet again on the other side of life's great door, I will keep aiming for the stars as you did. ***MSC2020***

Shocase

"You wouldn't plant a seed and then dig it up every few minutes to see if it has grown. So why do you keep questioning yourself, your hard work, and your decisions? Have patience, stop overthinking, and keep watering your seeds." – Steven Bartlett

DECLARATION

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

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ABSTRACT

The field of system dynamics and its simulations are criticised for the lack of validation, verification testing and model construction guidance. In contrast, the field of systems engineering specialises in those areas. The thesis aims to develop one general system dynamics approach which guides new system dynamists during simulation construction, with appropriate verification and validation tests. The approach is referred to as the Loop Stock Transform (LST) and used to translate conceptual system archetype models into mathematical simulations. A mixed research method approach is used to develop the LST consisting of a literature review on model formulation, systems engineering Vee Diagram, two rounds of the Delphi research method and simulations of the four system archetype case studies. The Delphi participant group consists of nine field experts with more than 100 years of combined system dynamics experience. The LST is iteratively evaluated in each Delphi round to improve group agreement levels and the LST method. The Delphi consisted of five Likert scale questions tested for agreement using the statistical Cohen's Kappa technique. Additional open-ended questions provide more insight into the review, while the content analysis is used to interpret the open questions.

The Cohen's Kappa value increased from 0.32 to 0.62 (substantial agreement). Only two of five Likert scale question results show support for the method in round one, while in round two, all five question results support the LST. The final LST uniquely adopts the Vee Diagram as a foundational paradigm with 18 different validation and verification testing points. Thereafter, the LST is applied to the Fixes that Fail, Limits to Growth, Eroding Goals and Escalation archetypes. All four simulations verified the unique behaviours and recommendations made by the system archetype literature. Delphi participants especially found the simulations valuable to generate deeper insight and understanding into the different archetypes. However, the participant concerns relate to the number of steps that the LST has, which can prevent future adoption in the absence of comprehensive learning material. The simulation results show that the adopted systems engineering validation and verification paradigm can reproduce the literature behaviours and insights. The Delphi results reveal overall support of the LST and that the LST can transform conceptual models into mathematical simulations. Future research opportunities include developing learning material, evaluating students' appetite for the LST, and more practical LST applications.

ACKNOWLEDGEMENTS

Thank you to my supervisor, Dr Andries Botha, who consistently offered me research guidance every month, despite his extreme schedule. Thank you for your patience, genius, and grit, especially when we had to face compromises. The quality of research was immensely enhanced through your inputs.

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Finally, I want to acknowledge God's strength, wisdom, and vision. Considering the global and personal losses experienced during this research, Jesus carried me through it all by His grace alone (Psalm 91:4).

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Table 1.1: List of Abbreviations

ABBREVIATION	DESCRIPTION
BLM	Black Lives Matter
CLD	Causal Loop Diagram
DYNAMO	Dynamic Modelling
EFF	Economic Freedom Fighters
GMB	Group Model Building
PPM	Pathway Participation Metric
SAM	System Architecture Map
SFD	Stock and Flow Diagram
LST	Loop Stock Transform
VF	Vryheidsfront
VVT	Verification Validation Testing

Table 1.2: List of Nomenclature

NOMENCLATURE	DEFINITION
Generic	
Accumulator	Entities that can gain, lose or maintain values over time
Axioms	The fundamental equations, structures, and processes used in a specific field
Behaviour	The observable/measurable patterns of a system or component
Dynamics	A continuous or productive activity or change (Merriam-Webster Dictionary)
Feedback	Results from a process/behaviour alter the process/behaviour itself, producing a different result

Flow	A system dynamics variable that controls the amount of change that a stock can undergo as a rate of change
Loop Stock Transform	The 11 step process is a detailed approach to construct dynamic mathematical simulations from conceptual causal loop diagrams - The detailed description is found in Chapter 4
Mathematical modelling	A model that uses mathematical operations and numerical variables to describe a part of a system. Such a model can reproduce the behaviour in a mathematical language
Method	A step by step process to guide the user in achieving a final goal/product
Model	Simplification of reality is useful to understand parts of reality
Narrative	Capturing connected events in a spoken or written format which can also be referred to as a story
Scenarios	A specific possibility is explored through the simulation
Simulation	The imitation of a system by using a computer model for understanding and investigation
Socio-technical problems	The challenges span over hardware, software, personal, and community areas
Stories	Mental models of reality captured into a coherent sequence of events to handle tension, conflict, or drama and relieve it
System	A set of interconnected elements working together to achieve a common goal
Systems Thinking	
Chaos	Behaviour that is perceived as following no pattern and not possible to predict due to the high levels of uncertainty
Complex	A system is complex when it consists of multiple different entities, with multiple different interactions, many of which are not fully understood, that is combined with feedback and structure so that the system's behaviour has unpredictability due to the emergence

Complicated	A system is complicated when it consists of multiple different entities with multiple different interactions that are well understood and produce behaviour that can be predetermined
Conceptual model	A high-level view of a problem captured in diagrams, pictures, simple stories, or drawings
Cynefin	A decision-making tool to assist managers in identifying the level of complexity in 5 domains (obvious, complicated, complex, chaotic, and disorder)
Iceberg model	A systems thinking tool that can investigate the relationship between events, patterns, structure, and mental models
Mental models	A conceptual understanding or story that the mind creates from learning/engaging with a system. The mind can use this model to understand historical behaviour and make decisions for future behaviour
Paper/Desk model	A specific type of conceptual model where diagrams and connections/interactions are illustrated visually to gain a holistic overview of the system
System archetypes	Describes the typical patterns of behaviour in organisations coined by Peter Senge in his book, The Fifth Discipline
System structure	The different components and their interactions within the system
Systems thinking	The holistic analysis focuses on how system parts interact to achieve specific goals
System Dynamics	
Causal Loop Diagram	Explains the behaviour of a system by showing a collection of connected nodes and feedback loops
Qualitative modelling	Some/All variables are mathematical abstractions/simplifications of intangible/unmeasurable aspects in reality like motivation, reputation, frustration, etc
Stock	An example of an accumulator in system dynamics
Stock Flow Diagram	A paper model which mainly uses the stocks and flows from the field of system dynamics

System dynamics	A computer-aided approach to policy analysis and design applied to dynamic problems in cross-boundary fields: management, environmental, engineering, psychological sciences, etc
Systems Engineering	
Cybernetics	The study of information systems and their integration and optimisation
Systems analysis	The process of studying a procedure or business to identify its goals and purposes and create systems and procedures that will achieve them in an efficient way - MerriamWebster Dictionary
Systems engineering	An interdisciplinary field of engineering that involves the engineering management on the design and managing complicated systems over the complete life cycle
Vee model	A primarily pre-specified and sequential process model where the model's core is a sequential progression of plans, specifications, and products used in systems engineering

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1 INTRODUCTION

The relatively young field of system dynamics has been able to inspire and confound many researchers. Jay W. Forrester founded system dynamics in the 1960s, a subset of cybernetics (Castellani, 2014). Cybernetics is the study of information systems and their integration and optimisation, which forms part of the systems engineering field. System dynamics deals with the mathematical modelling of complex and complicated challenges to enhance decision-making (Sterman, 2000).

1.1 Research Context

Research from Richardson (1986), Meadows (2008), Featherston & Doolan (2012), and Rees (2018) suggests that most students in system dynamics struggle with mathematical simulation construction. In contrast to the mathematical models, the Causal Loop Diagrams (CLDs), which are paper mental models, are learned faster (Kim & Anderson, 1998). An example of CLDs is the generic system archetypes (Senge, 1990), which represent typical system abstractions.

In the early history of system dynamics, Jay W. Forrester excluded CLDs as part of the modelling process (Meadows et al., 1972). Forrester used Stock and Flow Diagrams (SFDs) to evaluate the structure of a system. A few decades later, in the advent of the World I, II, and III system dynamics models, there emerged difficulty explaining SFDs to general audiences and obtaining their support (Meadows et al., 1972). The CLDs and system archetypes are then brought into the system dynamics models' explanations due to their similarity of feedback, delays, and holistic perspective on systems. Therefore, CLDs are critical tools to bridge the understanding between the mathematical stock-flow models and the conceptual systemic thinking (Drucker et al., 1997) (Senge, 1990).

However, the problem with the CLDs and system archetypes is their mathematical inconsistency, as Richardson points out (Richardson, 1986) (Richardson, 1997) (Richardson, 2020). CLDs and system archetypes lack essential detail and dynamics that need definition before a modelling structure can be developed. The problem is worsened since there isn't an established straightforward conversion from the CLD to a system dynamics simulation. Although many students interested in system thinking can learn and apply CLDs, according to Featherston & Doolan (2012), system dynamics' simulation adoption is slow. The mathematical simulations in system dynamics seem to be reserved to only a handful of experts due to their multidisciplinary nature and mathematical foundation.

A significant critique against system dynamics is the lack of verification, validation, and testing criteria for simulations (Featherston & Doolan, 2012), amplifying the gap in model development. In stark contrast, the field of systems engineering has a strong foundation in verification, validation, and testing (TCSE, 2019). McLucas and Ryan (2005) suggest that the system dynamics field may greatly benefit from incorporating these elements into the system dynamics method. The Vee diagram can add internal consistency and validation, which are unclear in system dynamics model development (McLucas & Ryan, 2005).

In 2013 a study conducted on how experts practised system dynamics revealed additional gaps in the system dynamics method. It was found that while the group as a whole supported a third of all the proposed practices, about two-thirds (60%) of the system dynamics practices were not supported by the group as a whole (Martinez & Richardson, 2013). The heterogeneous approaches might be due to the lack of methodological guidance, leading to experts developing individual methods.

In the past few decades, there have been attempts at bridging the gap between CLD's and system dynamics simulations (Binder, 2004) (Aranson & Angelakis, 2019) (Kim, 2000). In addition, the field's skill types and proficiencies have been quantified (Schaffernicht & Groesser, 2016). However, this research thesis focuses on integrating systems engineering principles with system dynamics to formulate an integrated simulation development approach. The approach is aimed at bridging the simulation development gap. The system archetype behaviours are well documented (Senge, 1990) (Meadows, 2008) and are used to validate the mathematical simulation results.

1.2 Problem

Even though system dynamics have frameworks for constructing mathematical simulations as proposed by field leaders like Forrester (1989) and Sterman (2000), the details on how to expand mental models into mathematical simulations are not defined. The lack of detailed guidance may lead to difficulty in learning simulation development, and the subsequent application of system dynamics becomes weakened. The South African system dynamics knowledge base has started growing, and a method to approach simulation development could aid as a catalyst for learning and adoption of system dynamics.

The main problem in the thesis is whether simple mathematical concepts can be combined with structural thinking to produce a generic system dynamics approach that can develop verified and validated system dynamics simulations from the conceptual system archetypes.

1.3 Research Questions

The critical research question is:

How can one general system dynamics simulation method be developed to translate four of the system archetypes into simulations successfully?

The critical research question results in the following sub-questions:

1) How can one coherent process be constructed to translate the Causal Loop Diagrams (CLDs) to Stock and Flow Diagrams (SFDs) and finally system dynamics simulations?
2) Can the final simulation replicate the system archetypes behaviour defined by Senge (1990)?
3) How do the experts in the system dynamics field evaluate the formulated approach and its practical application into four system archetype simulations?

1.4 Research Objectives

The main research objective is:

Develop a verifiable iterative system dynamics approach and apply it to four system archetype simulations with guidance from field experts.

Achieving the final research objective required smaller objectives as listed below:

1) Identify a coherent methodology by combining historical system dynamics methods in the literature with systems engineering verification and validation testing to translate causal loop diagrams into mathematical simulations.
2) Develop the four simulations by iterative application of the same approach. The four selected system archetypes increased in complexity, which allows the method's development and testing over a range of complexity variations.

3) Verify each of the four confirmed archetype behaviours with the simulation results.
4) Identify the outcomes and value of the systems engineering verification and validation tests.
5) Obtain system dynamics expert views and recommendations to evaluate the proposed methodology and associated simulations' applicability and validity.

1.5 Research Method

The mixed research methodology consists of a literature investigation on the historical system dynamics method, case studies on the four system archetypes, develop mathematical simulations for each case study, and finally, the Delphi research method (Linstone & Turoff, 2002). The simulation research method is used as the validation mechanism against the system archetype behaviours found in the case studies. The Delphi method is used as the verification mechanism, overcome the inter-observer reliability, and obtain expert influence on the system dynamics method development.

1.6 Overview of Thesis

The thesis chapter outline is given in Figure 1.1.

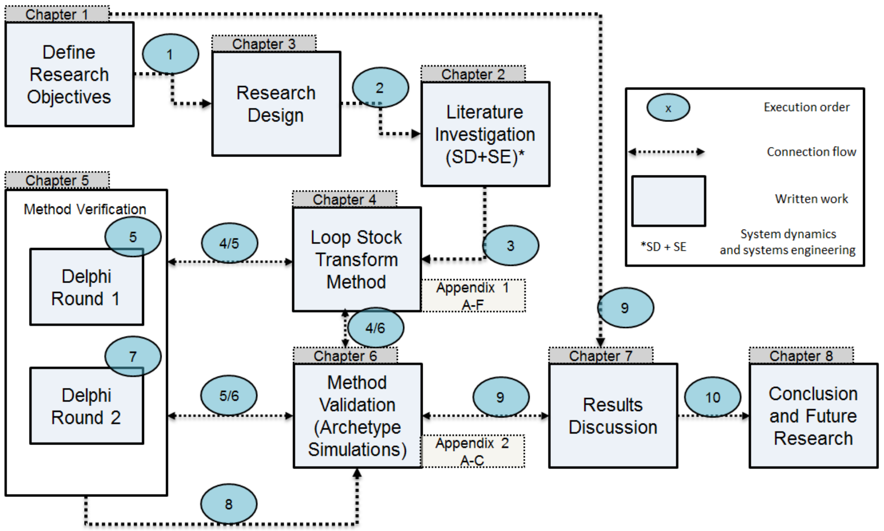

Figure 1.1: Thesis overview

The thesis' chronological order starts with defining the research objectives, then determining the research design and the literature investigation on the integration of system dynamics and systems engineering. The combined approach is defined as the Loop Stock Transform (LST). The first LST is identified through the literature investigation and tested in the Delphi round 1 by application to one system archetype. Delphi round 1 improves the LST and simulation before the second round. In the second round, the updated LST is applied to two system archetypes. Thereafter the feedback from the second Delphi round is used to conclude the LST. The Delphi approach is used as an external verification of research questions. The LST is then finally applied to four unique system archetype case studies for validation tests against literature. The results and conclusion chapters capture all the findings and future research opportunities.

1.7 Summary

The field of system dynamics had been created to understand and solve complex problems through dynamic mathematical simulations. Strong critiques had been made on the system dynamics field. The repeating critiques focus on system dynamics' lack of verification, validation, and misapplications. The challenges contribute to the difficulty in learning how to construct system dynamics simulations. System dynamics cannot help understand or solve a complex problem when it is not practised or understood. The conceptual CLD models are learned faster, yet their mathematical consistency flaws can lead to deceitful insight. The lack of a practical step-by-step approach to system dynamics simulation development and its verification is inhibiting the field's growth. The Vee diagram from systems engineering had been identified as a potential verification and validation mechanism. The main research question is to identify how such a stepwise process (LST) can be formulated to translate conceptual models into system dynamics simulations.

The main objective is to develop a repeatable iterative system dynamics method that can be applied to four system archetypes. The result will be four system dynamics simulations that can be tested against the established system archetype behaviours. A mixed research method is implemented consisting of a literature study on the system dynamics methodology, Delphi research method for external method verification, and four case study simulations on the system archetypes. The Delphi research method overcame inter-observer limitation with verification, and the four system archetype applications are able to test repeatability and practical validation.

2 LITERATURE

2.1 Background

“Thoughtful leaders increasingly recognise that we are not only failing to solve the persistent problems we face but are in fact causing them.” Sterman (2002)

This research focus is on the formulation of one general system dynamics simulation method to translate four of the system archetypes into simulations. Thus, there are two main components: Identifying such a general transition and how to ensure that the general transition can be applied successfully to the system archetypes. Before the method is formulated, the classical elements of system dynamics, system archetypes, and simulations are investigated. The concepts are defined and discussed in this first part of Chapter 2.

Examples of unscientific models can be a painting, photo, clothing model, movie, story etc. Humans are continually creating mental models of reality. Unscientific models are generally not quantifiable, and conventional scientific analyses are not conducted on them. Scientific models can be classified into four categories (Vonderembse & White, 1991): Mathematical, graphs and charts, diagrams/drawings, and scale models/prototypes. A diagrammatic (simplified) representation of models is found in Figure 2.1.

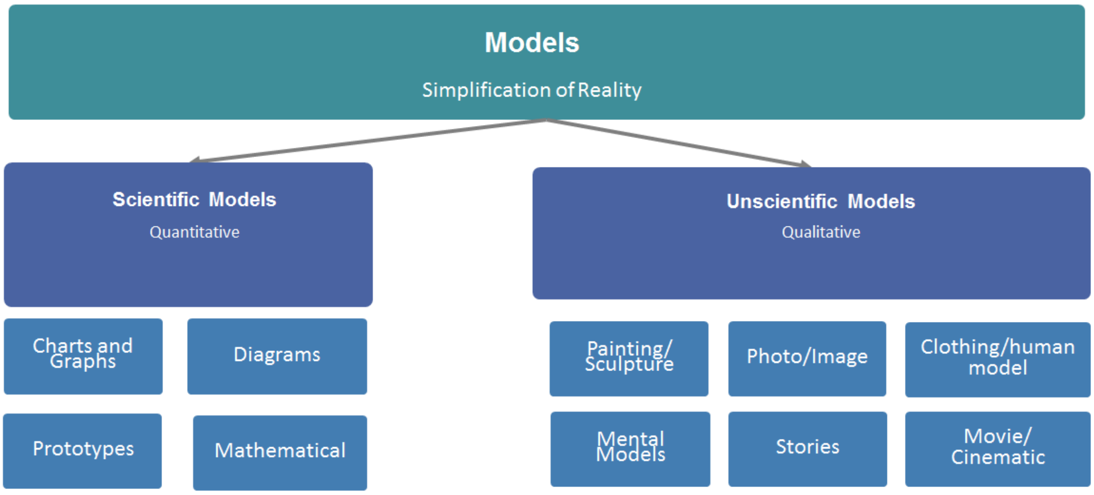

Figure 2.1: Simplified idea of models

Value of Scientific Models

Models, especially scientific models, are valuable because they offer managers/users the following three advantages (Vonderembse & White, 1991):

1) Simplify the complex problems for analysis: The simplified model allows the user to **understand** the process and consider **more** creative or alternative **solutions** that may enhance the overall system performance.
2) It allows the manager/user to evaluate alternative decisions and their results **quicker** and **cheaper** than reality: As an example, the manager can use a financial model to determine an optimal pricing strategy. In addition, the costs of experimenting with the real system to find the optimal pricing will be higher and slower relative to using a model.
3) It allows **scenario analysis** or 'What-If' questions. Many models allow changes that allow the user/manager to evaluate different decision outcomes. Scenario analysis can be invaluable to strategic planning, decision making, and testing of strategies and tactics.

All models are simplifications of reality; thus, all models have inherent errors. The famous statistical scientist Box Lightener wrote: "All models are wrong, some are more wrong than others, and some are useful." (Box & Norman, 1987). A model intends to be useful, but it can never be 100% accurate. However, models can be wrong, and without testing, validation and verification, the model can convey deceitful realities.

Models and Systems

The model is valuable when it allows the user to interact with a simplified reality without the risks and delays of tampering with the actual system (Vonderembse & White, 1991). In operations management, objective reality often consists of complex systems

(Forrester, 1961). Models are formulated to simplify and understand real and complex systems, as seen in Figure 2.2.

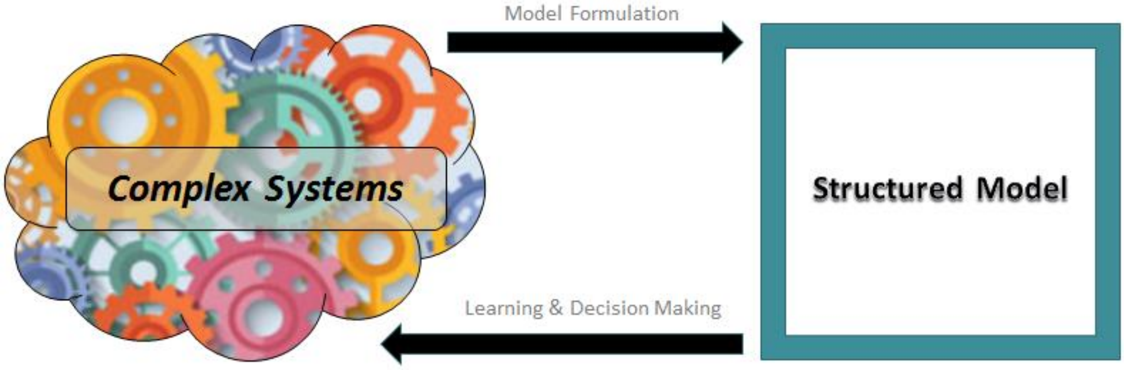

Figure 2.2: Graphical relation between complex systems and models

A system can be defined as a set of interconnected elements working together to achieve a common goal (Cambridge Dictionary). This goal can emerge out of the system and cannot be produced by the individual parts themselves. An example of a system is the human body which consists of interconnected elements like the brain, heart, and lungs. Furthermore, the emerging goal is to sustain human life through respiration (Cedar, 2018), as seen in Figure 2.3. Life is compromised when either one of these elements ceases its function. Systems are abundant, and almost all activities and behaviour seen in the world are found within systems.

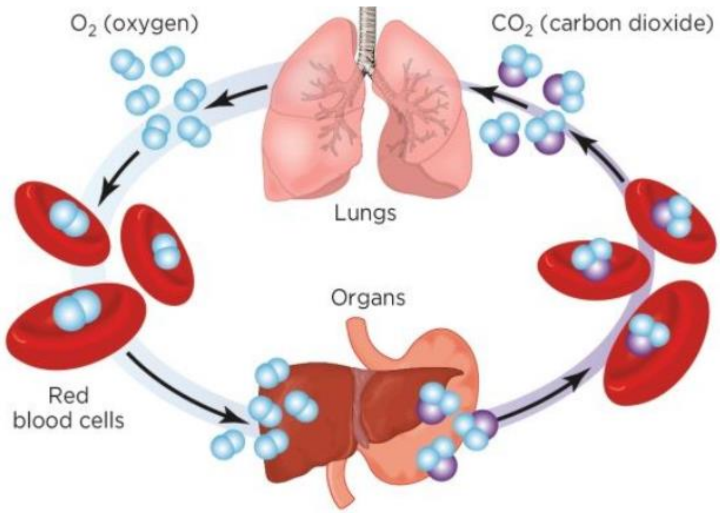

Figure 2.3: Respiration system of the body (Cedar, 2018)

In large scale hierarchies, some systems can be elements in larger systems, termed a system of systems (Nielsen *et al.,* 2015). For example, one human body is a system that is also part of a family, which is another system where each person has unique roles and responsibilities. Thereafter, the family (system) can be an element in a city's structure where different groups people have different career paths, which enable the city to sustain itself. Systems engineers often consider these ‘systems of systems’ as seen in Figure 2.4

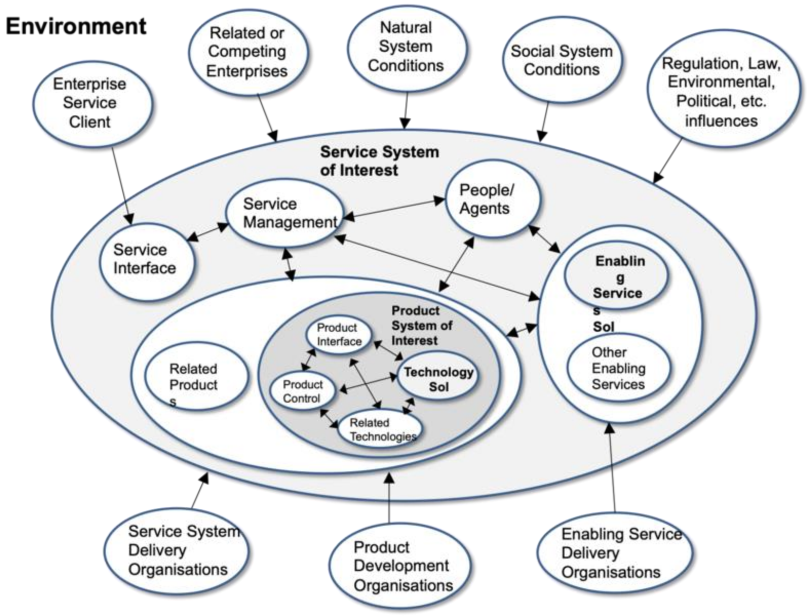

Figure 2.4: General types of engineered systems of systems (SEBoK, 2020)

Systems Thinking

Building on the theory of systems and models, system models can be defined as simplifications of the real world’s interconnected elements and their goals. There are multiple different types of system models, and the broad field of systems thinking is dedicated to the study and creation of these system models (Arnold & Wade, 2015). Systems have been studied for millennia, yet, the complexity sciences recently gave rise to the field of systems engineering, system dynamics, and a multitude of other areas (Castellani, 2018), seen in Figure 2.5. These fields use different types of system models to understand, develop, and create systemic solutions.

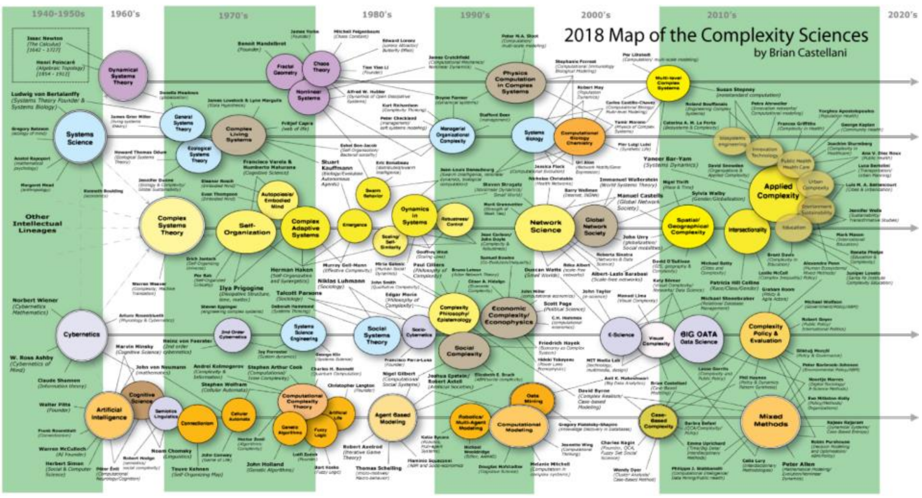

Figure 2.5: Map of the complexity sciences (Castellani, 2018)

Models and Dynamics

Models drawn on paper are mostly snapshots of stable systems, as in Figure 2.3 and Figure 2.4. However, in reality, most systems are dynamic. Dynamics is distinguished by continuous or productive activity or change (Merriam-Webster Dictionary, n.d.). Therefore, the system’s dynamics reference how systems are changing through time. A system's behaviour is captured by observing the main elements’ states and how they are changing as time progresses. As such, considering the concept of dynamics, static diagrammatic models are often insufficient to capture true system behaviour as real variable values are dynamic.

In the field of mathematics, dynamics have been studied for centuries (Newton, 1669). Time derivatives are often used to describe the relationships between system elements within the space of mechanical, electrical, chemical, aeronautical, etc., systems. Numerical estimation techniques are often used to solve the multiple differential equations in a system simultaneously (Arnold, 2008), especially when no exact calculus integration is possible. These types of dynamic solutions are referred to as simulations. Simulations are models that change with time and are often described with mathematics. Simulations can replicate some systems' dynamic behaviour like a pendulum’s movement (Palka *et al.*, 2016), seen in Figure 2.6. Next, complexity is added to the concept definitions.

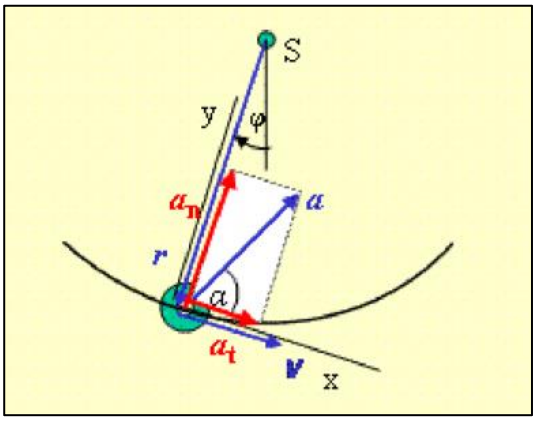

Figure 2.6: Pendulum dynamics mathematical description (Palka *et al.*, 2016)

Models and Complexity

Complex systems are often systems full of dynamics, strong interconnectedness and behave counter-intuitively (Helbing, 2009). A simulation model is advantageous in such circumstances to comprehend how the system will respond to different inputs. David Snowden (2011) established the Cynefin framework that can be used to classify and navigate different levels of complexity. The Cynefin framework is a system thinking diagrammatic model and can be seen in Figure 2.7.

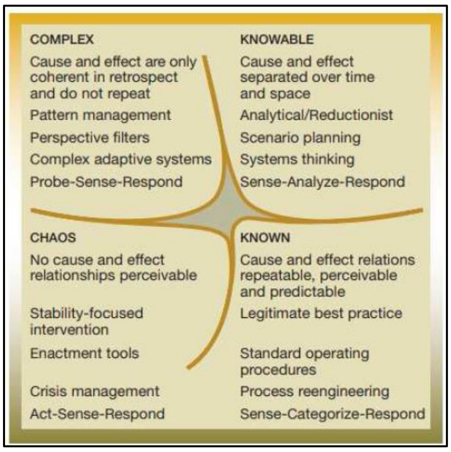

Figure 2.7: Cynefin framework (Snowden, 2011)

In the Cynefin model, there are five domains: Known, Knowable, Complex, Chaos, and Unknown. The unknown area is the grey centre. All systems start as unknown and then placed into one of the other quadrants using the Cynefin framework. A known problem is where all the relationships are fully understood and defined. The known problem can often be solved by using static models or procedures. In the knowable case, the connections might have time dynamics where complicated behaviour often emerges. Such a challenge can be solved using simulation models that take the changes into account to find the optimal scenario. Many engineering disciplines use optimisation simulations to solve these knowable problems (Amaran *et al.,* 2016).

The ‘complex’ case is where the system behaviour is counter-intuitive, and the best way to deal with these systems is to understand the mental models that have been established by field experts (Snowden, 2011). Mental models can be valuable, yet mental models are often neglected in quantitative simulation approaches due to the qualitative nature of narratives. In chaotic systems, the behaviour seems to have no pattern where there are no relations between cause and effect. Only short-term crisis management is useful in pure chaotic systems since no model can be constructed that can consistently represent reality. Pure chaotic systems are not standard, but one example could be the weather. Yet, with the increase in data collection and data processing power, the weather can slowly move into the complex domain. Although the excellent weather simulations’ precision has a limited forecasting range (Slingo & Palmer, 2011), the recent evolution of weather simulation affirms that as more information becomes available, some chaotic systems might move into the complex domain.

The other side of the complex scale is that technology's exponential growth leads to systems becoming more interconnected (Cristobal *et al.*, 2018); as more people (elements) are connected through technology, the system complexity increases (Page, 2009). Consequently, systems that are often seen as knowable become complex. An example of this is how social media can influence product perception and sales: A century ago, the marketing of a product would have been limited to a local maximum. News often remains in that local area and slowly diffuses to the rest of the country and slowly dissipating in impact. With the current technology in media, an event taking place in America can reach all over the world in a matter of minutes, like the tragedy of 11 September 2001. The increased access to information leads to more mental models being formed and shared about complex reality. Since all models are simplifications, different individuals' mental models are often in contradiction to each other.

Solving Complex Problems

According to Cynefin, the best way to deal with complex problems is to understand the stories created (mental models) by the humans working within them. Experts' mental models are a rich source of information and a foundation for useful models yet are often classified as unscientific and conventionally excluded from quantitative models (Forrester, 1961). The field of system dynamics is one of the unique quantitative science fields that can simulate people's mental models. System dynamics is interested in these mental models and often incorporates them into dynamic simulations. The simulation can be useful to understand elements of complex systems, justified by the Cynefin framework (Snowden, 2011).

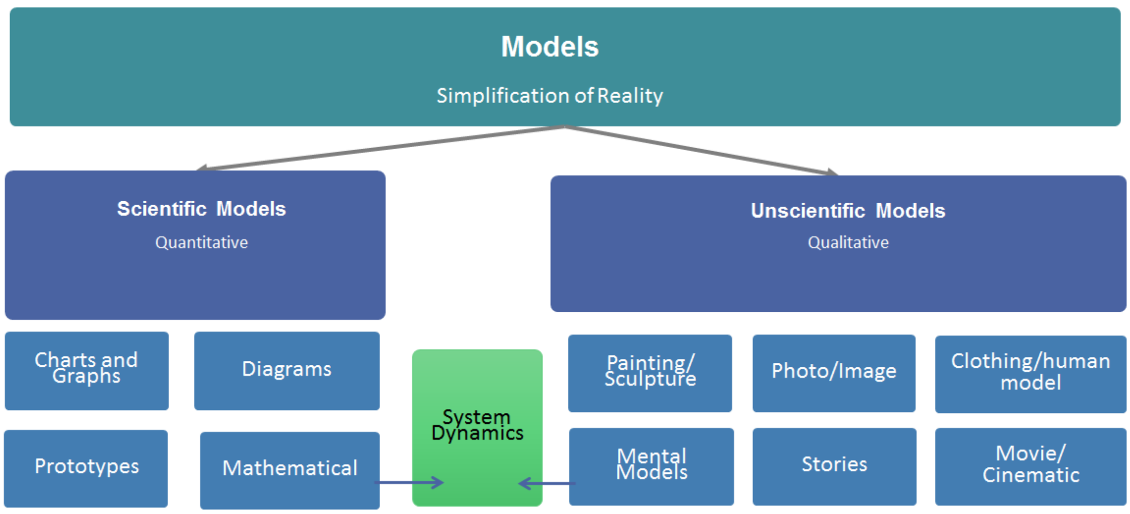

Figure 2.8: System dynamics connecting mental models and mathematical simulations

System dynamics modelling often follows two different routes: diagrammatic models and mathematical simulations. The diagrammatic models are complex pictures defined as Causal Loop Diagrams (CLDs) that can map some of the system’s causality, feedback, and interconnectedness (Haraldsson, 2004). The CLDs were invented in the

1970s to explain complex system dynamics simulations to a general audience (Meadows, 2002). In the 1990s, Senge wrote about eight unique CLDs that are common abstracted structures that repeat in reality throughout different fields (Senge, 1990). These CLDs were coined as System Archetypes (Senge, 1990). The application of CLDs grew significantly, and today they are also used in systems thinking (Haraldsson, 2004). Practitioners in fields outside of system dynamics, like health sciences, have utilised CLD models successfully (Baugh *et al.,* 2018) without creating mathematical simulations.

System dynamics is defined as the study of complex systems through modelling their behaviour which enhances decision-making (Azar, 2012), while modelling is an overarching idea that refers to creating/developing a model. A model can be defined as a simplification of reality that can be used to understand parts of reality (Bellinger, 2004). Many different model types exist, yet generally, there are two main types: scientific and unscientific models (Vonderembse & White, 1991).

Sterman (2002) explains how the lack of complex system understanding fuels tenacious problems. Sterman (2002) explains how understanding is improved through systems thinking and formal simulations. The process of constructing a formal simulation enhances complex system understanding and fosters the ability to solve persistent problems. Although Sterman (2002) advocates the importance of simulation construction in system dynamics, there are criticisms against the field (Featherston & Doolan, 2012). For example, experts have divergent opinions about the application methods in system dynamics (Martinez & Richardson, 2013). Another is that many experts classify the approach as an art form (Forrester, 1961) (Morecroft, 2015) and the lack of clear mathematical formulation steps lead to an elusive and isolated simulation construction process. It might very well be true that simulation construction enhances the understanding, yet, a simulation construction process that remains disputable, mysterious, and unguided inhibits simulation construction and the overall value of the field.

System Archetypes

The system archetypes have become a central part of system dynamics and overlap with systems thinking. The Limits to Growth Archetype is one of the most well-known as it reveals that constant economic growth is unsustainable. The book “Limits to Growth” explored the limitation on a global scale in detail (Braun, 2002). The archetype's power lies in its ability to show how anything that is growing will stop growing at some point due to the natural limits found in the real world. This can include the world population, bacterial growth, forest fires, the fishing industry, a pandemic virus, an oil-based economy, and even the smartphone explosion (Yu & Zhou, 2014). The generic archetype for Limits to Growth can be seen in Figure 2.9 below.

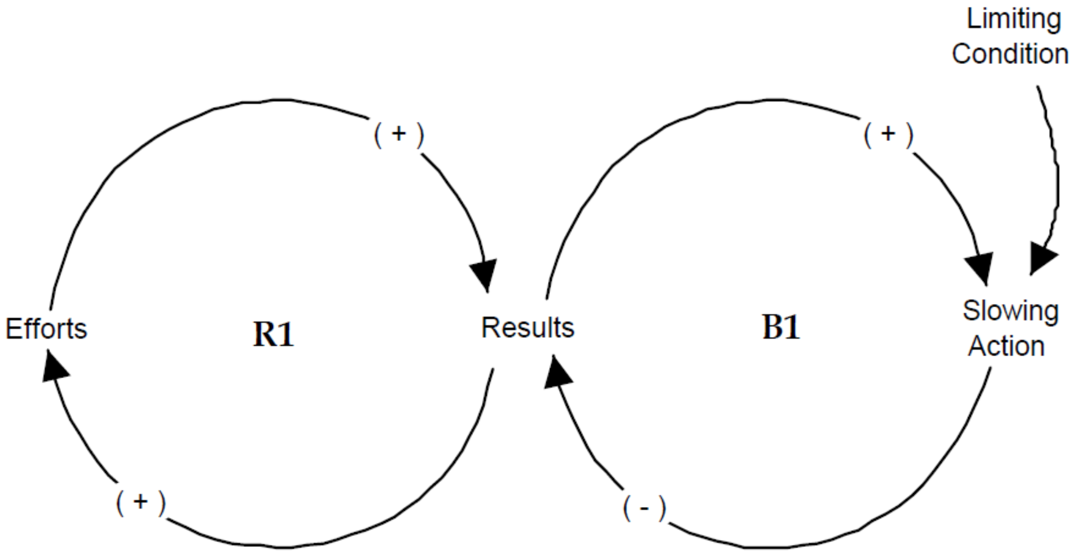

Figure 2.9: Limits to Growth archetype (Braun, 2002)

The diagrammatic model shows that more efforts produce more results (+). The larger the results become, the greater the efforts become (+), which in turn produces a larger result (+). This loop is referred to as a reinforcing loop since it amplifies the changes, which can also be defined as exponential growth/decay. In the global human population, the results variable would be the number of people, and the efforts would be the births that create exponential growth. The slowing action is strengthened by limiting conditions, like available resources, acting in on the system. The bigger the results (number of people), the stronger the slowing action becomes (deaths) (+) as more people are depleting the natural resources required to sustain the population. The stronger the slowing action (deaths) becomes, the less the results (number of people) (-). The second loop is a balancing loop which implies it is focused on establishing stability or equilibrium. An example of this behaviour over time for revenue and morale is shown in Figure 2.10, referred to as reference modes in system dynamics.

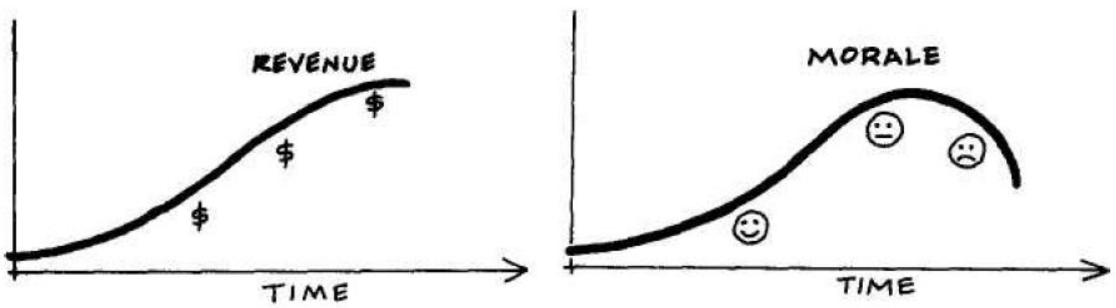

Figure 2.10: Limits to Growth archetype behaviour (Senge, 1990)

The behaviours in Figure 2.10 can also be the number of people. The number of people might grow slowly and then enter into an exponential growth phase. Thereafter the number of people stabilise and decrease due to the increase in deaths (slowing action). The same behaviour can be seen in a general population of bacteria (Bailey, 2018), Figure 2.11. In addition, the growth pattern may become cyclical as resources regenerate while bacteria populations remain low.

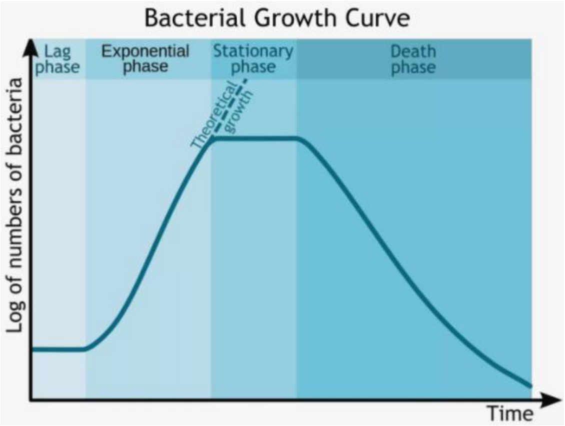

Figure 2.11: Typical behaviour of bacterial growth (Bailey, 2018)

System dynamics hypothesise that similar behaviours can be associated with similar underlying structures (Limits to Growth), which drive the system's dynamics (Forrester, 1961). Considering the CLD, Figure 2.10, and actual behaviours, Figure 2.11, a connection can be made where the initial exponential growth is driven by the reinforcing loop, while the stabilisation and possible decline are driven by the balancing loop. The general expected behaviour could be closely linked to the system archetype structure within these systems. However, the CLD models have been criticised with some major shortcomings (Richardson, 1986).

Although the generic structures of the CLD models can relate some of the behaviour to a structure, it cannot identify the driving forces, tipping points or levers in the system (Richardson, 1986). Secondly, the conceptual (mental) models that CLDs convey can also be biased and unverifiable. Thirdly, the notations of +/- do not consistently capture the same mathematical concepts and could lead to a misunderstanding of how the actual system functions (Richardson, 1986). Consequently, the misunderstanding can easily lead to misinterpreting the structure and incorrect deductions. Therefore quantification is required to verify and investigate the internal structural dynamics when analysing system structure (Andersen *et al.,* 1998). Nonetheless, the CLDs remain a powerful tool to capture, convey, and solve some problems.

Generic system archetypes exist to convey similar structures found in diverse applications, yet there are no generically defined mathematical simulation models that do the same (Forrester, 1961). One system archetype can simplify multiple mathematical simulations, and one mathematical simulation may contain various system archetypes (Forrester, 1999). The process of abstraction may allow the reduction in complex simulations to simpler reinforcing and balancing loops. The reversal of abstraction (building the stock and flow structure with mathematics from the CLD) is considered more of a creative endeavour by system dynamists (Forrester, 1961) (Morecroft, 2015). Thus, there are far fewer people developing system dynamics simulations relative to people who formulate conceptual CLDs (Scott, 2018).

The process of such a conversion from CLDs to mathematical simulations has not explicitly been defined with a generic set of system dynamics methodological steps as discussed in the next section 2.2.2. This thesis is focused on identifying such steps and applying them to four of the system archetype models. The system archetypes have behaviour patterns agreed upon by literature which is then used to validate the results from the mathematical simulation. Validation ensures that the model is useful and not wrong (Box & Norman, 1987). However, system dynamics' true value does not lie in its ability to mimic behaviour but rather in identifying system levers, counter-intuitive behaviour, and scenario analyses for decision-making (Sterman, 2000). A generic transition method between the CLD and mathematical simulation may be a stepping stone in widening system dynamics simulations to a larger audience.

2.2 The System Dynamics Method

The thesis identifies the generally agreed-upon system dynamics steps, thereafter combine them with the verification and validation paradigms of systems engineering. Next, the method is used to construct system dynamics simulations of four system archetype case studies. Finally, the method and simulations are independently evaluated by experts through the Delphi Research method.

In section 2.2, the historical methodologies in system dynamics are discussed, while the systems engineering methodology is discussed in section 2.2.2.9. The discussion is summarised in Figure 2.12.

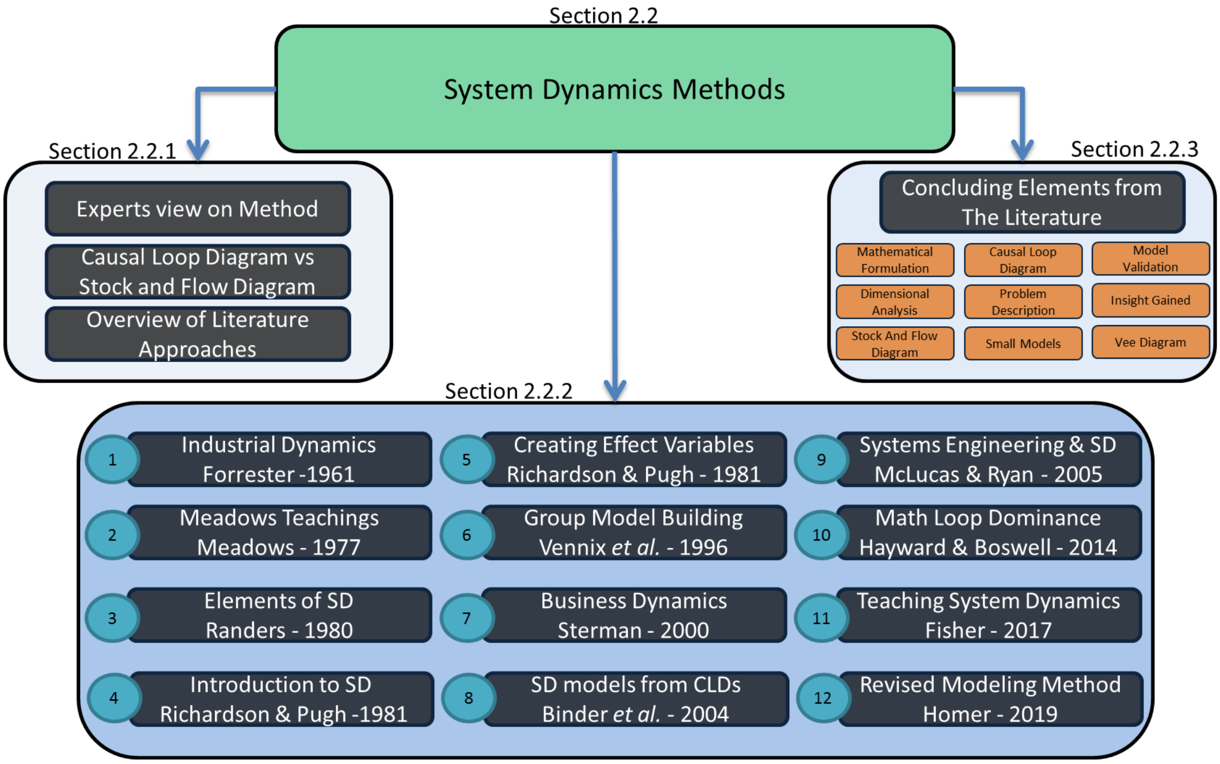

Figure 2.12: Summary of literature on system dynamics methods

In 1961 Jay W Forrester wrote the book: Industrial Dynamics under the MIT Sloan Management School. He combined his 16 years of control engineering experience with business management principles. The book is the seminal starting point for the emergence of system dynamics (Lane & Sterman, 2011). Industrial dynamics focused on supply chains, yet the field only gained viral momentum after applying it to socio-economics and global resource management. The book Urban Dynamics (Forrester, 1969) explores the counter-intuitive failures of creating low-income housing. The World Dynamics book (Forrester, 1971) explores the resource implausibility of indefinite exponential growth (Lane & Sterman, 2011). The book *Limits to Growth* used these principles and explored the global challenges further throughout the 1970s (Meadows *et al.*, 1972). The counter-intuitive nature of these books, combined with factual simulations, lead to large-scale interest, with many eager to learn, while others were eager to criticise the area and its simulation discoveries.

2.2.1 Expert's Methodical Approaches

Although the field's discipline is rooted in engineering, the principle of system dynamics easily and purposefully included other disciplines like business, economics, social, psychological, environmental, etc. Some of the diverse visionaries in the field who taught system dynamics were Forrester, Meadows, Randers, Richardson, Pugh, Sterman, Martinez, and Hayward. Multiple papers and books were written on applying the system dynamics methodology, as can be seen in Figure 2.14. The system dynamics field almost produces 300 works each year and reveals that it is still growing and driven by the International System Dynamics Conferences (Homer & Richardson, 2018).

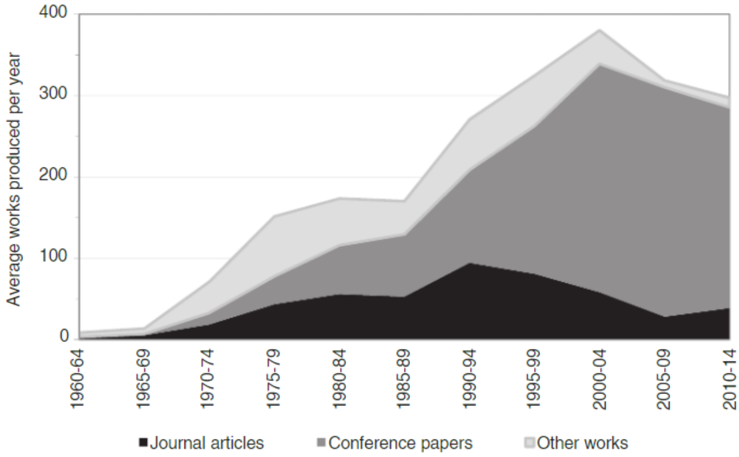

Figure 2.13: Average system dynamics work produced per year (Homer & Richardson, 2018)

About 13 publications (papers and books) on the system dynamics methodology were identified and reviewed. The citations with the number of steps for each of the author's methods are in Figure 2.14.

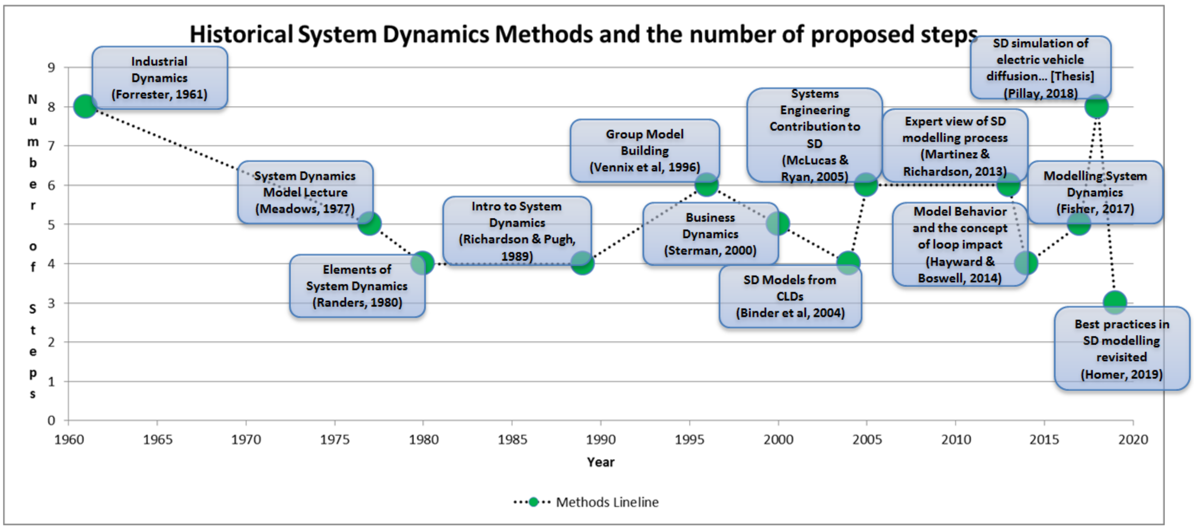

Figure 2.14: Historical system dynamics authors on method

The field has inadvertently grown and evolved, and differentiated methods emerged. Martinez and Richardson (2013) consulted 19 of the top experts to define the system dynamics modelling process. The study focused on identifying the best practices of system dynamics experts. The research identified a total of 198 practices, and these were classified into six different focus areas:

General System Dynamics Steps:

1) Problem Identification and Definition
2) System Conceptualisation
3) Model Formation
4) Model Testing and Evaluation
5) Model Use, Implementation, and Dissemination
6) Design of Learning Strategy/Infrastructure

The research found that 60%of the best practices given by one expert were classified as controversial or indistinct practices by the group as a whole. The finding indicates that the expert group as a whole is not aligned to one system dynamics methodology. The differences are further classified into the following four categories where the total number of disagreements are noted:

Main Categories of Disagreements:

1) Research Design – 4 category differences
2) Theory – 5 category differences
3) Method - 8 category differences
4) Procedures – 3 category differences

The *Method* had the most difference on best practices between the field experts. The research from Martinez & Richardson (2013) may lead to a negative perception of system dynamics, yet a third of the best practices were very well agreed upon. The agreed-upon practices are listed next.

Agreed Upon Practices:

1) Problem Identification and Definition:
    a. Talk and listen to clients
    b. The clear purpose of the model
    c. Reference Modes to explore mental models
    d. Ask why and identify causalities
    e. Dynamic hypothesis (this behaviour caused by that structure)
2) System Conceptualisation
    a. No definite recipe – approach from different angles
    b. Generate dialogue with problem owner’s that addresses their mental models and the dynamic hypothesis
    c. Start with major stock variables- draw from their reference modes; they should be nouns (NOT verbs NOR action phrases).

3) Model Formation:
    a. Work up through a series of simple to more comprehensive models.
    b. Dimensional consistency (from the beginning)
    c. All equations should make sense, and parameters must have real-life meaning.
4) Model Testing and Evaluation:
    a. Compare behaviour patterns against real ones (statistical measures of pattern fitting, NOT point by point fit).
5) Model use, implementation and Dissemination:
    a. The entire exercise must revolve around the problems of concern for the audience.
6) Design of Learning Strategy/Infrastructure
    a. Use simplified CLDs to tell the system stories repeatedly and in many ways – do not let the model tell its own story.

The practices were well established between most of the experts. The techniques above would likely be the most useful due to their high adoption rates by multiple experts. It is worthwhile to notice that these are general recommendations. The exact method of translating conceptual models like CLDs or Stock and Flow diagrams is not part of the research by Martinez & Richardson (2013). Next, the controversial techniques are described.

Controversial Practices Summary:

1) Problem Identification and Definition
    a. Whether to model the class of the system or the case at hand.
2) System Conceptualisation
    a. Iteratively using a CLD approach or a stock-and-flow approach to conceptualise. (Most agree to start at a model with identifying stocks)
3) Model Formation
    a. Whether to start small and iterate bigger OR formulate big chunks of models.
    b. Some believe that extreme condition tests are essential for testing the model; others not.
4) Model Testing and Evaluation
    a. Iterative test to validation –where the disagreement is on where in the process rather than whether it should be done. Some believe it should be done from the start, where others believe it should be part of the model formation.

5) Model use, implementation and Dissemination
    a. Timing of the proposed question. Should the question be asked in the beginning to prevent the wrong direction, or should it be formulated after an in-depth understanding is gained from the structure?
6) Design of Learning Strategy/Infrastructure
    a. The major difference between what is important in the models:
        i. The use of flight simulators as gaming versions for learning is not shared by everyone.
    b. The emphasis on the learning process and outcomes. It is difficult to sell understanding and deep knowledge compared to the ‘real’ model with equations (product).

It is worthwhile to note the following about these disagreements. It is not that any of the controversial approaches are inherently flawed but rather different polarised application ideas. Homer (2019) was a part of the participants, and in his opinion, these differences are a matter of preference rather than fundamentally contradictive. It would be appropriate to note that under the system conceptualisation category (2), there is a disagreement on either using a CLD or a Stock and Flow diagram (SFD) to conceptualise the model. The CLDs or SFDs discrepancy is an essential point for this research.

The CLD and the SFD are investigated further in the next section, 2.2.1.1.

2.2.1.1 <u>Causal Loop Diagram and Stock Flow Diagrams:</u>

Next, historical system dynamics methods are discussed to resolve the dispute for and against CLDs and Stock and Flow Diagrams (SFDs). Each of the 13 publications linked to the system dynamics methodology is investigated to identify how the system conceptualisation took place. A total of 10/13 methods refer to using both the CLD and the SFD, where two methods only refer to CLDs (no SFDs). Yet, Industrial Dynamics (Forrester, 1961) does not use CLDs nor SFDs, since, in 1961, some elements were referred to as causality diagrams for CLDs and levels and rates as SFDs. A graphical depiction of the connection between the SFD and CLD is in Figure 2.15 below.

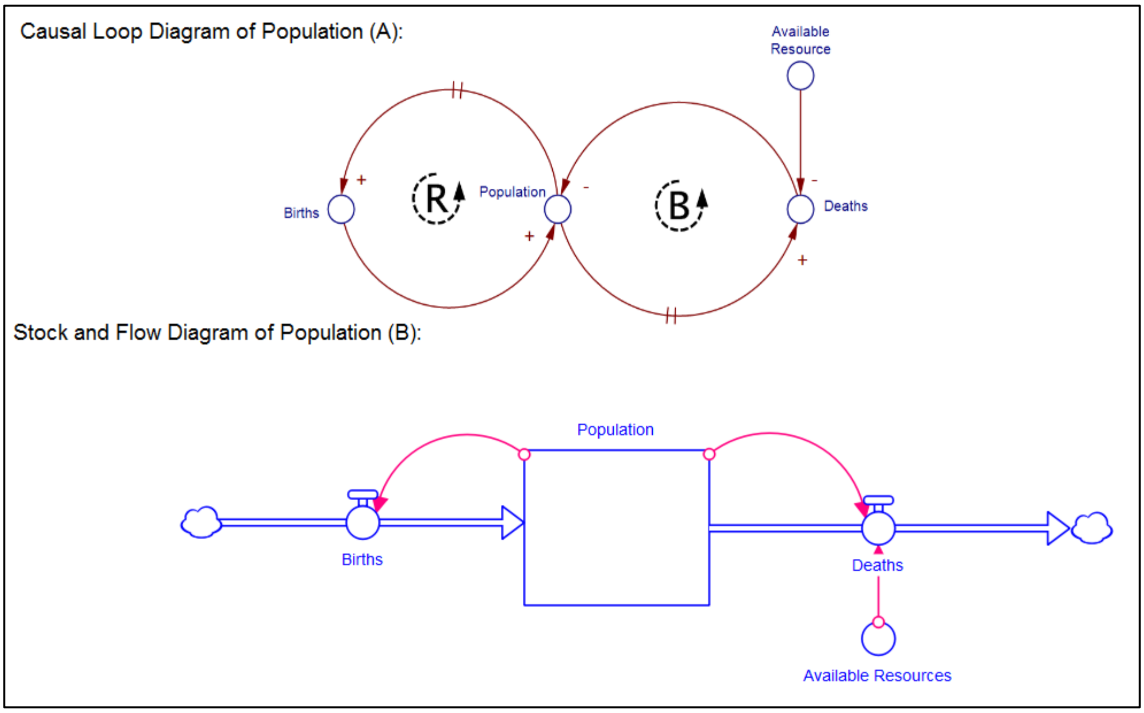

Figure 2.15: Causal Loop Diagram [A] and Stock and Flow Diagram [B]

One of the two methods that do not utilise the SFD is Vennix (1996), who initiated Group Model Building (GMB). The GMB focuses on using system dynamics as a qualitative consulting technique to create collaboration and systemic change through mental model adjustments (Andersen *et al.,* 1998). In this general approach, quantitative modelling is not always required, and dynamic hypotheses are mapped and discussed as CLDs. The simulation formation (equations) is generally outside the GMB boundary and thus does not necessitate the SFD. It is worth noting that some experts argue that a system cannot be correctly understood only through a CLD (Richardson, 1986) and that the CLD model needs formal testing (Homer & Oliva, 2001). The counter-argument is that a mathematical simulation can also mislead clients with false precision (Coyle, 2000).

The second method that does not use SFDs is from Pillay (2018), which might not include the SFD explicitly due to the software application used in this method. iSee Stella Architect is employed in the research, forcing the user to construct the model in an SFD format. The creation of the stocks and flows are thus inherently part of the model building process. This was not always the case as before STELLA/iThink was commercialised, the dominant language was DYNAMO (DYNAMic Modelling) (Lane & Sterman, 2011). DYNAMO is the reference software in all the methods of Figure 2.14 before the year 1990. DYNAMO, however, had no graphical layer for simulation construction, and thus an SFD on paper was essential to create the equations for stocks (Level), flows (rates), and auxiliaries (simplification equations). High-

Performance Systems created a revolutionary computer application (STELLA/iThink) that incorporated the SFD (Forrester, 1989) and received the reward for best contribution to system dynamics in 1994. Today, many other applications exist that have similar user interface elements, like STELLA and iThink, which resulted in DYNAMO becoming obsolete.

The paper and pencil drawing of SFDs was the starting point of system dynamics. Forrester strongly believed that the SFD is critical to understand the real dynamics created by systemic structures (Forrester, 1961), as seen in the first hand-drawn stock and flow model of Forrester, Figure 2.16.

In conclusion, the literature does indicate that historical system dynamics publications refer to the use of both the CLD and SFD when a mathematical simulation is constructed.

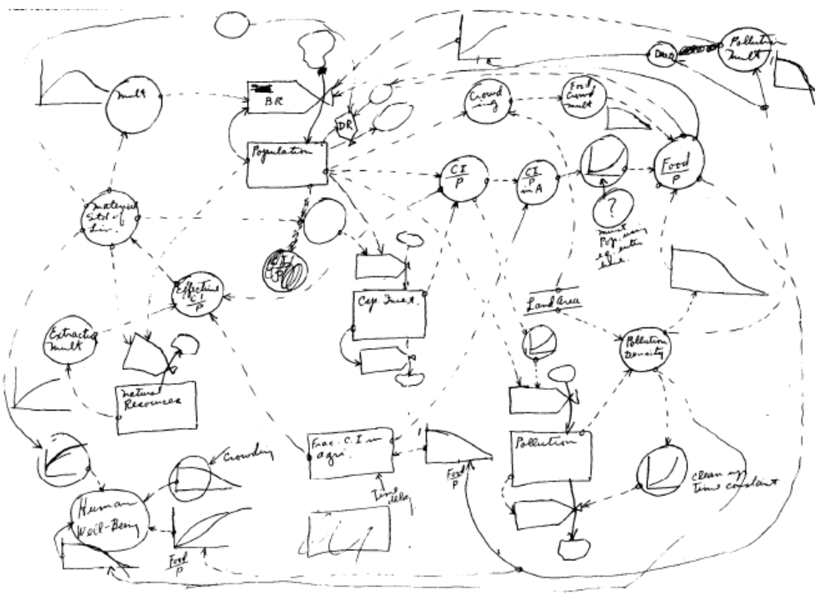

Figure 2.16: First hand-drawn stock and flow model (Lane & Sterman, 2011)

2.2.1.2 <u>Overview of Methodological Literature</u>

The focus of the thesis is on model formation, which overlaps with the system conceptualisation and model testing steps. The historical methods are filtered according to the conceptual to mathematical transitions. All the methods are categorised into the six different classifications used by Martinez & Richardson (2013).

The colour key in Figure 2.17 is applied to every method seen in Figure 2.18 and Figure 2.19.

Key
Problem Idenfitication/Defition
System Conecptualization
Model Formation
Model Testing and Evaluation
Model use, implementation
Design of learning strategy

Figure 2.17: Classification Key and Color

Dominant Language	DYNAMO (rate equation definition, no stock and flow diagram in program)				iSee Stella Market - Incorporated the SFD
	Industrial Dynamics	System Dynamics Model: Kaibab Deer	Elements of the SD method	Introduction to System Dynamics	Group Model Building
Year	1961	1977	1980	1989	1996
Author	Forrester	(Meadows at Dartmouth College, New	Randers	Richardson and Pugh	Vennix et al
Steps			*based on Forrester's		
1	Understand the type of model	Use words/contextual	Conceptualization (familiarize;	Identify Problem and System	Group Discussions
2	Conceptual understanding of	Define reference modes	Formulation (selecting levels,	Model Formulation:	CLDs iteratively in discussion
3	Define the purpose of the	Causal Loop Diagram (write	Testing (recreate ref modes, test	Model testing and development	Pre and post questions
4	Define the endogenous	Stock Flow Diagram	Implementation (test sensitivty,	Policy Analysis	Elaborate Questionnaires
5	Identify equations: Levels,	Equations (formulate rate			Semi-structured evaluation
6	Observe from multiple				Post Project Evaluation
7	Validation relative to				
8	Model Analysis				

Figure 2.18: First five literature elements on methodology

Dominant Language	iSee Stella; iThink; Vensim; PowerSim; GoldSim (Visual Icon Based)							
	Business Dynamics	Developing SD models from CLDs	What SD can learn from SE	Expert view of SD modelling Process	Mathematical modeling method of CLDs	Modelling Dynamic Systems	EV models (PhD Dissertation)	Revisited Modelling method
Year	2000	2004	2005	2013	2014	2017	2018	2019
Author	Sterman	Binder et al	McLucas and Ryan	Richardson and Martinez	Hayward and Bosswell	Fisher	Pillay	Homer
Steps			*ref J Forrester method					
1	Problem Articuluation	Label CLD	Describe the system	Problem Identification	Start with constructed CLD	Problem Articulation	Project Inception	Problem Definition
2	Formulation of dynamic	Iterative steps to transform	Convert the description to	System Conceptualization	Define CLD reference modes	Dynamic Hypothesis(	Councept to Context	Model Formulation
3	Formulation of simulation model	Structured CLD to SFD	simulate the model	Model Formation	Use double differentiation to	Buiild a Model (Describe the	Boundary Setting (CLDs)	Scenario Analysis (Test model to
4	Testing	Develop SFD to SD model	Design alternative	Model Testing and Evaluation	Define the multipliers and	Test the Model (Model same as	System Analysis	
5	Policy Design and evaluation		Educate and Debate	Model Use, Implementation		Policy Design and Evaluation	Model Development and	
6			Implement changes in	Design of Learning			Validation and policy insights	
7							Model Handover	
8							Model Maintenance and	

Figure 2.19: Last eight literature elements on methodology

The 13 authors above are not the only authors of the system dynamics methodology. For example, the Creative Learning Exchange created a hub of useful tools to enhance the learning and teaching of system dynamics in the educational context (Lane & Sterman, 2011). Many of these tools teach the fundamentals of how to think in systems. The work adds a lot of value to the first two steps shown in the key, Figure 2.17, but most of the studies were far less focused on the mathematical simulation and were thus excluded. Another contributor is the *“The Systems Thinker,”* which is also an online resource platform where experts give useful information about modelling (The Systems Thinker, 2018). There is a multitude of courses available on the International System Dynamics Society learning page. Some of these works are discussed in the thesis. The final contributor mentioned here is iSee Systems which hold regular webinars on model building through iSee Stella Architect software. The online tutorials are a good source for constructing models after the model conceptualisation, yet the equation formation process is not explored. In the next few paragraphs, each method will be discussed explicitly, surrounding the transition between the conceptual model to the mathematical simulation.

2.2.2 Historical System Dynamics Methods

In the following subsections, multiple documented system dynamics methods are investigated. The purpose is firstly to understand the evolution of the method since its initiation in 1961. The second is to identify the role that CLDs and SFDs have played in these methods. The third and final is to use the culminated literature to determine the generic system dynamics elements required for the Loop Stock Transform defined in Chapter 4.

2.2.2.1 Industrial Dynamics (1961)

Industrial Dynamics (Forrester, 1961) alludes slightly to the simulation models' mathematical equations and derivations. The equations and models are revealed in detail, but the process of obtaining them is not. This is true even though most of the conceptual supporting tools like CLDs and SFDs were not fully developed yet. The book discusses the general approach and then creates four detailed models through level/rate equations and using DYNAMO software to simulate them numerically. The general idea behind the modelling process was:

Basic Steps used in Model Formation:

1) Find reference modes of the system
2) Identify endogenous variables, system concepts, and model purpose
3) Create a causality diagram (showing all the feedback)
4) Draw the Level and rate diagram
5) Create their equations using generalised math.

The rest of the steps are outside the scope of this research. Forrester writes the following about the creation of the mathematical equations:

“The experimental study of mathematics does not rest on any math that cannot be taught in a few days any time after high school level” (p. 351 – Industrial Dynamics, 1961)

The book explores the explanation of how these ‘simple’ mathematics can create complicated behaviours. The book shows that it is mostly due to how the equations are formulated and due to multiple differential equations that are being solved simultaneously through numerical integration methods. Forrester (1961) explains that the detailed calculus of system dynamics would overwhelm most novices, yet mathematicians might appreciate the calculus. Therefore, the excerpt is quoted to show that the initial ideal of system dynamics was to equip a larger audience, outside pure mathematicians, with the ability to construct simulation models.

Stocks and Flows in Chemical Engineering

Forrester expects that the user will need to identify the ‘levels’ first. He advises that a good approach would be to look at the system as if time has stopped. Whatever remains in the system are usually the levels (Forrester, 1961) – the “snapshot” test. The variables that directly add or remove from these levels are the rates. The additional concepts are mostly the auxiliaries and delays. Forrester explains how most sciences would produce one long, complicated equation for a rate. The Industrial Dynamics approach is to break down the long equation into smaller auxiliary equations through mathematical substitution. Richardson and Pugh (1981) recommended that no more than three variables be connected to one auxiliary. These ‘simple’ mathematical auxiliaries are also found in other sciences like chemical reaction kinetics, as seen in Figure 2.20.

$$\boxed{\bar{a}A + \bar{b}B \Rightarrow \bar{w}W}$$

$$\boxed{\mathrm{r} = kC_A^{\alpha_A} C_B^{\alpha_B}}$$

Figure 2.20: Chemical reaction kinetics (Davis & Davis, 2003)

The k value (constant) in this rate has the same function as the *multiplier* concept that Forrester refers to in Industrial Dynamics (1961). The C_A is the concentration of component A. This concentration is the mass of species A stock divided by the volume of the system. The 'concentration' is thus an auxiliary equation. The same principle applies to component B. The concentrations are often utilised in chemistry due to the ease of measuring or obtaining concentration at the system's equilibrium points. Thus, there is a real-world link to chemistry equations, just as Industrial Dynamics emphasizes that model variables should be linked to real-world elements. The k multiplier is derived from experimental data fitting with an assumed reaction order of x and y. It seems that the same thinking in Industrial Dynamics can be applied to the rate equation creation of chemical engineering. Chemical engineering equations have clear axioms (Davis & Davis, 2003); in contrast, a set of clear axioms are not available for system dynamics equations.

Another core argument that Forrester uses is that the stock and flow structure of systems is the origin of all the system's dynamics and their equations (Forrester, 1961). Many structures are similar, even though the applications might be vastly different. A similar observation can be made on how heat moves through objects via temperature gradients, mass transfers through concentration gradients, and electrical current flows with voltage potential gradients (Vos, 2019). Similar mathematics exists for all three heterogeneous fields. As such, Industrial Dynamics proposes the idea that systems can be modelled from a systemic structural viewpoint to yield more insight into these drivers of behaviour. The mathematical analogy between the mechanical, electrical, and thermal fields is captured in Figure 2.21.

Element	Mechanical	Electrical	Thermal
Resistance	$\vec{v} = \vec{F}\,\frac{1}{b}$	$V = I\,R$	$\Delta T = \vec{q}\,R$
Capacitance	$\vec{p} = \int \vec{F}\,\mathrm{d}t$ $\vec{v} = \frac{\vec{p}}{m}$	$Q = \int I\,\mathrm{d}t$ $V = \frac{Q}{C}$	$Q = \int \vec{q}\,\mathrm{d}t$ $\Delta T = \frac{Q}{C}$
Inductance	$\vec{x} = \int \vec{v}\,\mathrm{d}t$ $\vec{F} = k\,\vec{x}$	$\Phi = \int V\,\mathrm{d}t$ $I = \frac{\Phi}{L}$	Not known

Figure 2.21: Analogy between different scientific fields (Vos, 2019)

Industrial Dynamics (Forrester, 1961) is an instrumental piece of literature; however, it does not identify a simple set of general equations that the beginner can use. Forrester (and others) also stress that the model creation process is more of an art (Forrester, 1961) (Morecroft, 2015) than a solely mathematical exercise. Simulation construction is also an iterative process where the simulation needs reconstruction several times to achieve the simulation purpose.

2.2.2.2 Teachings from Donella Meadows (1977)

The second author's work that will be discussed here is Donella H. Meadows while teaching in 1977 at Dartmouth, New Hampshire (Meadows, 1977). Meadows does not explicitly list her steps, but it can be deduced from the practical approach of simulating the Kaibab Deer Population as follows:

Basic Steps in Model Formation (Meadows, 1977):

1) Start with a word descriptive model
2) Obtain Reference modes
3) Create a CLD
4) Use the CLD to create an SFD
5) Generate the equations for the rates and auxiliaries of the SFD

Meadows (1977) can explain the model formation process and its associated equations to the class within an hour. Most of the equations follow the same simplistic definitions that Industrial Dynamics used for rates. Meadows (1977) used 'Effect' variables when non-linear relationships exist between variables. In the Kaibab deer example, the relationship between population density and the killing rate per wolf is a non-linear relation. Industrial Dynamics (1961) explains that the 'Effect' variable is the same as DYNAMO's definition of Table functions. The modeller would often need to decouple the dependent variable, population density, and show the killing rate's effect. Non-linear functions are relationships where the difference between x and y does not remain the same throughout the variables' domain (Fisher, 2020). These non-linear 'effect' variables are used in most methods, yet experts seem to differ on how many 'Effect' variables should be allowed within a model (Homer, 2019).

The reasoning behind forcing the modeller to reduce these effect variables is that effect variables are perceived as taking a modelling shortcut, evading some structures that create this non-linear relationship. A counter-argument for this could be that non-linear functions serve the same purpose as the 'orders' in the chemical engineering equations discussed previously. It shows the exponential effect that one stock (state variable) might have on itself or another stock. These relationships emerge from the complex interactions between the individual entities (seen in agent-based models), which lie outside of the scope of a system dynamics model. System dynamics aggregates many complex interactions, as discussed by Forrester, where he argued that for the same reason that individual gas molecules are not simulated to calculate the pressure of a system, many micro-interactions could be described as a general non-linear relationship (Forrester, 1961 - p.109). The non-linear relationship can be incorporated into the simulation using the effect variable/table function shown in Figure 2.22. The table functions or effect variables can create inaccuracy within the model when the relationship is not drawn precisely.

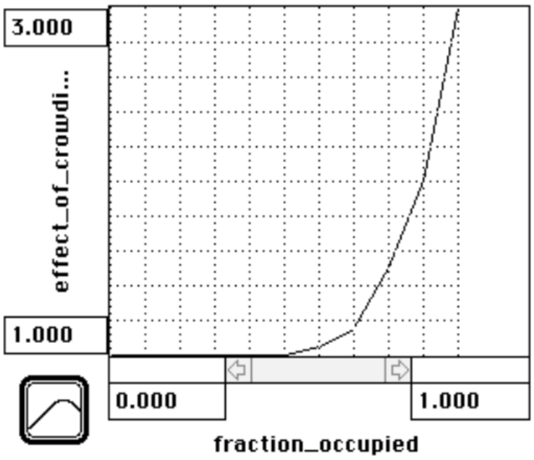

Figure 2.22: Example of the effect variable/table function (Martin, 1997)

Recent technological advances have allowed scientists to study the enumerable number of simultaneous interactions through computational fluid dynamics and agent-based modelling. Psychology shows how human behaviour is complex yet can be accurately simulated when humans exhibit herd behaviour (De Assis *et al.*, 2020). For example, Simulating all the decisions that one individual can make in traffic congestion would be very complex and lie outside the scope of system dynamics. However, simulating the overall congested traffic problem (consisting of many humans) could be a plausible system dynamics exercise. It might seem counterintuitive, yet considering the uncertainty principle at the atomic scale (Heisenberg, 1927), where an atom's position and velocity are impossible to know simultaneously, system behaviour can often become more unpredictable the lower the hierarchy of a system being studied (Heisenberg, 1927).

Non-linear or effect variables/table functions could be the system dynamics equivalent of these complex interactions that lie outside the system dynamics modelling scope or current hierarchy—the variable attempts to capture the complexities of individual components. Meadows show in the lecture that excluding the non-linear ‘Effect’ variable produces incorrect system behaviour (Meadows, 1977).

The practical lecture that Meadows produced in 1977 is an actual example of how to translate the conceptual CLD models to SFDs and into the mathematical domain that can be used to simulate the problem. The general equation formulation process, however, is not explicitly mentioned by Meadows. The equation formation process is, however, the critical part of this thesis.

2.2.2.3 The Elements of the System Dynamics Method compiled by Randers (1980)

Randers (1980) contains multiple articles written by system dynamics experts on the modelling method. Chapter 6 is specifically appropriate to the modelling transition from conceptual to mathematical models.

The high-level summary view of the method includes the four steps initially presented by Forrester (1961). The conceptualization step includes defining questions, timeframes, and a verbal description of the model, similar to Meadows (1977). The system should then be described conceptually with a primary system mechanism synthesized into a CLD. This approach fits closely with Meadows (1977) again. The second step (Formulation) is defined as selecting the levels, rates and describing determinants. Not many details are given on exactly how this would be achieved in all circumstances, but the following equation is used to describe general rates:

The general form of rate equations:

$$rate = Level\ \times normal\ fraction\ \times Multiplier$$

The Level can be the same Level to which the rate is attached or a different level. This formulation makes it easier to verify the normal fractions with actual data when the rates and levels are physically measurable elements in a system (Forrester, 1961 – p.152). A normal fraction can take many different forms, and Randers (1980) references the housing demolition fraction that Forrester used in Urban Dynamics (Forrester, 1969). Using this type of fraction creates an F-distribution behaviour and is defined as:

$$Housing\ Demolition = \frac{Number\ of\ houses}{Life\ time\ of\ houses}$$

Randers stresses the importance of dimensional consistency. The dimension of the level, in this case, would be the *Number of houses*. The dimension of a rate needs to be the dimension of the level per time unit. In this case, the dimension of the rate needs to be the *number of houses per time*. The normal fraction of the Housing Demolition equation would be one divided by the lifetime of houses. In this case, no multiplier is required, and the housing demolition equation can fit the general rate equation.

Multipliers are mostly initiated at a reference value of 1 (Randers, 1980). Practically, this ensures no change in impact when the driver of the multiplier is not acting on the rate. The multiplier value can then either decrease or increase the rate according to the effect another variable has on the rate. Meadows (1977) refer to multipliers as effect variables, Randers (1980) refers to Table functions (similar to Forrester), which were used in DYNAMO software simulation applications.

The variable ‘Lifetime of houses’ can be referred to as the first-order delay in system dynamics. Delays are an essential part of system dynamics models. Delays are discussed in detail by all three authors, Forrester (1961), Randers (1980), and Meadows (1972). The formulation of delays is discussed by Randers (p. 164, 1980), where each delay has two parameters: Adjustment Time and Order. Adjustment time is some reference time for the rate to take effect. The ‘Life time of houses’ in itself can be considered the adjustment time before the house is demolished. The order of the delay is an integer of 1 or higher that determines the shape of the delay. The higher the order, the stronger the effect would be on the rate. In the example of housing demolition, the order is kept at a value of 1. In practical systems, there might be multiple delays working together into one rate. Randers (1980) explores different ways on how to compile the final adjustment time. Forrester (1961) suggests that delays can be added together to produce one total adjustment time if the delays follow in series.

In conclusion, of this method, Randers (1980) revealed some insight into the general equations used for rates and the definition of the delays. Delays are concepts that are evident in CLDs and can be shown on SFDs. The next method discusses a beneficial technique to generate rate equations.

2.2.2.4 Introduction to System Dynamics Modelling (1981)

Richardson and Pugh (1981) produced the book “Introduction to System Dynamics Modelling” which covers the model creation process in a fair amount of detail. The first step (conceptualization) involves the system's graphic descriptions (reference modes), construction of the CLDs and SFDs. The purpose of the model is a crucial concept during this phase. Forrester also proposed that the only way to validate a model is by validating the model to its original purpose.

The model formation describes the core competencies required to build system dynamics models and then supplied the reader with six general types of rate equations. These equations are not an exhaustive list but intend to serve as a starting point for newcomers to the field. The six general types of rate equations are

The six differentiated type rate equations (Richardson & Pugh, 1981 - p.134):

$$R_1 = Constant \times Level$$

$$R_2 = \frac{Level}{Time}$$

$$R_3 = \frac{Goal - Level}{Adjustment\ Time}$$

$$R_4 = Auxilliary \times Level\ OR\ R_4 = \frac{Level}{Auxilliary}$$

$$R_5 = \text{Normal}\ Rate + Effect$$

$$R_6 = Normal\ Rate \times Effect$$

Rate 1 is usually an inflow rate. The inflow rate of a level/stock is a function of a level and some fractional constant. An example is when births are calculated in a population model using a constant birth rate. The births (people added to the population stock) are determined by multiplying the birth rate (constant) with the current population (Level). *Rate 2* is often used as an outflow where a delay exists. The outflow example is already explained in the Housing Demolitions, a function of the number of houses (Level) divided by the houses' lifetime (Time), as seen in Figure 2.23 below.

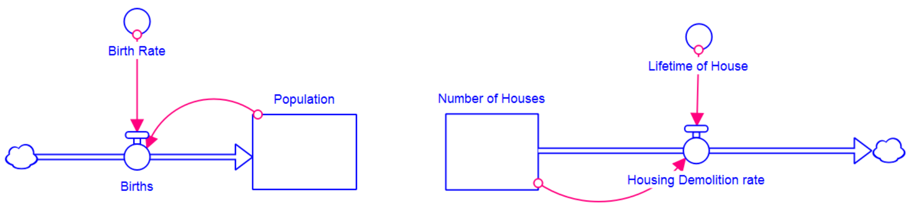

Figure 2.23: Graphical depictions of rate 1 and 2

Rate 3 is the goal-seeking behaviour often seen in systems where effort is put towards achieving a target. A typical example is where an inventory is being regulated according to the desired inventory count, Figure 2.24. The difference between the desired inventory and the actual inventory would give the stock manager the amount to order. The time required for the stock to enter into the inventory after the decision to order has been made is referred to as adjustment time. Rates can either be positive or negative and should be catered for in the type of flow. For example, if the stock manager has too much stock, the difference from desired would be negative, yet the manager cannot create negative orders. In such a case, the rate should only be kept as an inflow. In other instances, like advanced thermostatic control systems that can heat up and cool down a system, energy can flow into and out of the system through the control. In the advanced thermostat example, the flow can allow negative and positive numbers. Still, in the inventory management example, the flow can only be in one direction (which is the case for most flows).

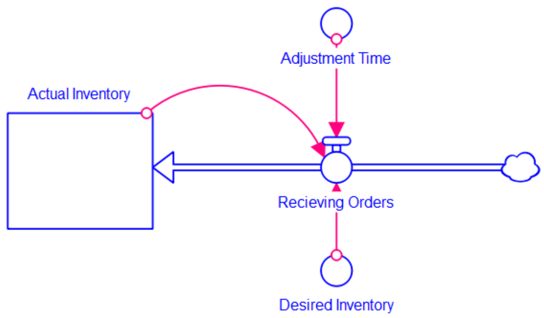

Figure 2.24: Graphical depictions of rate 3

The first three rate equations form the basis of all the rest of the equations. *Rate 4* is similar to *Rate 1* and *Rate 2*, with the differentiation of auxiliary variables. Auxiliary variables are used in the same way by the rate equation but have a different origin to the constants in *Rate 1* and *2*. In *Rate 1,* the birth rate is constant. If the birth rate becomes a function of other variables or levels, for example, economic welfare, the birth rate becomes an auxiliary and is not constant anymore. The same can be said of *Rate 2* that if the lifetime of houses becomes a function of another stock like maintenance or depreciation, the constant becomes an auxiliary. In this way, the auxiliaries allow multiple levels to impact the rate. The same can be used for the goal or adjustment time of *Rate 3*, seen in Figure 2.24.

The last two, *Rate 5* and *6*, use the rate equations of *1* to *4*. The normal rate in *rates 5* and *6* is the rate determined by the first four rate equations. The differentiation between rate 5 and 6 is that *Rate 5* adds an effect, and *Rate 6* multiplies with an effect. If the effect can dominate the rate equation, *Rate 6* (multiplication) should be used (Richardson & Pugh, 1981); if it can only slightly adjust the rate up or down, *Rate 5 (addition)* should be used. The concept is explained using the Housing equation from Urban Dynamics (Forrester, 1969):

Two different types of effects are considered, where one effect controls the lifetime of houses and the other can adjust the lifetime of houses. Firstly, the house construction quality will control the lifetime of the house; as such, the effect of construction quality would be a Rate 5:

$$Housing\ Demolition = \frac{Number\ of\ houses}{Life\ time\ of\ houses \times Effect\ of\ construction\ quality}$$

Secondly, if the houses are maintained regularly, the lifetime of houses would be adjusted (increased) and require a Rate 6 type of effect:

$$Housing\ Demolition = \frac{Number\ of\ houses}{Life\ time\ of\ houses \times (1 + Effect\ of\ maintenance)}$$

In the first case, a very poor construction process could lead to the house lifetime decreasing to almost zero. As such, it dominates the rate equation. While in the second case (Rate 6), the effect can slightly increase or decrease the lifetime of the house. The difference becomes clear when the two effects are assumed close to zero. In Rate 5, if the effect of construction quality is close to zero, the denominator in the equation will become close to zero, and the housing demolition rate becomes very high. Thus, the houses are demolished almost as fast as they are built due to poor quality construction. In Rate 6, if the effect of maintenance is close to zero, the denominator would become the lifetime of houses, and the rate would become like rate 2 (without the effect). In summary, when effects only adjust the rate, it is generally Rate 6, and if it can control the rate (take to zero), it is Rate 5.

The six equations can produce many different behaviours, especially when combined. Effects can be an auxiliary or a rate. Multiple rate types can be used additively in the same rate equation, or auxiliaries can be substitutes for other rate equations.

Only a few different types of equations are discussed, yet similar to the LEGO blocks, they can be combined to create different enumerable structures. Similarly, it is expected that these six equations could be useful in constructing many system dynamics rate equations through recombination. The six equations become the atomic equations that the proposed method is based on, described in Chapter 4.

2.2.2.5 Creating Effect Variables (Richardson & Pugh, 1981)

Richardson & Pugh (1981) also gives a few guidelines on how to draw CLDs and how to create the table functions, later referred to as effect variables, seen in Figure 2.22. Some of the main guidelines for making these effect variables are:

Process of Creating an Effect Variable:

1) Define three points on the graph (Beginning, middle, and end)
2) Define the shape of the graph (first and second-order differentiation)
3) Use max and min values for concrete variables and 0 and 1 for soft variables.
4) In multiplier-effects, one would indicate no change, while in addition-effects, the 0 would indicate no change.
5) Using reference lines to indicate limits may be useful to construct the effect relationship.

The approach given by the authors helps identify some general mathematical equations to convert the conceptual model into the mathematical space. The final effect variable creation process is based on this work and defined in Chapter 4 and Appendix 1-E. The next author uses a different application of the system dynamics method.

2.2.2.6 Group Model Building – (1996)

Vennix et al. (1996) explore the application of qualitative system dynamics through Group Model Building (GMB). In contrast to the strong mathematical foundation of the system dynamics simulation approach, the Group Model Building's output is mostly a qualitative conceptual model. These conceptual models are captured into a CLD. The method successfully altered participants' mental models through the model construction process (Vennix *et al.*, 1996). The approach focused on obtaining the participants' mental models separately and, after that, the group. The participants qualitatively undertake the model construction while the modelling team facilitates the process. The high-level steps that Vennix *et al.* (1996) followed can be described as:

Process of Applying Group Model Building

1) Group discussions
2) CLD's iteratively discussed and altered
3) Pre and post questionnaires
4) Elaboration questionnaire
5) Semi-structured evaluation interviews
6) The post-project evaluation of discussions

The approach reveals that CLDs already has value in achieving team cohesiveness and synergy (Vennix *et al.*, 1996). A few system dynamists like Richardson and Pugh (1981) would argue that qualitative CLDs are insufficient in describing the system's actual behaviour, resulting in misunderstanding the system levers. According to Richardson's arguments, the mathematical definition through simulation is critical, as it can resolve the logical inconsistencies that may be seen/unseen in the CLD.

2.2.2.7 Sterman – Business Dynamics (2000)

The purpose of the Business Dynamics book is to open the field of system dynamics to a broader audience. The book is arguably the modern foundation of system dynamics after Industrial Dynamics (Forrester, 1961). Sterman (2000) explains the five modelling steps with simulation examples. The steps are not unique literature but rather a summary of the established system dynamics process. The five steps with each of the sub-steps are given in Figure 2.25 below. The book strongly focuses on the formulation of the dynamic hypothesis, which includes the CLDs and SFDs. It references many of the same arguments already mentioned by the previous authors yet culminated into one book.

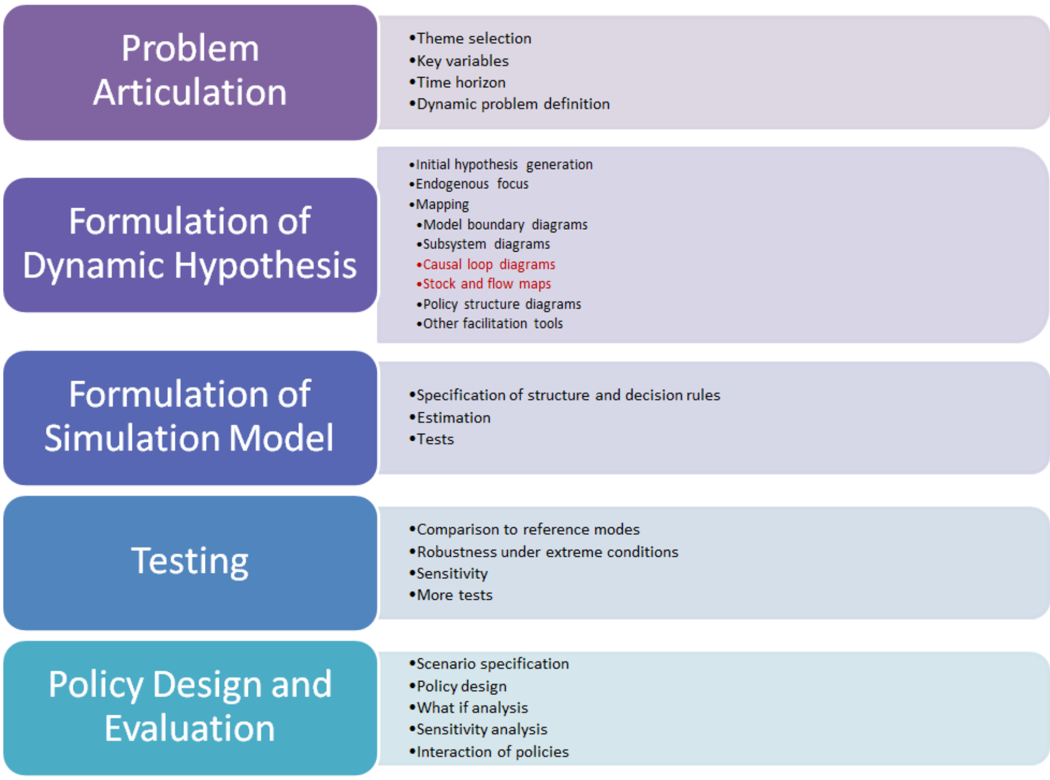

Figure 2.25: Method from Business Dynamics (Sterman, 2000)

Sterman (2000) explains that the mathematical equivalent of a stock and flow structure can be represented as the following (p.194 of Sterman, 2000).

$$Stock(t) = \int_{t_0}^{t} [Inflows(s) - Outflows(s)]ds + Stock(t_0)$$

The equation can be explained with the following concept: The future value of a stock is equal to the past value of the stock added to the stock's change in that time interval. The change is the difference between inflows and outflows of the stock at that time step. In addition, Sterman (2000) gives examples of how various fields use similar concepts for stocks and flows but with different terminology. In Table 2.1 below, more detail is given on the universality of stocks and flows (p.198 of Sterman, 2000).

Table 2.1 Universal concepts of stock and flow table (Sterman, 2000)

Field	Stocks	Flows
Mathematics, Physics, and Engineering	Integrals, states, state variables, stocks	Derivatives, rates of change, flow
Chemistry	Reactants and reaction products	Reaction rates
Manufacturing	Buffers, inventories	Throughput
Economics	Levels	Rates
Accounting	Stocks, balance sheet items	Flows, cash flow, or income statement items
Biology, Physiology	Compartments	Diffusion rates; flows
Medicine, epidemiology	Prevalence, reservoirs	Incidence, infection, morbidity, and mortality rates

Table 2.1 is not an exhaustive list but rather serve the purpose of making the user aware of how vast the usage of stocks and flows are. Sterman (2000) points out that an essential aspect of the SFD is to define a flow as being either continuously divisible or quantised. The quantised flows are when the flow can only be a specific size, like an oil tanker. There is no purpose in saying that 1.17 oil tankers are produced (flows). There can only be 1 or 2 oil tankers but not 1.17. The second is continuously divisible flows which are flows that appear to have any value between integers as well. A simple example would be water flowing through a tap. The flow is not limited by units of 1 kL, 1 L, 1 ml, or even less. The water flow seems able to be infinitely dividable. Many of the system dynamics models refer to forest thinking which uses large numbers of elements. The reason behind it is, even if the elements are discrete (quantised), the model will behave very similar to a continuously divisible model due to a large number of items in the stock.

2.2.2.8 SD models from CLDs (Binder *et al*, 2004)

In 2004 a paper was written on *"Developing system dynamics models from causal loop diagrams".* The four main steps that the article references are:

Process of Transforming CLDs to Simulations (Binder *et al.*, 2004)

1) Appropriately label the CLD: (Define stocks, flows, concrete, soft, units)
2) Iteratively transform the labelled CLD into a structured CLD.
3) Transform the structured CLD into an SFD.
4) Develop the system dynamics simulation from the SFD quantification.

It is helpful to note that Richardson & Pugh (1981) identified the six generic equations for stock rates which are useful in step 4. Step 1 flows directly out of the system variables' understanding where concrete variables are tangible or measurable variables, while soft variables could be information or intangible variables. An example of the structured CLD is seen in Figure 2.26.

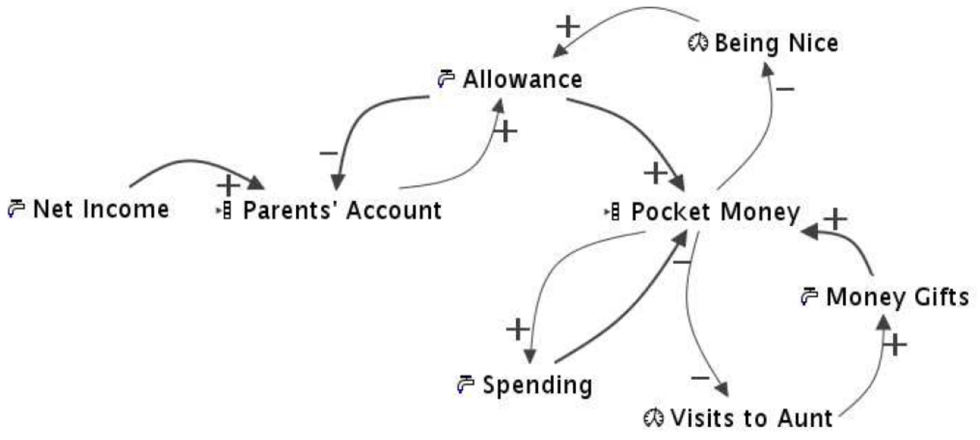

Figure 2.26: Structured CLD of pocket money model (Binder *et al.*, 2004)

The algorithm in step 3 uses logic checks and reconstructs the structured CLD into an SFD, as seen in Figure 2.27.

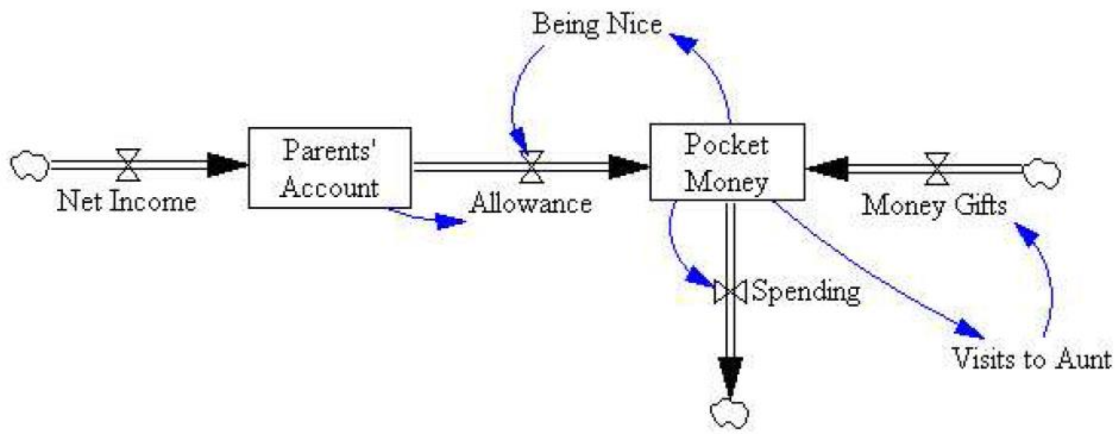

Figure 2.27: SFD of pocket money model (Binder *et al.*, 2004)

However, the article points out that steps 1 and 2 require iterative human cognition and problem dissemination to identify new unseen variables necessary for quantification. The recommendation aligned with other authors who have pointed out that system dynamics is partly an art form (Forrester, 1961) (Morecroft, 2015), especially when conceptualizing a problem.

2.2.2.9 Systems Engineering and System Dynamics (McLucas & Ryan, 2005)

McLucas and Ryan (2005) wrote a methodological paper where the authors investigated the possible synergies between the system dynamics method and the systems engineering methodology. The systems engineering approach is excellent for breaking down complicated reductionist challenges, designing, constructing, and implementing the solution. Systems engineering strongly focus on validation and verification, one of the more controversial aspects of system dynamics (Featherston & Doolan, 2012). System dynamics focuses on making sense of complex problems where the problems cannot be reduced and disaggregated into simple, well-understood, and documented elements. Often complex issues are intertwined with soft systems like human behaviour or perceptions and increase the difficulty of quantifying the systemic relationships.

Systems Engineering Value Proposition to Method

McLucas and Ryan (2005) proposed that the paradigms of testing, verification, and validation could improve the field of system dynamics. The Vee model from systems engineering exhibits the verification approach, as seen in Figure 2.28.

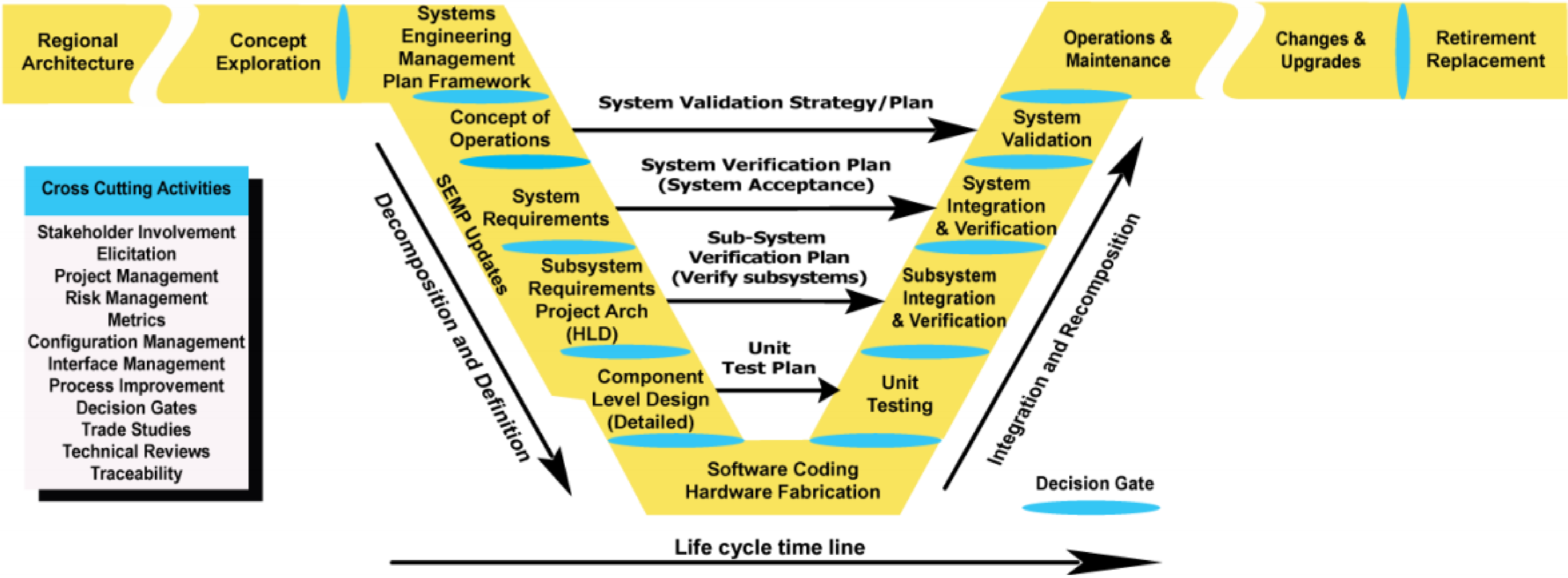

Figure 2.28: Vee diagram from systems engineering (Caltrans, 2009)

Each phase of the testing, verification, integration, and validation of the product is carried out about its conceptualization, requirements, and design. In such a way, the systems engineering approach ensures that the correct (quality) product is developed in the correct (method) way that meets the correct (demand) requirements. The article provides a fundamental alteration of the initial method proposed by Forrester (1961) to incorporate some of the systems engineering approaches and can be seen in Figure 2.29.

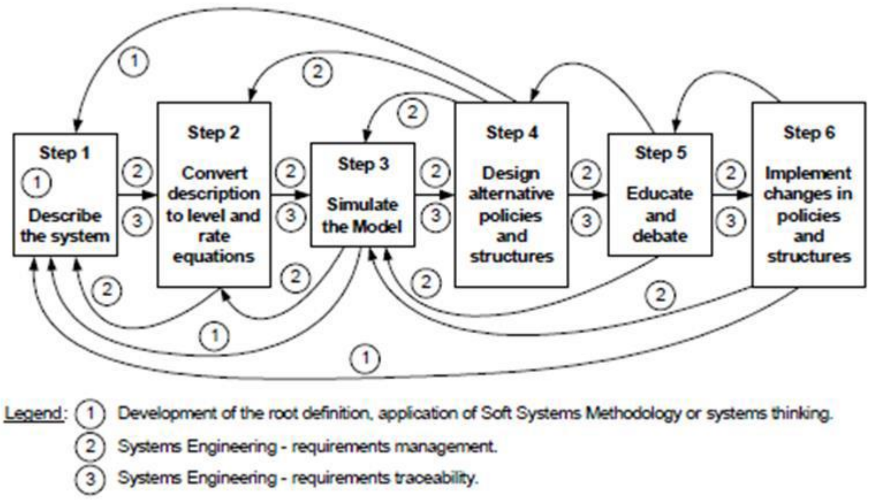

Figure 2.29: Proposed system dynamics and systems engineering integration approach (McLucas & Ryan, 2005)

In this proposed modified approach, the system dynamist would validate and verify the model based on the pre-defined model conceptualization phases where expected behaviour has been identified.

The systems engineering Vee diagram is a fundamental concept in the thesis, as it is used to address the shortcomings of validation and verification against system dynamics. The final transformation approach, Loop Stock Transform, in Chapter 4, is strongly dependent on the paradigm of the Vee diagram.

2.2.2.10 Mathematical Modelling Method from CLDs (Hayward & Boswell, 2014)

Hayward and Boswell (2014) wrote an article containing a method to quantify the 'strength' of the feedback loops found within the CLDs. The quantified 'strength' is referred to as the loop impact. The loop impact is based on the functional relationship between the second and first derivative from the Pathway Participation Metric (PPM) method discovered by Ford (1999).

Hayward classified the feedback loops' typical behaviour from CLDs as two different sets of reinforcing and balancing loops, as seen in Figure 2.30.

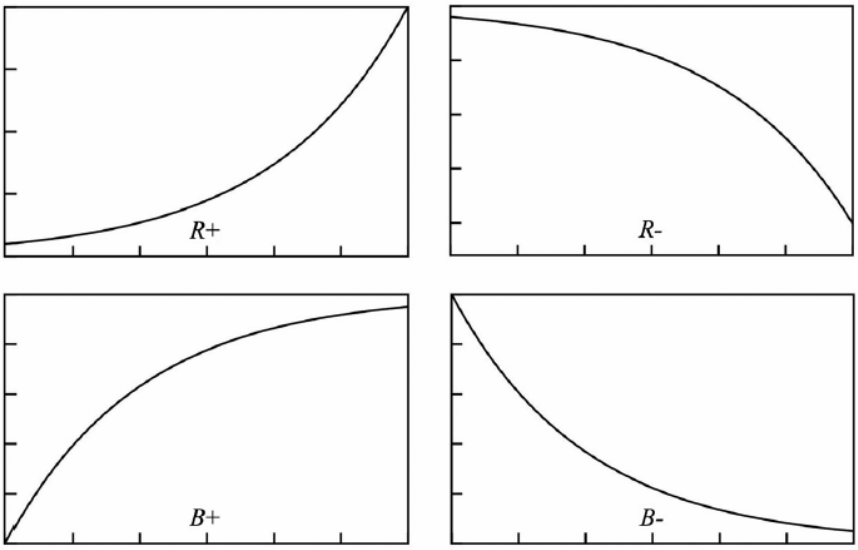

Figure 2.30: Atomic loop behaviours (Hayward & Boswell, 2014)

Figure 2.30, the '+' depictions show the value increases over time—the R+ shows that the increase is increasing at every step. In mathematical terms, this would mean that the first and second-order derivatives are both positive. In the B+ case, the value is also increasing over time (first-order positive), but the change is becoming smaller at every step (second-order is negative).

Applying the same logic as above, R- shows that both the first and second-order derivatives are negative. The B- is where the first order is negative and the second order is positive. This simplified explanation is the foundation of the quantification process behind the loop impacts. The following structure, Figure 2.31, from the article, is a basic model used to identify the loop impacts. Consider a CLD with three loops (B1, R, and B2).

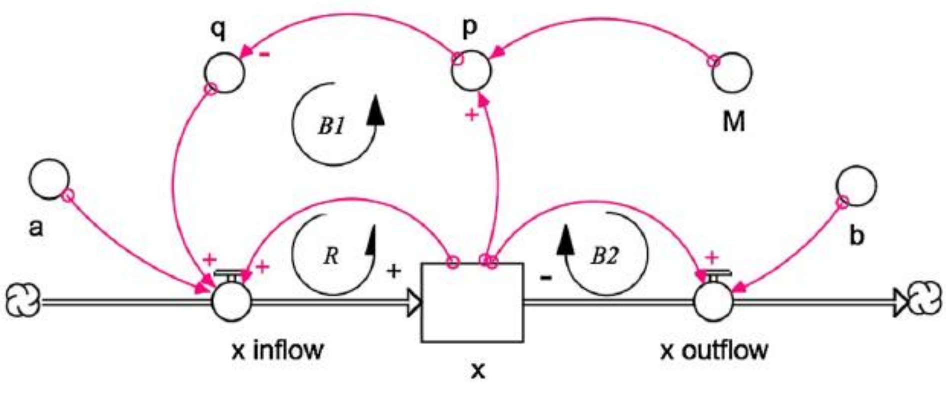

Figure 2.31: System dynamics mathematical model (Hayward & Boswell, 2014)

The equation for the net rate of change (inflow – outflow) is given as:

$$\dot{x} = ax\left(1 - \frac{x}{M}\right) - bx$$

It is quite interesting to note at this point that the equations fit well with the six equations identified by Richardson and Pugh (1989):

- The 'a' appears to be part of the rate equation 1
- The '(1-x/M)' seems to be part of rate equation 5 (auxiliary) combined with the type 2 rate equation (Level divided by constant).
- The 'b is also a part of the rate equation 1

The product rule of differentiation is used to determine the impacts of the loop:

$$\ddot{x} = [a\left(1 - \frac{x}{M}\right) - \frac{a}{M}x - b]\dot{x}$$

The loop impacts can then be identified by each term that is multiplied with the $\dot{x}$ derivatives as follows:

$$I_x(R) = a\left(1 - \frac{x}{M}\right)$$

$$I_x(B1) = \frac{-ax}{M}$$

$$I_x(B2) = -b$$

The advantage of defining these impacts above is that it becomes possible to identify the dominating behaviour. The prime impact value will dominate the behaviour of the stock. The results from the impact loop dominance behaviours are seen in Figure 2.32 below.

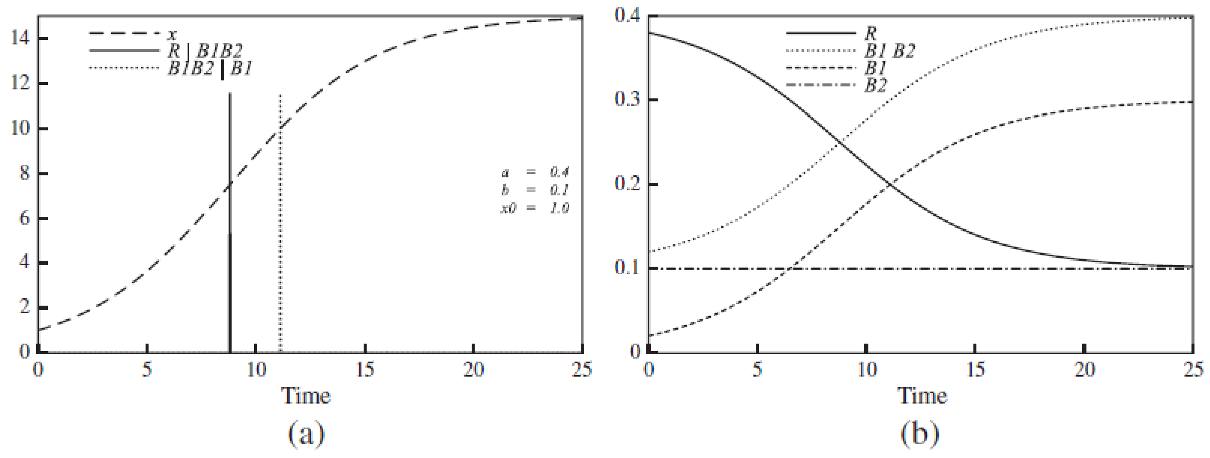

Figure 2.32: Loop dominance dynamics (Hayward & Boswell, 2014)

The strong mathematical application that is used in this study shows evidence for the mathematical depth of system dynamics. It also reveals the mathematical nature of how causal loop diagrams can be quantified and the numerical interpretation of reinforcing and balancing behaviour. It further hints towards a plausible method of establishing the link between CLD and SFD structures through mathematics. The author wrote two more papers in 2018 and 2019, respectively, by applying the method to many phenomena (Hayward & Roach, 2018) (Hayward & Roach, 2019). The second paper is published in pure mathematical journals.

This approach's drawback is that it requires the user to understand differential calculus to a much higher degree than the system dynamics methodology. Thus, the process is an excellent application for mathematicians and those interested in delving into the mathematics behind system dynamics. Yet, the average system dynamist in the field would not apply this approach in a practical sense. The paper's value to this thesis is that it shows the mathematical translation of CLDs and the mathematical interpretation of what reinforcing and balancing implies. The full method is too detailed for this study's boundary, yet some of the concepts are useful in quantifying the qualitative CLDs.

2.2.2.11 Teaching System Dynamics (Fisher, 2017)

Diana M Fisher wrote a teacher’s guide on system dynamics, which can be used in school classrooms to teach students. Fisher taught high school mathematics (9-month course) using system dynamics for a few decades after teaching a 10-week tertiary system dynamics course (Fisher, 2020). The book is not strongly focused on the mathematical definition of a causal loop diagram but rather on learning to think in systems and construct a system's structures.

Modelling Process Recommended:

The book (Fisher, 2017) provides a summary of building system dynamics models with the following main headings:

1) Problem articulation
2) Dynamic Hypothesis
3) Build a model
4) Test the model
5) Policy design and evaluation

The second step alludes to CLDs, but more focus is placed on the development of SFDs. In step 3, the model building steps only reference the structure and decision rules as focusing points when creating the equations.

The method adds value to this discussion since it refers to the dynamic hypothesis as a combination of CLDs and SFDs. It uses both to build the model and simulation. Unfortunately, the process of model equation formation is not explicit in the book.

There are multiple models built with the students in the material, and they do appear to converge to the equations given by Richardson and Pugh (1981) but do not explicitly reference them. At the International System Dynamics Conference, 2020, Fisher explained that the equation formation process is learned through studying existing systems dynamics models like the infection models or population models (Fisher, 2020). The material uses the study of established small system dynamics simulations for learning.

Fisher (2020) also explains that the Effect Variables/ Table function used by Meadows (1972), Richardson & Pugh (1981), and Forrester (1961) is an invaluable tool to learn how to build system dynamics models.

2.2.2.12 Revised Modelling Method (Homer, 2019)

Homer (2019) is one of the participants from the best practices study performed by Martinez & Richardson (2013). Homer has been hosting the Modelling Assistance Workshop at the International System Dynamics Conferences every year since 2001 (Homer, 2019). He argues that most of the disagreements were more of a mirage and that the study was not successful in identifying substantive differences in system dynamic modelling practices. He supports that the system dynamics community offer a broad menu of options at every step instead of one singular path. However, the failure to clearly define the process creates confusion and uncertainty for learners, experts, and observers outside the field of system dynamics (Homer, 2019). Therefore, Homer gave his ‘most used and ‘preferred’ approach to creating system dynamics models. The approach is summarised in Figure 2.33.

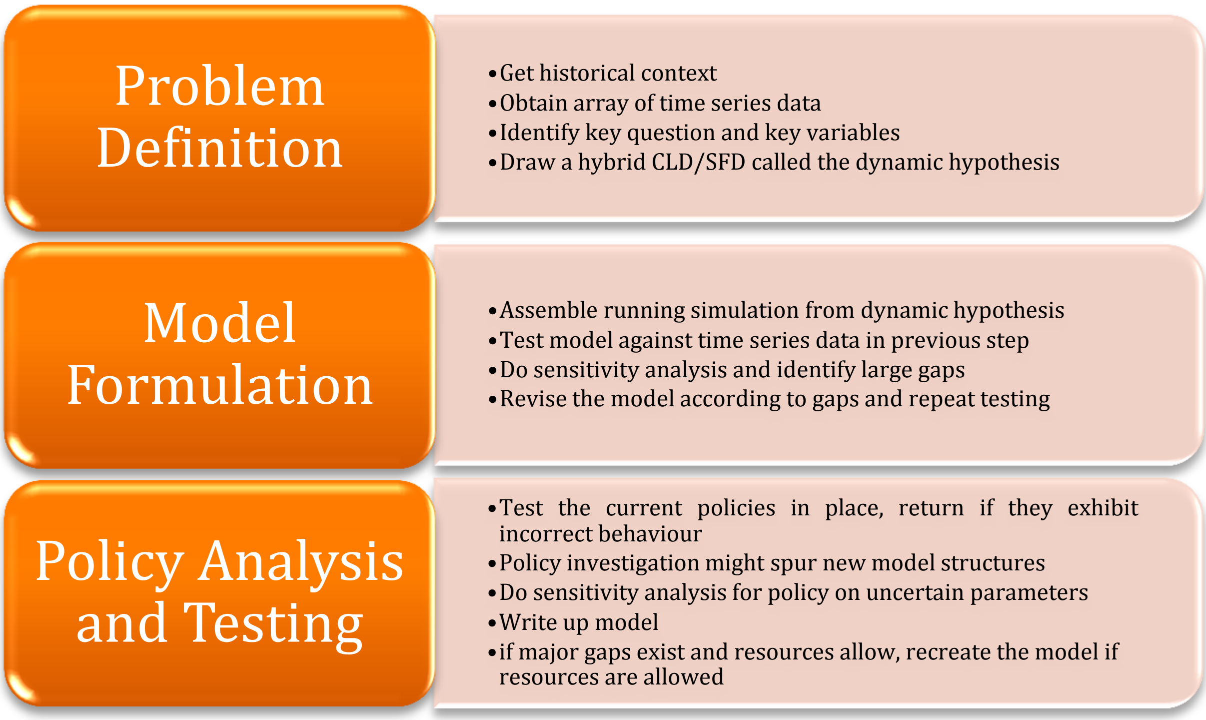

Figure 2.33: Recommended steps in system dynamics (Homer, 2019)

All steps in Figure 2.33 align with the previous literature and seem to summarize the significant steps. This article's advantage within this study is that it validates the previous literature on the usage of CLDs and SFDs within the more experienced modelling framework. It also provides a high-level perspective on the integrated system dynamics modelling process. The disadvantage is that the study does not define how the simulation equations are formulated from the dynamic hypothesis.

2.2.3 Concluding Remarks on the Method

In Section 2.2.2.1 to section 2.2.2.12, the system dynamics literature on the method is reviewed in a fair amount of detail. The literature is used to formulate one method which can transform system archetype CLDs into simulations with validation and verification. The following table is a critical review of the historical methods:

Table 2.2 Critical summary of methodological literature

#	Reference	Unique Elements	Critique
01	Industrial Dynamics (Forrester, 1961)	Problem description, stocks, flows, causality, feedback, dimensional analysis, validation to purpose	The field is still being formulated, and the approach is not yet clear
02	Kaibab Deer Simulation (Meadows, 1977)	Effect variables, the model construction process	The process of generation equations are not shared
03	Introduction to System Dynamics (Randers, 1980)	Details on model validation, delays, general mathematical rate equation	Lack of the process of creating new equations
04	Elements of System Dynamics (Richardson & Pugh, 1981)	Six different rate equations and their application	Lack the transformation from CLDs to SFDs
05	Effect Variables (Richardson & Pugh, 1981)	Method of constructing effect variables	Same as above
06	Group Model Building (Vennix et al., 1996)	Value of CLDs	Lack of SFDs and simulation construction
07	Business Dynamics (Sterman, 2000)	Insights of system dynamics, confirmation of unique elements above	Lack details of step-by-step simulation formulation
08	Simulations from CLDs (Binder et al., 2004)	The successful transformation from CLDs to SFDs	Lack of the process of generating equations
09	Systems engineering and system dynamics (McLucas & Ryan, 2005)	The paradigm of testing for validation and verification: system engineering	Lack of the application of simulation formulation
10	Mathematical Modelling from CLDs (Hayward & Boswell, 2014)	Mathematical analysis of CLDs	Lack of the simulation construction process
11	Teaching System Dynamics (Fischer, 2017)	Value of small models, effect variables and learning simulation	Lack the details of novel simulation formulation
12	Revised Modelling Approach (Homer, 2019)	Confirmation of key elements from above and the missing singular guiding system dynamic approach	Application examples of how to apply the method

The final Loop Stock Transform (LST) adopts the systems engineering Vee diagram, which is a foundational paradigm shift compared to historical methods (09 in Table 2.2). The reconstruction of the method into verification and validation elements will allow continuous simulation testing, evaluation and confidence building. The first step is to understand the problem and define a simulation purpose (01, 03, 04, 07 and 12 in Table 2.2). The divergence between the use of CLDs and SFDs (Martinez & Richardson, 2013) is resolved as being both tools, with more emphasis on SFDs (02, 04, 06, 09, 10, 11, 12 in Table 2.2). The value of CLDs is found in their ability to make sense of the problem and build group cohesiveness, in addition to having deep-rooted mathematical concepts (06 and 10 in Table 2.2). It is possible to transform the CLD to an SFD even though the conceptualization remains an art form (08 and 10 in Table 2.2). The dimensional consistency, general rate equations and effect variables are useful to quantify the SFD (01, 02, 03, 04, 05 and 10 in Table 2.2). Small model testing and validation are critical before the simulation is combined (09, 11 and 12 in Table 2.2). The final simulation is validated against the purpose, and the final insights should be documented and communicated (01, 09 and 12 in Table 2.2).

2.3 Transition Process

Considering the steps of the system dynamics methodology, the basis of all system dynamics simulations are SFDs. The first step in the system archetype transition is thus to ensure that a stock and flow description of the archetype can be created. After that, the mathematical transition can start.

The system dynamics methodology does not have an explicit standard of creating mathematical equations from stock and flow diagrams. Yet, Barry Richmond (founder of the High-Performance Systems and STELLA/iThink software) said that there is a strong connection between the use of nouns in language and the concept of accumulators (stocks/level) in system dynamics (High-Performance Systems, 2001).

In the real world, taking a few steps back from model creation, problems are often ill-defined. Real complex problems are often misunderstood, too large to fully appreciate, and our reactions frequently make the problem worse (Sterman, 2000). The first step is to make sense of the problem through some logical set of arguments, like CLDs. The CLDs allow the investigator to set boundaries and structure the problem into a set of simplified, comprehensible structures. The CLD, combined with system behaviour, can be used to create a dynamic hypothesis. The dynamic hypothesis is a foundation for the stock and flow diagram, which are rigid, mathematically more consistent and show small coherent structures. The SFD can be expanded into a simulation that is dynamic and testable. The simulation allows the investigator to test their dynamic hypothesis against real-world behaviours and structures. Furthermore, the simulation allows the investigator to identify insights, counter-intuitive behaviours and leverage points. The latter can be a powerful policy mechanism to induce structural changes instead of superficial solutions. The true value of system dynamics should be rooted in real-world policy levers and insights, which improves decision making in complex systems. A graphical model of the above is seen in Figure 2.34.

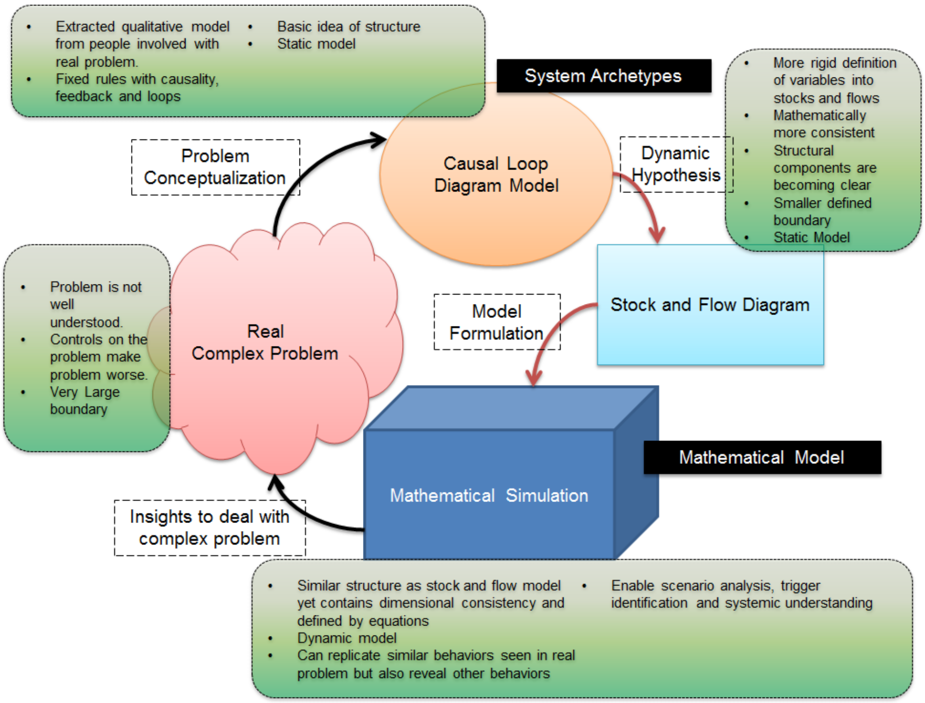

Figure 2.34: Overview of the system dynamics block process

The block diagram, Figure 2.34, is critically measured against the system dynamics literature in Table 2.2.

Table 2.3 Critical review between block process and literature

#*	Agreement	Disagreement
01	Focus on real-world problems, use simulations to change decision	The use of system archetypes and CLDs to formulate the dynamic hypothesis
02	The formulation of mathematical simulations and using them to test real-world problems	The use of system archetypes to conceptualize problems
03	Problem conceptualization, dynamic hypothesis, mathematical formulation and validation to purpose	The use of system archetypes and systems engineering
04	Problem conceptualization, dynamic hypothesis and detailed mathematical formulations	The use of CLDs in problem conceptualization
05	Incorporation of real-world non-linear dynamics	The use of system archetypes in the formulation process
06	The use of CLDs for problem conceptualization and understanding	Do not always need a mathematical simulation to create acceptance when a CLD can convey the same concept faster.
07	Agree with the whole block diagram	None

08	The use of CLDs for problem conceptualization and simulation formulation	None
09	That the final simulation should be validated against the purpose identified in the problem description	More validation and verification is required to build model confidence
10	The ability of CLDs to be used for mathematical consistency tests	Not much effort is made in problem conceptualization
11	System dynamics can be learned by studying historical accepted simulations	CLDs are only used as a basic reference point, and no clear transformation is used to create SFDs
12	Agree with the whole diagram	No disagreements

* The # references the same literature as in Table 2.2

The focus of this thesis is on the two red arrows (Figure 2.34): Dynamic Hypothesis and Model Formulation combined with the Vee Diagram. The system archetypes are specialised CLD models that will need to be transformed into SFDs. The SFD would then be transformed into a mathematical simulation. The generic transformation method, Loop Stock Transform, is the core focus of Chapter 4 and is applied to four different system archetypes in Chapter 6. In Chapter 5, the Delphi is used to verify the method and simulations from field experts. In Chapter 7, the final discussion is made on the proposed method, the application value, challenges, and possible future research.

3 RESEARCH DESIGN

A multi-method research approach is used to develop and test the Loop Stock Transform (LST) approach, which can translate system archetypes into simulations in a viable manner.

3.1 Research Questions

The three sub-research questions are found in section 1.3 and focus on:

1) The development of the LST approach
2) Test the simulations developed via the LST against literature
3) External evaluation of the LST and simulations by field experts.

The questions are addressed using a mixed research methodology:

1) Literature investigation on system dynamics, system archetypes, and systems engineering. The literature investigation ensures that the LST being developed is rooted in the correct fundamental theories of each field and addresses question 1.
2) Four verified and validated practical applications of the LST on system archetypes. The practical simulations establish a testable arena on the value, validity and verification of the LST approach, which addresses question 2.
3) The iterative Delphi research method (Linstone & Turoff, 2002) enables the LST to develop in agreement with an expert group of system dynamists and teachers of the field. The Delphi approach can address question 3.

The three mixed research methods and the execution thereof is explained in the next few sections.

3.2 Phase 1 - Introduction

Multiple different authors have written about the system dynamics method (Forrester, 1961) (Randers, 1980) (Richardson & Pugh, 1981) (Sterman, 2000) (Homer, 2019). A literature study on the system dynamics methodology enables the extraction of recurring simulation construction elements to establish the LST. The system archetype case studies establish a valid basis for the simulations developed by the LST. The Delphi research method can verify the method and simulation. The Delphi research method has the unique benefit of iteratively improving expert group consensus, system dynamics method improvements, and simulation verification.

The Literature Investigation

A few different methods are initially investigated, including mass online surveys, interviews, and questionnaires. Mass surveys require a large source of participants in the field of systems dynamics. Given the scarcity of field practitioners, this option has significant challenges. Interviews are useful when dealing with a small subset of experts. Nevertheless, the nature of conducting one-time interviews in series prevents experts to simultaneously make evaluations and provide improvements without being biased (Alshenqeeti, 2014). Online questionnaires can collect quantitative and qualitative data yet lack the iterative nature of improvement. Finally, the Delphi research method can provide both anonymous inputs and evaluation of the method in an iterative nature to reach a group consensus.

Two of the core principles of system dynamics are internal system relationships have causality and circular feedback, which drive behaviour (Palmer, 2017) (Forrester, 1961). In addition, a third unique characteristic of system dynamics is that stocks (state variables) and flows (differential equations) represented system structure (Forrester, 1999). For example, the stocks are defined as levels or accumulations within the system, while the flows or rates can deplete or add to the stocks (Kotir *et al.*, 2017). Figure 3.1 depicts the basic population structure in stock (square) and flows (arrows).

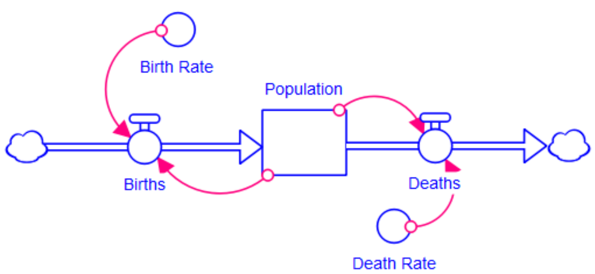

Figure 3.1: Stock and flow diagram of a simple population

The methodological literature survey starts with Industrial Dynamics (1961) and includes 12 methodological books, articles, and papers. Literature is selected based on the system dynamics method. In addition, systems engineering literature is another key focus area. As such, the Vee-diagram of systems engineering is included as a valuable addition to improve the identified method (McLucas and Ryan, 2005). The purpose of the literature study is to identify the first set of system dynamics steps.

Systems engineering is "an interdisciplinary approach and means, which enables the full life cycle of a successful product, service, and enterprise systems" (SEBok [2], 2020). Similar to system dynamics, the field of systems engineering is also cross-boundary and multidisciplinary. Systems engineering's utility is to identify show stoppers and then avert them, identifying and fixing errors fast with less cost and induce continuous process improvements (Buede & Miller, 2016). The system dynamics simulation development can benefit from identifying errors faster and more effectively (Featherston & Doolan, 2012) (McLucas & Ryan, 2005).

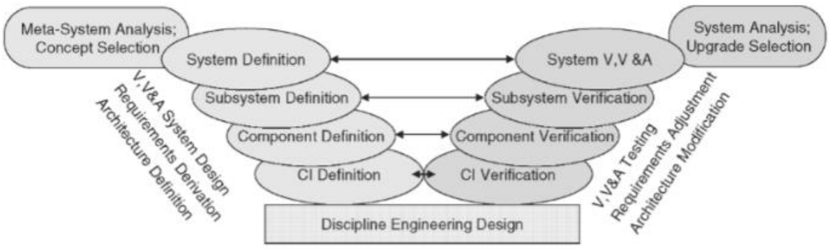

Figure 3.2: Traditional top-down systems engineering approach – Vee diagram (Buede & Miller, 2016)

The Vee diagram is one of the system engineering tools that are useful in identifying errors effectively. As seen in Figure 3.2, the method starts with a requirements specification defined in more detail iteratively from the system, subsystem, and component-level (Left side – deconstruction). The right side (construction) is how the system is reconstructed and tested iteratively against the left side (Buede & Miller, 2016). McLucas and Ryan (2005) proposed that systems engineering verification can be a valuable addition to the system dynamics methodology and, as such, incorporated into the LST.

The LST has to be validated and verified in order to build confidence. The identification of the correct LST is defined as verification, while the correct execution of the LST is defined as validation. Each Delphi round has specific questions which relate to verification. In Delphi round 1, questions 1 and 6 focused on verification. Validation consists of the development of the final simulations and the expert’s reviews in each Delphi round.

The system archetypes are chosen due to their accepted conceptual models, expected behaviours, and recommended approaches (Senge, 1990) (Kim, 2000) (Meadows, 2008) (Taborga, 2011). The expected behaviours and recommended strategies in the literature are chosen as the final validation criteria for the LST simulations. The system dynamics Delphi expert group evaluated both the LST and simulation(s) in each round. The LST improve in each of the Delphi round results.

The Delphi Research Method

The Delphi research method is infamous for being expensive. The method requires a large amount of time and resources from both the researcher and participants (Linstone & Turoff, 2002). The second disadvantage is that the method’s focus is on convergence and cannot identify if the group's collective opinion is universally correct. Therefore, a signed requirement and commitment form from each Delphi participant and consistent communication is utilised to overcome the first challenge. In addition, the identification of Delphi participants with a specific standard of system dynamics experience mitigated the risk of the second challenge.

According to the literature, typical Delphi results often lack statistical analysis (Meijering et al., 2013). As such, Cohen's Kappa is a recommended statistical analysis that improves the analysis of the Delphi group's agreement level (Pykes, 2020). Cohen's Kappa can measure agreement between two raters, whom each has to classify N items into C mutually exclusive categories (McHugh, 2012). Therefore, the Likert scale questions are implemented since it has five mutually exclusive categories (strongly disagree, disagree, disagree, agree, agree, and strongly disagree). The Likert scale determines the group's support (verification) level of the LST and simulation (Van Hecke & Kamerman, 2015). A major Likert scale disadvantage is that the narrow uni-dimensional criteria mask the genuine participant opinions (Likert, 1931). As such, the disadvantage is overcome by adding open-ended questions, allowing participants to expand on the answers in their Likert scale questions. Open-ended questions are analysed using the accepted content analysis technique (White & Marsh, 2006).

The agreement (Cohen's Kappa) value can range from 0 to 1: no agreement to perfect agreement. As such, a target agreement of 0.61 is defined as the target value, which represents substantial agreement. The target for the average support (Likert scale value) of the Delphi results is chosen as 66% since it is double the value from Martinez and Richardson (2013).

Initially, sixteen Delphi participants are identified who are either practising system dynamics experts or teachers interested in the field. In response, six of the individuals decline participation, and one participant retracts before the conclusion of the first round. Finally, a total of nine participants commits to the study and complete a consent form to protect their anonymity.

System Archetype Identification

Senge's (1990) eight system archetypes consist of separate components: variables, loops, and connections. The number of components denotes the archetype simplicity. Three of the most straightforward system archetypes are **Fixes that Fail**, **Limits to Growth**, and **Eroding Goals**. The fourth system archetype is chosen as **Escalation** due to structural loops' similarity to eroding goals yet exhibits different behaviour—Table 3.1 captures the ranked system archetypes. The expected behaviours and strategies from system archetype literature can validate the simulations produced through the LST (Senge, 1990) (Kim, 2000) (Meadows, 2008).

Table 3.1: Ranked system archetypes

Ref	Name	Archetype Elements			*Individual Contribution			**Final
		Number of loops	Number of variables	Number of Connections	Loop %	Variable %	Connection %	Relative %
3	Fixes that fail	2	3	4	33%	43%	36%	38%
5	Limits to success	2	4	5	33%	57%	45%	45%
1	Drifting Goals	2	5	6	33%	71%	55%	53%
6	Shifting the burden/Addiction	3	4	6	50%	57%	55%	54%
7	Success to the succesfull	2	5	6	33%	71%	55%	53%
2	Escalation	2	7	8	33%	100%	73%	69%
4	Growth and Underinvestment	3	7	9	50%	100%	82%	77%
8	Tragedy of the commons	6	7	11	100%	100%	100%	100%
	Max value in column	6	7	11	* Determined by dividing the numer of that element with the maximum value thereof			
	Min value in column	2	3	4	** Average of the indivuals			

The 12 literature sources on the system dynamics methodology establish the foundation of the system dynamics method. The methodology is then combined with the systems engineering Vee diagram to develop the LST.

3.3 Phase 2 – Delphi Round 1

After identifying the participants and establishing the first method from literature, the first Delphi round compilation starts. The system archetype in round 1 is the **Fixes that Fail** (easiest), applied to the example of borrowing money to increase available cash flow. The expected behaviour of Fixes that fail is replicated by the archetype simulation and the recommendations from Senge (1990) and Meadows (2008). The simulation is developed in iSee Stella Architect and published on the iSee Exchange to provide Delphi participants access. Google forms are utilised to construct the Delphi questions and collect data from the participants.

The first five questions of the Delphi round 1 is on a Likert scale and relate to validation and verification of the three research objectives. The second set of five Delphi questions are open-ended and expanded on the Likert scale questions. The questions are all focused on verifying that the correct LST steps are identified, verifying that the LST is useful, and the final simulations' validity.

3.4 Phase 3 – Delphi Round 2

After all the participants complete the first Delphi round, the results are analysed. The Likert scale questions are analysed for a group agreement level using Cohen’s Kappa. The research support is analysed using the group’s average support level (percentage agree/disagree). The open-ended questions are interpreted using the content analysis technique, which identifies and capture positive, negative, and improvements from the group.

Delphi round 1 is used to improve the LST, application of the LST, and the final simulations. In the second round of Delphi, the LST method is applied to two of the system archetypes: **Fixes that Fail** and **Limits to Growth**. In the second round, the **Fixes that Fail** simulation is based on a generic archetype to test the criticism made in the first round of Delphi. The **Limits to Growth** archetype is applied to the spread of a forest fire.

The simulation is validated by the expected behaviours given by Kim (2000). The final simulations are validated using the recommended approach from Meadows (2008) in resolving both archetypes. The full simulation development of both simulations based on the LST method is captured into a development document and shared with the Delphi participants. Google forms are used to collect the data from every participant. The first five Likert questions remain unchanged to evaluate the change in the Delphi group's agreement level. The second set of five Likert scale questions requests the group's evaluation of improvements from round one. Two open-ended questions are asked to capture more detail on the positive and negative aspects of the LST and simulations.

3.5 Phase 4 – Final Method

The results from the second round of Delphi are interpreted using Cohen's Kappa and content analysis. The final LST is applied to four system archetypes: **Fixes that Fail**, **Limits to Growth**, **Eroding Goals**, and **Escalation**. Each of the four archetypes considers challenges faced locally and globally in the year 2020. The **Fixes that Fail** archetype investigates policing protests (Bruce, 2012). The **Limits to Growth** archetype examine a forest fire (CDP, 2020). The **Eroding Goals** archetype simulates the matriculation rate in South Africa (BusinessTech, 2020). Finally, the **Escalation**

Archetype explores the social media's effect on the polarization between opposing communities (Brand, 2016).

3.6 Overview

The high-level overview of the research design (Figure 3.3) shows that it starts with a literature investigation on the historical system dynamics methodology (Chapter 2).

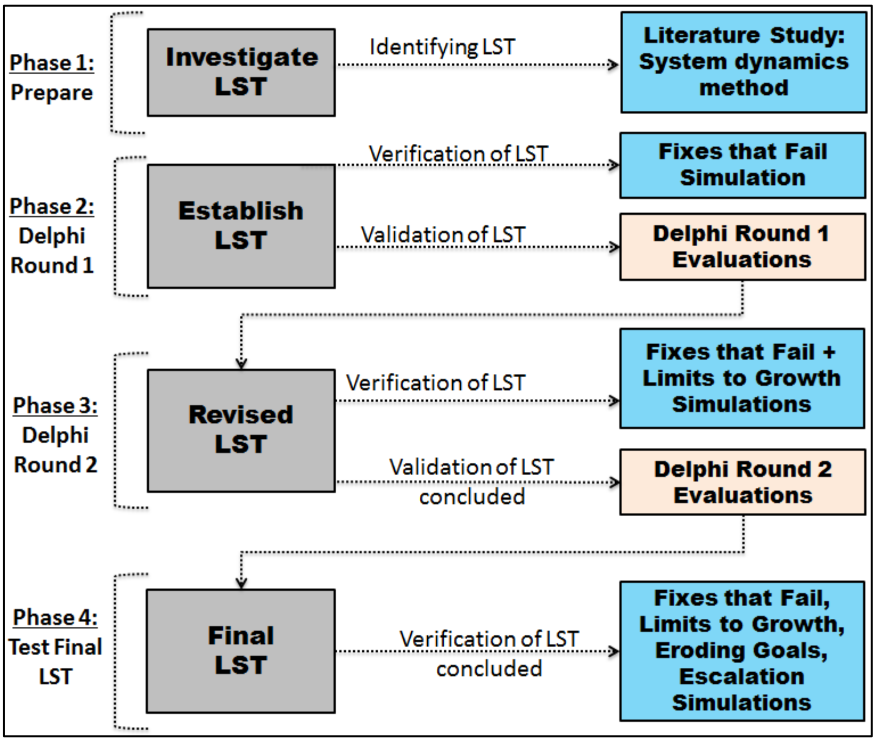

Figure 3.3: Designed research method

Figure 3.3 depicts the high-level overview of the mixed research method used in the thesis. Two rounds of Delphi are executed with pre-selected system dynamics experts. The LST evaluation and feedback in each round directs the revisions to reach a group consensus. The LST is tested for internal repeatability by applying the same approach to four different system archetypes. The simulations' results are tested for validity through the established behaviours and recommendations for each unique system archetype (Meadows, 2008).

The identification of the initial elements of the LST is in Chapter 2. Chapter 4 explores the final LST. Chapter 5 capture the Delphi verification on the method. Chapter 6 is the practical validation of the four system archetype simulations from the LST.

4 LOOP STOCK TRANSFORM

The Loop Stock Transform (LST) has eleven detailed steps. Systems engineering verification and validation are integrated throughout the transformation process. The formulated theory behind the LST is discussed in Chapter 2. The reviews and improvements from experts are discussed in Chapter 5. In this chapter, the details of the LST is explained.

The first critical research question is the focal point in this Chapter: "How can one coherent process be constructed from the CLD's to SFD's and finally a system dynamics mathematical simulation?"

4.1 Overview of Loop Stock Transform Formulation

The key concepts from the literature review consist of mathematical formulation (Richardson & Pugh, 1981), dimensional analysis (Sterman, 2000), stock and flow diagram (Forrester, 1961), causal loop diagram (Vennix *et al.*, 1996), problem description (Meadows *et al.*, 1972), small models (Homer, 2019), model validation (Randers, 1980) and insight discussion (Sterman, 2000). Thereafter the concepts are combined with the systems engineering verification and validation process (McLucas & Ryan, 2005). Finally, the LST improve iteratively through application to system archetype simulations and external tests, which are strengthened through the Delphi Research method.

The systems engineering principles infused the LST with multiple validations and verification tests. The initial requirements specification coincides with the problem description, where the final criteria of success (model behaviour and purpose) are defined. The left wing of the LST is where black box testing occurs (Buede & Miller,

2016) and sets the evaluation criteria for the right wing's side. The engineering design concept is found in the centre of the LST and includes all the major design elements before simulation construction starts. White box testing in the right wing ensures the verification of the development process and validation of the simulation results with the requirement specification found in step 1.

The following eleven steps are identified and integrated to create the LST:

1) Problem Description
2) Causal Loop Diagram
3) Stocks and Flows
4) Basic Stock and Flow Diagram
5) Dimensional Analysis
6) Mathematical Formulation
7) Detailed Stock and Flow Diagram
8) Small loop models and Validation
9) Integrated Model Testing and Validation
10) Sensitivity Analysis
11) Emerging Lessons

The two rounds of Delphi iteratively improves the initial LST to the revised version and the final LST, as in Figure 3.3. In the rounds, the expert group expands on the problem definition, simulation construction, sensitivity analysis, construction of delays, simulation verification, and interface development. The Delphi group’s final acceptance of the LST as a guide for newcomers is an external validation of the LST’s value. In the PhD seminars (Forrester, 1999), the LST improves on concepts like validation, dimensional consistency, testing, mental models, and stocks and flows formulation.

A crucial test is on the inter-repeatability of the LST. The same LST is applied to four increasingly complex system archetypes: **Fixes that Fail**, **Limits to Growth**, **Eroding Goals**, and **Escalation**. Each of the simulations is tested internally through the validation and verification frameworks of systems engineering. The major validation step is testing if the simulation can reproduce the accepted behaviours given by literature (Senge, 1990) (Meadows, 2008) (Kim, 2000) on each respective archetype. The final practical validation of the LST’s is captured in Chapter 6.

In the next few sections, the details of the final LST are described. The final visualised LST is in Figure 4.1.

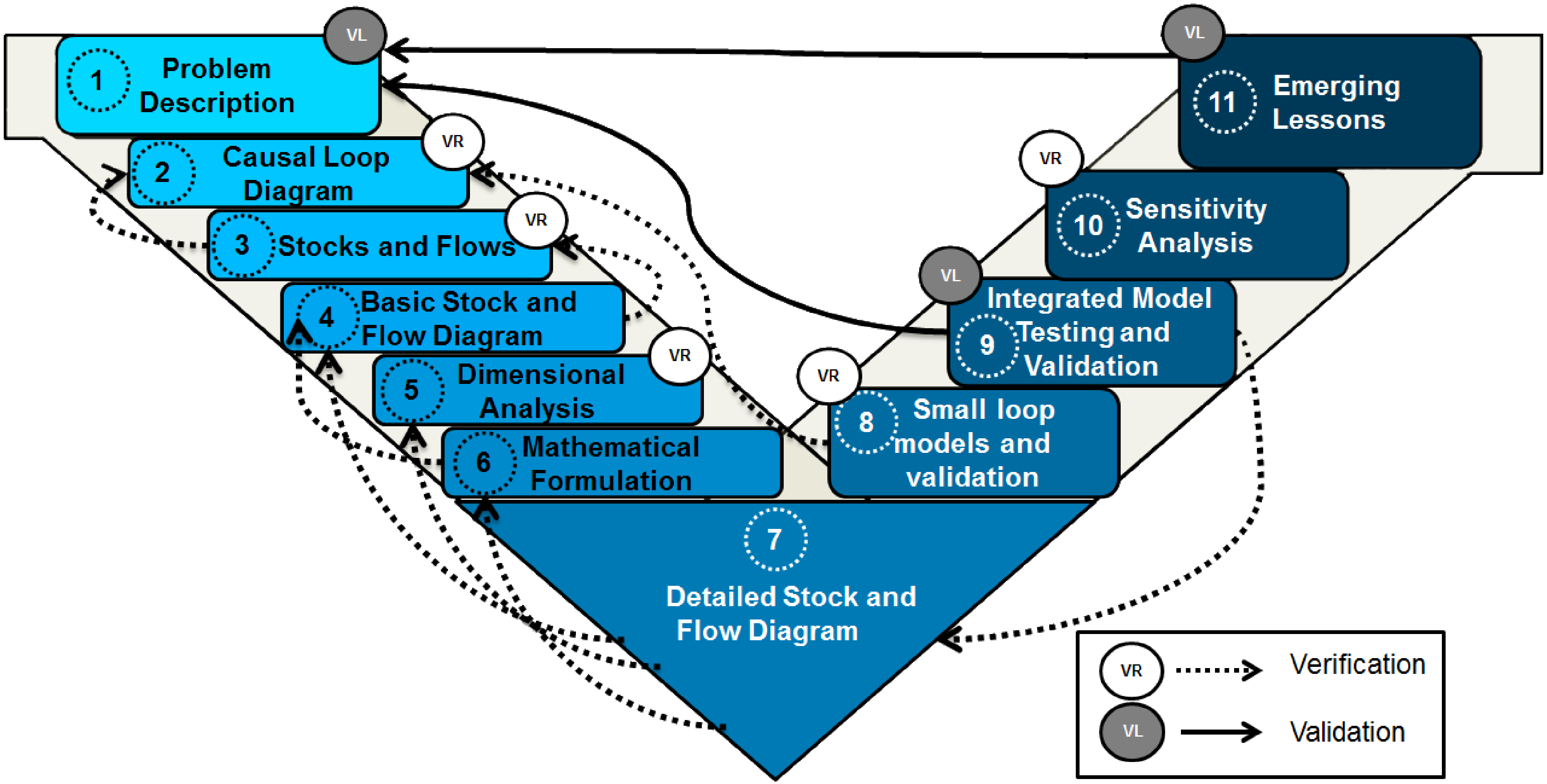

Figure 4.1: Final Loop Stock Transform (LST) steps

4.2 Agreements and Disagreements with Literature

The Loop Stock Transform's 11 steps are compared to the system dynamics literature reviewed in Chapter 2 and summarized in Table 4.1.

Table 4.1 Loop Stock Transform agreements and disagreements

#*	Agreement **	Disagreement **
01	All the methods refer to the importance of problem description, even though some do not explicitly reference them.	Two literature sets do not explicitly reference problem description: 08 and 10, yet there is no specific disagreement
02	Eight agree with using CLDs: 02, 06, 07, 08, 09, 10, 11 and 12	Two disagree: 01, 04
03	All methods except 06 use stocks and flows	06 does not disagree with using stocks and flows; it is just not part of the process they used
04	Same as step three above	Same as step three above
05	All of the methodologies are concerned with dimensional consistency, yet the following references them explicitly: 01, 02, 03, 04, 07, 08, 10, 11, 12	There are no disagreements, yet method 06 does not use direct references to dimensional consistency
06	Although all simulations have mathematical formulation, the following literature elements focused on the steps: 02, 04, 05, 08, 10, 11	Although there are no disagreements, the following elements had the least focus on mathematical formulation: 06 and 09
07	Only one reference makes use of a detailed blueprint before simulation construction: 09	Step seven is not found in system dynamics literature, and thus there is no direct disagreements and no agreements. It is a combination of the systems engineering and system dynamics processes
08	The following authors reference the importance of small model construction: 02, 03, 04, 07, 10, 11 and 12	There is no explicit disagreement to small models, yet the following author built large models: 01
09	All methods agree that the structures should be integrated and tested in some manner, yet systems engineering principles form the focus of the Loop Stock Transform: 03, 09	No disagreements yet the detailed mechanisms of testing system dynamics simulations seem void in 06
10	Not many methods explicitly reference this step, yet the following do: 01, 03, 04, 07, 09, 12	The following literature does not make mention of sensitivity analysis at all: 02, 06, 08, 11
11	The value of insights are discussed by all the methods	None

* - References the step number in the Loop Stock Transform

** - Numbers reference the literature component in Table 2.2

All the steps align well with the literature methods where the largest discrepancies are at steps 2, 7 and 10: CLDs, Detailed Stock and Flow Diagram and Sensitivity Analysis. In Chapter 5, the theoretical verification confirms the summary in Table 4.1.

4.3 Description of Steps

The descriptions below start with the step's purpose, followed by the sub-steps. No simulation software is required from steps 1 to 7. In steps 8 to 10, the simulation is developed using step 7 and any system dynamics software.

4.3.1 Step 1: Problem description

The purpose of the first step is to ensure that the problem is understood conceptually with words (Meadows, 1977), graphs/reference modes (Forrester, 1961), dimensions (Richardson & Pugh, 1981), and time (Sterman, 2000). Once the problem is understood, the simulation purpose can be defined and used as validation criteria for the final simulation (Forrester, 1961). The objective is similar to the requirements analysis used in systems engineering (Defense Acquisition University, 2001). Plausible starting points for the step are news stories, interviews with experts, literature, discussions (Fisher, 2020) and using them to identify patterns and structures (Gurdur & Torngren, 2018).

Sub Steps:

1. <u>Word Model (1.1):</u> Define the problem in one paragraph story (Meadows, 1977)
2. <u>Behaviour (1.2):</u> Identify patterns of behaviour over time (Kim, 1992) or reference modes (Richardson & Pugh, 1981).
3. <u>Purpose (1.3):</u> Define the purpose for creating the simulation (Forrester, 1961) – problem-based.
4. <u>Core Variables (1.4):</u> Identify core variables (3-6) with dimensions (Richardson & Pugh, 1981) (Forrester, 1999). Test that variables are linked to purpose and/or problem.
5. <u>Time frame (1.5):</u> Identify the duration and resolution of time for simulation (Kim, 1992).

4.3.2 Step 2: Causal Loop Diagram

The CLD can capture the dynamic hypothesis (Homer, 2019) of the problem yet lacks the formal description and interpretation of simulations (Richardson, 1986). The CLD captures the systemic feedback, delays, and causality structure behind the story in step 1. The CLD is faster and easier to compile than a fully developed simulation, allowing more efficient iterations. The CLD's purpose is to capture the basic structure of the model's behaviour.

Sub Steps:

1. Core Story (2.1): Identify core story from step 1 (Kim & Anderson, 1998)
2. Create Causal Loop Diagram (2.2): Use the rules in Appendix B-2 (Kim, 1992) to formulate the CLD of the core story. Test CLD against story and problem.
3. Atomic Loop Behaviours (2.3): Each loop has an expected behaviour. Identify the primary variable in the loop, the inflowing arrow sign, and the loop type. The loop-type (Reinforcing/Balancing) and sign (+/-) points to four different expected behaviours, captured in Figure 4.2.

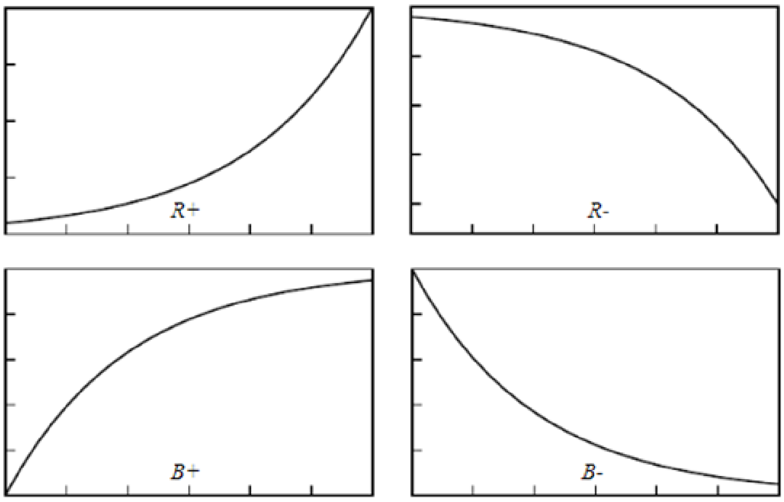

Figure 4.2: Atomic behaviours (Ford, 1999) (Hayward & Boswell, 2014)

4.3.3 Step 3: Stock and Flow

Stocks and flows are classified as the structural representation behind the behaviour (Forrester, 1999). The stocks and flows are mathematically consistent, unlike CLDs, and can be identified using the CLD in step 2. Stocks and flows can be derived from any concept that can be spoken of in a meaningful way (Forrester, 1999). Stocks are accumulations within a system (Forrester p.68, 1961). In general sciences, the stocks are state variables of the system (Vos, 2019). Flows are the only elements that can change a stock's value (stocks cannot alter stocks directly). In general mathematics, flows are often considered differential equations (Vos, 2019).

Sub Steps:

1. Snapshot test (3.1): Identify stocks from CLD using the snapshot test: Stocks are the variables that remain when time freezes or the system ceases to function (Forrester, 1961). Variables that store/release resources are mostly stocks. If none of the variables are stocks, the CLD needs more definition as the stocks can be hidden between CLD variables.

2. Test stocks for nouns (3.2): Each stock variable needs to be a noun. There are ten types of nouns (Dictionary.com, 2020).
3. Test each loop for stocks (3.3): Each of the CLD's loops needs at least one stock (Warren, 2018). Refer to step 3.1 and 3.2 if the loop needs a stock.
4. Identify the flows (3.4): Identify how each stock is changing (Forrester, 1961). How does the stock increase (inflow) and/or decrease (outflow)?
5. Delays and ageing chains (3.5): Identify if some stocks are aggregated concepts that need disaggregation (Warren, 2018). Stocks often become aggregated when delays exist in the CLD. Appendix 1-F is created to aid in the development of delays and ageing chains.

4.3.4 Step 4: Basic Stock and Flow Diagram

The individual stocks and flows from step 3 are combined into one coherent structure in step 4. The basic stock and flow diagram give a high-level view of the simulation structure to formulate the missing elements and details in the next few steps. The previous two steps are combined through the system architecture map (SAM) (Pillay, 2018) to create the basic stock and flow diagram.

Sub Steps:

1. System Architecture Map (SAM) (4.1): The SAM conveys the flow of calculations expected in the final simulation (Pillay, 2018). The flow is defined by combining the connections in the CLD with the Stocks and flows. An Example of such a diagram is found in Figure 4.3.

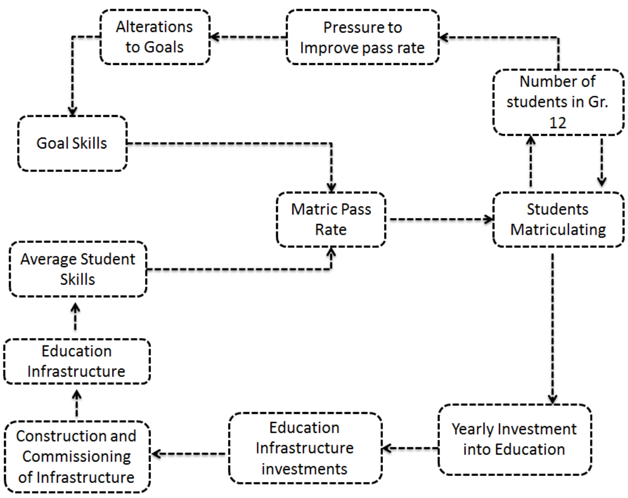

Figure 4.3: System Architecture Map (SAM) of the Eroding Goals system archetype simulation

2. Separate Stock-flow sets (4.2): Draw each stock and its flows as defined in step 3.

3. Merged stock and flow diagram (4.3): The separate stock-flow sets can then be connected using the SAM from step 4.1. The result is one connected stock and flow structure.

4.3.5 Step 5: Dimensional Analysis

The basic stock and flow diagram often lack dimensional consistency. In this step, the dimensions of each variable are defined, and gaps are identified. Some variables might be qualitative, making them dimensionless with a range of 0-1 or 0-100.

Sub Steps:

1. Stock Dimensions (5.1): Define each variable's dimensions, starting with stocks, then flows, and finally, the rest. If possible, define dimensions in green.
2. Flow Dimensions (5.2): Every flow has the same dimension as the stock counterpart, with the addition of being per unit of time (rate).
3. Complete Dimensions(5.3): The rest of the variable dimensions can be defined considering the stocks' and flows' dimensions. At the end of the step, all variables will have dimensions.
4. Dimensional Gaps (5.4): Dimensions have been defined, yet dimensional consistency throughout the structure is not. Each variable that is a function of another needs to be checked. The check is to identify if the dependant variable's dimensions can be produced from the independent variable dimensions. If not, a dimensional gap is placed and will be used in the next step. An example of dimensional gaps is captured in Figure 4.4. Two gaps exist since 'kg' and 'calories' are not equal (Gap01), and a normal rate/time is not defined (Gap02).

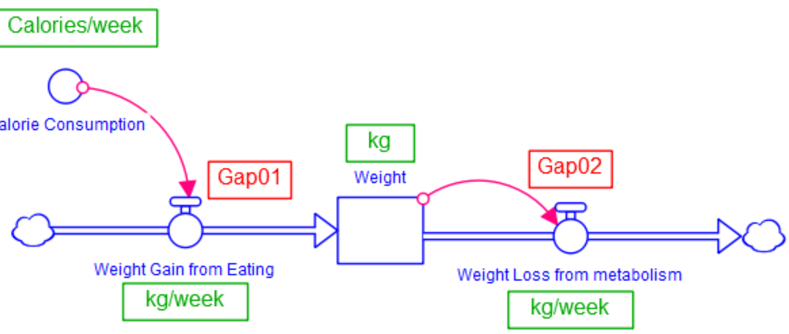

Figure 4.4: Identifying the dimensional gaps

4.3.6 Step 6: Mathematical Formulation

The mathematical equation formulations are done using Appendix 1-A, the structure in step 4, and the dimensional gaps in step 5. The general equations from Richardson &

Pugh (1981) are used as guidelines. Where necessary, there might exist effect variables where Appendix 1-E is used. In the case where ageing chains occur, Appendix 1-F can be consulted.

Sub Steps:

1. Missing Variables (6.1): Use gaps in step 5.4 and Appendix 1-A to identify possible equations for each gap.
2. Effect Variables (6.2): When there are non-linear effects that one variable has on another, effect variables can be defined using Appendix 1-E.
3. Equation Formulations (6.3): Iteratively applying steps 6.1 and 6.2, most equations can be derived and listed in this step.
4. Stock Stages / Aging Chains (6.4): If any stages or ageing chains exist in the structure, each flow needs either an average residence time or a probabilistic fraction of leaving the stock (Warren, 2018). Appendix 1-F can be consulted.
5. Final Dimension Checks (6.5): The structure is rechecked for dimensional consistency, including all the new variables generated from steps 6.1 to 6.4. If any dimensions are still not consistent, step 6 should be applied again.

4.3.7 Step 7: Detailed Stock and Flow Diagram

Step 7 is the foundational diagram for the model construction. The detailed SFD is created from the culmination of all the preceding steps and the Polaris for step 8. Once step 7 is complete, the simulation construction can be done in most system dynamics software packages. The disadvantage of only starting to construct the simulation at step 8 is that structural flaws might only be discovered in step 8, necessitating at least one iteration of the preceding steps. The advantage is that it does not limit the developer to any specific software. Another advantage is that it develops a deeper understanding of structure and equations when constructing system dynamics simulations. The following sub-steps recommend specific colours for ease of element in the detailed SFD.

Sub Steps:

1. Detailed Diagram (7.1): Add all structures Step 4, dimensions in Step 5 and 6, and effect variables in Step 6 to one diagram.
2. Indicate Equations (7.2): Equations can be represented with *Ex*, where *x* refers to the equation number in step 6 using red colour.
3. Indicate Dimensions (7.3): All variable dimensions captured on the design document in green colour.

4. Non-Linear Relationships (7.4): The effect variables need a graph showing the assumed/established relationships on the diagram.
5. Simulation inputs (7.5): Identify all variables that have no inputs. These variables are exogenous/inputs into the system and can be coloured in red.

An example of the final detailed stock and flow diagram can be seen in Figure 4.5. The units are labelled in green, the equations are referenced in red, and the non-linear relationship is captured above the effect variable.

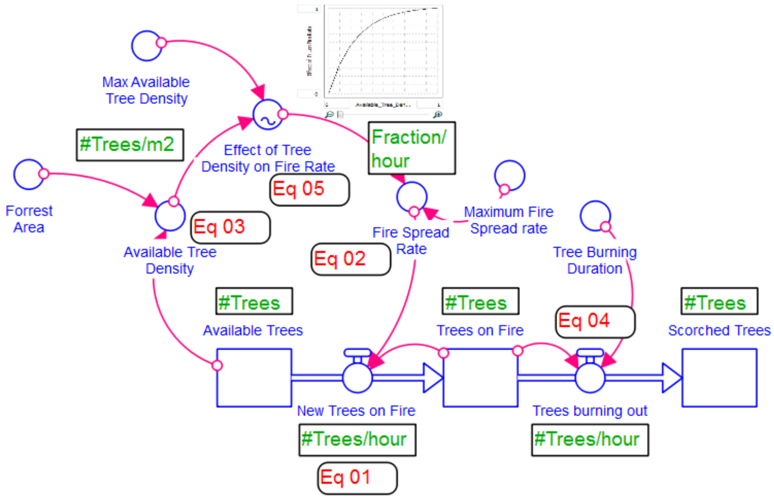

Figure 4.5: Detailed stock and flow diagram of the forest fire simulation

4.3.8 Step 8: Small Model Constructions and Testing

Step 8 is the first step on the construction (right) wing of the LST. The step is focused on building small models first (Homer, 2019) and then iteratively test each small model. Small simulation structure behaviours are validated with the loop behaviours identified in step 2. Small structures are built and tested independently.

Sub Steps:

1. Smallest Loop (8.1): Use the CLD in step 2 and identify the smallest loop. Trace the smallest loop into the detailed stock and flow diagram, step 7.
2. Construct Loop (8.2): Use specific software to construct the smallest loop identified in step 8.1.
3. Define constants (8.3): Define all constants for the small loop, starting with stocks, followed by exogenous variables identified in step 7. If no data is available, define initial stocks with simple values like 0, 1, 100, etc.
4. Test atomic behaviours (8.4): Test if the small structure can reproduce the expected behaviours from step 2. If not, investigate and correct the structure, equations and/or loops.

5. Next Loop (8.5): Once the first loop is complete, steps 8.1 to 8.4 can be repeated for the next loop. The process is repeated until all the loops are constructed and tested.

4.3.9 Step 9: Integrated Model and Testing

In step 9, the separately validated small models are integrated and then tested. As in the systems engineering process, emergent behaviour is often discovered during integration (Buede & Miller, 2016). The integrated model is validated with the behaviours identified in step 1. The structural behaviour is verified with equilibrium and disturbance tests.

Sub Steps:

1. Integration (9.1): The small simulations can be integrated using the layout in the design diagram of step 7.
2. Equilibrium test (9.2): Identify and test an equilibrium point (where all flows are 0). If not possible, attempt to find dynamic equilibrium, where the sum of all flows is 0 or very close to 0. If neither is possible, identify stable oscillations.
3. Define Disturbance test (9.3): Use the pulse function to introduce a pulse (Standard ISA-S26, 1968) into one input variable. The ripple effect of the pulse can be tested against the story in Step 1.
4. Reproduce Reference Modes (9.4): Test if the structure can reproduce the behaviour identified in step 1.

4.3.10 Step 10: Sensitivity Analysis

The sensitivity analysis can reveal the tipping points of variables and/or the leverage variables within the simulation structure. The tipping point is where the overall system behaviour changes drastically with a small change in the leverage variable. The leverage points are vital as they often reveal key variables to monitor and the direction in which to change them.

Sub Steps:

1. Identify variables (10.1): Consider all the exogenous variables (red) in step 7 and select at least three variables of interest linked to the purpose and problem in step 1.
2. Sensitivity range (10.2): Choose a universal variation percentage for all three variables. The recommended range is between +-90% and +-99%. At +-95%, the minimum value would be 5% and the maximum value 195% of the initial.

3. Sensitivity Points (10.3): A minimum of 5 sensitivity points are required. The first sensitivity point would be the minimum value, and the last would be the maximum value defined in step 10.2. Increments are the difference between maximum and minimum divided by the points minus one. Example: Initial value is 10, 5 points, and range is +-95%. The minimum value would be 0.5 (5% of initial), and the maximum would be 19.5 (195% of initial). The increments would be 19.5-0.5 = 19, divided by 5-1=4 points: 19/4 = 4.75 for each increment. So the final points are: 0.5; 5.25; 10; 14.75 and 19.5.
4. Analysis (10.4): Each of the variables is then comparatively run for each sensitivity point. The minimum value is often an extreme minimum test, while the maximum value could be an extreme maximum test. The extreme minimum test is used as an additional verification test on if the simulation crashes. The percentage change in the focus variable is divided by the sensitivity percentage change for each point. The absolute value of the division provides the strength of the leverage point.
5. Ranked Leverage Points (10.5): The absolute value defined for each of the points in step 10.4 is used to rank the leverage points from highest impact to lowest impact.

4.3.11 Step 11: Emerging Lessons

The final step's purpose is to capture and communicate the simulation's insights to improve the mental models of recipients for enhanced decision making (Forrester, 1999). The lessons should primarily focus on the counter-intuitive behaviours identified in steps 9 and 10. The process can be documented as a report, discussion, oral presentation, or interactive learning lab simulation, as is done in Chapter 6.

Sub Steps:

1. Emerging Insights (11.1): Use the leverage points from the sensitivity analysis of step 10 and alter variables simultaneously. Identify the hopeful and fearful scenarios and determine the tipping point. Identify insights from simulation, counter-intuitive or unexpected behaviours. Summarize the findings here.
2. System Leverage Points (11.2): The leverage points and their strength can be discussed here in the context of the real problem described in step 1.
3. List of variables (11.3): Capture all the variables, their units, and descriptions here which allow users of the simulation to understand what each variable represents and the assumptions that underlie the simulation.

4.4 Internal Tests

The system dynamics method has been criticized for its lack of validation criteria during model construction (Featherston & Doolan, 2012). The verification, validation, and testing from systems engineering have been proposed as a plausible method improvement option (McLucas & Ryan, 2005). Verification relates to how well the simulation is being constructed (Serendepity, 2010). In the LST, verification relates to the internal consistency between the left-wing (development) and right-wing (construction). Validation relates to whether the constructed simulation is the right simulation for the problem (Serendepity, 2010). In the LST, validation relates to how well the simulation results can reproduce the behaviours in step 1. The ability to internally test model development allows the user/educator to evaluate model development, identify problems early and identify specific system dynamics skills which the developer needs to improve.

Test #; Step #; Description

1. Step 1: Test purpose (1.4) with the problem (1.1)
2. Step 1: Test core variables (1.5) to the problem (1.1)
3. Step 2: Test if the story (2.1) fits with the problem (1.1)
4. Step 2: Test CLD (2.2) with Appendix 1-B.
5. Step 2: Test CLD (2.3) against the story (2.1)
6. Step 3: Test that stocks (2.2) are nouns with dimensions
7. Step 3: Test that each loop has at least one stock (3.3)
8. Step 3: Test if any stocks are aggregations as in Appendix 1-F (3.5)
9. Step 5: Test that all the variables in the diagram have dimensions (3.3)
10. Step 5: Test if variable dimensions consistent (3.4)
11. Step 5: Test if all equations have been defined with correct dimensions (5.4)
12. Step 7: Test that all dimensions and equations are found on the Detailed SFD (7.3)
13. Step 8: Test if the separated small models can produce the atomic loop behaviours in step 2 (7.4)
14. Step 9: Test for equilibrium or constant oscillations (9.2) states in the integrated model
15. Step 9: Test if disturbance tests fit with the story in step 1.
16. Step 9: Test if the simulation can reproduce reference modes from step 1 (9.4)
17. Step 10: Test if simulation malfunctions at extreme conditions (10.3)
18. Step 11: Test if the levers and insights can be applied to reality (11.3).

The list of validation tests is 1, 2, 3, 15, 16, and 18. The list of verification tests is 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 17. The extent to which the development process is verified and validated can be measured independently to identify where students/developers need improvement. The internal tests are valuable as it allows the evaluation of simulation development and faster error identification. The tests resulted from the systems engineering incorporation and are a unique element of the LST system dynamics method.

4.5 Method Development and Validation

The LST is externally verified through the Delphi research method, discussed in Chapter 4. In addition, the LST is validated through the practical application of the methodology. In each round of the Delphi, the LST is applied to specific system archetypes to create dynamic simulations. The first two steps of the LST focus on the development of the CLD. The CLD generated for the Fixes that Fail generic archetype in Delphi Round 2 can be seen in Figure 4.6.

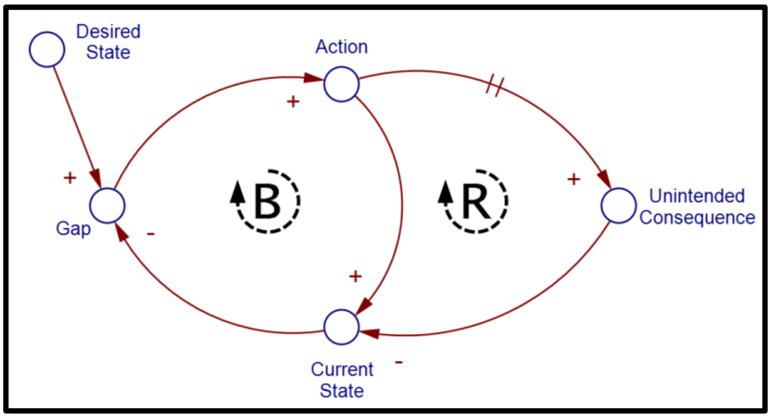

Figure 4.6: The Fixes that Fail generic Causal Loop Diagram

In the second round of Delphi, the CLD is kept generic to compare generic and specific system archetype simulations. The generic variables make the application of the LST more challenging as there is little to no context in generic variables. The Limits to Growth archetype is explicitly applied to the growth of a forest fire. The CLD developed in Step 2 of the LST can be found in Figure 4.7.

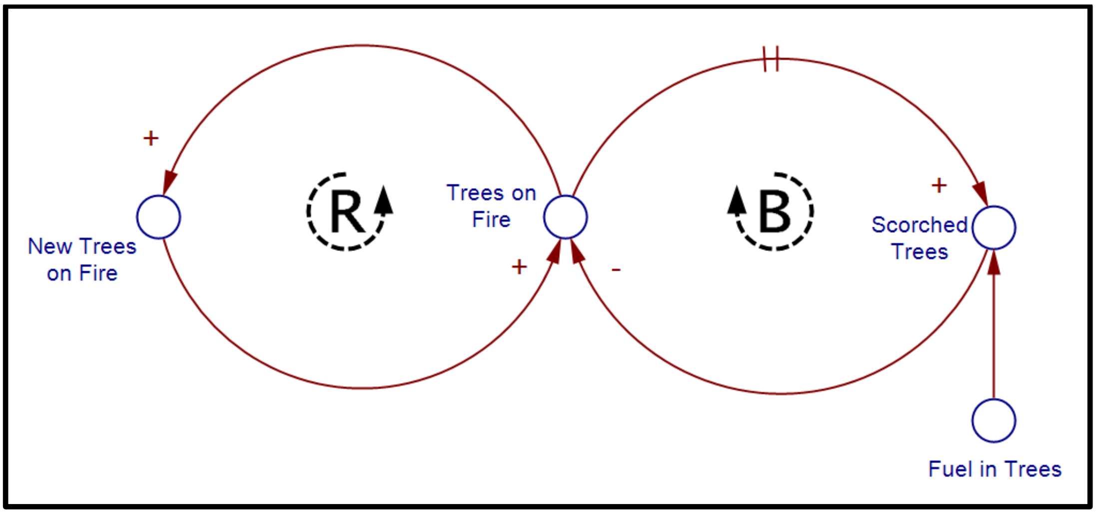

Figure 4.7: The Limits to Growth – forest fire Causal Loop Diagram

Steps 8 to 11 of the LST are used to develop the simulation and the interface for the simulations. The final interface for **Fixes that Fail**, the generic model, is captured in Figure 4.7. Even though it is more challenging with generic variables, the behaviour, unintended consequence, and the current state resemble the expected behaviours defined in the literature (Senge, 1990). The alignment between the practical simulation and literature expected behaviours function as a validation agent on the LST.

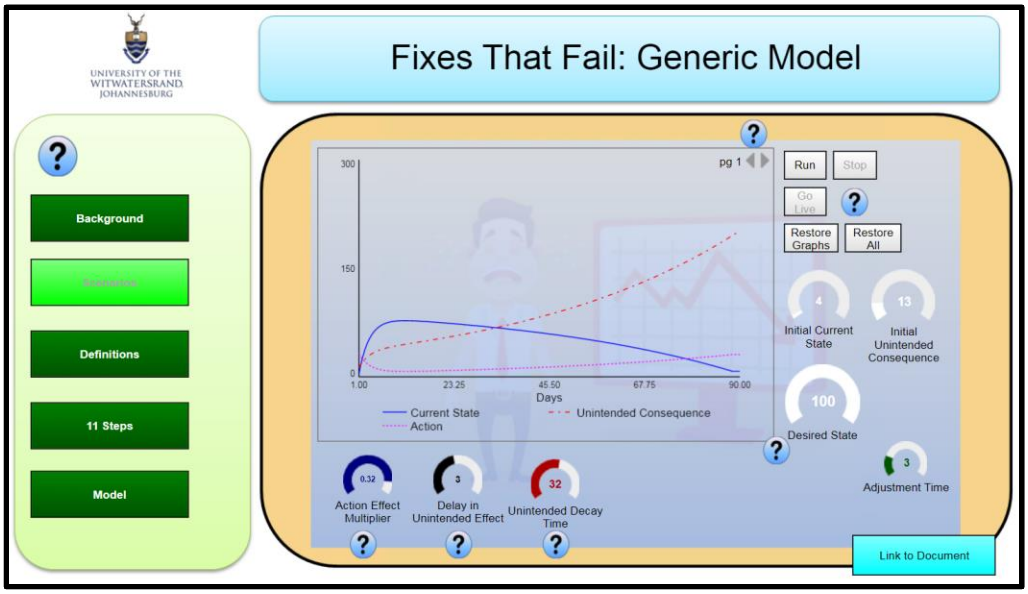

Figure 4.8: The Fixes that Fail generic archetype model

The link to the Fixes that Fail simulation can be found at the following link:

https://exchange.iseesystems.com/public/corne/fixes-that-fail---generic-model/index.html#page2

The Limits to Growth Forest Fire simulation can be seen in Figure 4.9. The trees on fire are the archetype's performance variable, which exhibits the expected growth and decay from literature (Senge, 1990).

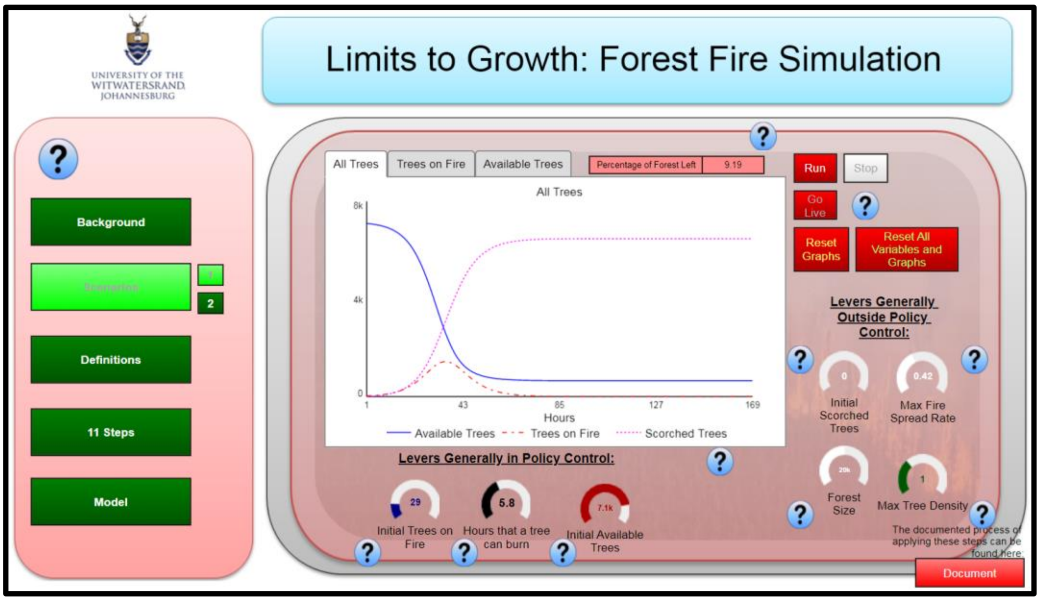

Figure 4.9: Limits to Growth: forest fire simulation

The final simulation can be accessed through the link below:

https://exchange.iseesystems.com/public/corne/forest-fires-limits-to-growth-archetype/index.html#page2

The final LST is applied to the four system archetypes, translating them into four unique mathematical simulations. In this manner, each simulation's behaviour is tested against the expected system archetype and focus problem behaviour. The full details on the practical validation of the LST can be found in Chapter 6.

4.6 Conclusion

The purpose of the research is to identify one coherent system dynamics simulation construction method. In this chapter, that method is described in detail. The LST all have sub-steps and six appendixes (Appendix 1:A-F) to guide the user. The verification, validation, and testing concepts from systems engineering produced testing criteria for model development in addition to the structural development enhancement. The left wing of the LST (Steps 1 to 6) captures the simulation structure's development from the first principles. In the centre, step 7, is the blueprint that can be used universally with any system dynamics software. The right wing of the LST (steps 8 to 11) is the simulation's construction and insight abstraction.

In the next chapter, Chapter 5, the method is validated and verified through system dynamics experts in the Delphi research approach. In the chapter after that, Chapter 6, the LST's application on four system archetypes is demonstrated. The demonstration validates the method against inter-repeatability and expected literature behaviour.

5 Theoretical Verification

5.1 Introduction

Building confidence in the LST of Chapter 4 requires external verification from field experts. Therefore, the expert group is tasked to evaluate the LST and resultant simulations through the iterative rounds of the Delphi research method. The group provides improvements and criticisms on the LST. The Delphi approach consists of two rounds, where each round has a preparation step, feedback request step and feedback interpretation step.

5.1.1 Delphi Group Demographics

Before Delphi round 1, each participant completes a set of questions to ascertain the group demographics. The nine participants are asked for their years of system dynamics experience, type of system dynamics experience, and finally, the step in the system dynamics method that is most difficult to learn for new students. The first demographic result is found in Figure 5.1 below. Most of the group fall into two categories: more than 20 years' experience or between five and ten years' experience. The estimated total experience of the group ranges between 102 and 160 years.

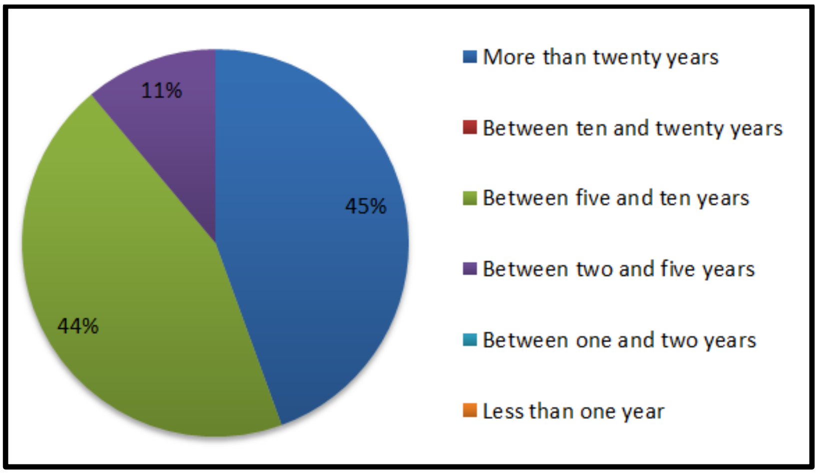

Figure 5.1: Years of experience in system dynamics Delphi group

Considering that system dynamics was found in 1961, the experienced pool of greater than 100 years is acceptable. The second question reveals that the three dominant areas of experience within the field reside with researchers, lecturing, and consulting in Table 5.1 below.

Table 5.1: Type of Experience in Delphi Group

Type of Experience	Participants Experienced the type	Percentage of Group
Researcher (used in post-grad, written papers, attended conferences)	8	89%
Lecturing in the field (teaching, guiding, conducting workshops)	7	78%
Consulting (building models, group model building, to industry)	7	78%
Student of the field (used in under-grad, workshops, courses)	4	44%
Community organizing, building, development	1	11%
Independent Researcher;Focused on Theory and Application; CTO	1	11%
Winner of Forrester Award Twice	1	11%

The group's experience is focused on the teaching (lecturing) and application (consulting) of the field. Therefore these experience areas qualify the group to evaluate the LST system dynamics method. The final question reveals that most students are perceived to struggle with the model formulation and system conceptualization steps.

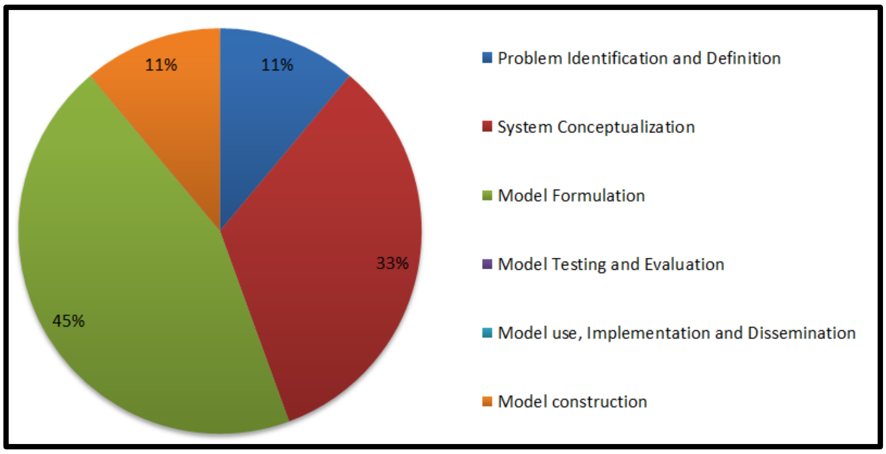

Figure 5.2: Most difficult system dynamics step to newcomers

The model formulation is the focal point of the research and might be have primed the nine participants' to accept the Delphi participation invitation. System conceptualisation is often defined as the creative part of system dynamics (Forrester, 1999), which might be why conceptualisation is more challenging to learn.

5.1.2 Delphi Questions

The researcher tests for the three research questions listed in Chapter 1 for verification via the Delphi research method. The three focus points relating to the research questions in Chapter 1 are:

1) The method represents the correct system dynamics techniques from literature (coherent process from literature, question 1)
2) The usefulness and application of the 11 step method (usefulness of method and application into the simulation, question 3)
3) The usefulness, learnability, and value of the final archetype simulation (simulation linking system archetype behaviour, question 2)

The three focus points are linked to each of the five Likert scale questions, visible in Table 5.2.

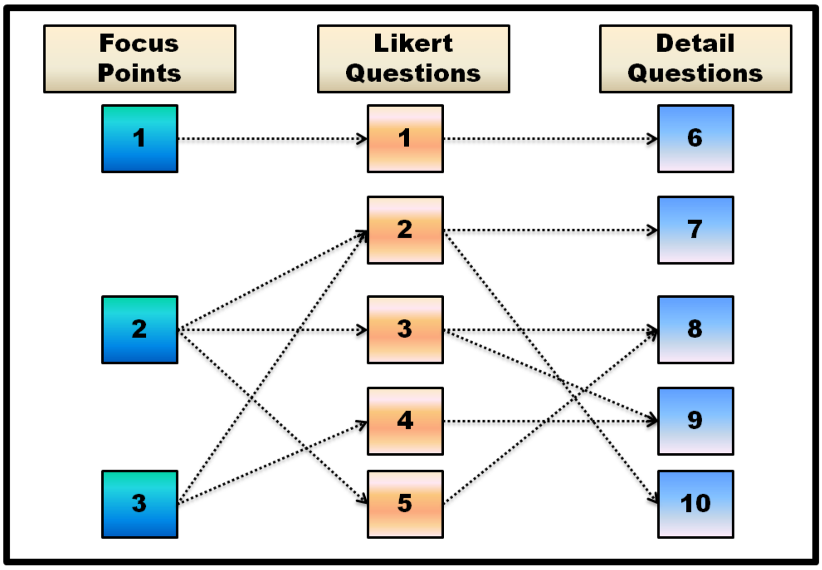

Figure 5.3: Graphical relation between the focus points and Delphi questions.

Questions 2 and 4 are asked in the negative disposition. Likert scale literature (Likert, 1931) recommends that some results should be asked with the negative disposition to overcome positive biases which might exist within the group. Questions 2 and 4 are used to verify focus points 2 and 3, respectively.

Table 5.2: First set of Likert scale Delphi questions (Short)

#	Likert Scale Questions	Focus Point
1	The 11 Steps seem to contain the correct system dynamics elements.	1
2	The 11 Steps will NOT be useful to newcomers to the system dynamics field	2+3 (neg)
3	The application of the 11 steps seem to be able to deepen the understanding of the archetype	2
4	The final simulation is NOT able to demonstrate the fixes that fail archetype in a simulation	3 (negative)
5	The modelling approach is expected to be useful in a workshop or training application	2

As explained in Chapter 3, the five open-ended questions are used to overcome the uni-dimensional limitation of the Likert scale. Participants are allowed to type 32 000 characters for each question using Google Forms. The open-ended questions are captured in Table 5.3.

Table 5.3: Second set of Delphi questions (open-ended)

#	Question	Question link
6	Considering how you would normally model a system (or teach modelling), how much do these steps align with or differ from your approach?	Question 1
7	Based on your opinion, how much experience/education/training would you deem necessary to be able to learn the execution of the 11 step process?	Question 2
8	Would you say that the modelling steps are able to aid in creating a slightly more structured approach and allows a deeper understanding of the structure behind the archetype?	Question 5 + 3
9	The final model allows you to interact with the applied system archetype (Fixes that Fail) in a model format. How valuable is the final simulation in learning more about the system archetype? Why?	Question 4 + 3
10	In your opinion, do you think that the 11 steps lack critical elements that would discourage newcomers to the field of system dynamics? If so, which elements?	Question 2

Focus point 1 is the only independent focus point while. The initial LST is applied to the Fixes that Fail archetype. The simulation focuses on the trap of borrowing money to reduce cash flow problems, found in Figure 5.4. The simulation is constructed using the iSee Stella Architect software and uploaded to the iSee Exchange server for ease of access to participants.

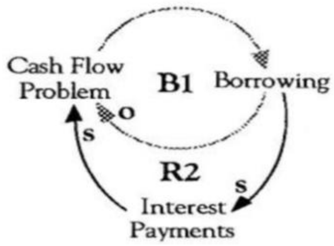

Figure 5.4: Fixes that Fail on borrowing money (Systems Thinker, 2018)

The full documented set of how the simulation is developed through the application of the LST is shared with the participants. Thereafter, the participants are requested to answer Questions 1 to 10 after engaging with the simulation and development document. The link to the online simulation is:

https://exchange.iseesystems.com/public/corne/fixes-that-fail-borrow-to-pay-debt/index.html

5.2 Delphi Round 1

5.2.1 Results

The Delphi round 1 was sent out on the 10th of May 2020; four weeks were given to complete the request. After seven weeks, all participants (9/9) completed the online Delphi questionnaire.

Table 5.4 Translated results to focussing points Delphi round 1

Participant	Q1	Q2	Q3	Q4	Q5
ID1	1	1	0	0	1
ID2	0	0	0	1	0
ID3	1	1	1	1	1
ID4	1	-1	1	1	-1
ID5	1	-1	1	1	-1
ID6	1	1	1	1	1
ID7	1	0	1	1	1
ID8	1	1	1	1	1
ID9	1	1	0	1	0
Avg	89%	33%	67%	89%	33%

The first quantitative results are focused on the Likert scale questions. The five Likert scale options are translated into numeric elements: 1, 0, and -1. When the question is framed in a positive disposition (Q:1+3+5), the possibilities of ‘agree’ and ‘strongly agree’ are 1. Questions stated negatively (Q:2+4), the ‘disagree’ and ‘strongly disagree’ would be 1. The value of 0 is allocated to the neither agree nor disagree option. The value of -1 is allocated to the other options. The participant’s identity is protected; therefore, each participant is referenced with ID1 to ID9. The ID allocation remains consistent throughout Chapter 5. The translated results are captured in Table 5.2.

The average score of each question reveals the average support of the group for the focus point behind that question. A value of -100% means no support, 0% indicated uncertainty, and 100% revealed full support from the group. The results in Table 5.2. show Question 1 and 4 are at the highest support (89%). Question 1 explicitly tests focus point 1, which reveal that the group supports the notion that the LST contains the correct system dynamics elements.

Question 4 (89%) also tests the third focus point, which reveals some support, yet it is countered by question 2 (33%), which reveals there are disagreements with focus point 3. The focus point relates to the usefulness, learnability, and value of the emerging simulation. Question 3 (67%) and 5 (33%) both related to focus point 2, combined with question 2 (33%). Focus point 2 has the lowest support, which relates to the usefulness and application of the LST. The expert group scores only validate focus point 1 at higher than the acceptance criteria set at 67%. As such, testing points 2 and 3 are not successfully verified in Delphi round 1, which necessitated a second round of Delphi.

The statistical analysis of the quantitative Likert scale is conducted using Cohen's Kappa technique, as explained in Chapter 3. The interpretation standard of Cohen's Kappa value is captured in Table 5.5.

Table 5.5: Interpretation of Cohen's Kappa values (McHugh, 2012)

Cohen-Kappa Value Range	Description
≤0	No agreement
0.01-0.2	None to slight agreement
0.21-0.40	Fair agreement
0.41-0.60	Moderate agreement
0.61-0.80	Substantial agreement
0.81-1.00	Almost Perfect agreement

Cohen's Kappa is calculated for every unique combination in the group. The nine participants have 36 unique sets of 2 participant groups. The Cohen's Kappa results for every combination, every ID, and the group average is found in Table 5.6.

Table 5.6: Cohen's Kappa results for Delphi round 1

#	ID1	ID2	ID3	ID4	ID5	ID6	ID7	ID8	ID9
ID1	**0.14**	-0.25	0.41	-0.18	-0.18	0.41	0.06	0.41	0.41
ID2		**0.12**	0.13	0.13	0.13	0.13	0.25	0.13	0.33
ID3			**0.50**	0.17	0.17	1.00	0.64	1.00	0.44
ID4				**0.24**	1.00	0.17	0.29	0.17	0.17
ID5					**0.24**	0.17	0.29	0.17	0.17
ID6						**0.50**	0.64	1.00	0.44
ID7							**0.37**	0.64	0.17
ID8								**0.50**	0.44
ID9									**0.32**

First value is the average for that ID to the group

Group Average	0.32
Group Deviation	0.15

The average Cohen's Kappa for the group is 0.32, which translates to 'Fair Agreement'. The target agreement set in Chapter 3 is 'Significant Agreement'. Therefore, it is not achieved in Delphi round 1. Each individual's agreement with the group is captured in blue, the first column of each ID. ID2 has the lowest agreement (0.12), while ID3, ID6, and ID8 have the highest agreement (0.5). Both the lowest and highest agreements lie within two standard deviations (95^{th} percentile) of the group.

The content analysis method is applied to each question to systematically analyse the long open-ended questions (White & Marsh, 2006). Each answer is used to code the main concepts (2-3 words) for each participant's response. The concepts are then classified into three different categories: Green (supportive), yellow (areas of improvement) and red (criticisms against method/research). Concepts that are similar in nature are combined into coherent ideas. Finally, the total number of referenced concepts to each idea is counted. The main ideas and their counts are visible in Table 5.7.

Almost half of the participant group has positive comments on the method, application, and system archetype simulation. About a third of the comments are recommendations on improving the method, application, and simulation. About 18% of the comments are direct criticisms against the LST and simulation, which relate to fundamentally opposing ideas to the research's assumptions.

Table 5.7: Contextualized ideas from long questions

Type	Context Ideas	Idea Counts	Total Counts
Positive	It will enhance the learning process through deeper understanding and insight	19	45 - 48%
	The steps should be learnable by people who have some modelling experience at tertiary level and take atleast 6 months to learn	15	
	The steps create a better structure for learning the SD process and is alligned with the official SD method	11	
Areas of Improvement	The interface can be improved by using better defined terms and model parameters. Supervised learning with the interface can be valuable	11	31 - 33%
	Alligns partially with expert approaches with missing elements on explicit model validation and problem definition. CLD formulation should be done differently	10	
	The steps are not for beginners and has the same general problem of system dynamics being difficult to learn.	10	
Negative	The root problem is not in defining appropriate steps but in the structure and perspectives of society on mathematics and the world.	5	17 - 18%
	The 11 steps are not alligned well and will not be usefull to beginners but rather discourage them from learning System Dynamics	6	
	The 11 steps are too many and too complex for beginners. It also has a few missing elements.	6	

The highest idea count is found in the positive section, at about 50% of the total ideas. The positive ideas show that the LST improve understanding and most likely teachable at the tertiary level in 6 months (semester course). The LST is able to infuse more structure to the learning process of system dynamics. One of the main positive comments reference the concept of **Learning Insights** (counted seven times):

"…I think this specific simulation is valuable in learning insights about this specific situation. And, for most of the archetypes, it would be very valuable because people don't generally already understand the others." – Participant comment in support

The improvement areas are about a third of the total and are mainly focused on interface improvements: definition of terms, supervised learning/guidance, how to use the simulation. More detail should be given to the problem definition and model validation. The stocks and flows should be a more significant focus point than the CLD. Another impression that exists is that the LST could not be as useful for beginners since the steps may be too many and too complex. The most prominent repeating concept for areas of improvement is '**Interface needs work**' (counted – 5 times):

"The final model is relatively good. I generally add a good amount of text to my final simulations, to explain what is happening, what might happen, and for whom is it happening? What are some of the unintended consequences of outlier thresholds for model parameters? So, while the simulation is fine, I think it would be useful to just

give more context below the model. Purpose, use, goals, stakeholders…." – Participant comment for improving the approach

Criticisms contributed to less than 20% of the total ideas. Two of the comments stand in direct contrast to the positive remarks: the alignment to the general system dynamics approach and not being useful to newcomers. One of the repeating arguments is that the real problem is not the lack of structure to learn system dynamics but rather the perception of learning scientific fields like mathematics. The criticism concept repeated mostly is 'Steps not the Problem' – 3 times:

"There is a critical element missing that the steps do not really address (neither does the standard method directly) and that is problem discovery. I would normally use the term "problem definition" but, by definition, in SD the reference mode defines the problem. But how do you get to that? There is non-modelling skills involved (here and in developing a dynamic hypothesis) and some people who enter the field are more interested in that side than in the modelling. Obviously, this is outside the scope of your effort and there are any number of books that cover this." – Participant comment in critique of the method.

5.2.2 Summary Round 1

Some of the main themes that emerge from the comments in round 1 are:

- The target teaching arena should be tertiary education, with a one-semester course
- The LST and application can induce deeper Insights
- Considerable improvements should be made to the simulation interface
- Many of the steps need refinement
- The root problem is not the lack of steps but rather the infamous reputation of mathematics and science
- A few major changes are required on problem conceptualization, SFD vs CLD approaches, and model sensitivity testing and verification.
- The suggestions refer strongly to the improvement of the interface to assist learning and understanding gained from the simulation. Supervised learning is an ideal suggestion for the simulation interface.

5.3 Delphi Round 2

5.3.1 Preparation of Delphi Round 2

The following changes are made to the LST used in round 1:

- Step 1 is changed to the problem description
- Validation added in steps 8 and 9 with steps 1 and 2
- Cosmetic changes on the steps and simulation interface
- Steps 3, 9, and 10 are given more detail in the sub-steps
- The simulations are accompanied by explanation videos.

The first five Likert scale questions are kept the same to measure the change in the agreement, yet five additional Likert scale questions are added to measure the improvements on the method from round 1. Instead of five open-ended questions, only two open-ended questions are asked in Delphi Round 2. The five additional Likert questions can be found in Table 5.8. The 11 steps in Table 5.8 reference the LST.

Table 5.8: Additional Likert scale questions

#	Likert Scale Questions	Reason
6	The application of the 11 steps enhances the system learning through deeper understanding and insight gained through simulation formation.	Another question to confirm the focus point 2
7	The generic system archetype simulation is more useful than the specific system archetype simulation? (Fixes that Fail > Forest Fire)	Testing the perception between generic and specific archetype (Negative)
8	The 11 steps have certain elements that can be excluded to simplify the generic simulation construction process.	Testing if some steps can be excluded, critiques from Delphi 1 (Negative)
9	The improvements made to this round of Delphi have enhanced your understanding of the simulation.	Testing the improvements from round 1
10	The 11 steps CANNOT improve the learning and/or teaching of system dynamics.	Another question on the ability of the steps to improve learning/teaching of system dynamics focus point 3 (Negative)

The two open-ended questions (Q11+12) are captured below. The two questions query the positive and negative elements respectively of both method and simulation:

- **Question 11:** What elements in the 11 steps and the final simulations worked well and will be useful to people interested in learning/teaching/practising system dynamics?
- **Question 12:** What elements in the 11 steps and simulations would prevent interested people from learning/teaching/practising system dynamics?

In the second round of the Delphi, the LST is applied to two system archetypes: Fixes that Fail and Limits to Growth. The LST in Delphi round 2 produced the two CLDs found in Figure 4.6 and Figure 4.7, respectively. The CLDs are then further expanded into full simulations with interfaces as described in Chapter 6 by Figure 4.8 and Figure 4.9. Finally, the full development documentation for both simulations is shared with the Delphi round 2 questionnaires via Google Forms.

5.3.2 Results of Delphi Round 2

The second Delphi round questions and material were sent out on the 6th of July 2020 to each participant personally. All participants submitted their inputs within nine weeks after the request was made. The quantitative results from the first five Likert scale questions are discussed in Table 5.9.

A significant improvement takes place in Delphi round 2. All five questions are supported more than the required 66%. Three questions (1,2 & 5) are supported by 100% of the group. The lowest score is 78% for question 3. Question 3 relates to the usefulness of the LST.

Table 5.9: Quantified results of Delphi round 2 first questions

Participant	Q1	Q2	Q3	Q4	Q5
ID1	1	1	1	1	1
ID2	1	1	0	1	1
ID3	1	1	1	1	1
ID4	1	1	1	1	1
ID5	1	1	1	1	1
ID6	1	1	0	1	1
ID7	1	1	1	1	1
ID8	1	1	1	1	1
ID9	1	1	1	0	1
Avg	100%	100%	78%	89%	100%

The results indicate that there is still some uncertainty on learner adoption. Therefore the Delphi group achieves validated group consistency at the second round. Next, the verification of the group's agreement level is statistically determined using Cohen's Kappa analysis, Table 5.10.

Table 5.10: Cohen-Kappa analysis of each participant combination agreements in second Delphi round question set 1

#	ID1	ID2	ID3	ID4	ID5	ID6	ID7	ID8	ID9
ID1	**0.76**	0.35	1.00	1.00	1.00	0.35	1.00	1.00	0.35
ID2	-	**0.39**	0.35	0.35	0.35	1.00	0.35	0.35	0.04
ID3	-	-	**0.76**	1.00	1.00	0.35	1.00	1.00	0.35
ID4	-	-	-	**0.76**	1.00	0.35	1.00	1.00	0.35
ID5	-	-	-	-	**0.76**	0.35	1.00	1.00	0.35
ID6	-	-	-	-	-	**0.39**	0.35	0.35	0.04
ID7	-	-	-	-	-	-	**0.76**	1.00	0.35
ID8	-	-	-	-	-	-	-	**0.76**	0.35
ID9									**0.27**

First value is the average for that ID to the group

Group Average	0.62
Group Deviation	0.20

The average Cohen's Kappa value for the group is 0.62, which is classified in the 'Significant Agreement' category, which achieves the set Delphi target. In this round, the lowest Cohen's Kappa elemental values are 0.04 for two combinations: ID9-ID2 and ID9-ID6. In this round, ID9 has the least agreement with the group at an average of 0.27. Six (67%) of the group has an agreement value of 0.76 with the rest of the group. There are a total of 16 combinations with a value of 1, which relates to 'perfect agreement'. Overall the minimum (0.27) and maximum (0.76) fall within two standard deviations from the average (0.62), which indicates that each participant fell within the 95th percentile of a normal distribution (no significant outliers). In summary, both the Delphi round's verification and validation are achieved in the second round, negating a third Delphi round.

The results from the second set of Likert scale questions in round 2 (Question 6-10) is seen in Table 5.11.

Table 5.11: Reclassified Delphi Round 2 results for second short questions set

Participant	Q6	Q7	Q8	Q9	Q10
ID1	1	1	1	1	1
ID2	1	1	-1	1	1
ID3	1	1	-1	1	1
ID4	1	1	1	1	1
ID5	1	-1	0	1	1
ID6	1	0	1	-1	1
ID7	1	1	-1	1	1
ID8	1	1	-1	0	1
ID9	1	0	1	1	1
Avg	100%	56%	0%	67%	100%

The average Cohen's Kappa for the results in Table 5.11 is 0.45 with a deviation of 0.14. Cohen's Kappa reveals that the group is more aligned than in the first round, given the new set of questions. Question 6 and Question 1 relates to focus point 1 and verifies the 100% support seen in Question 1. The 100% support in Question 10 reveals that the group agrees that the LST can improve system dynamics learning and/or teaching. The LST is intended to enhance the system dynamics learning process. Most of the group supports that the specific simulations are more useful than the generic version (Q7), and most of the group supports that the method improvements are valuable (Q9). It must be declared that ID6 only evaluated the generic simulation, which may have led to disagreements/uncertainties compared to the group. Question 8's result reveals that the group is split into two opposite sides: half the group believes that the number of steps could be reduced/simplified, while half of the group thinks that the number of steps cannot be simplified/reduced any further. Next, in the two open-ended questions, the polar views are explored further.

The open-ended questions are processed through the content analysis technique, and the results are captured in Table 5.12.

Table 5.12: Open-ended question content analysis theme results

#Repeats	%ofMax	Type of Content
16	100.0%	Need more Teaching Aids
12	75.0%	Alterations /Additions to existing steps
11	68.8%	Specific Steps Valuable
6	37.5%	Steps as a whole
5	31.3%	Learning and Formulation
3	18.8%	Mistakes in docs/model
3	18.8%	Don't use generic archetypes
2	12.5%	Too many steps for newcomers
1	6.3%	Not as usefull steps
1	6.3%	Confusing research purpose

Color Code:
Positive
Improvements
Negative

A total of 60 ideas are generated from the two open-ended questions (Q11+Q12) — almost half (28/60) of the ideas relates to the first two points in Table 5.12. The largest number of references is related to the requirement for more teaching aids (16) for the LST. The theme falls outside the research boundary, yet it indicates that the group supports the LST and wants to apply it in a teaching environment. The result cross-references to question 1, 6, and 10, where all three questions achieved 100% support. The second highest counted idea references the requirement for more alterations/additions to existing steps.

The positive ideas contribute to just above a third (22/60) of the idea counts. The group reveals their support for specific steps like dimensional analysis, stocks/flows identification, and problem description. Most of the group indicates that all the steps are valuable, and none deserve exclusion. The final positive comments related to the simulations ability to convey complex ideas through a structured formulation and learning process. One of the positive comments is captured here:

"Continuous learning: although I'm biased towards the mathematics, this is the first time that I found the mathematical interpretation secondarily important. The interactivity is critical." – Positive remark from Delphi participant

More than half all the ideas (33/60) refer to areas of improvement. About half of the improvement ideas reference the need for more teaching tools to enable the learning of the LST (16/33). One of the comments referencing the concept is:

"The 11 steps could work as a scaffolding to learn about model development and archetypes. Now that the 11 steps have been identified and clarified, more thought should be given to the learning process - how novice users can be guided through the 11 steps in a way that will cause learning to happen and will give them the aha

experience of getting insight into a tough problem, rather than giving up in incomprehension." – Participant comment on teaching tools

Some of the other improvement requests are to develop appendixes for specific steps and a more detailed description of the steps. One participant recommends that the LST process starts with stocks and flows instead of the CLD. In addition, the same participant suggests that simulation construction should begin before step 8 to prevent frustrating/unnecessary iterations. Another participant suggests that a large number of steps can be learned effectively by slowly introducing each step, one by one, through specific application and ending the explanation with the iterative nature of the LST.

One participant expresses that the least practical step, which can be excluded, is the sensitivity analysis. The suggestion is made since newcomers to the field might be less familiar with such a step's concept and value. However, a different participant lists the sensitivity analysis as one of the most valuable steps to show the structural behaviour and identify levers. The polar opposition in sensitivity analysis corresponds well with the results from Question 8. No other step or sub-step is recommended for exclusion even though almost half the participants indicates some steps can be reduced/simplified in question 8. The result indicates that the disagreements are most likely due to the improvement suggestions made to the LST. Thus none of the steps is excluded.

The most repeated negative remark (3/6) relates to the simulation of generic archetypes. It is recommended that generic archetypes should never be used as a simulation, as it is not their intended purpose. The quote from the participant can be seen below:

"As to units, I think it was a mistake to approach this generically, which is too abstract - exacerbating the units problem. People need something concrete to ground their understanding. I introduce its generic form and explain its characteristics, but then immediately move to a real example. Since this exactly mirrors the firefighting most all of us have experienced in our professional lives, people pick it up very quickly. You should be aware that the archetypes are not meant to be models - not a single one. They are commonly recurring feedback structures that each represents an entire class of models, much like the Design Patterns for object oriented programming. Trying to treat them as models leads to all sorts of issues (try to do so with shifting the burden - good luck!)." - Participant comment on generic archetype

The second-highest negative remark (2/6) mentions that delays are poorly handled by the LST and need more definition. The final criticism (1/6) is that the process is expected to be too difficult to learn without proper teaching material. The skills required for steps 5 to 11 are expected to be too challenging for high school students.

5.3.3 Summary of Delphi Round 2

Delphi round 2 achieves both the support and agreement level targets (66%; 0.61). The major themes which emerged from the content analysis are:

- **Need more teaching aids**: The method is accepted, and the next focus area of research has been identified.
- **Alterations/additions to existing steps**: The changes requested are included in the final steps found in Chapter 4.
- **All steps are valuable**: There is no group agreement on excluding any steps, yet many of the participants mention that all steps are useful.
- **The value lies in learning and formulation**: The real value of the LST is that it can improve understanding, education and formulation of complex problems, like the system archetypes.

The three research questions (refined into focus points) are all successfully answered and validated through the experts' Delphi group. In addition to the group's agreement on the LST and its value, the group also identifies the future research opportunity of creating learning material for both facilitator and learner. Although the pedagogical elements fall outside the scope of this research, the recommendation shows the group's appetite for teaching the LST.

5.4 Conclusion

The purpose of the study is to identify a set of verified system dynamics steps that can consistently produce viable simulations from the system archetypes. In this Chapter, the method and simulations are validated and verified. Validated through the support analysis of the Likert scale questions and verified through the Cohen's Kappa statistical agreement within the group.

The support for the focus points increase from 62% in round 1 to 94% on average in round 2. The average Cohen's Kappa agreement increases from 0.32 (Fair Agreement) in round 1 to 0.62 (Significant Agreement) in round 2. Both the support and agreement targets (67% and Significant Agreement) are achieved at the end of the second Delphi round. In addition to the quantitative analysis, a qualitative study using the content analysis technique reveals positive improvements and negative elements.

The group's central positive ideas about the LST are the increased understanding of complex problems and that all the steps are valuable for newcomers. The improvements pertain mainly to the recommendation on a future research avenue where training material should be created for the LST. The unfavourable ideas primarily focus on the inappropriate application of generic system archetypes. The Delphi research method improves both the LST through expert influence. Hereafter the four system archetype case studies are translated into mathematical simulations, found in Chapter 6.

6 Practical Validation

6.1 Chapter Purpose

The main purpose of the chapter is to complete a validation test on the simulations produced with the Loop Stock Transform (LST). The validation is approached with the system archetypes, which are conceptual models with established behaviour traits defined by systems thinking literature. For example, Meadows (2008) refer to the system archetypes as traps due to their destructive nature. In addition, the generic system archetypes are transboundary patterns, and in this thesis, they are chosen based on stories of complex problems faced on both a global and local level. The stories and archetypes are used as validation components.

The term “validation” relates to whether the constructed simulation is relevant to the identified problem (Serendepity, 2010). For example, the problem can remain elusive after the simulation has passed all verification tests; therefore, validation criteria are essential. In light of this, system archetypes are ideal case studies since they have loosely defined conceptual structures, expected behaviours, and insights that can be used to validate the simulation constructed with the LST. The LST is applied to four specific system archetypes, which are discussed in the next paragraphs.

The first system archetype is named “Fixes that Fail”. It is concerned with three elements, namely problem symptom, unintended consequence, and fix. The latter is used to solve the problem symptom, which initially works. After some delay, the unintended consequence worsens the problem symptom. A typical and simple example of this is fixing a squeaky wheel with water lubricant instead of oil. In the LST, the archetype is applied to the global Black Lives Matter protests against police violence in May 2020.

The second archetype is Limits to Growth. This particular system archetype has four elements, which are performance, improvement action, slowing action, and limit. As performance increases, the ability to increase performance develops (typical growth cycle) to a certain point. After that point, some type of limit comes into play and triggers the slowing action. The slowing action grows as the performance grows, which leads to the performance slowing down or decreasing. A typical example of this is seen in how populations grow and reach equilibrium. In the LST, this archetype is applied to a forest fire, such as the destructive Australian firestorms of 2019/2020. Firestorms are the application of the second system archetype, while the third system archetype is discussed next.

The third system archetype is called Eroding Goals, where this archetype is focused on achieving a specific goal through two mechanisms: The first mechanism is investing in the ability to reach the goal, which increases skills/performance, and, as a result, the goal is then reached. Yet, reaching the goal through skills investment takes time and thus slower than the second mechanism. The second achieves the goal by lowering the targets for success. This loop is much faster than the first, and when the first loop takes too long to produce results, the second loop is often engaged to satisfy pressures from management/self. The boiled frog is a typical example of this archetype. In the LST, the archetype is applied to the South African education system, specifically the matriculation results.

The final system archetype is Escalation. The Escalation archetype has two, almost identical, balancing loops that work against each other in the following manner: Firstly, the performance of one group triggers a perceived threat by a second group. The latter then increase their own performance until it exceeds the first group’s performance. Subsequently, the first group then perceives the second group as a threat and, as a result, increase their performance. The two balancing loops merge and produce an unseen reinforcing loop. Practically, the nuclear arms race is a typical example of Escalation. In the LST, this particular archetype is applied to the social media polarisation seen in the increase of extremist ideas in American and South African politics in 2020. In conclusion, the four simulations are documented case studies.

The detailed development documentation for each simulation is captured in Appendix 2-A to Appendix 2-D. This chapter is focused on the validation between the applied system archetype story and the simulation behaviour. The simulations are constructed using the LST and validated with the archetype behaviours. The archetype simulations are further validated with recommendations from the literature.

6.2 Fixes that Fail: Policing Protests

"Sir, please, I can't breathe… Water. Mama… don't kill me… I'm about to die… everything hurts… Mama" (Global Sisters Report, 2020). These were the last words of 46-year-old George Floyd while being pinned down by a police officer on 25 May 2020. Floyd pled for his life for just under 9 minutes. An earlier incident was that of Ms Breonna Taylor (26), who was killed by police in her own home during an unannounced raid on March 13, 2020 (New York Times, 2021). Consequently, multitudes of similar cases came to light all over the United States, triggering the large-scale Black Lives Matter (BLM) protests on 29 May 2020. Furthermore, these protests were supported by diverse groups of people and businesses. Hence the protests continued for 200 days in fluctuating numbers (Aljazeera a, 2020).

The abovementioned protests resulted in global outcries about racism, specifically against black people (Global Times, 2020). In response to outcries, USA President Trump claimed he did not know about the police violence and later called the BLM movement a symbol of hate (BBC, 2020). Consequently, the BLM protests affected the vote perception in November 2020, and some believe that it partially contributed to the victory of President Biden (Aljazeera a, 2020). However, not all protests were peaceful, and protestors did cause damage (O'Reilly, 2020); nevertheless, the outcome was successful in that there were decisions made to reduce the use of police violence across America. Hence, the BLM movement is arguably the biggest and most successful protest movement yet, globally (Aljazeera a, 2020).

Likewise to the global picture, authorities have used law enforced violence throughout history, and South Africa is no different. The historical behaviour of South African protests can be found in Figure 6.1 below. For example, one of the tragic protests is the Marikana massacre, where 34 striking miners were killed and 78 were injured in August 2012 (Bruce, 2012).

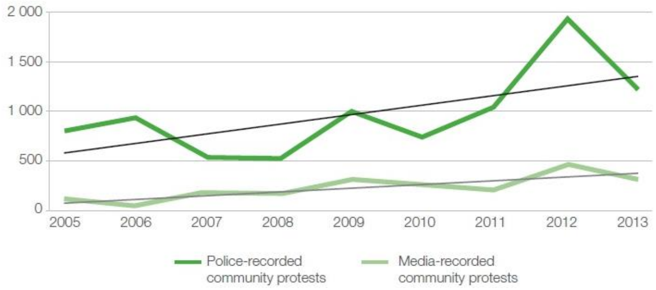

Figure 6.1: South African community protests estimated between 2005 and 2013 (Alexander *et al., 2018*).

Although violence does indeed scatter protestors and control them temporarily, it also induces more anger and fear in communities. The fear and anger spread, and protests often return with more numbers and/or more force. This is an example of the Fixes that Fail system archetype where the quick fix is to use the police force to reduce the protest problem. However, the unintended consequence is the repression and further aggravation of communities. After some time, protests return worse than before. The CLD of the applied system archetype is captured in Figure 6.2.

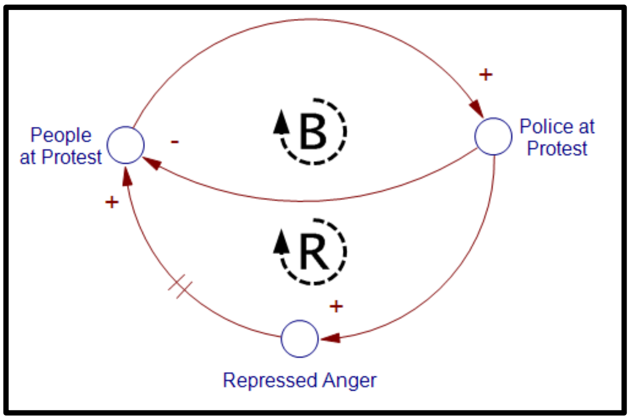

Figure 6.2: Causal Loop Diagram – Fixes that Fail – of protest control

The balancing loop is the short-sighted solution to fix the problem, namely the symptom of protests. If there is no unintended consequence, the loop can solve the problem. However, the unintended consequence creates a reinforcing loop that worsens the problem symptom and requires more policing power. Hereafter, the CLD is developed into a detailed SFD through steps 2 to 7 and captured in Figure 6.3.

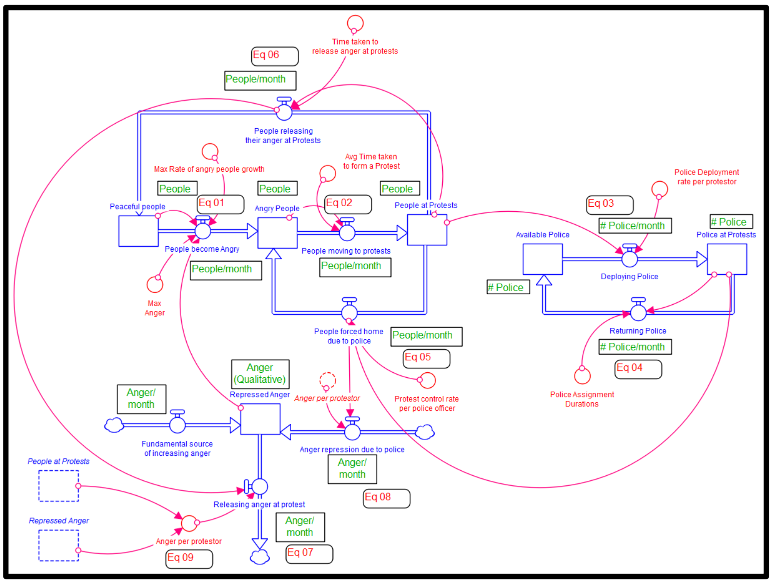

Figure 6.3: Detailed stock and flow diagram of the Fixes that Fail simulation

The development process reveals two different ageing chains, namely protestors and police. At first, the protestors are assumed to be peaceful; they then transitioned to angry and, finally, to protest. On the other hand, the police are assumed to be limited by the available police who will be deployed to the protest site and return after their assignment is complete.

The expected behaviour (Braun, 2002) of the Fixes that Fail system archetype is captured in Figure 6.4. The problem symptom is the protestors, while the unintended consequence is their repressed anger.

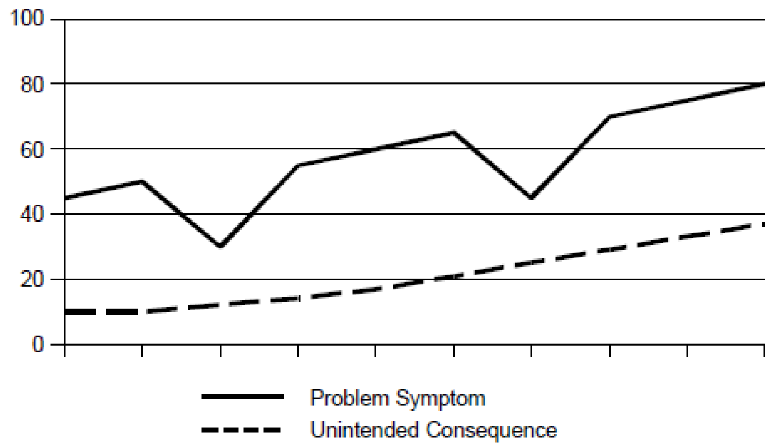

Figure 6.4: Expected behaviour of the generic Fixes that Fail archetype

The simulation is constructed in step 8 and combined in step 9. The simulations' behaviour is captured in Figure 6.5.

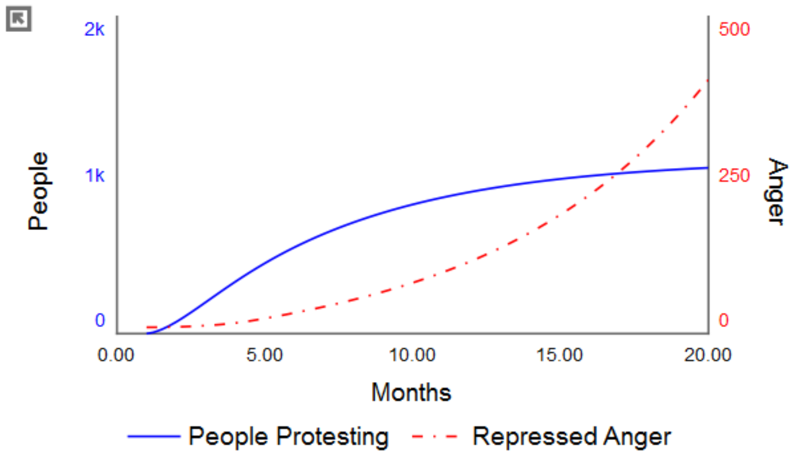

Figure 6.5: Fixes that Fail simulation result

As can be seen above, the numbers of protestors are increasing, and anger grows exponentially, as expected from literature (Braun, 2002). However, the difference, in this case, is that the behaviour from Braun (2002) assumes the quick fix is a discrete event application, while in the simulation, it is a continuous simulation; since In Delphi

Round 1, participants recommend that system dynamics simulations should avoid discrete events.

The simulation is tested and finalised in step 9, and the structure is able to replicate the behaviour identified in step 1 and captured in Figure 6.6 below.

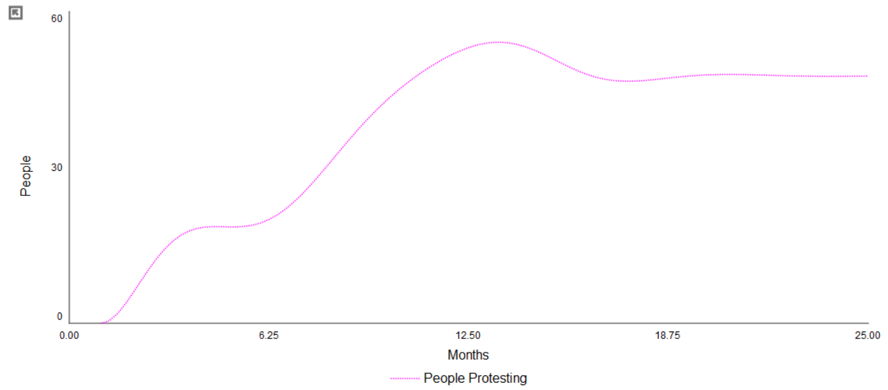

Figure 6.6: Simulation reproduction of step 1 behaviour

According to Meadows (2008), the archetypes also functions as system traps since victims fall into them unexpectedly and cannot escape. However, Meadows (2008) suggests the way out of the archetype's trap is to (counter-intuitively) let go. In the context of the simulation (Figure 6.3), it relates to the protest control rate per police officer. Hence the sensitivity analysis is conducted on the control rate – which relates to the extent of force used by the average police officer. Hence the result of the analysis is captured in Figure 6.7.

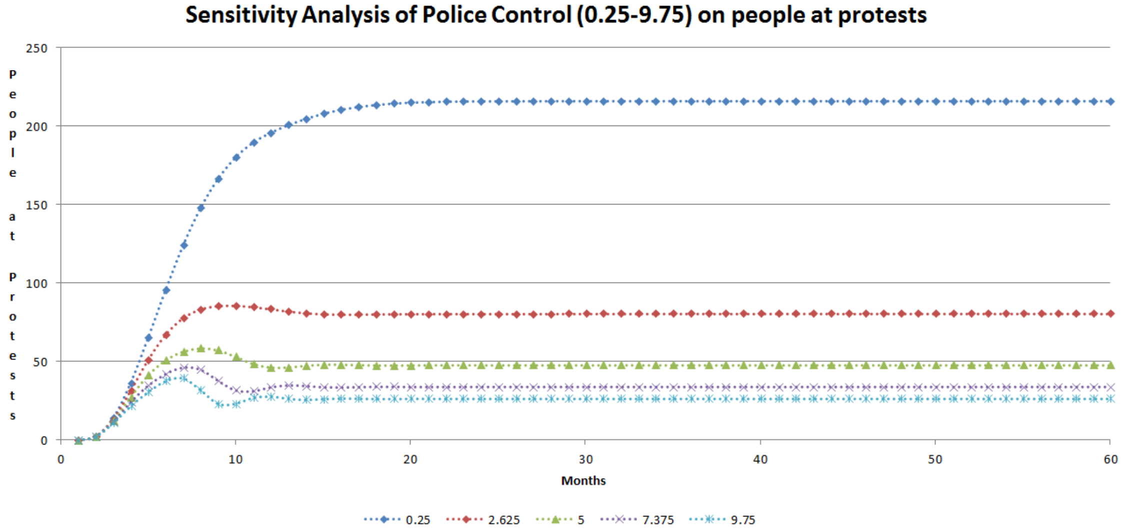

Figure 6.7: Sensitivity analysis of police control (force)

The sensitivity analysis reveals that this is indeed the strongest component in the set of variables used. Meadows (2008) has mentioned that if the control (police force) is strong enough, it could keep the problem symptom at bay in the short term. This is shown by the light blue scenario (9.75) in Figure 6.7. In reality, this phenomenon is observed when totalitarian control is exercised upon communities. However, the long-term consequence of such decisions has led to destructive historical systems of control. Therefore, the simulation behaviour is validated by the literature' expected behaviour (Braun, 2002) and the recommended solutions (Meadows, 2008).

By combining the lessons learned through the sensitivity analysis and the reduction in police control rate to 0, the simulation reveals a scenario in which the community returns to being peaceful, as seen in Figure 6.8.

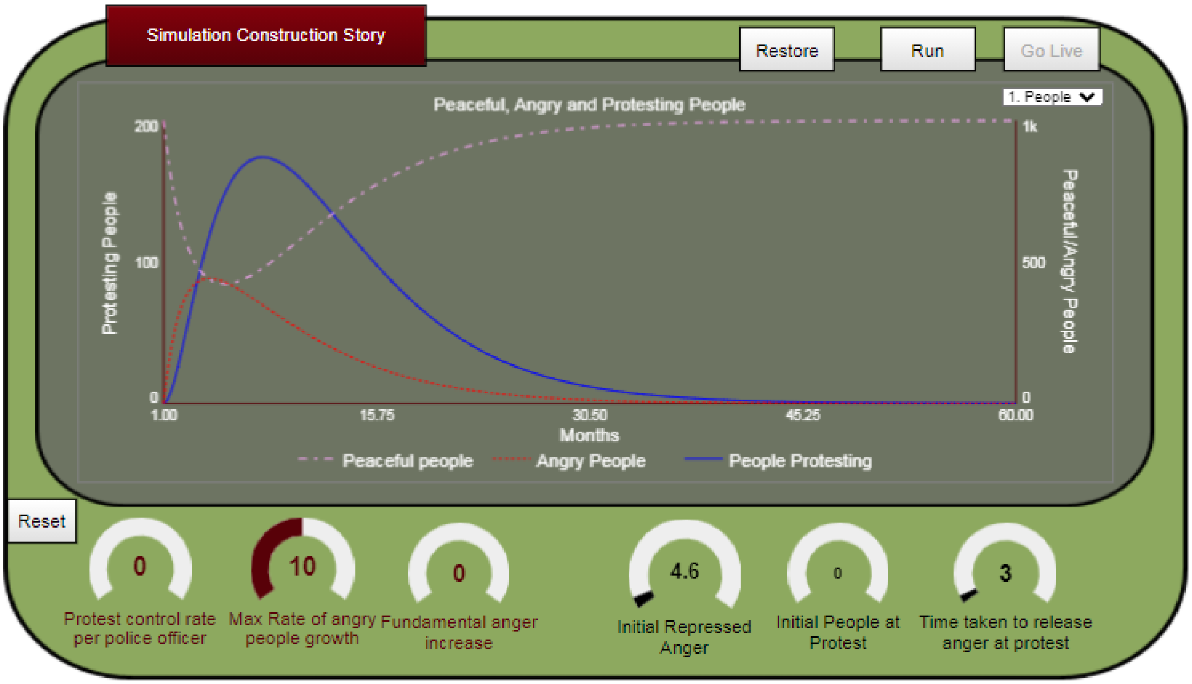

Figure 6.8: Simulation interface of Fixes that Fail

The scenario above does, however, indicate that it takes a significant amount of time to resolve the protests and hinges on the ability of authorities to listen instead of trying to control. In summary, the simulation development process has revealed that the consequence of the police force is detrimental to the system. Furthermore, it is possible to control the protests without police violence, yet this requires more of the authorities' time and attention. The alternative options are a system that induces more protests or, alternatively, a totalitarian authority where ultimate control is exercised, where both of these approaches lead to destruction in the simulation and also seen in history. The full simulation development is captured in Appendix 2-A, and the final online simulation can be accessed here: https://exchange.iseesystems.com/public/corne/fixes-that-fail---protests-and-policing

6.3 Limits to Growth: The Forest Fire

India MacDonell, a 19-year-old teenager, grew up with her father on a small farm in Victoria, Australia. On the 30th of December 2019, she saw an almost spectacular sight on the horizon: the shades of crimson and gold mingled with dark satin were moving closer. India's father has faced fire storms alone before, but on that day, India was determined to help save their home. Yet, neither India nor her father realised how terrible the firestorm was going to become. (ABC News, 2020)

A few months later, on 9 March 2020, the firestorm finally burnt out and left 18.6 million hectares of destroyed land. The firestorm consumed 5 900 buildings in its wake, killed at least 34 people, while more than one billion animals perished (UNEP, 2020). While India and her father were able to save their home and lives, many thousands of people, and more than a billion animals, were not that fortunate. The fire was started by a seemingly insignificant event such as lightning, glass, or human activities, but how could such a small event spark such terrible destruction? What conditions and structures enabled the exponential and uncontrollable firestorm? More specifically, can the LST be applied to this story to generate more insight and understanding to prevent/control future firestorms?

The condensed word model of a forest fire can be expressed as follows:

"A raging **forest fire** will continue to **expand** until it runs **out** of **fuel.**"

(Systems and Us, 2020)

Fire, expansion, and fuel are three key concepts from the one-sentence model. Firstly the story is expanded into a CLD found in Figure 6.9. In the case of the CLD, the left (reinforcing loop) showed the exponential growth (expand) of the forest fire, while the right (balancing loop) shows the slowing down (fuel depletion) of the fire.

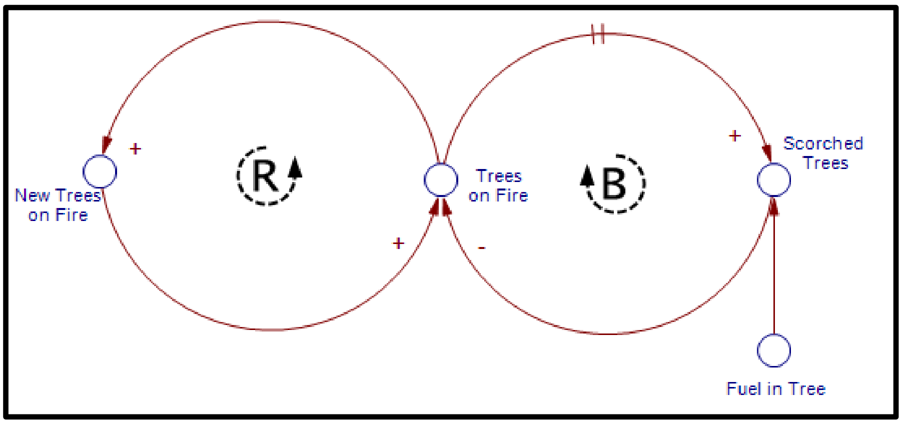

Figure 6.9: CLD of Limits to Growth applied to forest fire

In addition to the CLD, the typical fire behaviour is found in Figure 6.10. Fires grow slowly initially, go through an exponential growth stage, reach a peak, and then slowly decay. Hereafter, the behaviour and CLD is expanded through the LST.

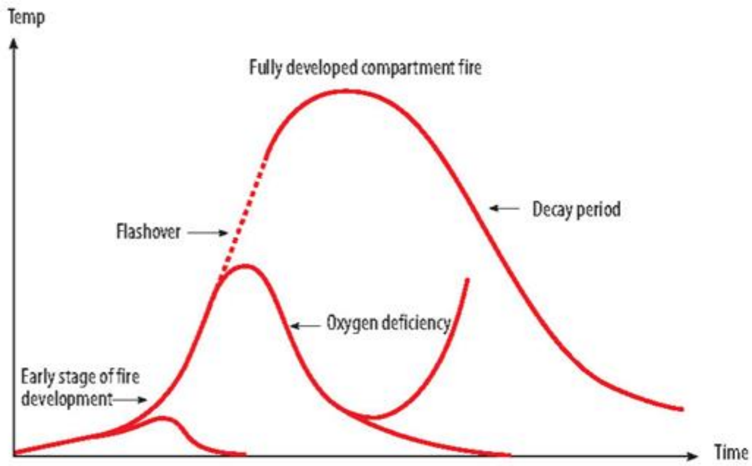

Figure 6.10: Pictograph of fire behaviours (Bengtsson, 2018)

As such, steps 2 to 7 is applied to generate the detailed stock and a flow diagram of the forest fire, Figure 6.11. As a consequence, the diagram is the blueprint before the simulation is constructed, and it already reveals some deeper insight into the structure: For example, the available trees, more specifically their density, is a driving force in the growth of the fire. In addition, the blueprint reveals the tree burning duration as a new variable.

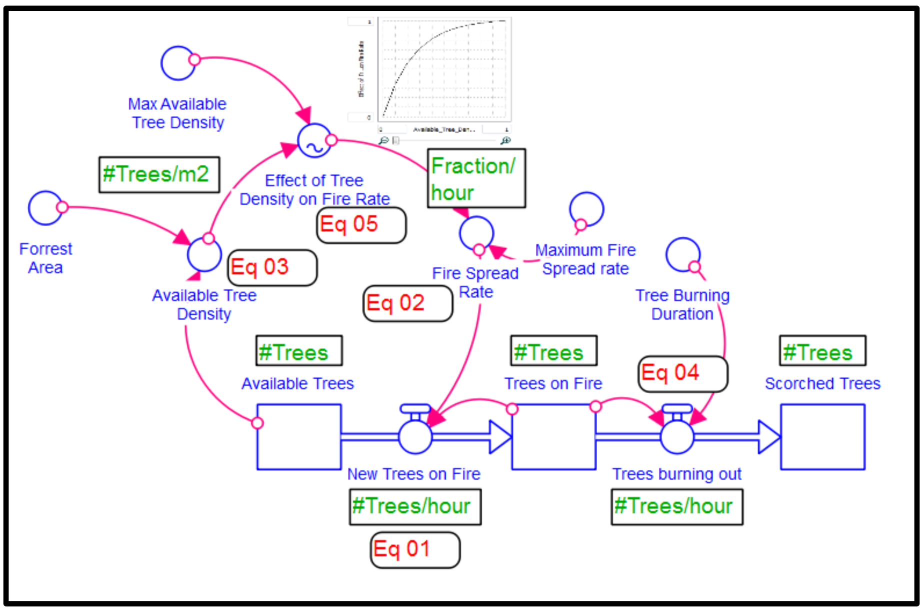

Figure 6.11: Detailed stock and flow diagram of the forest fire simulation

As mentioned before, the expected behaviour for the trees on fire variable is exponential growth and then decay. As expected then the same behaviour is seen of the integrated simulation in Figure 6.12. Thus the simulation reproduces the same expected behaviour as identified in step 1.

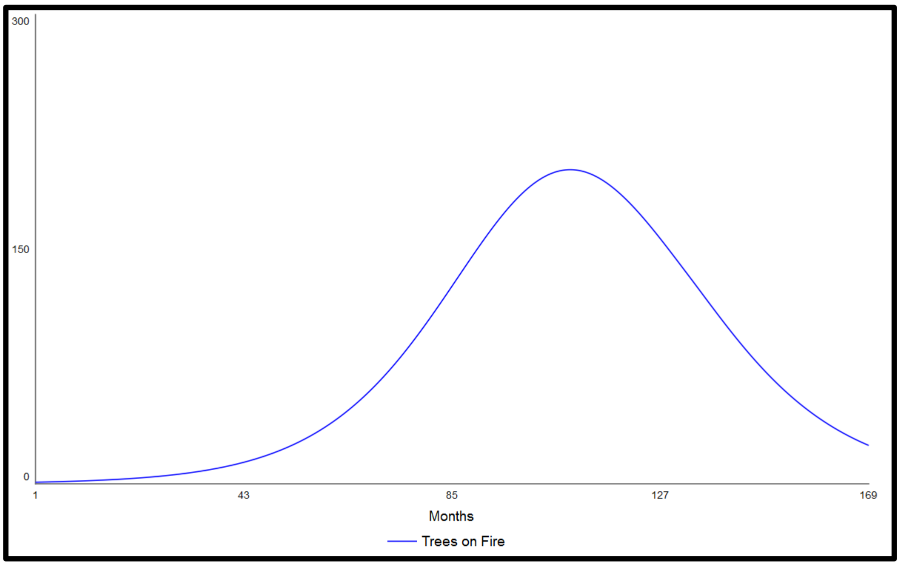

Figure 6.12: Forest Fire simulation result in step 9

Senge (1990) (p. 80) suggests that one of the best ways to deal with the system archetype is to identify what the limiting factor is and use that as leverage. In the CLD of Figure 6.9, the limiting agent is identified as the fuel in the tree, which translated to the tree burning duration variable of Figure 6.11. Therefore the sensitivity analysis is conducted on the tree burning duration and visible in Figure 6.13. Hence the analysis confirms that the tree burning duration is a strong lever in this structure.

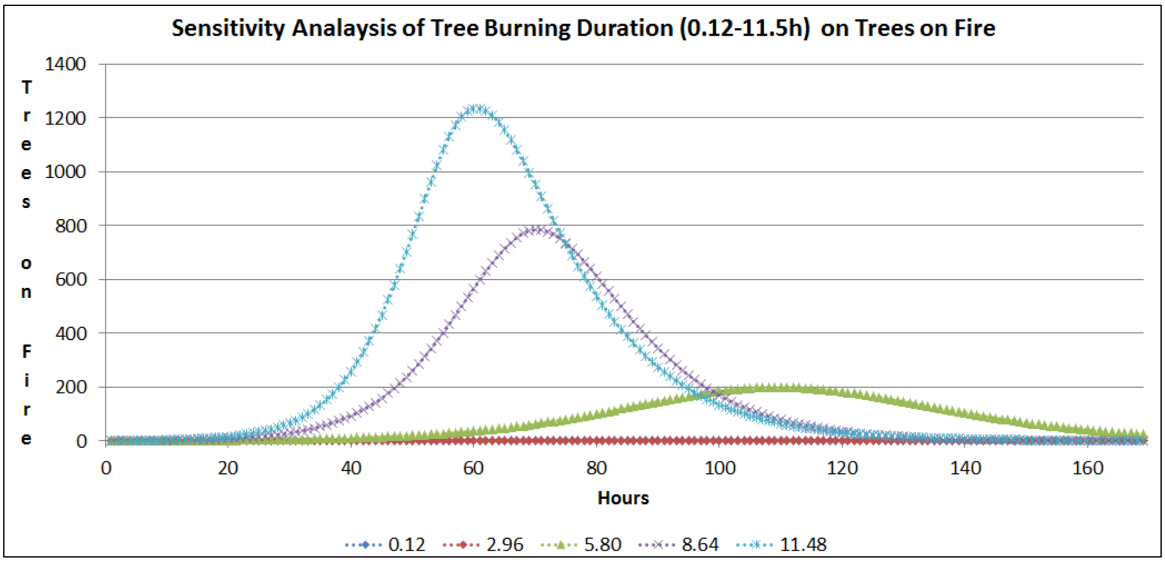

Figure 6.13: Sensitivity analysis on tree burning duration

In addition, Meadows (2008) suggests that another lever in the Limits to Growth archetype is identifying the drivers behind the growth loop and slowing them down. In the detailed SFD (Figure 6.11), the variables that accelerate growth are the available trees (tree density) and the max fire spread rate. The sensitivity analysis of the available trees is captured in Figure 6.14 and reveals that it is the strongest lever in the structure.

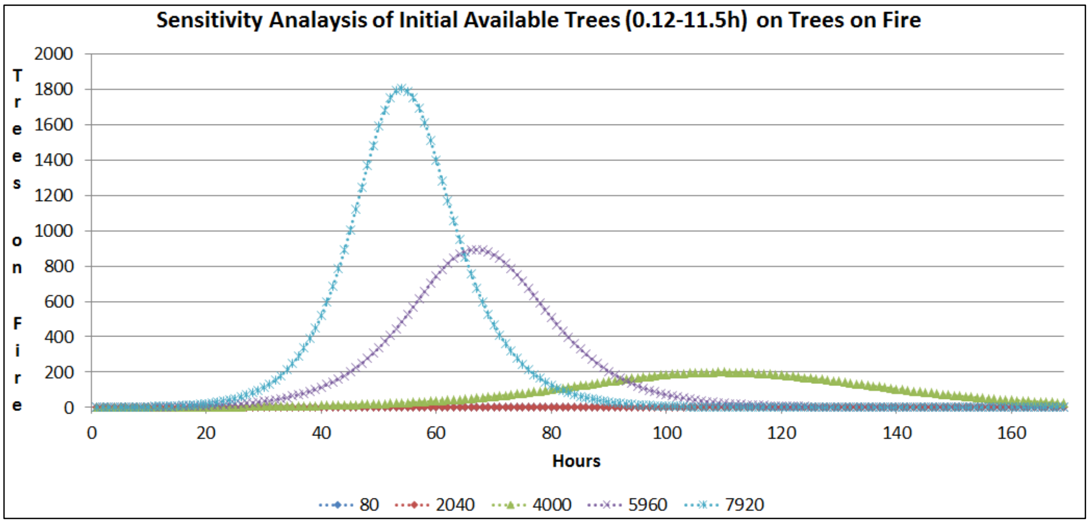

Figure 6.14: Sensitivity analysis on available trees

The initial trees on fire (size of the starting fire) have little to no impact on the level of destruction experienced by the simulated forest. Likewise, the sensitivity analysis reveals the initial trees are not a lever as just like the suggestions by the system archetype literature (Senge, 1990) (Meadows, 2008). As such, the simulation replicates the literature's expected behaviour and insights on leverage points. In short, the synchronised results are a validation of the simulation produced by the LST. Hereafter, the isolated levers are combined to test the emergent behaviour.

As a consequence, the insights from the simulation can aid to understand the forces behind the great Australian bush fires of 2019/2020. The initially available trees refer to the initially available fuel in the area. The density of the fuel is not just a function of trees that are alive but also of trees that have died. According to Deb *et al.* (2020), a few factors aligned in the above-mentioned bush fires; some of these include ongoing drought, wind speed, dead and live fuel moisture, and the big coverage of specific types of vegetation. The density of fuel (dead and live fuel) is one of the levers found in the simulation. Another lever in the simulation is the burning duration, which relates directly to the type of vegetation. Finally, an increase in the wind speed would increase the maximum fire spread rate of the simulation and empower the reinforcing growth loop. Subsequently, the simulation can test the impact of simultaneous increases in the initial trees, burning duration and maximum fire spread rate, visible in Figure 6.15. Thus the three variables are increased by 10% each (4k trees to 4.4k trees, hours of burning from 5.8 hours to 6.4 hours and max fire spread rate from 0.42 to 0.46 trees per hour).

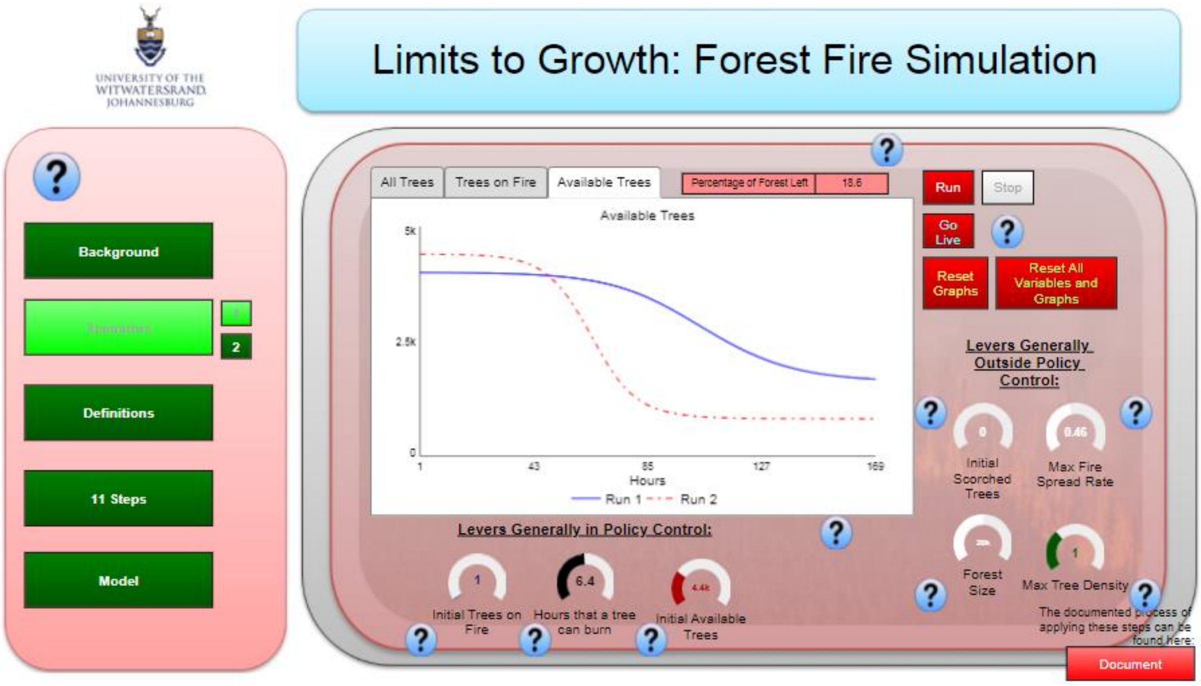

Figure 6.15: Impact of a simultaneous increase in leverage variables

The initial simulation run in blue (Figure 6.15) left 42% of the forest trees unburnt. A 10% increase in the three leverage point variables resulted in only 18% of the forest left after the fire. The slight increases in these variables reveal a similar scenario as seen in Australia.

The insights gained from building and analysing the simulation reveal major levers in the firestorms, namely: reduce the initial trees/deadwood, which can be an indication of the forest's natural diversity. Secondly, take special care during hot and windy weather. The most controllable aspect might be the initial trees in the forest. In addition, the usual small fires are essential in the prevention of these large firestorms, which the simulation also confirmed. If the tree density can be controlled in the simulation, the spread of fire can be reduced significantly. The theory is validated by practical forest management strategies, where Figure 6.16 (Global Change, 2020) is an example. In the forest management case, the tree density is controlled on the left while not on the right side of the American forest. The value of such an approach is clearly shown by Arizona's 2002 Rodeo-Chidiski fire.

Figure 6.16: Managed forest (left) and unmanaged forest (right) (Photo Credit: Jim Youtz, U.S. Forest Service)

The simulation, developed by the LST, is not only able to replicate the behaviour of the generic system archetype but also the behaviour of the focus problem. Furthermore, the literature recommendations on how to manage the archetype are found to be true in the simulation's leverage points, which validated the insights derived from the simulation. Beyond the validation, the simulation is able to show how slight changes in weather and vegetation conditions in Australia may have led to the extreme firestorm.

Counter-intuitively, the real culprits behind the destruction are not the lightning or glass or even humans who may have started the initial fire, but rather a large amount of fuel in the bush, droughts, wind, and lack of biodiversity. Another counterintuitive finding is that to save the bush from destructive fires; we need to allow controlled fires to run their course. In summary, the lessons learned about bush fires are amplified when considering the impact that climate change will have on the leverage variables identified through the simulation development process. The fully documented forest fire simulation development can be found in Appendix 2-B, and the simulation can be accessed at the following link:

https://exchange.iseesystems.com/public/corne/forest-fires-limits-to-growth-archetype/index.html#page1

6.4 Eroding Goals: Matriculation Rates

Naledi Memela grew up in Umlazi, Durban's largest township. He was moulded by two polar opposite worlds: white-collar supreme school by day and dusty soccer fields at night. His white friends dreamed of careers in medicine, engineering and becoming CEOs, while most of his black friends' highest goals were to become part-time mechanics one day. He navigated his way through race inequality as well as inequality in belief systems. Naledi chose to research the belief systems of successful people and adopt them. At the age of 28, he was already a registered professional engineer. He had started a business and almost completed an engineering Master's degree. Furthermore, he was the manager of a centre of engineers. He captured one of his core beliefs just before his fatal car accident in October 2020, as follows:

"Don't pray for easier lives. Pray to be stronger men".

In 2018, only 11.5% of all professional engineers in South Africa were black (IOL, 2019); Naledi became one of them. What type of belief system allowed him to achieve so many goals at such a young age, while most people never do? In 1990, the Menzi High School in Umlazi had a matric pass rate of only 26% (Pattillo, 2010). The Principal, Felix Msholololo, started his tenure in 1990 and, with great vision, integrity, and empathy, led the school for decades. In 2007, South Africa had its last Apartheid-era curriculum exam. The old system hid poor-performing students by classifying them into Standard Grade or Higher Grade. Because the new outcome-based education unified the two classes, in 2008, it was expected that matric pass rates would fall without the disguised performance gaps. As expected, South Africa's matriculation rate dropped from 65.2% in 2007 to 62.5% in 2008 (BusinessTech, 2017). Newspapers tracking Menzi High were pleasantly surprised to find that its pass rate kept increasing from 2002, and, in 2008, the school achieved a pass rate of 97.8% (IOL, 2019). Hence Menzi High's performance leaves the question: How did the previously disadvantaged school improve its pass rate from 26% to 97.8% in less than 20 years? Pattillo (2010) studied the school and found that each class at Menzi had more than 60 learners on average and was critically under-resourced. Despite this disadvantage, Mr Msholololo's leadership inspired both teachers and students to achieve their dreams, which became the catalyst for the school's success. Furthermore, he had an unwavering vision and direction for the school for 20 years, even though the results were not visible in the first ten years.

The two stories above emphasise how individuals with strong values and consistent effort can achieve seemingly impossible feats, even if the results are not tangible at first. One of the reasons why these individuals had such an impact could be that they overcame the system trap into which most people fall, namely Eroding Goals. The word model for this particular archetype is the opposite of the quote from Naledi Memela, and the opposite could be: Do not pray to be stronger men; pray for easier lives. Furthermore, in the context of education, the word model could be:

“It is too difficult to improve education in South Africa; it is easier to reduce the standards”.

In step 1, the behaviour of South African matriculation rates from 1995 to 2019 is found and captured in Figure 6.17.

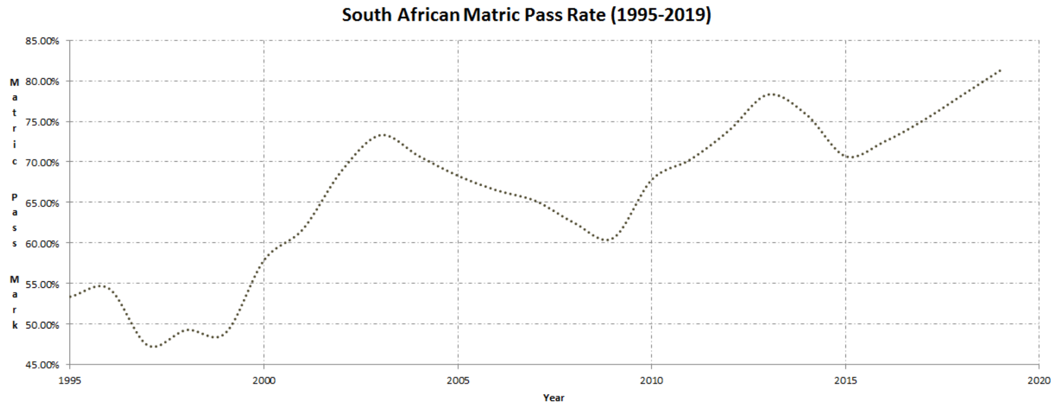

Figure 6.17: South African matric pass rate (MyBroadband, 2020)

While the South African pass rate reveals that there seem to be cycles within the average pass rate, global changes occur relatively slowly. In contrast, the dip in 2008 and 2009 is expected due to changes in the curriculum. In addition, another large dip and slow growth after 1994 are due to a more inclusive education system after the abolishment of Apartheid. As a consequence, after the Apartheid regime, many students returned to the formal education system.

Subsequently, the CLD drawn from the word model is captured in Figure 6.18. In the case of the first balancing loop (B1), it is focused on achieving the matric pass rate through long-term investment in education. Yet, there are significant delays in the investment in education before the system quality improves, which is exacerbated by the additional structural delay of the 12-year student cycle. Educational investments often take more than ten years before bearing any tangible fruit.

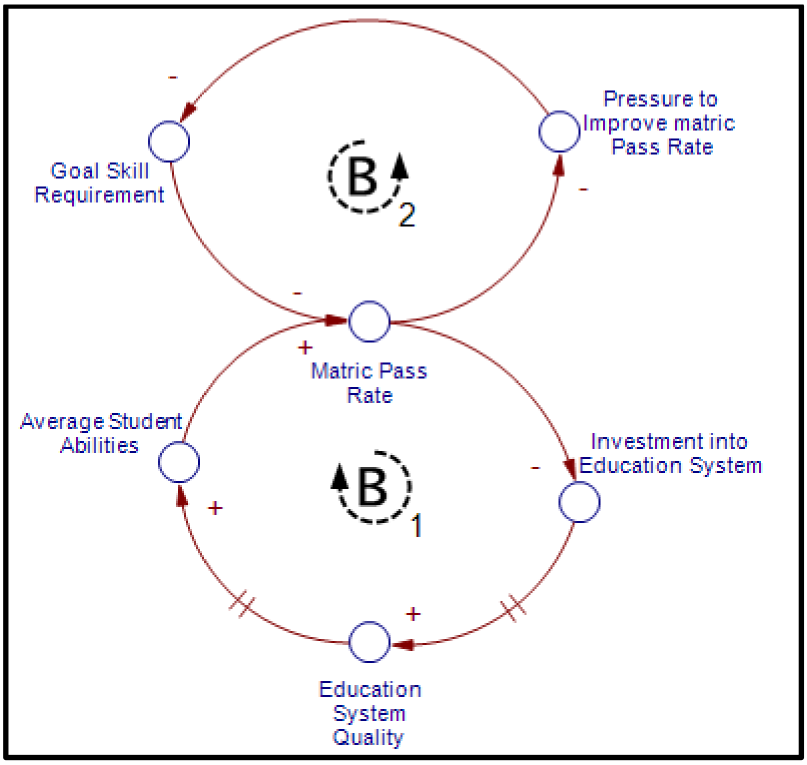

Figure 6.18: CLD of Eroding Goals on matriculation rate

The delays in results from such investment while the matric pass rate is not improving put pressure on government/leaders to take more action. The higher pressure to take action leads to the search for faster alternatives. Hence, the faster option is to reduce the goal skills required in matric defined in the top balancing loop (B2). Since loop B2 operates faster than loop B1, the desired matric pass rate can be reached faster through loop B2. In short, the two loops (B1 and B2) increase the pass rate yet are in direct competition. The next step is to expand the CLD.

Thereafter the CLD is expanded into a detailed SFD from steps 2 to 7 and visible in Figure 6.19. Through the development process, the two delays in the CLD lead to the identification of two ageing chains, namely the students' progress through the education system and the education investments to infrastructure.

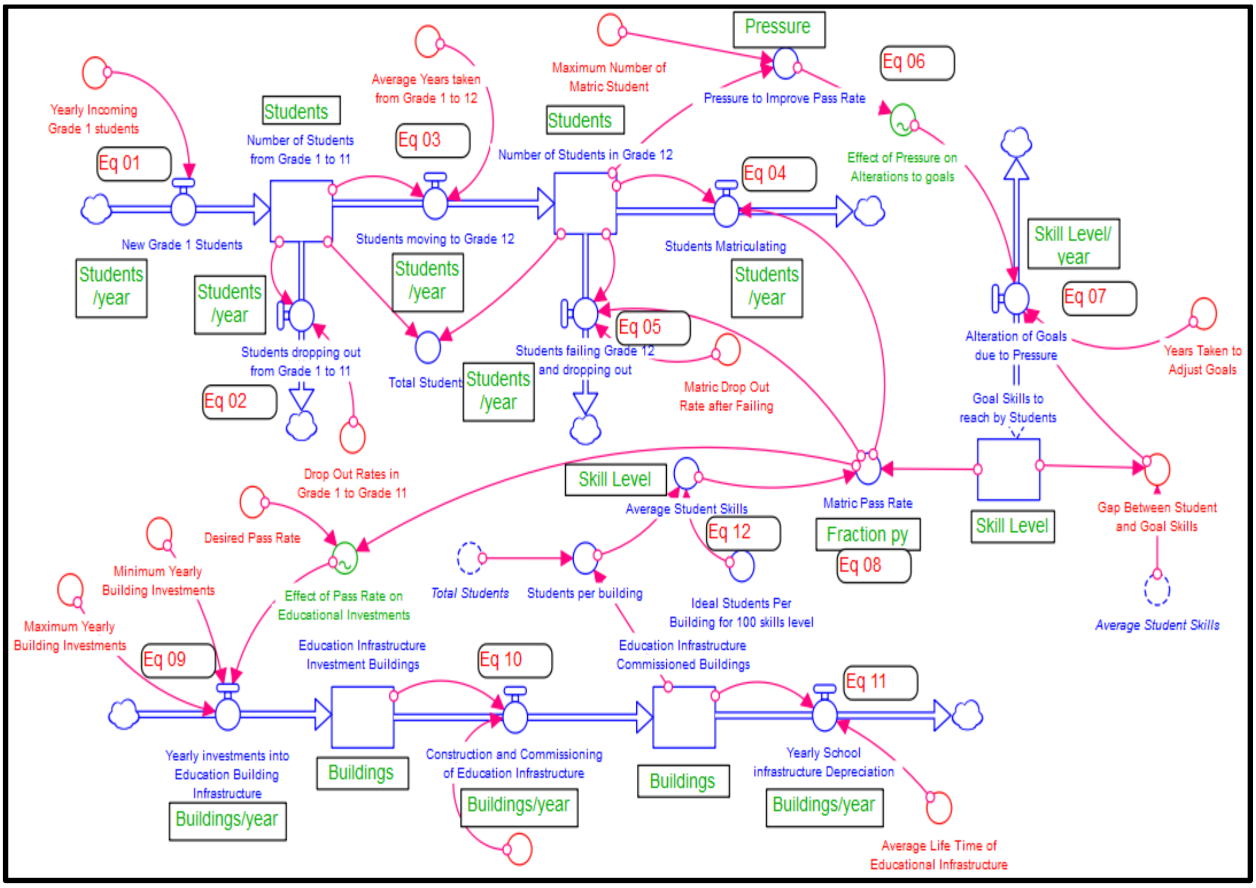

Figure 6.19: Detailed stock and flow diagram of the education simulation

Braun (2002, p.6) defines the archetype's behaviour as a slow decline in the actual performance and goal of the system, while the gap is perceived to oscillate, seen in Figure 6.20.

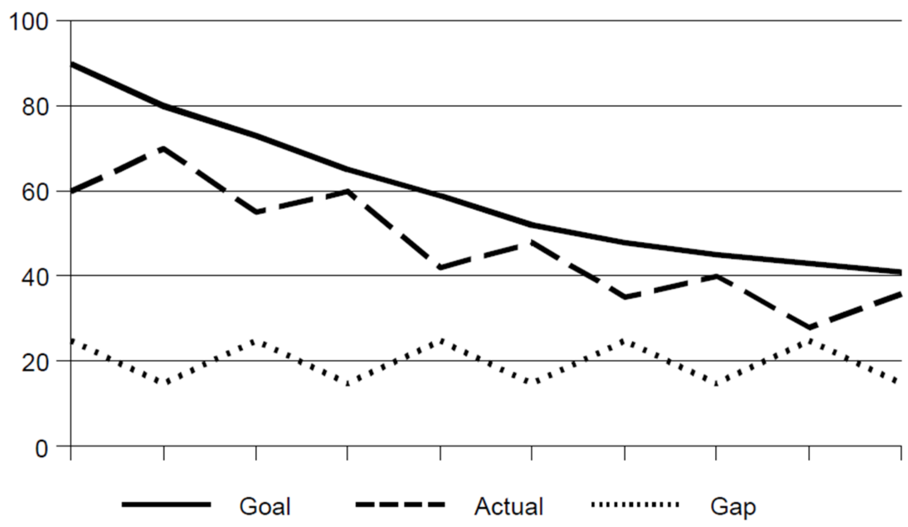

Figure 6.20: Typical behaviour of Eroding Goals (Braun, 2002) p. 6

In steps 8 and 9, the simulation is constructed with the addition of an influx of students at time step 5. As a result, the step-change in student inflow mimics the 1994 influx of students into the South African education system. The results of the integrated simulation can be seen in Figure 6.21.

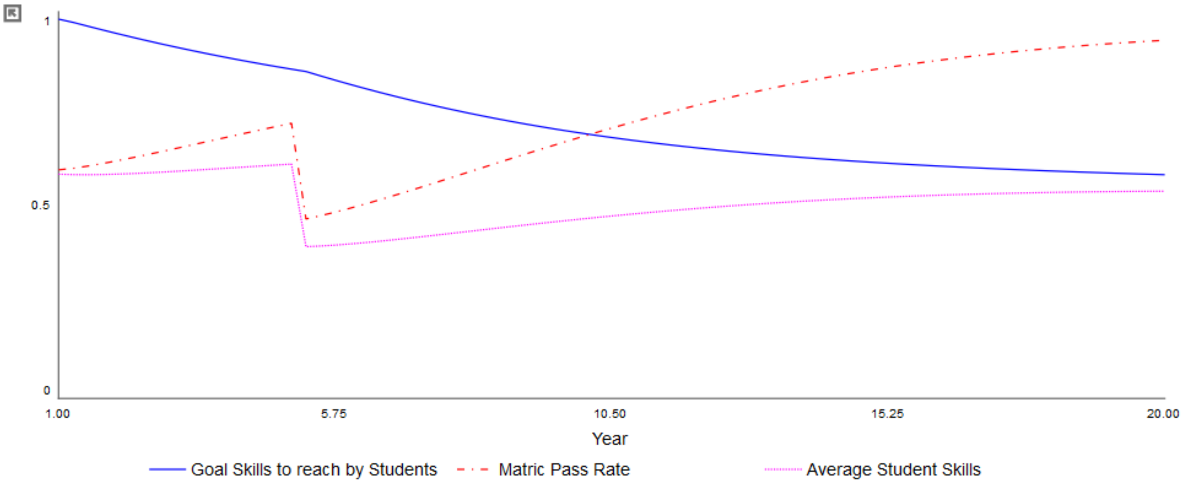

Figure 6.21: Education simulation reproduction of reference modes

The goal skills are slowly decreasing, and the matric pass rate is slowly increasing, while the average student skills are slowly reaching equilibrium. The goal skills from the simulation are able to replicate the goal's expected behaviour from the system archetype in Figure 6.20. Meadows (2008) maintained that the way out of the Eroding Goals archetype is to set absolute performance standards. This means, no change in the matriculation paper difficulty should be allowed. In short, the detailed SFD defines the variable controlling the paper difficulty as the goal adjustment delay.

The simulation is assessed for a sensitivity analysis on the goal adjustment delay. The initial value is ten years, which is then varied between 0.2 and 19.8 years. The results are captured in Figure 6.22. The variable is found to have the strongest impact compared to the desired pass rate and education infrastructure build time. The result from the simulation is thus validated with the recommendations from the literature.

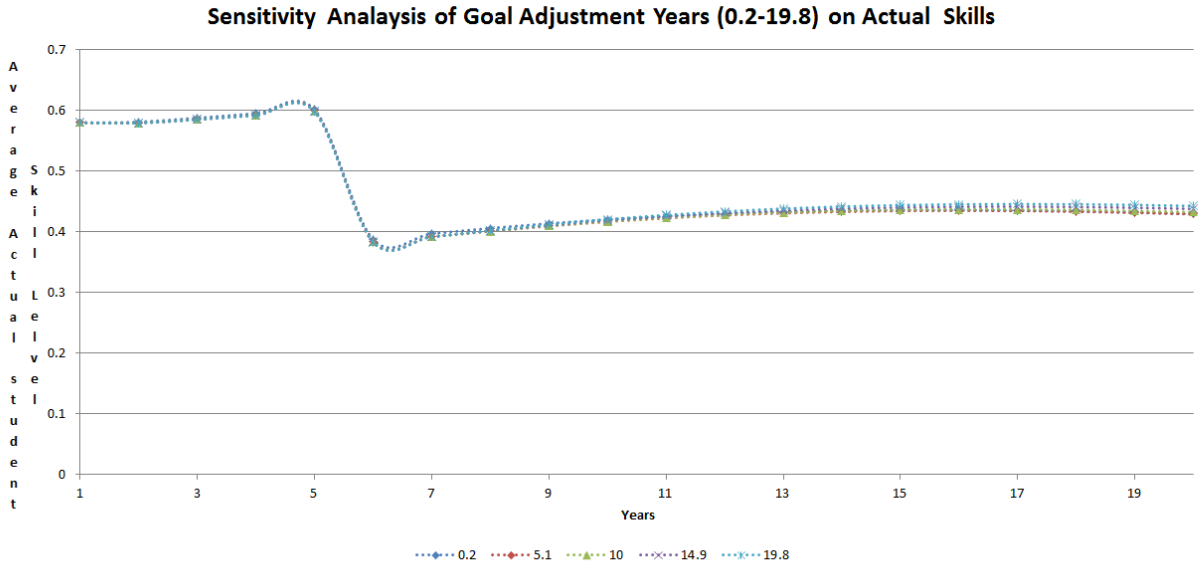

Figure 6.22: Sensitivity analysis on goal adjustment time

The second strongest lever found in the sensitivity analysis is the desired pass rate. Hence the identified pass rate lever can alter the simulation behaviour. Consequently, the variable reveals that there had to be a drive within the structure to improve the matric pass rate. In addition, the sensitivity of the build and commissioning time reveals that it is the weaker lever of the three. Yet large delays in build time had a strong negative impact. In summary, the strongest levers are found, and in the next paragraphs, the combined effect is analysed.

As a result of the sensitivity analysis, a scenario is investigated where the goal adjustment delay is increased to 40 years, the desired pass rate kept at 100%, and the years to build infrastructure reduced to 5 years, as visible in Figure 6.23.

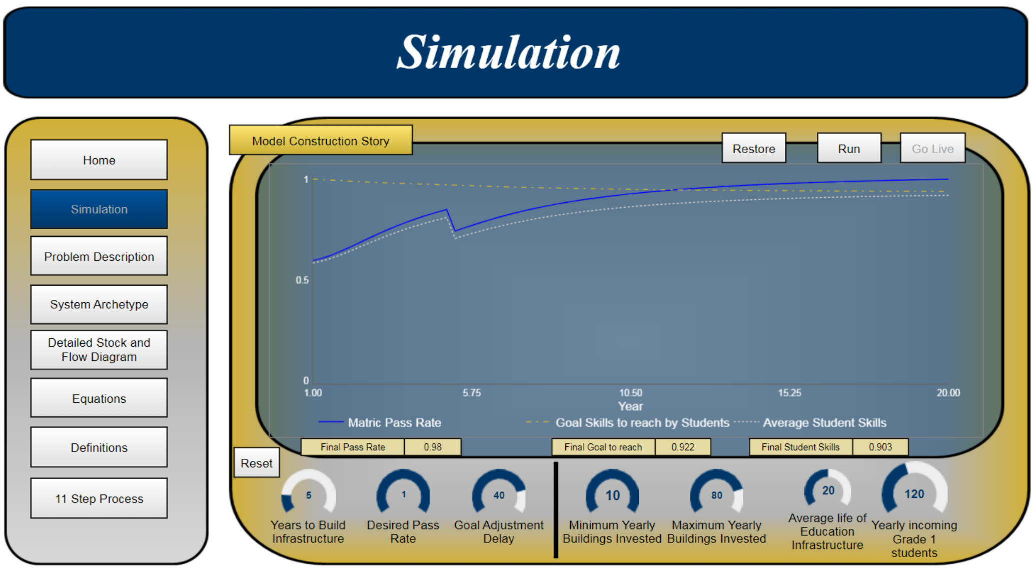

Figure 6.23: Combined effect of all three levers in Eroding Goals

The combined effect of uncompromised goals, high standards of goals, and reducing the time to build infrastructure improved the pass rate and skills significantly. The final pass rate is 98%, and the average student skills above 90%. In summary, the final pass rate fits well with the 97.8% pass rate achieved by the school of Menzi (Pattillo, 2010).

The simulation is validated against the expected behaviour and how to escape the trap from literature sources (Braun, 2002) (Meadows, 2008). In addition, the simulation reveals that developing a culture that sets high goals, prevent the lowering of those goals and invests into skills break the Eroding Goals trap. Naledi Memela and Felix Msholo both exhibited these internal qualities, and both achieved goals which are deemed impossible by many.

The full simulation development can be found in Appendix 2-C, and the final simulation can be accessed here:

https://exchange.iseesystems.com/public/corne/eroding-goals---south-african-education-system/index.html#page2

6.5 Escalation: Social Media Polarisation

The traffic robot turns red, but she does not want to stop here. At night Johannesburg is dangerous, and fear is crawling down her spine. She convinces herself that everything will be okay and comes to a halt. Suddenly she hears a loud crash, and glass shatters; she is pulled out of her car and is left in shock to see a few men grab her valuables and running off. Her fear was realised, and hysteria started building up within. Her mind floods with pictures of racially motivated hate crimes across the country. Her fear is replaced with unstoppable anger and hatred as she loses control. Vicky Momberg went on a racist rant hurling the *k-word* 48 times at police officers and 10111 operators who were trying to assist her (Timeslive, 2018). Her actions were caught on a cell phone video and spread like wildfire across the country. Vicky was found guilty on four accounts of *crimen injuria* and sentenced to two years in prison. Raghoonandan, the magistrate, said, ‘Some may think the sentence is harsh (but) it must send out a clear message for people who use the K word’ (Timeslive, 2018). Vicky Momberg, the first woman, imprisoned for racist speech in South Africa (New York Times, 2018).

The event described above is the result of a structural problem in South Africa. In recent elections, the extremist political parties had grown more: The Economic Freedom Fighters (EFF), one of the newest parties, grew from no support to taking 6.35% of the votes (StatsSA, 2019). The party leader, Julius Malema, openly sang the ‘Kill the Boer, kill the farmer’ song with his supporters (News24, 2019). The Vryheidsfront (VF) Plus is seen as the polar opposite and grew from 0.83% to 2.38% of the votes. VF Plus associate themselves with and defend extremist artists like ‘Steve Hoffmeyer’ (News24, 2019), who made public outcries against white genocide in South Africa, classified black economic empowerment as destructive and strong opinions that link to white supremacy.

In October 2020, Senekal experienced the two extreme world views clash. Brendan Horner, a white farmer, was killed, and his body found tied to a pole on his farm. The president, Cyril Ramaphosa, appealed to South Africans to ‘resist attempts… to mobilise communities along racial lines, yet the racial tensions grew anyway (Reuters, 2020). The farmers outside Senekal accused the government of failing to protect them from violent crimes (BBC, 2017) (Naidoo, 2020), while EFF leaders complained that the government had allowed the continued domination of South Africa’s economy by whites, while black South Africans remain poor as in Apartheid. The farmers interpreted EFF’s actions as denying the protection of farmers, while EFF interpreted the complaints of the farmers as white supremacy: white lives matter more than black lives.

The irony is that both sides are trying to bring balance to a destructive cycle, yet their combined reactions reinforce the destructive cycle. This is the Escalation archetype.

In the 2020 elections, America experienced the Escalation archetype between the Democratic and Republican parties. On January 6, 2021, Pro-Trump supporters broke into the U.S. Capitol in response to Biden's victory at the November elections. Overall, the group believed that they are fighting against a corrupt democratic system even though there was no solid evidence (PBS, 2021). The violence at the Capitol resulted in five people's deaths (CNN, 2021). Trump claimed innocence, yet on his Twitter account, on Dec. 19, he wrote, "Big protest in D.C. on January 6^{th}. Be there, will be wild" (PBS, 2021).

Trump used the Twitter media platform far more than any president before him. He obtained a lot of influence through the social media platform yet was known for controversial tweets (Sky News, 2020): denying the dangers of the COVID-19 pandemic, supported the link between vaccination and autism, denying global warming, dismissing Barack Obama etc. The Twitter post, which may have initiated the Capitol protest was on November 18, 2020 (Aljazeera b, 2020):

"…AND I WON THE ELECTION. VOTER FRAUD ALL OVER THE COUNTRY!" – Donal J. Trump (@realDonaldTrump – Twitter)

Around the world, some people embraced the tweet, and other people were appalled by it, while most people shared it with others. In a few moments, the world was influenced by the tweet and extremists from both sides of the political spectrum obtained new fuel. On 08 January 2021, Twitter announced an immediate permanent suspension of old president Trump's account, effectively silencing him from Twitter forever.

The Escalation archetype is enhanced in today's social media generation, where Trump's tweets can reach billions of people personally in a moment. The archetype can be captured by one of the oldest Biblical verses:

"eye for an eye, tooth for tooth, hand for hand, foot for foot" - Exodus 21:24

The concept is found in almost all religions and cultures since it deals with the action required against an injustice. It would only be fair to take away from the thief what he stole from the innocent. The intent is to bring balance to injustice: When the thief is called to justice and suffers the fate he forced on others, he will not do it again. The assumption is that suffering will lead to internal reflection and behaviour change. Most of the time, the assumption is wrong since innocents and guilty are concepts controlled by the observer. The farmers see themselves as innocent victims of racial crimes, while

EFF sees themselves as innocent victims of decades of racial oppression. The actions are taken to make their perceived enemy's feel the pain they experience and expect the pain to balance the injustice, yet the combined effect of the two balancing loops create a reinforcing loop: Escalation. The same is seen in American politics and most likely other global and local politics. Social media amplifies the cycles due to the rapid spread of biased/incorrect information. The two balancing loops and their impacts on negative (hate) speech between Group A and B are captured in Figure 6.24.

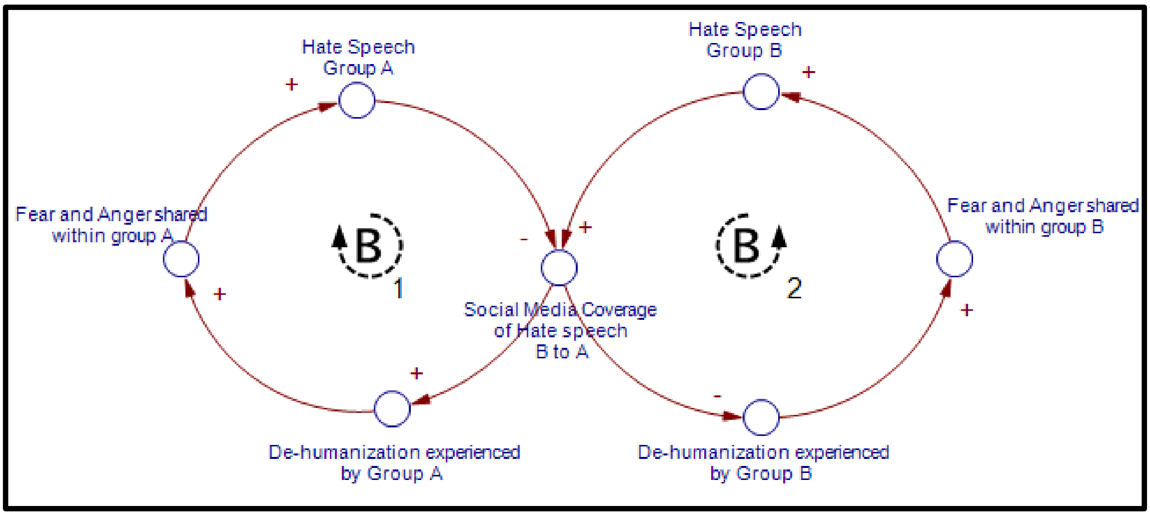

Figure 6.24: Causal Loop Diagram of social media polarisation

In isolation, loops B1 and B2 would have created a balanced system, like the 'eye for an eye' was intended to. In the case of the two groups living by that paradigm, it creates an invisible reinforcing loop that destroys both groups. As a result of the two balancing loops, the combined CLD produces a destructive reinforcing CLD. Hereafter the CLD is expanded into a detailed SFD from steps 2 to 7 and captured in Figure 6.25. The development process reveals that the structure is composed of (at least) two different states that the population could be in. With regard to the states, people could either be in a neutral or biased state. As a result, people constantly move between neutral and prejudiced ideas grounded on their experiences, beliefs, and media exposure.

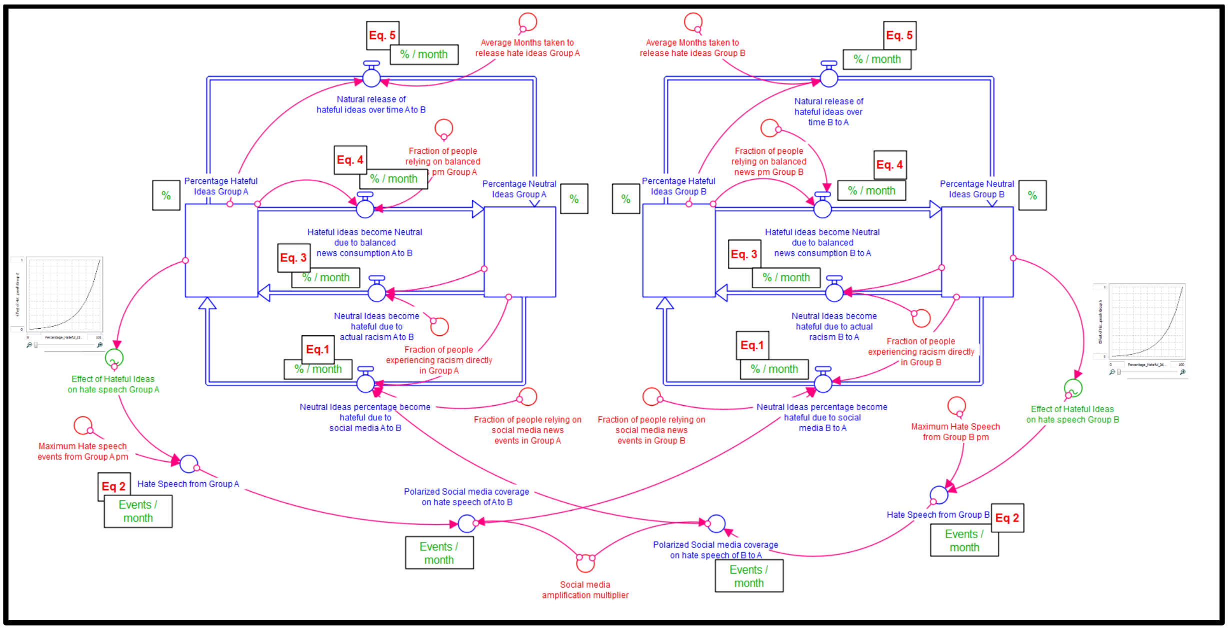

Figure 6.25: Detailed stock and flow diagram of the media polarisation simulation

According to Braun (2002), the expected behaviours of both Groups A and B will increase (escalate) in time, as seen in Figure 6.26.

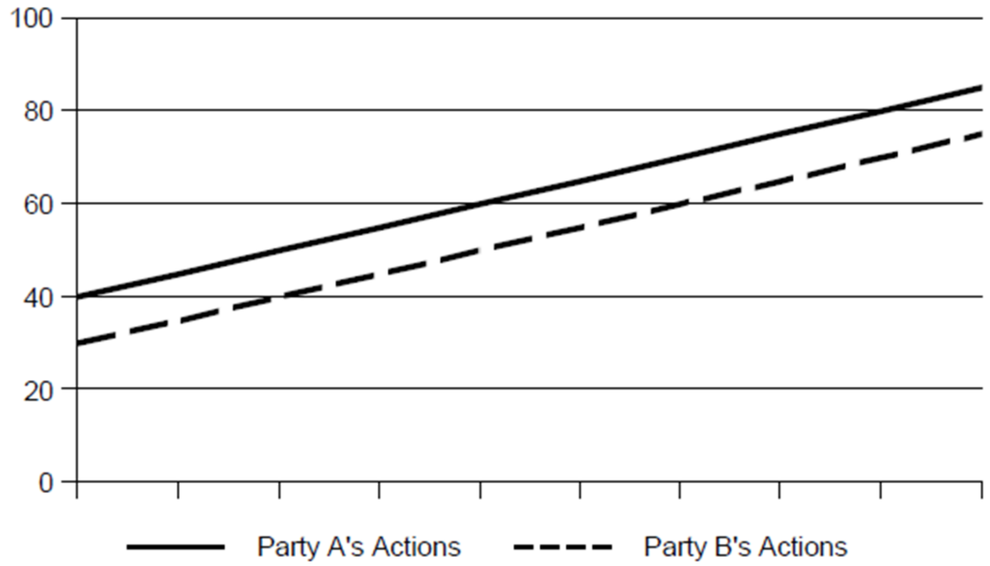

Figure 6.26: Expected behaviour of Escalation, as captured by Braun (2002)

The simulation is constructed in step 8 and combined in step 9. Within step 9, the simulation is tested with a pulse in order to evaluate the simulation response. As a result, the pulse in negative ideas towards Group B is found in Figure 6.27.

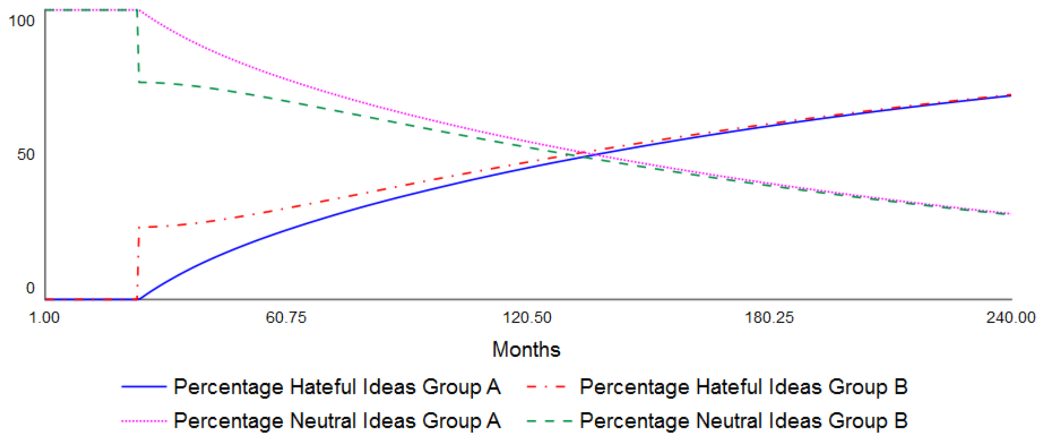

Figure 6.27: Disturbance test two on media polarisation simulation

Although there is only a short pulse in the negative ideas towards Group B, the strong balancing loop immediately resulted in retaliation from Group B on A, and the Escalation archetype took hold of the behaviour. The combined simulation results, seen in Figure 6.27, show that the negative ideas and actions of both Group A and B are increasing (escalating), as confirmed by Braun (2002) in Figure 6.26. Because of each group's limited perspective, their actions drive the escalating behaviour, as expected. In brief, the behaviour validates that the simulation constructed with the LST produced the same expected behaviours as those of the general Escalation archetype. Although the behaviour is validated, the recommended insights are tested next.

In addition to expected behaviours, Meadows (2008) (p. 126) recommend that the best way to escape the archetype is to avoid getting into it. If the groups are already in the trap, at least one of the groups should decide to unilaterally disarm, refusing to compete. Consequently, the disarming breaks the reinforcing effect. Therefore the disarming mechanism is identified with the detailed SFD (Figure 6.25) as the fraction of people using social media as news sources. Thereafter a sensitivity analysis is conducted on the fraction of people reliant on social media news sources, and the results are captured in Figure 6.28.

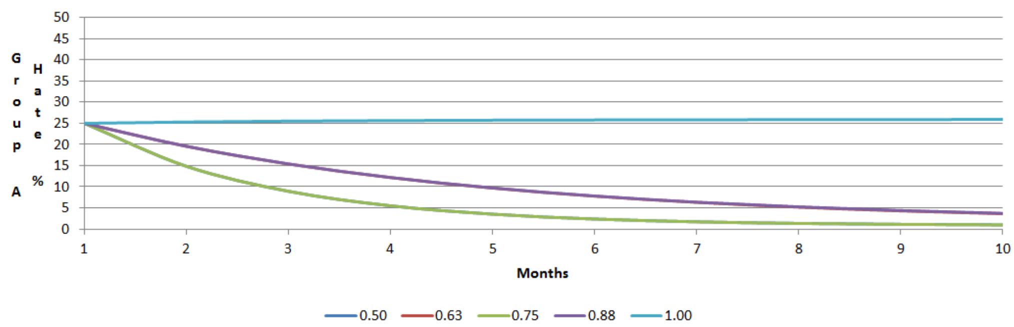

Figure 6.28: Sensitivity analysis results on the fraction of people reliant on social media

An interesting finding from the simulation is that social media did not have such a strong impact when accessed by below 75% of people; in fact, it is only when more than 90% of people rely on social media for news that the Escalation archetype becomes driven by it. The recommendation from Meadows (2008) is thus proven that once people disengage themselves from utilising social media for news sources, that their negative ideas are slowly reduced. The simulation results are thus validated by the literature recommendation (Meadows, 2008).

In addition to the reliance on social media, another emerging variable is found to be incredibly effective at disengaging the archetype. Namely, the time that is taken to release negativity. For example, it is found that simulated communities who are able to forgive more readily (release their negativity) had a higher chance of escaping the Escalation trap. In the same way, forgiveness is just another mechanism of unilateral disarming (Meadows, 2008). Enabling groups to cultivate forgiveness and release their negativity after 24 months (2 years) produced the results found in Figure 6.29.

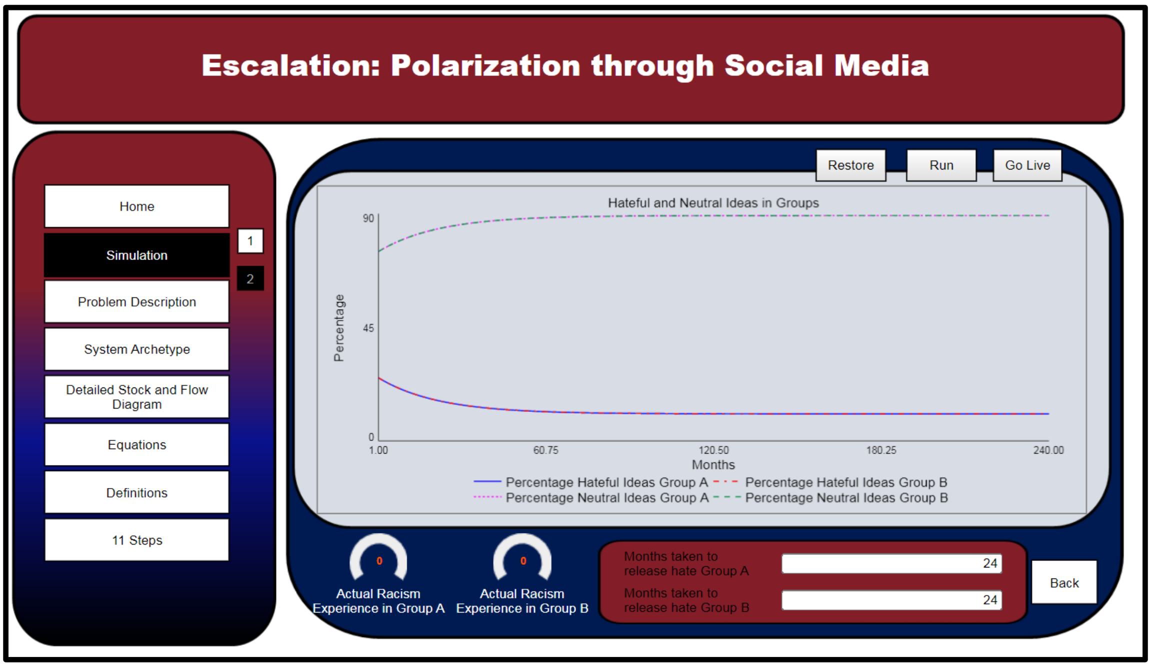

Figure 6.29: Interface of the escalation archetype simulation

Although there are underlying portions of the group that hold onto negative ideas, the values reach equilibrium at about 10%, and the two communities stopped developing negativity. It reveals an underlying structural issue, which means that It might not be that social media is the root cause of Escalation, but only a mechanism to amplify the structure's response. Hence, if people are naturally more forgiving, social media would not have the power to spread negativity and anger as it has.

The emerging insight on forgiveness and its power is seen in the simulation and has been validated by the late president Nelson Mandela. After 27 years in prison due to the Apartheid regime, he said the following (Yarali, 2019): “As I walked out the door toward the gate that would lead to my freedom, I knew if I didn’t leave my bitterness and hatred behind, I’d still be in prison”. The relinquishing of President Mandela’s negativity had arguably saved South Africa from a civil war because it disengaged the Escalation archetype, which is fuelled by the negative emotions and reactions between groups. On forgiveness, Mandela wrote:

“Forgiveness liberates the soul, and it removes fear. That’s why it’s such a powerful weapon.”

The full simulation development can be found in Appendix 2-D, and the final simulation can be accessed here:

https://exchange.iseesystems.com/public/corne/escalation-polarization-through-social-media/index.html#page2

6.6 Conclusion

The four system archetypes (Fixes that Fail; Limits to Growth; Eroding Goals, and Escalation) is transformed from general archetypes into specific example simulations (policing protests, forest fire, matriculation rates, and social media polarisation).

Each of the simulations explored actual challenges that are faced globally and in South Africa. These included the police brutality at protests, the Australian bush fires of 2020, the South African matriculation rates, and the role that social media giants such as Facebook, YouTube and Twitter have played in the polarisation of people groups.

The simulations are able to replicate the literature behaviours. The simulations also support the leverage points in these archetypes, as identified by Senge (1990), Braun (2002), and Meadows (2008). Furthermore, the simulations reveal a multitude of behaviours that are generated from just one structure. Therefore there is no unilateral correlation between specific structures and behaviours. Similar findings are discussed at the Jay Forrester Doctoral Seminar (1999), where it is emphasised that one structure can produce multiple different behaviours.

In Chapter 6, the following research objectives are achieved:

a) Develop four simulations.
b) Validate each simulation.
c) Identify the expected and unexpected outcomes from the application of the method.

The achievement of these objectives links back to the second critical research question: Can the final simulations replicate the system archetype behaviour as defined by Senge (1990)? Within each simulation's step 9, the simulations reproduce the expected behaviours. Furthermore, they are able to affirm the identified leverage points. Thus the method's inter-repeatability has been tested and proven. In addition, the LST has also been validated with literature in all four system archetype case studies. In summary, the simulations are both verified and validated from historical system archetype literature.

In closing, future research is recommended into the application of the method to a learning environment in order to identify the shortcomings and improvements needed for system dynamics newcomers. Finally, another future research option that may prove useful is to apply the method to systems in which data is available to investigate how the simulation can add insight into more quantitative applications.

7 Result Discussions

7.1 Chapter Purpose

In this chapter, the results from each of the preceding Chapters are summarised and discussed. The discussion focuses on the research questions and objectives.

The value of the research design, method, and simulations are summarised, and opportunities for future research are discussed.

7.2 Research Questions and Objectives

The main research question highlighted in Chapter 1 is: How can one general system dynamics solution method be formulated to translate four of the system archetypes into simulations successfully?

The main research question is further broken down into three critical research questions found in Chapter 1.3. Specific research objectives are formulated to answer the critical research questions. Each of the research objectives is investigated within the preceding chapters:

Research Objectives:

1) **Identify a coherent System Dynamics Method**: In Chapter 2, a thorough Literature investigation is conducted on the different approaches and practices for system dynamics simulation construction. Thereafter, the research is condensed into the initial LST, which improves through two rounds of the Delphi approach found in Chapter 5 – theoretical verification.

The final viable LST is refined through practical validation of system archetypes. Chapter 4 discusses the final LST.

2) **Develop four simulations**: In Chapter 6, four different system archetype simulations are developed via the LST.
3) **Test each simulation**: The LST is formulated with 18 different testing points shown in Chapter 4.4. The tests are used for verification and validation throughout the simulation development process, as seen in Chapter 6 and Appendix 2-A to 2-D. All four simulations can replicate the behaviours identified by Senge (1990).
4) **Identify expected and unexpected behaviours and challenges**: In Appendix 2-A to 2-D, multiple different behaviour modes are explored in Steps 10 and 11 for each of the simulations.
5) **Compare system dynamics experts and teachers views' and recommendations on the method**: In Chapter 5, the LST and simulations are shared with the 9 Delphi Participants. The group has at least 100 years of combined system dynamics experience. The expert views are explored via the Delphi Method using the Likert scale and open-ended questions. The Likert scale questions are evaluated using the Cohen-Kappa statistical test for change in the level of agreement between Delphi rounds. The open-ended questions are analysed using the content analysis technique. The feedback is used to improve the LST as explained in Chapter 3, and the final LST is seen in Chapter 4.

7.3 Successful Research Points

The following section conveys the preceding chapters' results and the elements that support how each research question is answered successfully. The research questions are found in Chapter 1.3.

Research Question 1:

The first research question directly relates to the first two research objectives. A literature survey is conducted on the system dynamics method to identify a coherent system dynamics approach. Twelve different system dynamics literature sources are consulted in Chapter 2.2.2, and the main ideas are summarised in Table 2.2.

The concepts are used to identify the first LST. The LST is applied to the Fixes that Fail archetype (borrowing money example) and sent to the nine Delphi participants. Thereafter the Delphi participants' feedback in Section 5.2.1 and 5.3.2 is incorporated into the LST to produce the second iteration of the Loop Stock Transform. In the next round of Delphi, the LST is applied to two system archetypes (**Fixes that Fail** and **Limits to Growth**). The feedback from the second round also improves the LST. The final LST is found in Chapter 4, Figure 4.1:

1) Problem Description
2) Causal Loop Diagram
3) Stocks and Flows
4) Basic Stock and Flow Diagram
5) Dimensional Analysis
6) Mathematical Formulation
7) Detailed Stock and Flow Diagram
8) Small loop models and Validation
9) Integrated Model Testing and Validation
10) Sensitivity Analysis
11) Emerging Lessons

Thus, the first research question is successfully answered with the LST identified from the literature, which further improves through the two Delphi round reviews.

Research Question 2:

The second research question is answered by applying the LST from Chapter 4 on four different system archetypes, captured in Chapter 6. In each of the four simulations, the expected behaviours are replicated, respectively, as discussed in sections 6.2, 6.3, 6.4, and 6.5.

The **Fixes that Fail** system archetype simulation is applied to policing protests. The simulation results found in Figure 6.6 show that as more policing takes place, it temporarily slows down the number of people at protests. Shortly after that, the number of protesters increases again as suppressed anger led to more people joining the protest. The simulation also confirms Meadows's (2008) recommendation on resolving the archetype by using less force on the symptomatic problem.

The **Limits to Growth** system archetype is applied to a Forest Fire, as seen in section 6.2 and Appendix 2-B. The simulation behaviour in step 9.4, Figure 6.12, show how the simulated forest fire grows exponentially, reaching a plateau, and then starts dying out. The simulation output confirms the same behaviour pattern for a real fire seen in Figure 6.10. The simulation’s performance is validated by the description from Senge (1990), as found in Figure 6.4. The simulation confirms Meadows's (2008) advice that the growth rate should be kept as slow as possible to control the fire. In the forest fire case, it is effectively achieved by controlling the forest's initial tree density.

The **Eroding Goals** system archetype is applied to the Matriculation rate of high school students in Section 6.4 and Appendix 2-C. The simulation results are seen in Figure 6.21, which shows how the matric pass rate increases as the goal skills reduce and the average student skills barely improve. The general system archetype behaviour, which is shown in Figure 6.20, reveals how the goal decreases to maintain the gap at a minimum while the actual skills are unaffected as the gap is closed. The simulation confirms Meadow's advice (2008): disallowing control on goal adjustments counters the archetype.

The **Escalation** system archetype is applied to the social media polarization effect. The simulation's behaviour, seen in Figure 6.27, reveals how both groups' hateful ideas increase continuously. The expected behaviour from Senge (1990) is found in Figure 6.26 and confirms the same trend. The simulation demonstrated the advice from Meadows (2008): the archetype can be weakened by breaking at least one group's balancing cycle.

All four simulations replicated the behaviours identified by Senge (1990) and confirmed Meadows's (2008) advice in the management of each system archetype's destructive cycles.

Research Question 3:

The third research question is based on the LST's perceived usefulness and the product simulations' validity. The question is mainly addressed in Chapter 5, where the 9 Delphi Participants review and improve the LST.

Three focus points are identified based on the research questions in Chapter 5:

1) The method consists of the correct system dynamics techniques.
2) The application of the method is useful and valuable.
3) A final simulation is a valuable tool for gaining insight into the system structure.

In the first Delphi round, there are five short Likert scale questions and five open-ended questions. Each of the Likert scale questions is designed to relate to at least one focus point and at least one open-ended question, seen in Figure 5.3. The acceptable support percentage is chosen as 70%, which is more than double that of the agreed-upon system dynamic practices found by Martinez & Richardson (2013).

First Delphi Round

There is a 100% response rate after seven weeks (the requested completion duration was four weeks) in the first round. Questions 1 and 4 are at 89% (8/9) support. The other three short questions are below 70%. Focus point one support is reached at the first Delphi round, which is a validation of a successful literature study, Chapter 2. The statistical Cohen-Kappa analysis on the first round’s short questions reveals a score of 0.32 related to ‘Fair Agreement’ as seen in Table 5.6 and Table 5.5, respectively.

The open-ended questions (6 to 10) are analysed by utilising the content analysis research technique. The technique is first applied to each of the questions separately. The keywords are extracted from each of the respective answers. Each keyword represents an idea. The count of each keyword is then added up for each question. Similar keyword concepts are combined into context ideas, and the number of counts is summarised in Table 5.7. The context themes are grouped according to positive (green), areas of improvement (yellow), and negative (red) categories.

Section 7.4 discuss the disagreements in detail; nonetheless, 48% of the ideas supports the LST and product simulations. The feedback confirms that the technique and simulation provided profound insights and aided the system dynamics learning process. There are, however, multiple suggestions for improvement, which are then merged into the method.

The influence that the Delphi Participants' feedback had on the method can be seen in sections 5.2.2, 5.3.3, and 5.4. The second round is compiled and sent out to the Delphi participants.

Second Delphi Round

The second round of Delphi also obtains 100% (9/9) participation after a duration of 9 weeks. There are additional five Likert scale questions (ten in total) and only two open-ended questions. The first five Likert scale questions are kept the same to measure the improvement/deterioration of the group’s alignment from round one.

In the second Delphi round, the first five questions' average support level is above 70%. Three of the questions are at 100% support towards the focus points. The result proves that there is significant progress from round one to round two. The average Cohen Kappa increases from 0.32 to 0.62, seen in Table 5.10. The value of 0.62 is related to ‘Substantial Agreement’; the target agreement level is thus achieved (0.60).

The open-ended questions reveal an overall shift in the focus of improvement areas of the simulation method. Most ideas relate to the need for teacher guides for the LST, seen in Table 5.12. Although the suggestion is outside the scope of the current research, it reveals an area of future research. The proposal also supports the notion that the participants accept the LST and the developed simulations' value. In summary of Delphi's second round: the average support is above 70% for all five Likert Scale questions, an average Cohen-Kappa value reveals ‘Substantial Agreement’ and that the participants are ready to move the research into a future stage of teaching application.

In conclusion, through the two iterative rounds of the Delphi method, the third research question is answered. All three focus points support the final LST.

7.4 Research Shortcomings

The next sections explore the research shortcoming in relation to the research questions.

7.4.1 Research Question 1: Loop Stock Transform

Although the research is able to identify one coherent generic LST which translated the system archetype examples into simulations, the following arguments can be made against the LST.

1) **The Loop Stock Transform remains arbitrary:** Despite the strong foundation in literature and review of external system dynamics experts and teachers, a different researcher might identify slightly different elements. Martinez & Richardson (2013) revealed that many system dynamics experts use methods that are unique to them. The combination of approaches from the nine Delphi participants and the researcher’s own bias has influenced the final LST found in Chapter 4.
2) **A different problem**: Some Delphi participants argue that the problem does not lie in the approach taken to teach/learn system dynamics but rather that the field is inherently challenging due to the strong mathematical basis. The argument challenges this research thesis' problem statement, section 1.2, since a part of the LST is formulated to aid the learning curve of system dynamics. If this argument is the real root cause, then the only way to solve the learning difficulty is to improve the global skills in mathematics or remove mathematics from system dynamics. The first is an ideal goal, yet it requires global effort and not achievable in one research thesis. Removing mathematics from system dynamics has been attempted using CLDs as models, yet the dangers of only having CLD models are explored by Richardson (1997) (2020) and not recommended by Forrester (1999). As a compromise, the LST provides a

bounded mathematical set of equations that can reduce the mathematical complexity in the system dynamics learning curve.

3) **The LST is not simple**: The original point of departure of the research is to identify the smallest set of steps required to expand the system archetypes into simulations. Yet, the Delphi participants have identified the LST as too complicated for high school students. The participants entertained the notion that the LST can be taught as a semester course at the third-year university level. However, the LST remains challenging. Therefore, the LST does not remove complexity from system dynamics simulations. Yet, it does supply a stepwise process that is internally consistent and testable to aid the learning process.
4) **The final approach has limitations**: The LST summarises challenging concepts used by experts in the system dynamics field. The simplification leads to significant limitations in certain areas. The ability to simulate qualitative mental models leads to a reduction in quantitative precision. Thus, it is expected that a weak point in these simulations would be replicating historical data with precision. However, the historical trends could still be generated, albeit unprecise. Another limitation is the given set of equations. These equations are used in most simulation equations, yet many real equations lie outside the equation boundary of Appendix 1-A. In addition, delays are also simplified. In the LST, only standard 'reservoirs' are used for stocks to limit the number of concepts to learn. In practice, other delayed stocks like conveyors, queues, and ovens are more efficient and numerically exact. Yet each would require additional knowledge that lies outside the LST. The standard reservoirs are chosen due to their universal inclusion in all system dynamics software.
5) In **summary**, these limitations will become a ceiling in the learning curve of system dynamics after they become proficient at using the LST. At the ceiling point, the learner has overcome significant parts of the system dynamics learning curve. Thereafter, they can focus on learning more advanced system dynamics skills available in other system dynamics literature.

7.4.2 Research Question 2: The Simulation Behaviours

1) **Ambiguity in trend confirmation:**

The simulation results are captured in Step 9.4 for each of the four simulations of Chapter 6. The results are validated against the behaviours identified in step 1 for each respective simulation set. Considering the **Fixes that Fail** simulation results in Figure 10.18 relative to the historical data in Figure 10.1, the following ambiguity becomes apparent: Although both behaviours show an increasing trend, which is used as trend confirmation, there are noticeable differences in the behaviours. The differences pertain to the time horizon, rate of increase, and the y-axis definition. Therefore the trend confirmation has inherent ambiguity. The ambiguity in trend confirmation may lead to incorrect deductions or bias confirmation of the simulation's results.

2) Structure not deducible from behaviour:

Although the simulation process in Step 1 starts with understanding the system and identifying appropriate behaviour trends, the behaviour is not sufficient to describe the structure. One example of the phenomenon becomes apparent when considering the results in Chapter 6 found in Figure 10.19, Figure 10.20, Figure 10.21, and Figure 10.22. The simulation's behaviour changes drastically when specific parameters are altered. This finding's importance is that the same structure can represent multiple behaviours (Senge, 1990) under different circumstances: The results in Figure 10.24 for the protesting people in the **Fixes that Fail** archetype appears slightly similar to Trees on Fire in Figure 10.48 for the **Limits to Growth** archetype. A particular critique against using the behaviour to verify the structural confirmation, as done in the thesis, is that the variables within a stock and flow structure could be altered to induce a biased behaviour. In theory, one system could have produced all four archetype behaviours. Hence, fixed structure-behaviour sets are not the best validation criteria.

3) Interface development investment:

One of the critical acceptance points of the research expressed in Chapter 5 is that the final simulation and interface are insightful. One of the primary reasons for the insight and focus is possibly the quality of the simulation interface. The iSee Stella Architect software enables the developer to design a useful user interface for the end-user. The interface does not alter the stock and flow structure and is fundamentally different from the LST where the simulation is developed. The interface development is time-consuming and not a requirement of the LST; however, it creates an improved user experience. This improvement might be a critique against this research as the acceptance of the final simulation might be partly due to the large investments into the simulation interface.

7.4.3 Research Question 3: Critiques from Delphi

In Chapter 5, Table 5.7 and Table 5.12 shows Delphi's content analysis results in rounds 1 and 2, respectively. In sections 5.2.2 and 5.3.3, the discussion of the results is captured. The significant critiques from the Delphi Participants on the LST are:

1) **Different Problem:**

Section 7.4.1. discussed that five ideas (hundred total) express that the real problem in system dynamics is not the lack of system dynamics guidance but rather the global perception of mathematics being a rare/difficult skill.

2) **Do not use generic archetypes**

The **Fixes that Fail** simulation in the second Delphi round is developed on the generic archetype. The second round's most consistent negative idea is on the use of generic archetypes for simulation formulation. The participant group identified that a generic formulation creates confusion, incoherent identification of stocks and flows and that the generic archetypes are always meant to be applied to specific examples. The concept of creating generic archetype simulations is thus countered and led to the final four simulations found in Chapter 6 being specific examples of each generic system archetype.

3) **Too many steps for newcomers**

The number of steps is a repetitive critique against the LST. One of the participants with extensive high school teaching background explained that the first four steps might be plausible at the high school level. The rest of the steps, especially the iterations between steps, would be too complicated for high school students. The criticism indicates that the LST are not necessarily a process that will solve the system dynamics' learning curve problem. The LST only give a guideline, yet the facilitator/teacher/lector's modelling ability will be crucial to teach system dynamics through the LST.

4) **Confusing research purpose:**

One of the participant critiques against the research is that they are confused about what they are evaluating. The confusion arose from the multiple evaluation criteria used by the Delphi participants: Evaluate if the method is aligned to system dynamics, evaluate if the method application has merit, and evaluate if the final simulation is useful. The participants strongly argue for more teaching aids to assess the second point (method application). This aspect is a possible future research avenue.

Summary

In Chapter 7, the research method and results are discussed. Furthermore, the results are evaluated on how well the research questions are addressed. Finally, the method and results are critically reviewed on their strengths and weaknesses. In the next Chapter, the strong points in the method, results, and future research opportunities are summarised.

8 CONCLUSION

8.1 Chapter Purpose

The chapter's purpose is to consolidate how the research question has been addressed, where it fails to address the questions and capture the recommendations for future work.

8.2 Research focus

Chapter 2 discusses how problem-solving and general decision-making are mostly associated with strong mental models hidden within the mind of the decision-maker. Although external data is available, the information in mental models is often neglected in a scientific context. Systems thinking explore mental models by using multiple approaches and summarise the models with static diagrams of the process. Systems engineering creates methods to step through the process of solving complex problems systematically. The approach is often characterised by reducing the system into subsystems, components, and elements. The systems engineering field has a strong foundation in verification, validation, and testing. Even though systems engineering can be applied to most problems, it is focused on systems of tangible nature and not qualitative dynamics.

System dynamics can process qualitative systems and their dynamics found in mental models. Yet, the field lacks the structured verification, validation, and testing fundamental to systems engineering. There are no exact guidelines that are internally consistent with model development, testing, verification, and validation within system dynamics. Thus, the research question is to investigate, develop, apply, and evaluate the performance of such a method.

8.3 Research Value

In the next two sections (8.3.1 and 8.3.2), the thesis's valuable parts are summarised.

8.3.1 Strong Points of the Research Method

- **Correct System Dynamics Elements**: The method identified in Chapter 2 and improved by the Delphi Participants in Chapter 4 is successfully identified as an accurate representation of system dynamics.
- **Systems Engineering Value**: The addition of the systems engineering testing, verification, and validation addresses some of the criticisms against the system dynamics approach (McLucas and Ryan, 2005). The value of the addition is discussed in Chapter 4, seen in section 4.3.
- **Peer-Reviewed Approach**: The LST and its application are analysed and reviewed through two iterations of the Delphi method. The Delphi group consisted of nine global participants with more than 100 years of combined system dynamics and teaching experience.
- **Method Supported by Experts**: The peer-review process on the method and simulations led to the final LST being supported by 100% of the participants.
- **Internal Simulation Validation**: The final Loop Stock Transform is internally validated by application to four system archetypes in Chapter 6, which we're all able to replicate expected behaviours defined by Senge (1990) and Meadows (2008).
- **Statistical Agreement**: The Cohen-Kappa statistical method is a good approach to establish the agreement between participants (Meijering *et al.*, 2013). The first five Likert scale questions had an average Cohen Kappa agreement value of 0.23 (‘Fair Agreement’ on 36 combinations). In the second round, the average increases to 0.62 (‘Substantial Agreement’). The statistical agreement of 0.62 confirms that the Delphi approach is successful in improving the group agreement.
- **Statistical Support for LST**: The five Likert scale questions in the first round reveal that the group supported two of the five questions above the required 70% setpoint. In the second Delphi round, all five questions are supported by at least 70% of the group (Table 5.9). Three questions are supported by all (100%). The Likert scale peer review reveals significant improvements in the LST between the iterations and that the final LST and simulations successfully answer the research questions.

- **Documented Simulation Development**: One of the lacking elements in system dynamics applications is detailed documentation on model development (Rahmandad & Sterman, 2012). One of the main reasons for this gap is the document's length and the compilation resource requirement. In this research (Chapter 6 and Appendix B), the simulation development process is summarised, which is often not fully disclosed in the literature. The documentation process is valuable due to the scarcity of this type of literature.

8.3.2 Strong points of the Final Loop Stock Transform

- **Guidance to newcomers:** The LST can guide newcomers, independently verified in Chapter 5.
- **Testing Points (V, V, T)**: Incorporating the systems engineering approach led to 18 internally consistent testing points (section 4.3). The testing points enable an objective evaluation, as well as a teaching aid on system dynamics model development.
- **Four Mathematical Simulations**: The internal validation of the LST is to iteratively apply the same method on four of the system archetypes to convert the system models into mathematical simulations. Therefore the LST is repeatedly validated with four mathematical simulations in Chapter 6.
- **Successfully Validated Simulations**: In all four of the system archetype simulations, the simulation reproduces the expected behaviours from literature (Senge, 1990) (Meadows, 2008) and confirm the strategies for approaching each respective archetypical trap.
- **Valuable Simulation Interface**: An unforeseen valuable aspect is identified by the Delphi Participants in round 2. The final simulation interfaces are identified as invaluable teaching aids to dynamically illustrate the system archetypes in a story format. The value is identified by one of the Delphi participants: a practising high school physics teacher with exposure to systems dynamics.

8.4 Future Research Opportunities

8.4.1 Research method:

- **System dynamics remains an art form**: In Jay Forrester’s PhD. Seminar (1999), one of the key discussions, is based on the lack of axioms in system dynamics. Forrester (1999) explains that system dynamics is an art form similar to any profession, which requires experience and creativity to solve problems, likened to engineering. The argument implies no definite set of skills, equations, or steps can describe all system dynamics simulations' development processes. Furthermore, the idea also indicates no fundamental equations or basic simulation structures that underpin the field. Throughout this thesis, the fundamental processes, equations, and tests are investigated to identify such axioms. Although techniques, equations, and tests are identified and approved by experts, the final method does not include all skills, abilities, and tests found in system dynamics. One of the gaps and possible future areas of research would be to delve deeper into the system dynamics method's pure axioms.

- **Delphi Method**: The typical Delphi approach lacks guidance and agreed on standards of results interpretation and analysis (Fink-Hafner *et al.,* 2019). The method is time-consuming for both the participants and the researcher. A limitation to the approach is that the results cannot be confidently generalised to a larger population due to the small sample size, the limited views from experts, the uneven spread of expertise, and different personal agendas (Nambisan et al., 1999) (Nierderman *et al.,1991*) (Hsu and Standford, 2007). The procedure is limited to the quality of feedback and the researcher's discretion (Donohoe and Needham, 2009). In this specific study, one participant dropped out due to the confusion of using the online interface before the first round concluded, which led to the final nine participants. These limitations on using the Delphi approach can justify a parallel Delphi research study on the same LST to validate the researcher's discretion, limited sample size, and generalisation, which counter the Delphi findings.
- **Cohen-Kappa**: The Cohen-Kappa technique is used to measure the agreement level between two participants. In this Delphi approach, there are nine participants, which lead to 36 unique combinations of two sets. As referenced in Chapter 5 (Table 5.6 and Table 5.10), the average value of Cohen-Kappa is masking the individual agreement levels (O'Leary *et al*., 2014). In the second round, the smallest Cohen-Kappa value is 0.04 for one combination set of participants, and the largest Cohen-Kappa is 1.00 (perfect agreement) for 16 different combinations. The Cohen-Kappa statistical method only validates the agreement between participants. It does not validate if the agreed term is objectively aligned to the global population outside the sample size. A repeat of the Delphi method and Cohen Kappa analysis on a different group of experts can be a future research area to confirm or challenge the results found in Chapter 5.

- **Likert Scale**: The Likert scale's major disadvantages relate to the uni-dimensional scale, while the problem space is multi-dimensional (Likert, 1932). The five Likert scale options are not equidistant and do not capture the participants' opinions. The five scales are further reduced to only three ranks for the statistical analysis phase. The 100% agreements located in questions 1, 2, and 5 are masking many opinions that cannot be identified with the Likert scales. The content analysis is used to explore the views behind the Likert scale answers, yet a different set of Likert questions could produce more insights.
- **Content Analysis**: The quality of the research process behind the content analysis is dependant on the discretion used by the researcher. The researcher defines the coding process and sentences created from the coding words. A future research opportunity can be for two or three researchers to do the content analysis independently to verify the content analysis's final results.
- **Documentation of Simulation Development:** A large amount of time required to evaluate the simulations' documentation is expected to have inhibited the quality of model evaluation. A future research opportunity is to investigate the simulation development documentation in more detail.

8.4.2 The Loop Stock Transform

- **The Complicated Number of Steps:** In both the Delphi rounds, one of the persistent negative aspects of the LST is that the number of substeps and the iterative nature of the steps is too complicated for high school students. The LST is expected to be teachable at a third-year university level. A future research investigation can evaluate if the LST can be simplified for high school students.
- **Ambiguity in Simulation Results:** The final simulations are able to produce multiple different behaviour sets. The comparison in step 9 with the initial behaviour defined in step 1 can contain ambiguity from the developer. A future research study can be on how well the 18 different tests can prevent model development mistakes.
- **Untested on Learner Group:** The LST had not been tested on a group of students to analyse the real value of learning and applying the technique. A future research endeavour can test how well a learner group can learn, apply and adopt the system dynamics methodology using the LST.

- **Equation Limitations**: The generic list of equations in Appendix 1-A contains the equations used in most system dynamics simulations. These equations are useful in describing most of the interactions, yet not all equations in a system dynamics simulation can fit this generic set. A recommended future study can focus on evaluating the extent to which these equations can fit into well-known system dynamics simulations and where improvements can be made.
- **An Alternative Approach to Teaching Mathematics**: In the second round of Delphi, one of the significant positive comments, section 5.3.2, is that the application of LST reveals an alternative way to teach mathematics. A possible future research area can be to explore the underlying mathematical concepts in system dynamics and their ability to aid in learning mathematics in a simulation environment.

8.5 Thesis Summary

The research questions are successfully answered through three mixed-method approaches: the study of the system dynamics and systems engineering methodologies, an external peer review through a Delphi research method, and applying the final method to case studies on four of the system archetypes.

The results consist of the Loop Stock Transform (Chapter 4) with a complete peer-reviewed evaluation captured through the two rounds of Delphi (Chapter 5). The four system archetype simulations are able to generate more profound insights into the system structure, replicate the expected behaviours and validate the proposed solutions from literature (Chapter 6). The research design's positive and negative aspects, LST, and simulations are summarised in Chapter 7. Finally, in Chapter 8, the valuable aspects and the areas of improvement of the research and process are summarised.

The thesis captures the research that leads to the derivation of a generic set of system dynamics steps, combined with systems engineering, that can be applied to static system archetype models to develop dynamic mathematical simulations. The technique is denoted as the Loop Stock Transform (LST).

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10 APPENDICES

APPENDIX 1-A: EQUATION SHEET

Normalize:

$$n = \frac{x - x_{min}}{x_{max} - x_{min}}$$

Where:

n – Dimensionless value between 0 and 1

x – the original value of the variable

x_{min} – Minimum value of the variable

x_{max} – Maximum value of the variable

Reverse Normalization:

$$x = n \times (x_{max} - x_{min}) + x_{min}$$

All the formulas together would then be (Richardson & Pugh, 1981):

$$R_1 = Constant \times Level \quad (1)$$

$$R_2 = \frac{Level}{Time} \quad (2)$$

$$R_3 = \frac{Goal - Level}{Adjustment\ Time} \quad (3)$$

$$R_4 = Auxilliary \times Level\ OR\ R_4 = \frac{Level}{Auxilliary} \quad (4)$$

$$R_5 = Normal\ Rate + Effect \quad (5)$$

$$R_6 = Normal\ Rate \times Effect \quad (6)$$

$$n = \frac{x - x_{min}}{x_{max} - x_{min}} \quad OR \quad n = 1 - \frac{x - x_{min}}{x_{max} - x_{min}} \quad (7)$$

$$x = n \times (x_{max} - x_{min}) + x_{min} \quad (8)$$

Logic Equation - Decision /Events:

These contain logical arguments that when a certain condition is true, then a certain action will be taken; otherwise, a different action will be taken. In such cases, the IF THEN ELSE logic will be used:

IF {condition} THEN {Action taken when condition is true} ELSE {Action taken when condition is false} (9)

APPENDIX 1-B: CAUSAL LOOP DIAGRAMS

The following are direct extracts from Guidelines for Drawing Causal Loop Diagrams written by Daniel H Kim (Kim, 1992).

1. Use nouns when choosing a variable name. Avoid verbs and action phrases because the action is conveyed in the loop's arrows. For example, "Costs" is better than "Increasing Costs" because a decrease in Increasing Costs is confusing. The sign of the arrow ("s" for same or "o" for the opposite) indicates whether Costs increase or decrease relative to the other variable.
2. 2. Use variables that represent quantities that can vary over time. It does not make sense to say that "State of Mind" increases or decreases. A term like "Happiness," on the other hand, can vary
3. Whenever possible, choose the more "positive" sense of a variable name. For example, the concept of "Growth" increasing or decreasing is clearer than an increase or decrease in "Contraction."
4. Think of the possible unintended consequences as well as the expected outcomes for every course of action included in the diagram. For example, an increase in "Production Pressure" may increase "Production Output," but it may also increase "Stress" and decrease "Quality."
5. All balancing loops are goal-seeking processes. Try to make explicit the goals driving the loop. For example, loop B1 may raise questions as to why increasing "Quality" would lead to a decrease in "Actions to Improve Quality" By explicitly identifying "Desired Quality" as the goal in loop B2, we see that the "Gap in Quality" is really driving improvement actions.
6. Distinguishing between perceived and actual states, such as "Perceived Quality" versus "Actual Quality", is important. Perceptions often change slower than reality does, and mistaking the perceived status for current reality can be misleading and create undesirable results.
7. If a variable has multiple consequences, start by lumping them into one term while completing the rest of the loop. For example, "Coping Strategies" can represent many different ways we respond to stress (exercise, meditation, alcohol use, etc.)
8. Actions almost always have different long term and short-term consequences. Draw larger loops as they progress from short to long-term processes. Loops B1 show the short-term behaviour of using alcohol to combat stress. Loop R2, however, draws out the long-term consequences of this behaviour, showing that it actually increases stress

9. If a link between two terms requires a lot of explanation to be clear, redefine the variables or insert an immediate term. Thus, the relationship between “Demand” and “Quality” may be more obvious when “Production Pressure” is inserted between them.
10. A shortcut determining whether a loop is balancing or reinforcing is to count the number of “o’s” in the loop. An odd number of “o’s” indicates a balancing loop (i.e. an odd number of U-turns keeps you headed in the opposite direction); an even number or no “o’s” means it is a reinforcing loop. CAUTION: After labelling the loop, you should always read through it to make sure the story agrees with your R and B labels.

APPENDIX 1-C: SUMMARY OF LOOP STOCK TRANSFORM

Step 1: Problem Description

1) Define the problem in one paragraph story (word model).
2) Identify patterns of behaviour and reference modes.
3) Allocate dimensions to the graphs in sub-step 2.
4) Define a purpose for the model based on the problem.
5) Identify some core variables (3-4) variables.
6) Identify the total duration of the simulation and at what resolution of time.

Step 2: Causal Loop Diagram

1) Identify the core story behind step 1.
2) Use the rules of the CLD to construct it (Appendix B)
3) Test that the story being told by the CLD is the story represented in the problem
4) List the expected isolated loop behaviours using the atomic loops (Appendix D)

Step 3: Stocks and Flows

1) Start with using the snapshot test to identify stocks from the CLD in the previous step:
    a. If time freezes or the system ceases, what remains are stocks
    b. Stocks can be something that stores/releases resources or information.
2) Ensure that the stocks are nouns
3) Each loop should have at least one stock
4) Identify what flows in and out of the stocks
5) Check if any stocks have aggregated compartments that might need to be split with delays (Appendix F)

Step 4: Basic Stock and Flow Diagram

1) Use subsystems diagram (system architecture map) to trace every variable back to a stock
2) Draw out the stocks and flow sets individually first
3) Use the subsystem diagram to connect the different sets of stocks and flows

Step 5: Dimensional Analysis

1) First, allocate dimensions to all the stocks
2) Allocate dimensions to the flows that are connected to the stock
3) Allocate dimensions to the rest of the variables based on the stocks and flows.
4) Identify gaps in the dimensions using a question mark.

Step 6: Mathematical Formulation

1) Use gaps in dimensions to identify missing variables that fulfil the dimensional requirements.
2) Identify any effect variables that convert one variable into another with a non-linear relationship (Appendix E)
3) Use the equation sheet (Appendix A) to match the generic equations to the specific structure.
4) If there are stage fractions in a stock, split the stock into separate parts and identify the stage fraction or residence time of the elements inside of it. (Appendix F)
5) Construct the generic equations for the delays with the definitions in sub-step 4.

Step 7: Detailed Stock and Flow Diagram

1) By combining step 4 and step 6, the new detailed stock and flow diagram can be drawn.
2) Reference the equations on the variables with the colour red and Ex, where x is the equation number.
3) Indicate dimensions with green
4) Draw the non-linear relationships above/below the effect variables

Step 8: Small Loop Models and Validation

1) Identify the smallest loop in the CLD of step 2.
2) Build only the structures associated with that loop using the step 7 diagram and assuming any structures outside the loop as constant.
3) Define the initial value of the stock and determine the rest of the initial values in that model based on static calculations/estimations from the stock.
4) Test the simulation behaviour against the expected loop behaviours defined in step 2.
5) Go to the next loop

Step 9: Integrated Model Testing and Validation

1) The small models are all connected, as seen in step 7.
2) A static equilibrium is identified where the conditions are such that all flows are 0. If a static equilibrium is not possible, search for a dynamic equilibrium where stocks are constant and flows balance out.
3) Make a step change in one of the external variables and observe if the system can re-establish equilibrium
4) Test if the model can reproduce the reference mode in step 1.

Step 10: Sensitivity Analysis

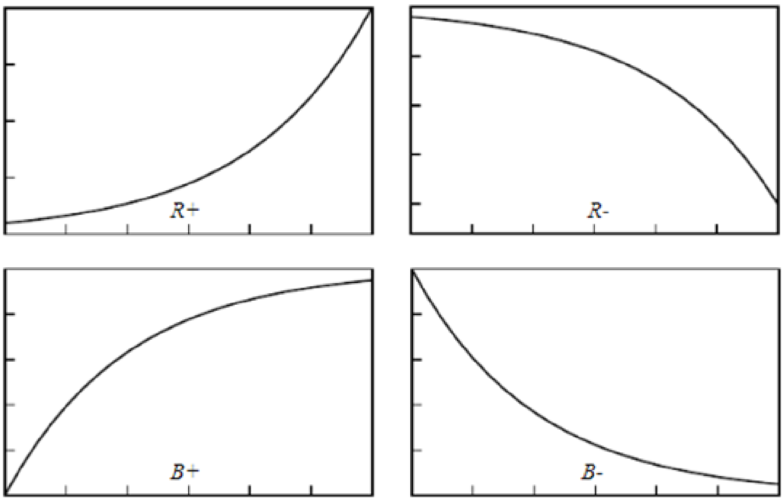
1) Identify three external variables (constant inputs) that can be affected most in reality.
2) Choose a common percentage variance, e.g. 50%.
3) Determine the points of sensitivity for each variable, e.g. if the initial value is 2, the range will be 1 and 3. If ten sensitivity intervals are chosen, the values will range from 1, 1.2, 1.4 to 3.
4) The percentage change on the core variable is tracked for each sensitivity
5) The variables are then ranked in order to leverage variables and points.

Step 11: Emerging Lessons

1) The first focus is on identifying alternative behaviour modes relative to the original in Step 1 and investigates what causes them.
2) The deeper insights gained in the transition from the CLD (system archetype) into the simulation environment.
3) The list of additional variables generated through the process not seen in the CLD.
4) Summarize the leverage points discovered in step 10.

APPENDIX 1-D: ATOMIC LOOP BEHAVIOURS

Considering a second-order structure where neither the first or second-order derivative is 0, there will exist four different patterns of behaviour.



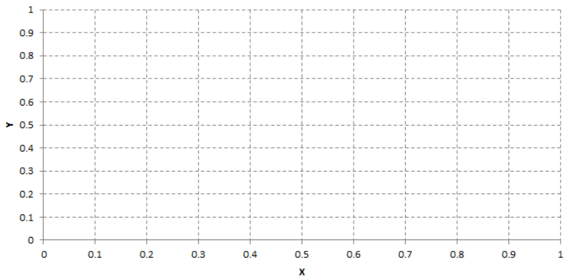
(Hayward, 2012) (Kampmann & Oliva, 2006) (Ford, 1999)

When considering a specific loop, the direction of the link flowing into the variable (+/-) combined with the label of the loop (R/B) will determine the isolated loop behaviour.

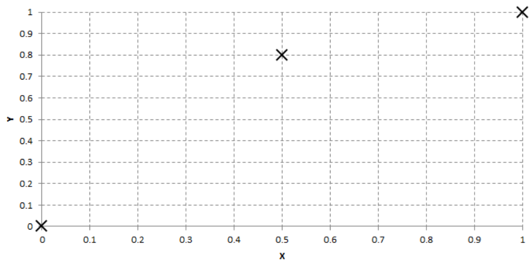
The final behaviour of the model is determined by the complex simultaneous workings of all the loops, but the dominant loop will dominate the emerging pattern.

APPENDIX 1-E: EFFECT VARIABLE GENERATION PROCESS

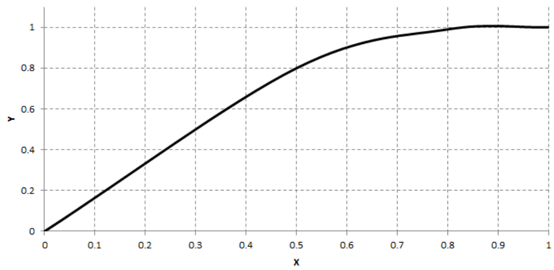
1) Define the name as the Effect of 'X' on 'Y', where X is the preceding (independent) variable, and Y is the final variable (dependent)
2) Create an effect variable between the two variables that have a non-linear relationship. First, ensure the X variable is dimensionless by using the normalization functions in Appendix A. Draw an **X/Y coordinate** with the *available tree density* as the x and the *fire spread rate* as the y-axis:



3) Define **three points** on the graph:
   i. When X is at 1, what is Y? Example: 1
   ii. When X is at 0, what is Y? Example: 0
   iii. When X is at 0.5, what is Y? Example: 0.8



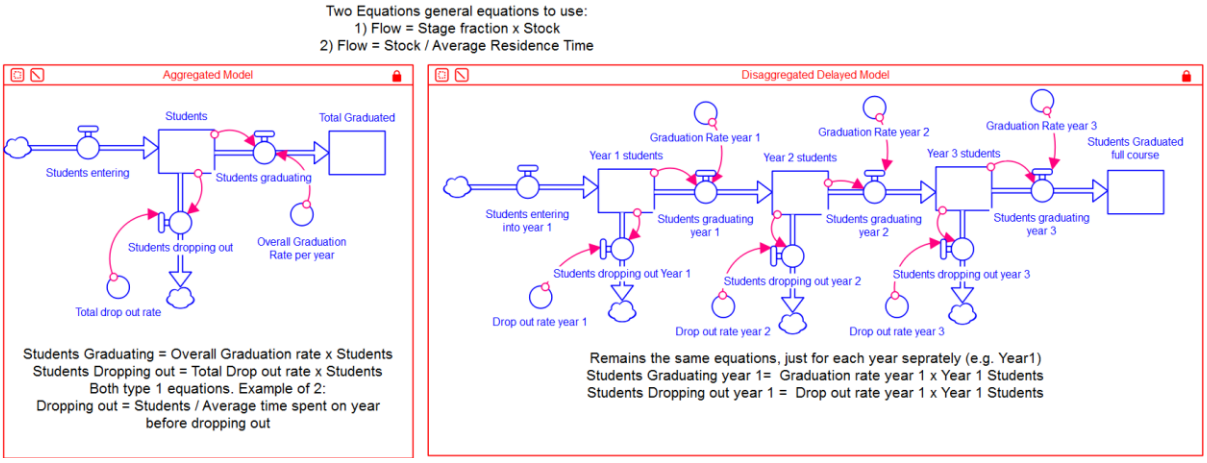
4) Connect the points in a **continuous function**:



5) Define the minimum and maximum values of the X and Y variables.

APPENDIX 1-F: CREATING AND DEFINING DELAYS

Some stocks might have been simplified to a level where the true dynamics are not present. Consider a university system and the stock of a number of students in the university. If the stock stays at this level, the number of students leaving will be a function of the total number of students at the university. Using equation two from Appendix 1-A, there is no chance that a student enters university and graduates in one year. This is not possible, and thus the stock needs to be aggregated into separate stocks. The appendix uses the work from Chichakly (2020).



Steps to make the transition:

1) Test the logic of the rate change, e.g. can a student enter the university and graduate in one year? The answer is no, and the delay needs to be disaggregated; go to the next step.
2) Identify the number of stages within the stock. In this case, there were three stages, one for every academic year, since years cannot be skipped.
3) Disaggregate one stock into three stocks with distinct names. The sum of the stocks may still represent the initial stock, yet every stock has the outflows associated with the initial one. In this case, every disaggregated (child) stock inherent the graduating and dropping out flow logic from the original (parent) stock.
4) The equations are mostly one of the first two equations in Appendix 1-A, either using a rate or a residence time.
5) Each of the aggregated stocks will have its own rate/residence time for each flow.

APPENDIX 2-A: FIXES THAT FAIL SIMULATION DEVELOPMENT

The LST method explained in Chapter 4 is applied to the Fixes that Fail archetype. The general system archetype is specialized in the phenomena where police are deployed to control protests. The full LST method application is documented here.

The final online simulation can be accessed here:

https://exchange.iseesystems.com/public/corne/fixes-thta-fail---protests-and-policing

10.1.1 Step 1: Problem Description

10.1.1.1 Word Model (1.1):

In general this phenomena is created when an aggravated community would voice their concerns yet authorities brush the concerns off or no action is taken to address the concerns. This leads to the anger in the communities to grow. The frustration and anger can grow to a point where the community starts organizing protests or riots to gain media attention in order for their concerns to be heard. The protests will often lead to authorities that send out police forces to break up the riots. The policing does reduce the people at the protest / riot yet it also represses the anger experienced from the protesters, as their concerns are seemingly pushed aside again. Given some time, the protest/riot returns and often with a higher intensity/volatility.

The problem symptom is the size of the riots. The riots are quick fixed with police force deployment, while the unintended consequence is that it represses anger, which leads to more protests/riots.

10.1.1.2 Behaviour over time (1.2):

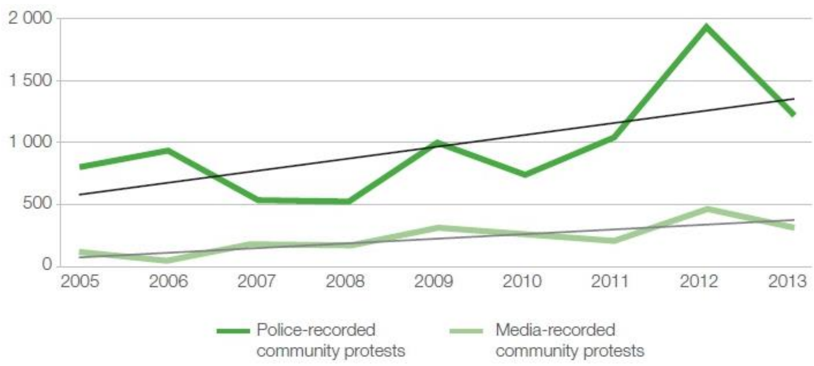


Figure 10.1: South African Community protests estimated between 2005 and 2013 (Alexander *et al., 2018*).

The y-axis refers to the total number of community protests in the database of the University of Johannesburg's Centre for Social Change. The data shows that there are fluctuations in the protests throughout the years, yet every few years there is an upsurge. The upsurge seems to be increasing, especially after 2009.

10.1.1.3 <u>Purpose (1.3):</u>

The purpose of the model is to apply the LST methodology to transform the fixes that fail system archetype policing protests. The end goal is to develop a system dynamics mathematical simulation that is able to replicate the expected behaviours and afford new insights.

10.1.1.4 <u>Core Variables (1.4):</u>

The main variables and their expected dimensions:

1) People at Protests - #people
2) Police at riots - #police
3) Repressed anger – Qualitative (anger) (non-dimensional)

10.1.1.5 <u>Time Frame (1.5):</u>

A 5 year time frame at the resolution of months

10.1.2 Step 2: Causal Loop Diagram

10.1.2.1 <u>Core Story (2.1):</u>

South Africa has sometimes been referred to as the 'protest capital of the world' (Rodrigues, 2010) since it has one of the highest rates of public protests globally (Alexander, 2012).

Here are just a few sampled protests (Moeti, 2015): Harrismith in 2004, Symphony way in 2008 that lasted over a year, Marikana miner strikes 2012, Soweto 2013, FeesMustFall in 2015 and 2016, ZumaMustFall strike in 2017 and 2019 Service delivery strikes across the country.

Some of the reasons behind these strikes include unequal and segregated distribution of land, housing demand, poor service delivery, government corruption, unemployment, police brutality etc. The state has sometimes resorted to handling these protests with police violence and there are an estimated 54 people who have lost their lives through police brutality (Bruce, 2012) post-apartheid (1994). The worst incident (after 1994) is the Marikana Massacre in August 2012 where 34 striking miners were killed and 78 were injured, while allegedly only one pistol was recovered from the strikers (Bruce, 2012).

The protesters' degree of violence has also been escalating over time, where property, buildings, statues and ward councilor homes have been burnt down (eNCA, 2019).

The patterns of protests have arguably been taking place since the 1970s (long before the abolishment of Apartheid) and are increasing due to a structural problem in society where the poor people percieve the need to rebel before service delivery is obtained (Alexander, 2010).

10.1.2.2 Create Causal Loop Diagram (2.2):

The three main variables in the Fixes that Fail Archetype are: Problem Symptom, Fix and Unintended Consequence. The problem symptom is defined as the people at the protest, the fix is the police at protest and the unintended consequence is repressed anger. The Fixes that Fail archetype (in CLD format) for this system can be seen below.

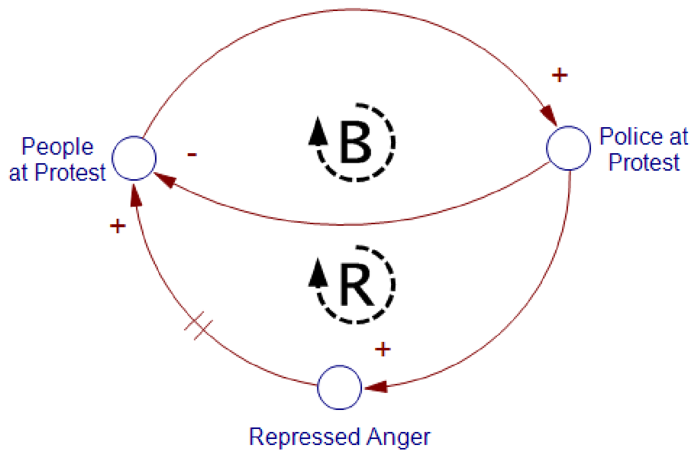


Figure 10.2: Causal Loop Diagram – Fixes that Fail – of Protest control

Two different loops are formed: One balancing and one reinforcing.

10.1.2.3 Atomic Loop Behaviours (2.3):

1) **Loop B – The Fix**: As the number of people at a protest increases, so does the deployment of police and the number of police at the protest increases (+). As the number of police at the protest increase, they will round up the protest and disperse the protest which decreases the people at the protest (-). There are a total of 1 negative interaction, which is why the loop is balancing. The connection into the people at the protest is negative, which relates to an expected loop behaviour of B-.
2) **Loop R – The Fail**: As the police at the protest increase and send people home, the core issue that the protest was for, is not resolved and the protestors' anger is repressed. In time the increased repressed anger (+) leads to even

more people attending the protests (+), which leads to more police (+) required and even more anger (+). The end result is that there are no negative connections which define the loop as Reinforcing. The connection to people at protest is (+) which leads to an expected loop behaviour of R+.

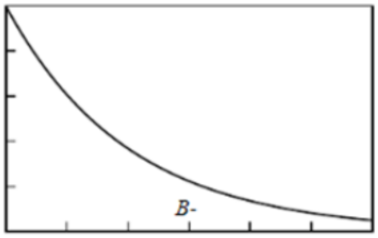


Figure 10.3: Expected Loop Behaviour for Fix (Balancing Loop)

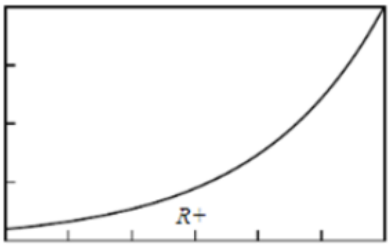


Figure 10.4: Expected Loop Behaviour for Fail (Reinforcing Loop)

The two loops are thus in direct competition with each other on the same variable: people at protest. The nature of the fixes that fail archetype tends to indicate that as time proceeds, the Fail (R+) behaviour starts dominating the structure.

10.1.3 Step 3: Stocks and Flows

10.1.3.1 <u>Snapshot test (3.1):</u>

When time freezes all the variables listed in the CLD (Figure 10.2) will remain: people at protests, police at protests and the repressed anger (tension). These will thus become the stocks.

10.1.3.2 <u>Test stocks for nouns (3.2):</u>

- People at Protests: The word “People” is a collective noun, with dimension number of people.
- Police at Protests: Police is a collective noun, with dimension number of police.
- Repressed Anger: Anger is an abstract noun and thus qualitative and dimensionless (anger)

10.1.3.3 <u>Test each loop for stocks (3.3):</u>

- Loop B: Police at Protest and People at Protests (2 stocks)

- Loop R: Police at Protest, People at Protests and Repressed anger (3 stocks)

10.1.3.4 <u>Identify the flows (3.4):</u>

Three stocks exist, each with its own flows:

- People at Protest:
    - Inflow: People joining the protest
    - Outflow: People forced home due to police
    - Outflow: People finishing protest and leaving
- Police at Protest:
    - Inflow: Deploy Police
    - Outflow: Police Returning
- Repressed Anger:
    - Inflow: Fundamental problem causing anger
    - Inflow: Anger repression due to police forcing people home
    - Outflow: Anger expressed and released at protest

10.1.3.5 <u>Delays and aging chains (3.5):</u>

People at Protest:

The people attending the protest is the end result of a chain of stocks. In this case it is assumed that people are originally peaceful then become angry and the angry people will attend the protests. The *people at protest* stock should thus be aggregated as:

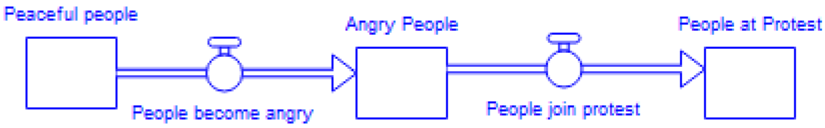


Figure 10.5: Delay Chain of peaceful to protesting people

Police at Riots:

In a similar sense the police that are going to the protest needs to be available first. After the police were at the protest, they will return to being available. As such the one stock becomes two interconnected stocks:

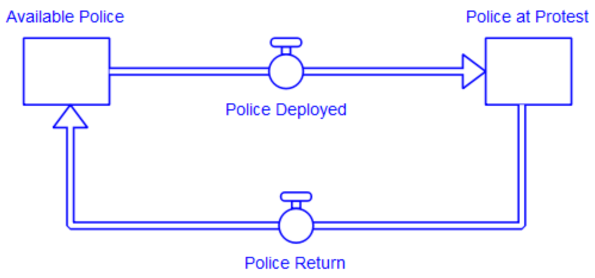


Figure 10.6: Delay chain of police deployment

Repressed Anger:

The repressed anger is kept as a simple one dimensional stock even though in psychological terms there are multiple processes taking place to reach repressed anger. In the context of the purpose and scope of the simulation, it is assumed that repressed anger is sufficient as a singular stock.

10.1.4 Step 4: Basic Stock and Flow Diagram

10.1.4.1 System Architecture Map (4.1):

Combining the stocks and flows identified in the previous step with the connections highlighted in the causal loop diagram the following sub-system diagram or alternatively referred to as the system architecture map can be seen below:

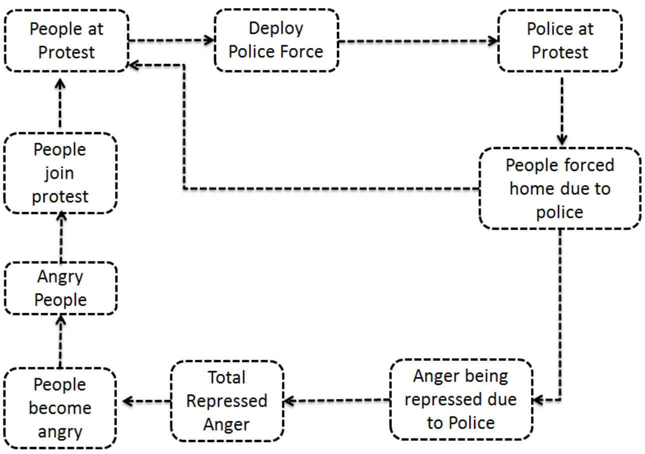


Figure 10.7: System Architecture Map model of Fixes that Fail

The individual stock and flow structures given in step 3.5 can then be connected using the SAM above and create the basic connected Stock and Flow Diagram in step 4.2.

10.1.4.2 Separate Stock and Flows (4.2):

Seen in step 3.5.

10.1.4.3 Merge to one Stock and Flow Diagram (4.3):

The combined diagram is captured below in Figure 10.8.

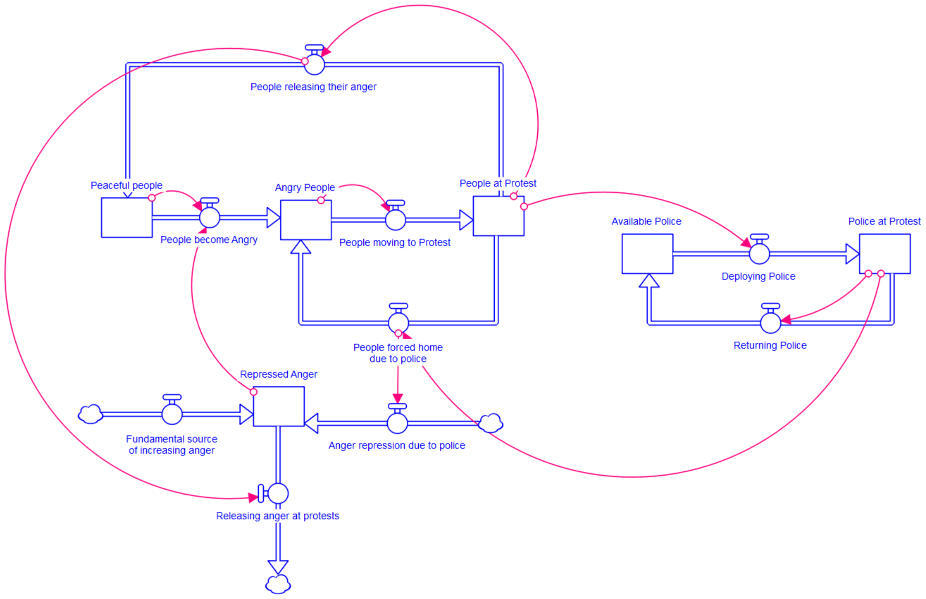


Figure 10.8: Basic Stock and Flow diagram of Policing Protests

10.1.5 Step 5: Dimensional Analysis

Allocate dimensions to the stocks, flows and rest of the simulation variables found in the basic stock and flow diagram.

10.1.5.1 Stock Dimensions (5.1):

- **Number of people:** peaceful, angry and protesting people stocks.
- **Number of police:** available police and police at protest
- **Anger** (qualitative non-dimensional): repressed anger stock.

10.1.5.2 Flow Dimensions (5.2):

- **Number of people per month:** people become angry, people moving to protest, people forced home and people releasing their anger.
- **Number of police per month:** deploying police and returning police.
- **Anger per month:** fundamental source of increasing anger, anger repression due to police and releasing anger at protests.

10.1.5.3 Complete Dimensions (5.3):

- Currently there are no other variables

10.1.5.4 Dimensional Gaps (5.4):

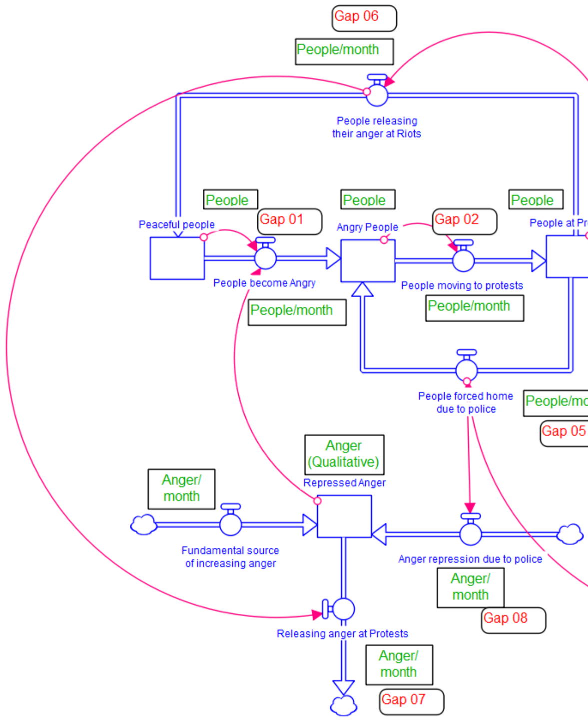


Figure 10.9: Gaps in Dimensions

The dimensional gaps are identified in Figure 10.9 and the associated equation (Ex) are derived from Appendix 1-A. For example, E1 refers to the first equation found in Appendix 1-A.

1) Gap 01: Needs a Multiplier to convert Anger (max anger) as well as a normal rate (maximum rate of movement), E4. The multiplier of max anger, creates an effect variable multiplied with normal rate.
2) Gap 02: Needs a time divider, time taken to form protest, E2
3) Gap 03: Needs a normal rate per person at protest, E1
4) Gap 04: Needs a time divider, assignment durations, E4
5) Gap 05: Needs a normal rate, people movement rate per police officer, E1
6) Gap 06: Needs a time divider, time taken to release anger, E2
7) Gap 07: Needs a multiplier, anger per person at protest, E1
8) Gap 08: Needs a multiplier, anger per person at protest, E1

The anger per person at protest, should be a division between repressed anger (total anger) and number of people at protest. This formula would produce the average anger per person.

10.1.6 Step 6: Mathematical formulation

10.1.6.1 <u>Missing Variables (6.1):</u>

1) Gap01: **Maximum anger** is required to change the repressed anger into a non-dimensional variable that can be used in an effect translation. (anger)
2) Gap01 (2): The maximum rate of people becoming angry, is defined as **the maximum percentage of angry people growth**. (% per month)
3) Gap02: The time for people to attend protests, is defined as the **average time taken to form a protest**. (Months)
4) Gap03: The normal rate per person at riot is defined as the **Police deployment rate per protestor**. (police/month per person)
5) Gap04: The **police assignment duration** is define as how long the police stays at the protest (months).
6) Gap05: The normal rate is defined as the **protest control rate per police officer**. The variable is a direct indication of the amount of force used by the police (people controlled/month per police officer)
7) Gap 06: The time taken to release anger (months).
8) Gap 07: In order to determine how much anger is released when a person leaves, the **anger per protestor** is required (anger/person)
9) Gap 08: In order to know how much anger is repressed, the **anger per protestor** is required again (anger/person)

10.1.6.2 <u>Effect Variables (6.2):</u>

It is only Gap01 that needs an effect variable that connects the repressed anger to the people becoming angry. The creation process of this effect variable is given below and based on Appendix 1-E:

1) The name: The effect of repressed anger on angry people transitioning
2) The X/Y Coordinate system:
   a. X – Repressed Anger divided by Maximum Anger (non-dimensional)
   b. Y – Effect on people becoming angry (non-dimensional multiplier)
3) Define the three points:
   a. When repressed anger is 0, the effect should be 0.
   b. When repressed anger is at 50%, it is assumed that people would get angry just below half the maximum rate, which leads to a slight exponential curve.
   c. When repressed anger is 1, then effect should be 1.
4) Connect the points to produce the final graph:

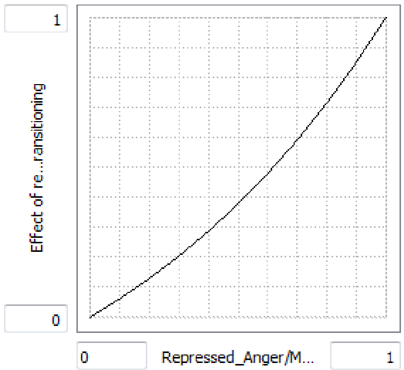


Figure 10.10: Effect variable in Fixes that Fail

5) Define the minimum and maximum values:

Repressed Anger:

Min = 0; Max = 100

Effect on multiplier:

Min = 0; Max = 1.

10.1.6.3 <u>Equation Formulations (6.3):</u>

Merging the ideas above with the generic equations as given in Appendix 1-A, the following equations were created:

1) $People\ become\ Angry = Effect\ of\ repressed\ anger\ \times Peaceful\ people\ \times Max\ percentage\ angry\ people\ growth$
2) $People\ moving\ to\ protests = \frac{Angry\ People}{Avg\ time\ taken\ to\ form\ a\ protest}$
3) $Deploying\ police = \ Police\ deployment\ rate\ per\ protestor\ x\ People\ at\ protest$
4) $Returning\ Police = \frac{Police\ at\ Protests}{Police\ Assignement\ Durations}$
5) $People\ forced\ home\ due\ to\ police = Protest\ control\ rate\ per\ police\ officer\ \times Police\ at\ Protests$
6) $People\ releasing\ their\ anger\ at\ riots = \frac{People\ at\ protests}{Time\ taken\ to\ release\ anger\ at\ protests}$
7) $Releasing\ anger\ at\ protest = Anger\ per\ protestor\ \times people\ releasing\ their\ anger\ at\ protests$
8) $Anger\ repression\ due\ to\ police = Anger\ per\ protestor\ \times people\ forced\ home\ due\ to\ police$
9) $Anger\ per\ protestor = \frac{Repressed\ Anger}{People\ at\ Protest}, as\ long\ as\ people\ at\ protest > 0$

10.1.6.4 Stock Stages / Aging chains (6.4):

The stage fraction equations have already been defined in equations 1 to 6 seen above, step 6.3.

10.1.6.5 Final Dimension Checks and Multipliers (6.5):

All the dimensions were rechecked and found to be in order. No additional conversion multipliers for dimensional consistency are needed.

The final list of variables, their definitions and dimensions can be seen below.

Table 10.1: Variable table for Fixes that Fail Simulation

Variable Name	Description	Dimension
Maximum Anger	The anger value at which the maximum growth rate in angry people will take place.	Anger [qualitative]
Max percentage growth of angry people	The maximum percentage movement from peaceful to angry people in one month.	% per month
Average time taken to form a protest	The time taken for angry people to establish and attend a protest.	months
Police deployment rate per protestor	The rate at which the police force will deploy officers to the protest site, depending on the number of protestors at the site.	Police/month/person
Police assignment duration	The time that a police officer will be assigned to the protest control area.	Months
Protest control rate per police officer	The rate at which one police officer can move protestors away from site. This can be associated with the extent of force used.	People/month/police
Time taken to release anger at protest	The time taken for the protestors to calm down after protesting.	Months
Anger per protestor	The average distribution of all the groups anger into individual protestors.	Anger/person

In the next step the detailed stock and flow diagram can be found, which is a blueprint used in model construction.

10.1.7 Step 7: Detailed Stock and Flow Diagram

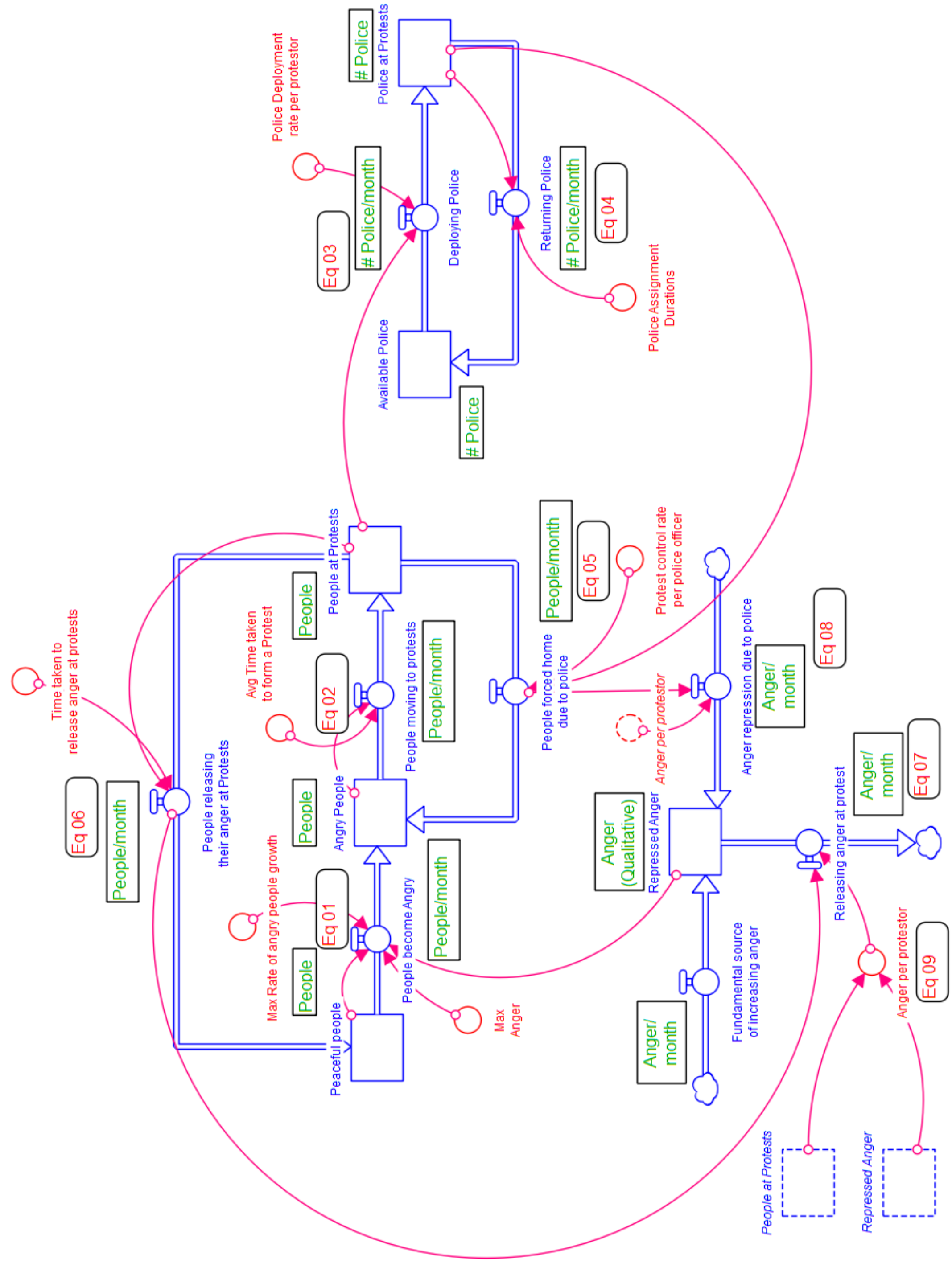


Figure 10.11: Detailed Stock and Flow Diagram of the Fixes that Fail Simulation

10.1.8 Step 8: Small loop models and validation

10.1.8.1 Smallest Loop (8.1):

The smallest loop identifiable in the CLD is the Balancing loop: The Fix

10.1.8.2 Construct Loop (8.2):

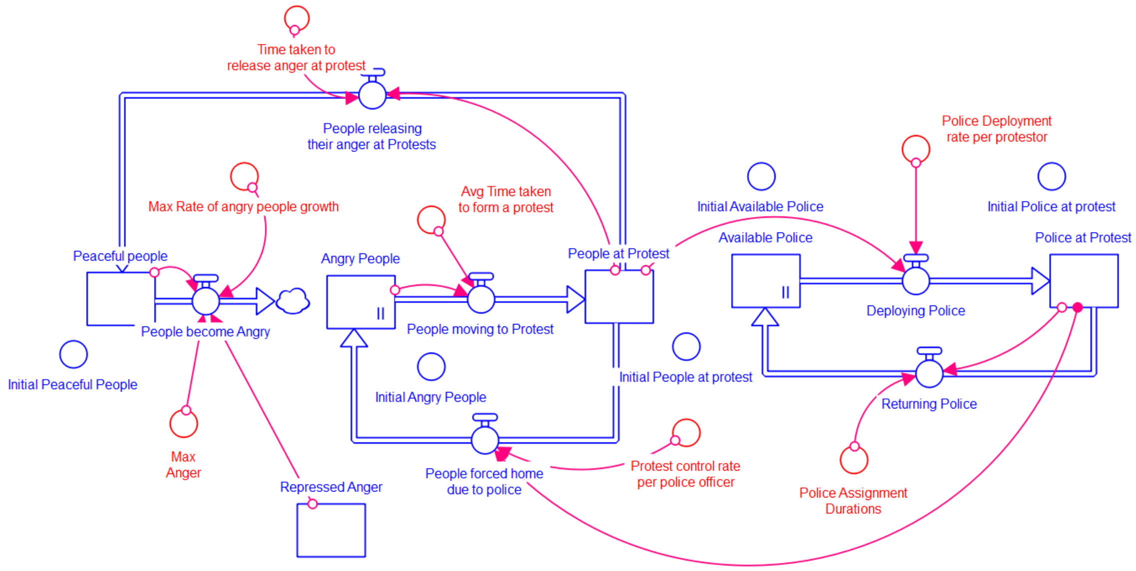


Figure 10.12: Smallest loop constructed into simulation format

10.1.8.3 Define constants (8.3):

Stocks (Chose simple arbitrary values like 0, 10, 100 and 1000. Each new value is chosen in relation to the value already chosen for the preceding variables):

Initial Peaceful people – 1000

Initial Angry people – 100

Initial People at protest – 0

Initial Available police – 100

Initial Police at protest – 0

Repressed Anger - 10

Other Variables (Red):

Max Anger – 100

Max Rate of Angry People growth – 10

Average Time taken to form protests – 10

Police Deployment rate per protestor – 0.2 [1 for every 5 protestors]

Police assignment durations – 3

Protest control rate per police officer – 5 [1 officer can control 5 protestors]

Time taken to release anger - 2

10.1.8.4 Test Atomic behaviours (8.4):

The result for the number of people at the protest is seen in the graph below.

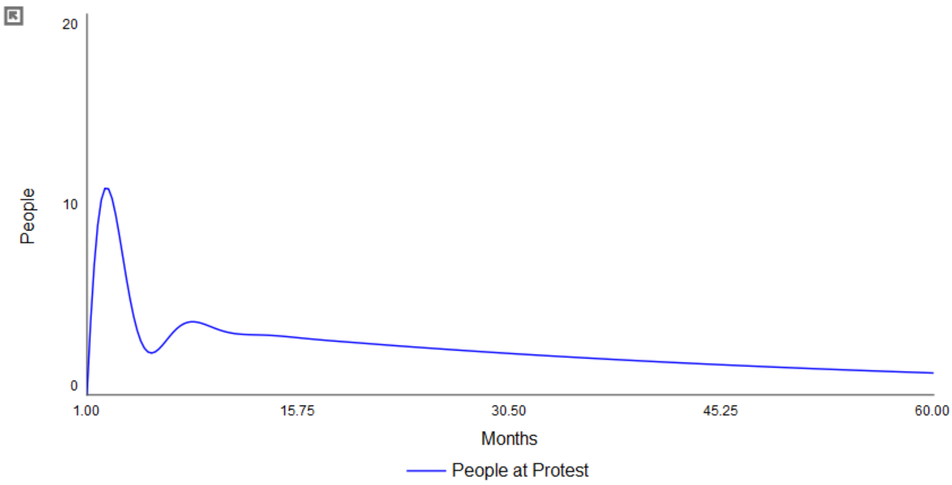


Figure 10.13: Smallest loop constructed into simulation format

The behaviour of this loop in isolation fits closely with the B- behaviour as seen in step 2.3. The major difference being the initial oscillation taking place as it takes time for police to be deployed.

10.1.8.5 Next loop (8.5):

No new stocks are required, only the equations that are already defined in step 6 needs to be added to the previous loop.

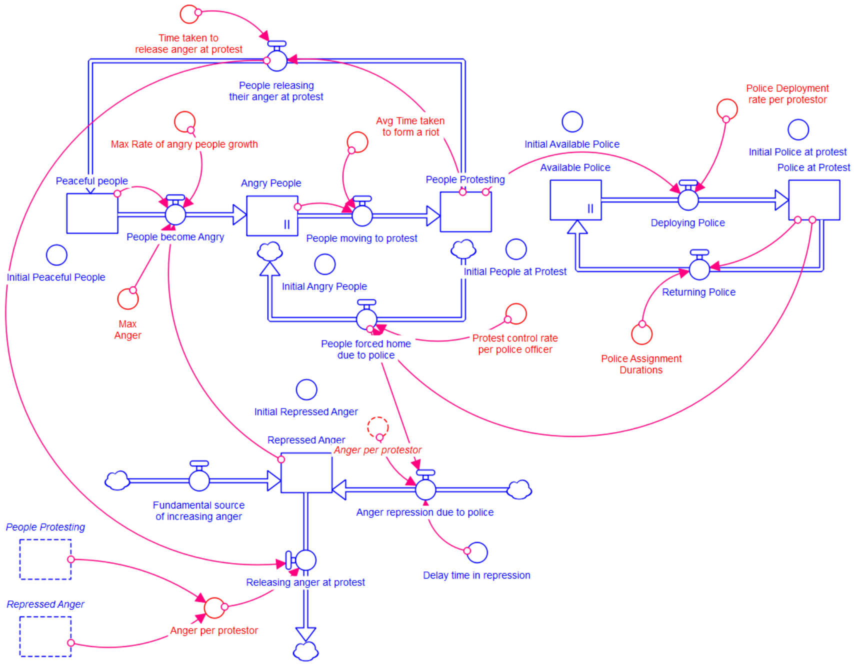


Figure 10.14: Second Loop Construction of Fixes that Fail

The complete structure is now built, yet some of the flows are disconnected in order to test only the reinforcing loop behaviour. The disconnected flows are the flows starting at people protesting and ending at angry people. The time taken to release anger at protest was increased to 100 M, in order to negate the return to peaceful, which is not found in the original CLD.

The result of people and anger is shown in the diagram below.

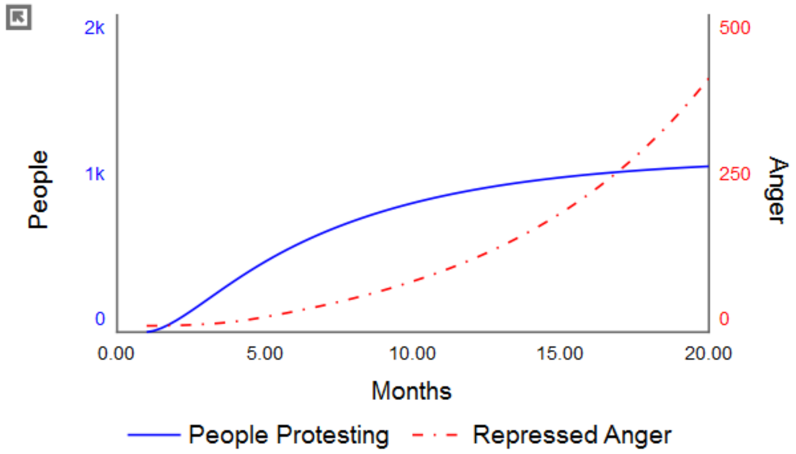


Figure 10.15: Second Loop Simulation result

The anger is growing exponentially as the R+ defined in the causal loop diagram evaluation, yet the people protesting is initially growing exponentially and then tapers down. The reason for this tapering down is due to the number of available people. Initially there were 1000 peaceful people and after the 20 months, almost every person has become part of the protest (no peacefull people left). This still resembles the reinforcing growth or R+ but with a limitation on the maximum people. If there was an infinite amount of people, the people protesting would keep growing exponentially.

10.1.9 Step 9: Integrated model testing and verification

10.1.9.1 Integration (9.1):

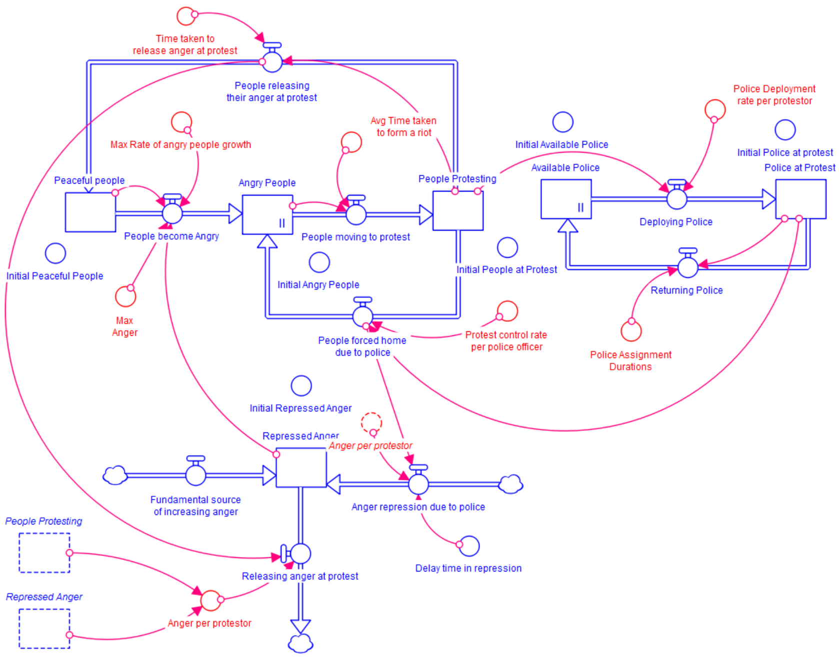


Figure 10.16: Integrated Fixes that Fail Simulation

10.1.9.2 Equilibrium test (9.2):

One of the theoretical static equilibrium points would be when there is no repressed anger, angry people or protesting people initially and there is nothing that is creating anger. As such the following changes are made to the inputs:

Initial angry people = 0

Initial repressed anger = 0

The peaceful people are kept at 1000, fundamental source of increasing anger are kept at 0, as well as the initial protesting people are kept at 0. Testing the model at these conditions shows the following results:

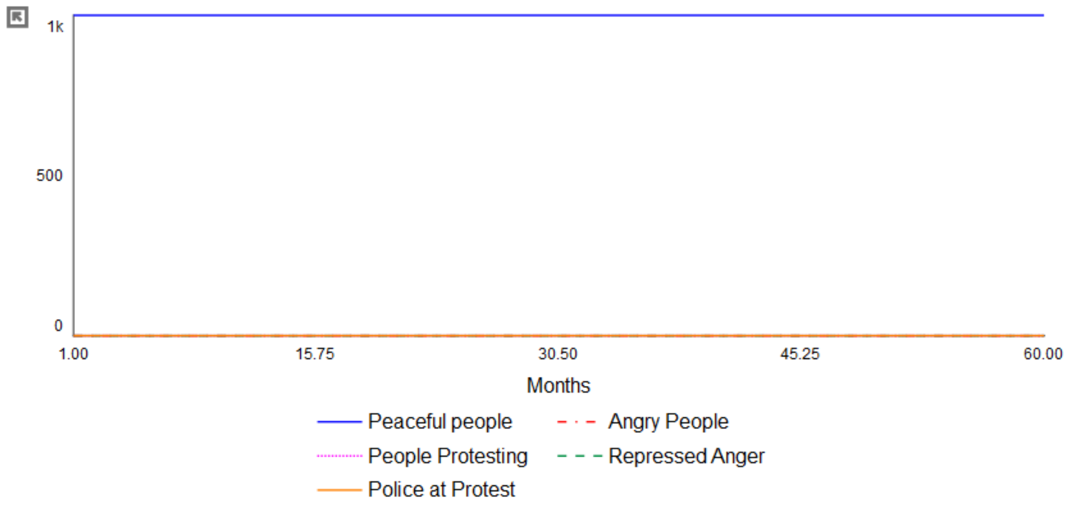


Figure 10.17: Equilibrium Fixes that Fail Simulation Test

The peaceful people are thus static at 1 000 throughout the simulation and none of the stocks are changing values. The model can thus replicate the static equilibrium point where the archetype is not engaged.

10.1.9.3 <u>Disturbance test (9.3):</u>

A hypothesis test will be conducted on the model that induces a pulse into the repressed anger. This can be thought of as an event that causes the community anger, similar to corruption, unequal treatment or police violence. A pulse is chosen to take place at a time of 20, a value of 5 and thereafter never takes place again. The first result shows the change in people distributions and the anger in the community:

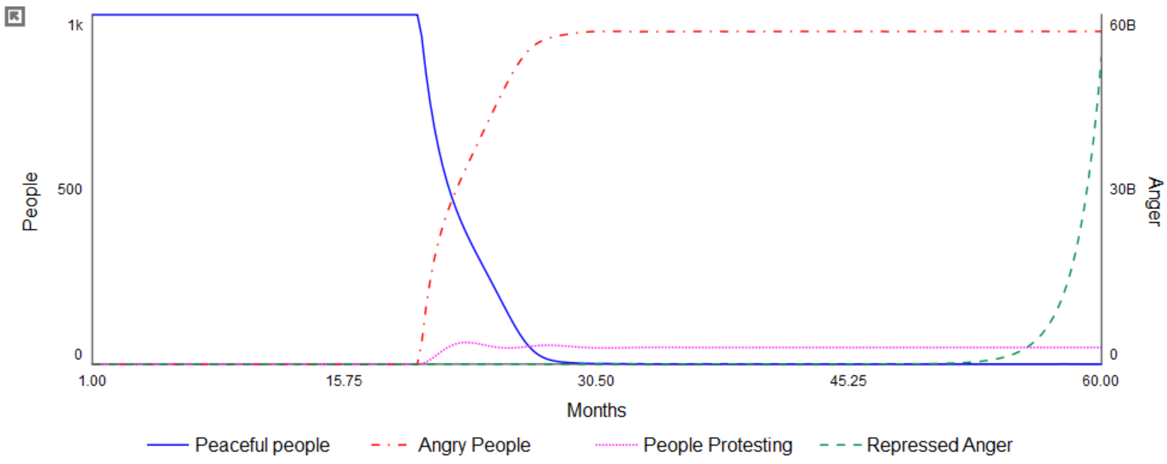


Figure 10.18: Disturbance result on people

The peaceful people are at 1000 until the pulse event takes place. After the event, people start becoming angry and protests start taking place. The protests reach the first maximum and then reduce again. It resurges a few months later and decreases slightly again. Yet there are constant protests taking place and the end result is that the whole community has transformed from being peaceful to being angry. The anger itself is also growing exponentially. The second graph below shows the behaviour of the police:

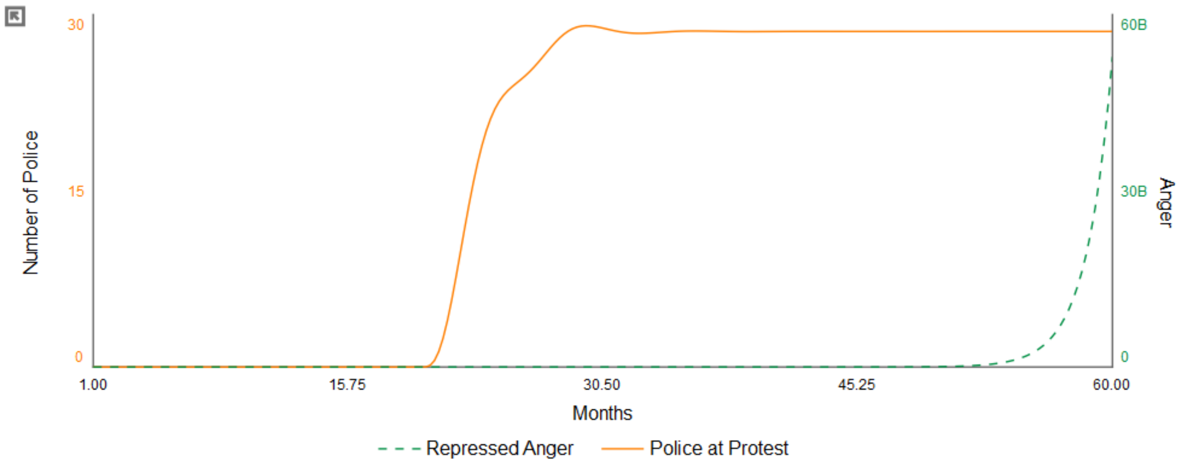


Figure 10.19: Disturbance result on police

The police force was not allocated to the protestors before time 20, as there were no protests taking place. After the pulse, police started being allocated to break up the protests. The protests was reduced temporarily, seen by the first maximum in the previous graph. However, the problem is not resolved and more police are required to manage the protesting situation. At the of the simulation run a constant police force is required to man the constant protests that are taking place, while the anger is growing exponentially.

In reality when anger levels would become this large, the protestor's violence or structural damage could start, which requires more policing but also the possibility of more violence against protestors. This is not explicitly explored in the model, yet it would be an interesting addition to the model.

10.1.9.4 <u>Reproduce Reference Mode (9.4):</u>

The behaviour identified in step 1, shows that the number of protests is increasing over time, yet there are fluctuations in those events. Removing the pulsed anger event from the simulation and choosing an initial repressed anger value of just 1 (with no fundamental source of anger increase) the following behaviour is obtained for the number of people protesting in the initial 1 000 peaceful people:

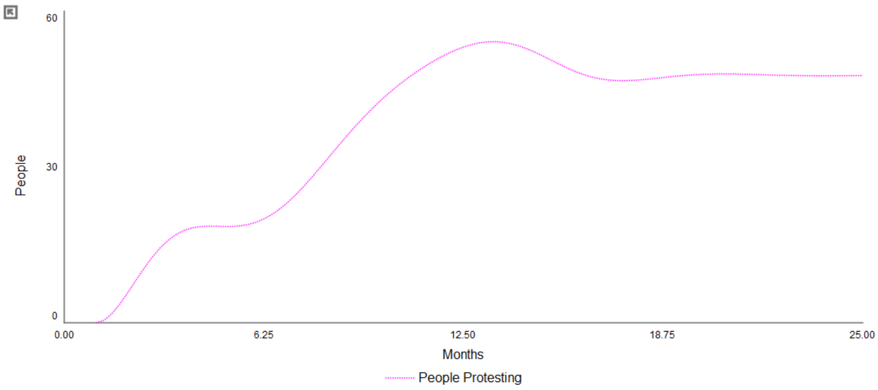


Figure 10.20: Structural increase in protesting people

The simulation behaviour also shows how protests are increasing due to the internal mechanisms and interactions between police and protestors. The initial trigger might be removed yet there is enough internal momentum to keep the archetype alive. The behaviour in Figure 10.20 compares well with the historical behaviour seen in Figure 2.3.

10.1.10 Step 10: Sensitivity Analysis

10.1.10.1 <u>Identify variables (10.1):</u>

The list of all the externally driven variables was defined in Table 10.2. Each variable was tested and three variables were identified with a reason why:

Table 10.2: Identification of all Fixes that Fail Input Variables

Variable Name	Value	Units	Chosen	Reason
Maximum Anger	100	Anger [qualitative]	No	
Max percentage growth of angry people	10	% per month	Yes	This is the mesaurement of the communities' inherent volatility to become angry. This is an argument often used by critiques on communities protesting
Average time taken to form a protest	6	months	No	
Police deployment rate per protestor	0.2	Police/month/person	No	
Police assignment duration	3	Months	No	
Protest control rate per police officer	5	People/month/police	Yes	The force that police use have historically been viewed as part of the problem and policy intervention point
Time taken to release anger at protest	2	Months	No	
Fundamental anger increase	0	anger/month	Yes	This is the fundamental source of anger creation like corruption. Surely a policy point, yet difficult to implement to 0
Initial Peaceful	1000	people	No	
Initial Angry people	0	anger	No	
Initial Protestors	0	people	No	
Initial available Police	100	people	No	
Initial Police at Protest	0	police	No	
Initial Repressed anger	0	anger	No	

The three chosen variables are thus:

1) Maximum percentage growth of angry people (akin to the volatility of the community)
2) Protest control rate per police officer (akin to the amount of force police are using)
3) Fundamental anger increase (akin to the original source of anger induction i.e. corruption)

10.1.10.2 Sensitivity Range (10.2):

The sensitivity range is selected at 95% lower and higher. The base, minimum and maximum values were captured in Table 10.3 below

Table 10.3: Sensitivity range of Fixes that Fail

Sensitivity Range of 95%			
Variable name:	Initial Value:	Min	Max
Max percentage growth of angry people	10	0.500	19.500
Protest control rate per police officer	5	0.250	9.750
Fundamental anger increase	1	0.050	1.950

10.1.10.3 Sensitivity Points (10.3):

The sensitivity point values are determined by using the max and min values divided by the number of runs minus one. In this case the number of runs were arbitrarily chosen as 5. The values for each of the three scenarios for each of the 5 runs were captured in Table 10.4 below.

Table 10.4: Sensitivity Points for Fixes that Fail Simulation

	Sensitivity Points	Value for each run#				
Scenario	Variable name:	1	2	3	4	5
1	Max percentage growth of angry people	0.500	5.250	10.000	14.750	19.500
2	Protest control rate per police officer	0.250	2.625	5.000	7.375	9.750
3	Fundamental anger increase	0.050	0.525	1.000	1.475	1.950

10.1.10.4 Analysis (10.4):

Community Volatility:

The initial maximum percentage growth of angry people were 10%, which was linearly increased from 0.5% to 19.5% in 5 different simulation runs. The results from these runs was captured in Figure 10.21:

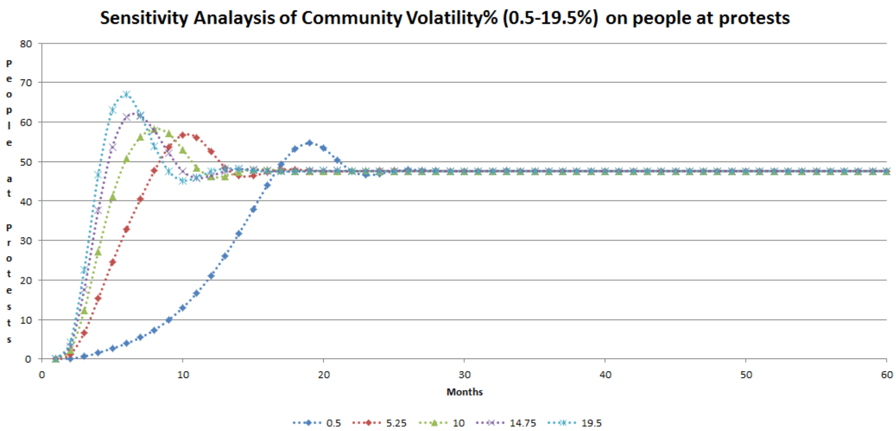


Figure 10.21: Sensitivity on Volatility

The interesting phenomena here is that it seems like no matter how quickly the community becomes angry, the final number of protests remain the same. Another interesting deduction is that the more volatile the community (larger percentage rate), the faster the equilibrium is obtained and suggests that communities that take longer to become angry might take longer to resolve conflicts, yet end up in the same position. It seems that the reactivity of communities should be higher since the end results are the same, yet reached faster. The sensitivity table below (Table 10.5) confirms that there are no changes to the final equilibrium points:

Table 10.5: Sensitivity Table for Volatility

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-95%	-48%	0%	48%	95%
Final Percentage effect	0%	0%	0%	0%	0%

Extent of Police Control:

The protest control rate per police officer was initially 5 but now varied between 0.25 and 9.75. The results for the analysis is found below in Figure 10.22:

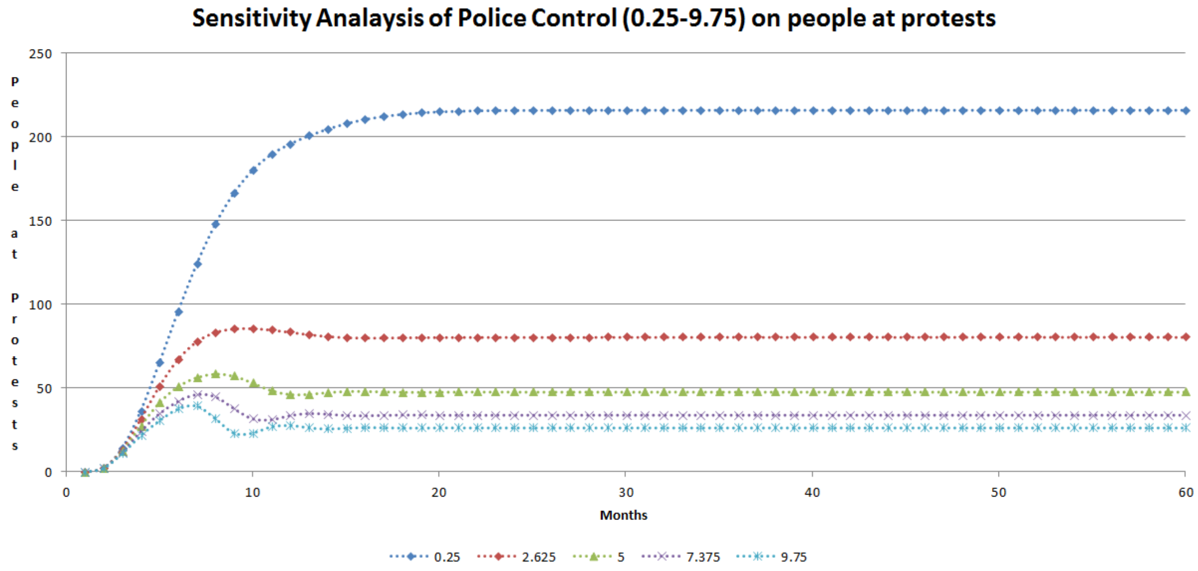


Figure 10.22: Sensitivity on Police Control (Force)

The interesting observation here is that the less police control is used, the more people protest and the protest group grows drastically between the policing control rates. The smaller the controls however, the smoother the transition between equilibrium points, as with the 9.75 control, there seems to be three oscillations. The final percentage effect changes are seen in Table 10.6.

Table 10.6: Sensitivity Table for Police Control (Force)

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-95%	-48%	0%	48%	95%
Final Percentage effect	353%	69%	0%	-29%	-45%

The first observation is that the relation between cause and effect is opposite in nature meaning that the larger the control exercised, the smaller the protestor groups become. The second is that beyond a certain level of control, the effect diminishes on the group's size which shows that even if extreme force is used, it will never be able to reduce protests to nothing. The final observation is that reducing the control has a much stronger impact on the protests, which suggests that if no police force is used, that protestor groups would grow incredibly large and create more risks.

Fundamental Sources of Anger:

The *fundamental source of anger increase* was initially at 1 anger increase per month. The value was then varied between 0.05 and 1.95 incrementally and the results were captured in Figure 10.23. As the variables represent the fundamental source of the anger, it is expected that as the fundamental source decreases, that the protests will also decrease and less protests take place. The results show the following:

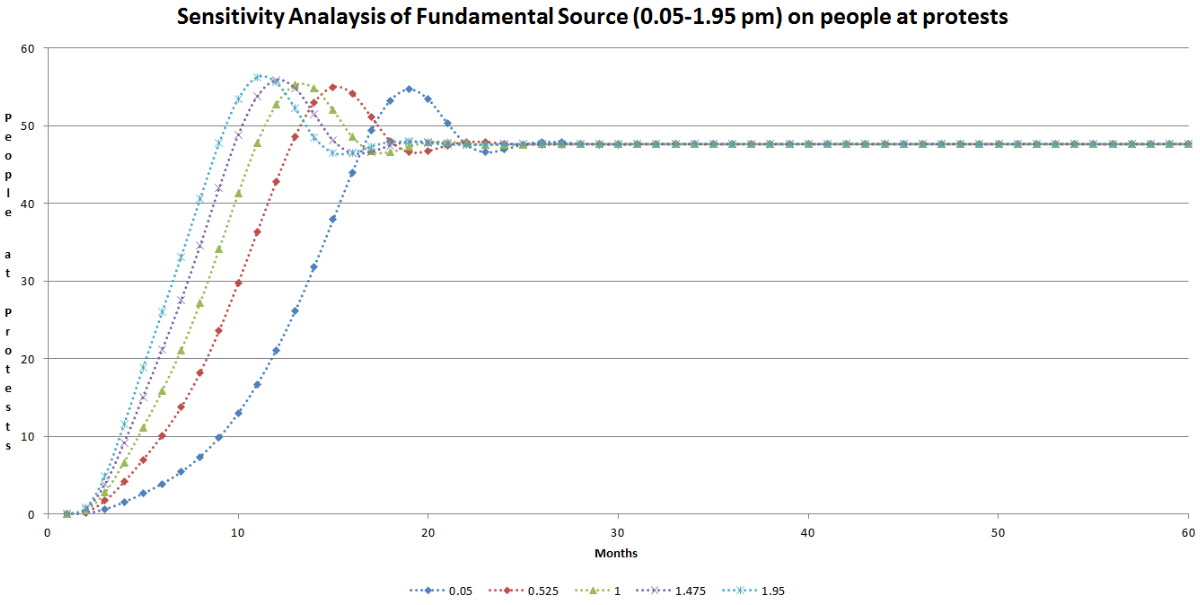


Figure 10.23: Sensitivity on Fundamental Source of Anger

The counterintuitive results show that changes made in the fundamental source of anger, does not make an impact on the final number of protests. It does indicate that as the source increases, the time when the peak protestors are reached, actually decreases, from around month 10 for 1.95 to month 20 for 0.05.

It is quite apparent that there seems to be no difference between the different runs of this scenario. The sensitivity table for the scenario is seen in Table 10.7.

Table 10.7: Sensitivity Table for Fundamental Source of Anger

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-95%	-48%	0%	48%	95%
Final Percentage effect	0%	0%	0%	0%	0%

The table confirms that there is no measurable difference between the different parameter runs after 60 months.

10.1.10.5 Ranked Leverage Points (10.5):

In the simulation, the leverage rankings of the variables investigated are:

1) **Extent of police control** – The force of police control utilised has the largest impact on the behavioural change and is a direct consequence of government policy and decision. This is the strongest lever identified yet.

2) **Community Volatility** – The volatility of communities are not directly within the control of government yet it tends to indicate that even if communities are very volatile or not, the end result will remain the same when the strategy of police brutality is used.
3) **Fundamental anger source –** The initial source of anger is the least strongest lever in the system. This means that even if the initial source of the anger is resolved when the strategy of using police force to control protestors are continued, the protests will grow independently from the original source of anger.

10.1.11 Step 11: Emerging Lessons

The simulation was then reinitialized to start from an equilibrium point by changing the 'fundamental anger increase' back to 0. In step 10 it was interesting to see that the structure only needed a slight push to initiate the system archetype that can produce very strong behaviours. It is similar to how one small change in air flow, could create a completely different weather pattern due to the complex chaotic nature of weather systems. The behaviour here is not as complex as weather yet it does show the inertia in the system is kept due to the structure within it and not due to external drivers.

10.1.11.1 <u>Emerging Insights (11.1):</u>

The simulation model reveals the following interesting scenarios:

- **Inherent Volatility of people**: The first sensitivity analysis showed that as long as groups are able to become angry, the rate at which they become angry is not a leverage point in the system. The rate might affect how fast the new equilibrium is reached, yet it does not influence the final equilibrium point. It almost seemed like it would be better for communities react faster to excel the transition process.
- **The extent of force used by police**: The analysis on the protest control rate per police officer revealed that this was one of the strongest leverage points in the system. It was true that as the force increased, that the final equilibrium number of protestors decreased, yet the suppressed anger increased exponentially. The end result may be less protests, yet it also reveals that the whole community has transitioned from peaceful to angry and protests will continually take place. In reality the protests will most likely become violent which creates many more problems which are not simulated by the model.
- **The fundamental source of anger**: The analysis on the fundamental anger increase revealed that as long as there is an initial amount, even if small, the

system archetype is triggered and the internal workings of the structure manifests. Once the archetype is in motion, relieving the original source of anger while keeping the policing structures in place, would not stop the archetype's destructive force.

- **Overall analysis**: According to Meadows (2008) one of the best ways to face the Fixes that Fail Archetype is to let go, i.e. stop controlling the system. In the system the control is defined by the protest control rate. When the protest control rate per police officer is put to zero, the following scenario appears:

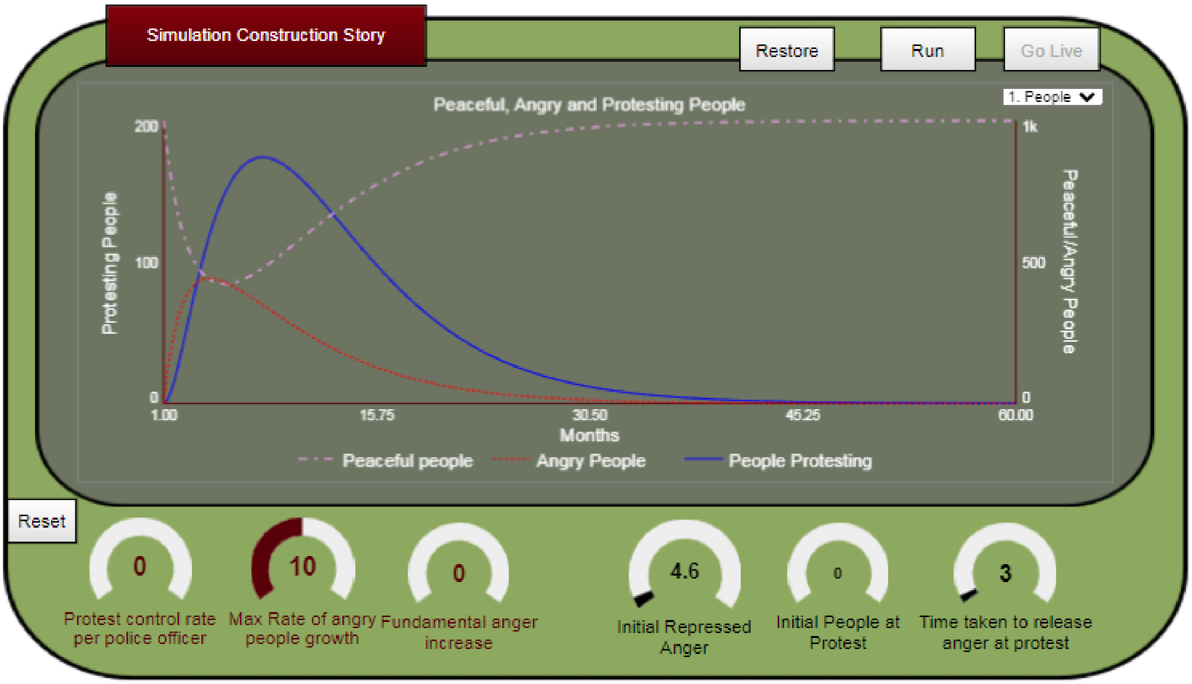


Figure 10.24: Simulation Interface of Fixes that Fail

It is interesting to note that initially the angry people and protesting people increase drastically, yet allowing people to protest, hearing them out, allows them to release the frustration that is building up in the community and the media to voice their concerns/challenges. As people are being heard and action is taken to address the concerns, the anger reduces and after some time, the protests decrease. The solution thus fits very well with Meadow's suggestion on how to counter the fixes that fail system archetype. The challenge with this approach is that it takes much longer than the police control scenario and it also assumes that authorities will listen and acknowledge the protestor's concerns. If the protestors are not heard, the time taken to release anger will increase drastically and the end result would be enormous protests and chaos.

10.1.11.2 System Leverage Points (11.2):

After creating the simulation interface and engaging with the model several times, two strong leverage points emerged:

1) **Protest control rate per officer:** As explained in step 11.1, the less violence that is used by police the better the long term result would be. The price however is that it will take much longer for the protests to calm down and there still needs to be systems in place where authorities hear and listen to the public outcry.
2) **Time taken to release anger at protest:** The variable relates to the protestors' outcries being heard and addressed. The more they are heard and addressed, the faster protestors would be able to release their anger and return to being peaceful. If the outcries are never heard by authorities, the protests will continuously grow without police control. The only way to manage the protests in a case where authorities do not listen, is to use extreme force which does reduce protests, but also creates more repressed anger and fear. There are multiple examples of these types of tyrannical government systems in the past and even today, which do work but not sustainably or equitably.

10.1.11.3 List of Variables (11.3):

The following are variables/concepts that emerged through the modelling process

Table 10.8: Table with major variables and definitions (Fixes that Fail)

Variable Name	Description	Dimension
Maximum Anger	The anger value at which the maximum growth rate in angry people will take place.	Anger [qualitative]
Max percentage growth of angry people	The maximum percentage movement from peaceful to angry people in one month.	% per month
Average time taken to form a protest	The time taken for angry people to establish and attend a protest.	months
Police deployment rate per protestor	The rate at which the police force will deploy officers to the protest site, depending on the number of protestors at the site.	Police/month/person
Police assignment duration	The time that a police officer will be assigned to the protest control area.	Months
Protest control rate per police officer	The rate at which one police officer can move protestors away from site. This can be associated with the extent of force used.	People/month/police
Time taken to release anger at protest	The time taken for the protestors to calm down after protesting.	Months
Anger per protestor	The average distribution of all the groups anger into individual protestors.	Anger/person

This concludes the simulation development of Fixes that Fail applied to Policing Protests.

APPENDIX 2-B: LIMITS TO GROWTH SIMULATION DEVELOPMENT

In this section, the LST method explained in Chapter 4 is applied to the Limits to Growth archetype. The general system archetype is specialised in the phenomena of how forest fires spread and die out.

10.1.12 Step 1: Problem Description

10.1.12.1 <u>Word Model (1.1):</u>

One of the applications of the Limits to Growth Archetype is Forest Fires (Systems And Us, 2020). The general definition is that a reinforcing loop will run into a resource constraint that creates a balancing loop.

The specific application chosen is the Forest Fire. Here is the word model (Systems And Us, 2020):

“A raging **forest fire** will continue to **expand** until it runs **out** of **fuel**”

10.1.12.2 <u>Behaviour over time (1.2):</u>

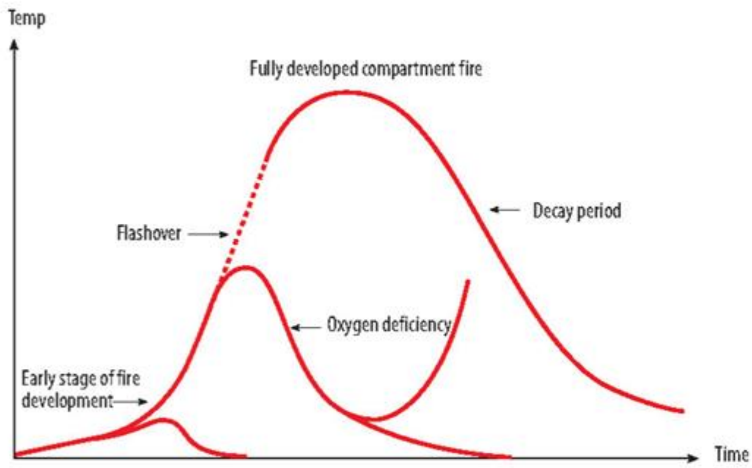


Figure 10.25: Pictograph of Fire Behaviours (Bengtsson, 2018)

10.1.12.3 <u>Purpose (1.3):</u>

Create a dynamic mathematical simulation by applying the LSTs unto the system archetype model of Limits to Growth applied to the Forest Fire. Can any new insight be gained from the simulation that might be counter-intuitive yet validated in reality?

10.1.12.4 Core Variables (1.4):

Available Trees (Fuel): The trees in the forest that are not on fire but can catch fire. (**Number of Trees)**

Trees on Fire (Forest Fire): The trees that are currently burning and that will burn out after some time (**Number of Trees**).

Fire Jumping to new Tree (Expand): The action where the fire spreads to an available tree, changing the available tree into a tree on fire (**Trees per hour**).

10.1.12.5 Time Frame (1.5):

- Forest Fires can last for days and possibly even weeks but not normally for more than months on end. As such the simulation time frame will be chosen as **one week** and modelled on an **hourly basis**, thus **169 hours**

10.1.13 Step 2: Causal Loop Diagram

10.1.13.1 Core Story (2.1):

The core story is how the small fire starts in a large forest. The fire then starts growing, first slowly but within a few hours it can spread exponentially across the forest. The fire however does start dying out as the amount of fuel in the forest becomes less and less, until there is not enough fuel to sustain the fire and it dies out.

10.1.13.2 Create Causal Loop Diagram (2.2):

The generic Archetype CLD structure is given next:

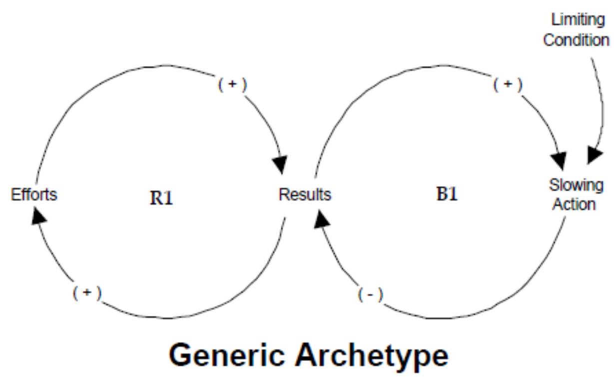


Figure 10.26: Limits to Growth General Archetype (Braun, 2002)

Considering the rules of CLDs, the first being that all variables should be nouns, the "efforts" and "slowing actions" are not. A noun relating to **efforts** might be the **"Worker/Grower"** and the **slowing action** might be the **"Obstacle/Slower"**.

Results: Trees on Fire

Grower: New Trees on Fire – The trees that has caught fire in the last hour.

Limiting Condition: Fuel in one tree has is being burnt up.

Obstacle: Scorched Trees – Trees that have completely burnt out and have no more fuel left to burn.

The specific applied CLD story is shown next.

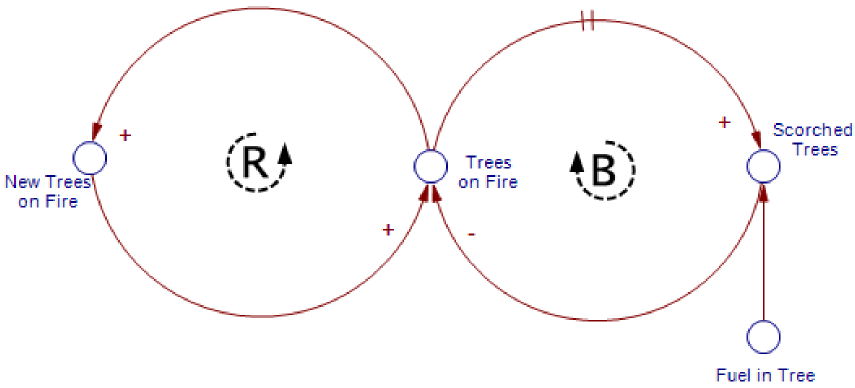


Figure 10.27: Limits to Growth Applied to Forest Fire

As the *number of trees on fire* **increases**, there are more trees able to spread the fire and such, there is an **increase** in *new trees on fire*. The more *new trees are on fire*, the **more** *trees are on fire*. This is the **Reinforcing** effect of the fire spreading.

Conversely, the **more** *trees that are on fire*, the **more** trees are burning. After some time the burnt trees run out of fuel and become *scorched trees*. The limit here is the *amount of fuel* in the tree that determines the how long the tree can stay on fire. As the *number of scorched trees* **increase**, **fewer** *trees are on fire*. This produces a **Balancing** effect on the system.

10.1.13.3 Atomic Loop Behaviours (2.3):

The R+ loop is the fire spreading loop. The fire grows exponentially as shown by the expected atomic behaviour below. The R+ loop can be allocated since the **interaction** between *New Trees on Fire* and *Trees on Fire* is **positive**, while the loop is overall **Reinforcing (R+):**

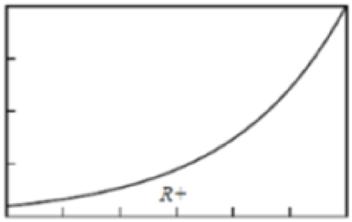


Figure 10.28: Reinforcing loop Expected Loop Behaviour

The B- loop is the fire running out of fuel resulting in scorched trees. The reduction in available fuel balances out the growth of the fire. The B- can be allocated since the interaction between *Scorched Trees* and *Trees on Fire* is **negative**, while the loop is overall **Balancing (B-):**

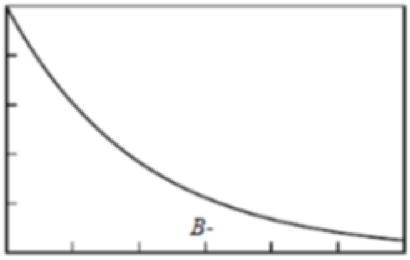


Figure 10.29: Balancing Loop Expected Loop Behaviour

10.1.14 Step 3: Stocks and Flows

10.1.14.1 <u>Snapshot test (3.1):</u>

1) Trees on Fire (**number of trees**)

2) Available Trees (**number of trees**)

3) Scorched Trees (**number of trees**)

10.1.14.2 <u>Test stocks for nouns (3.2):</u>

1) Trees on Fire: Common noun, which is visible and countable

2) Available Trees: Common noun, which is visible and countable

3) Scorched Trees: Common noun, which is visible and countable

10.1.14.3 Test each loop for stocks (3.3):

1) Balancing loop has two stocks: trees on fire and scorched and trees

2) Reinforcing loop has two stocks: trees on fire and available trees

10.1.14.4 Identify the flows (3.4):

New Trees on Fire: The flow will turn the available trees into trees that are on fire. The rate of this change is assumed to be linked to a fire spreading rate (fraction of trees on fire per hour):

Figure 10.30: Flow between available and trees on fire

Trees burning out: The trees only stay on fire for a certain time and then they die out. The change is thus driven by the average duration that the tree is on fire, which is directly related to the amount of fuel inside of an average forest tree.

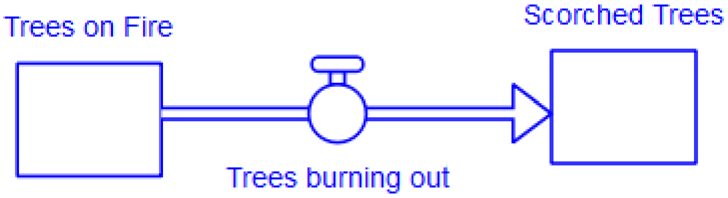


Figure 10.31: Flow between trees on fire and scorched trees

10.1.14.5 Delays and aging chains (3.5):

The available trees, trees on fire and scorched trees are already the aggregated process of the spread of fire and as such it is already accounted for. The two flows inbetween, especially the trees burning out, have delays associated with them (duration of tree on fire) that is will represent the delay seen in the balancing loop of the CLD in Step 2.

10.1.15 Step 4: Basic Stock and Flow Diagram

10.1.15.1 System Architecture Map (4.1):

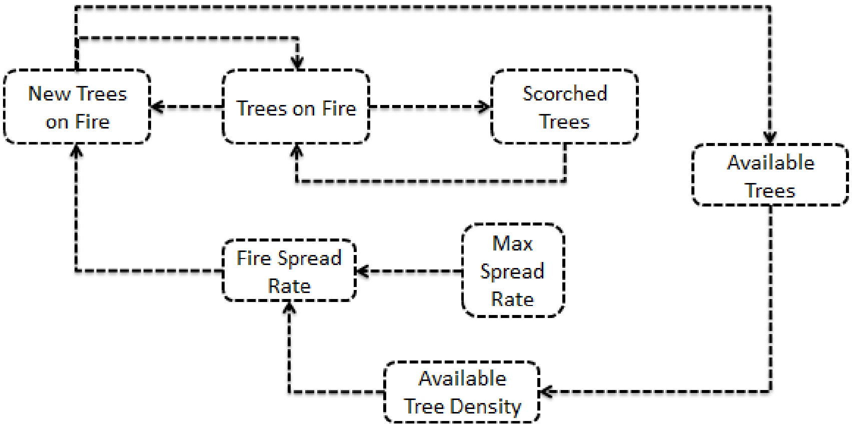


Figure 10.32: System Architecture Map for Forest Fire simulation

10.1.15.2 Separate Stock and Flows (4.2):

The separate stocks and flows are already defined in step 3.4.

10.1.15.3 Merge to one Stock and Flow Diagram (4.3):

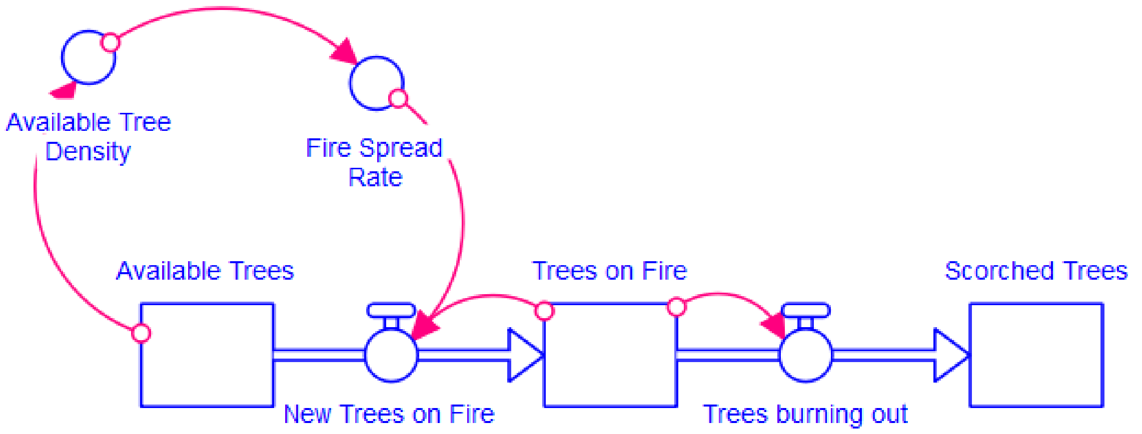


Figure 10.33: Basic Stock and Flow Diagram of Forest Fire simulation

New variables:

Fire Spread Rate: The fraction of the current trees on fire that spread fire to new trees every hour (**fraction of trees on fire per hour**).

Max Fires Spread Rate: The maximum fire spread rate of that tree type (fraction of trees on fire per hour)

Available Tree Density: The number of available trees over the forest area. (**Trees per m²**)

10.1.16 Step 5: Dimensional Analysis

10.1.16.1 Stock Dimensions (5.1):

Steps 5.1-5.3 is shown on the diagram below

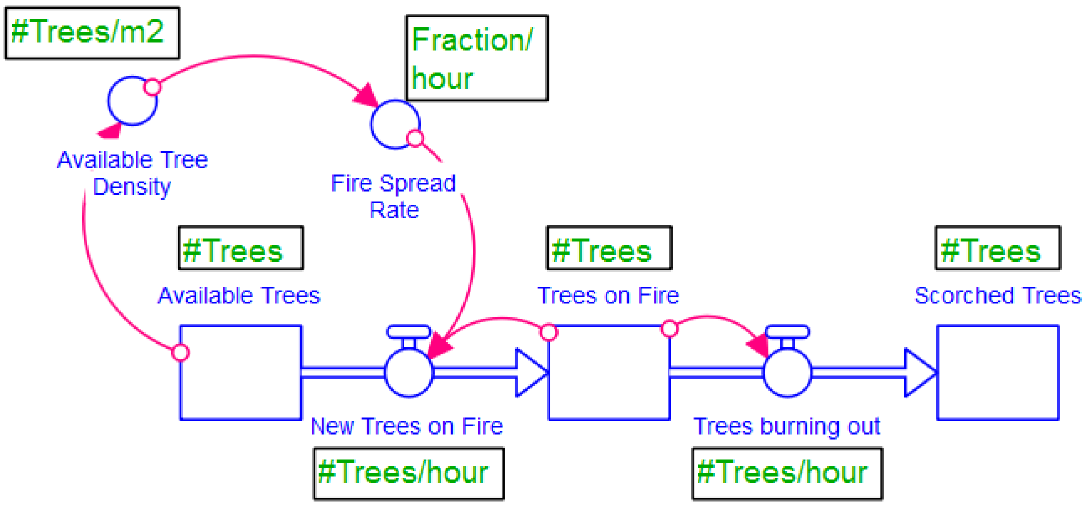


Figure 10.34: Identified all dimensions in basic stock flow diagram

10.1.16.2 Dimensional Gaps (5.4):

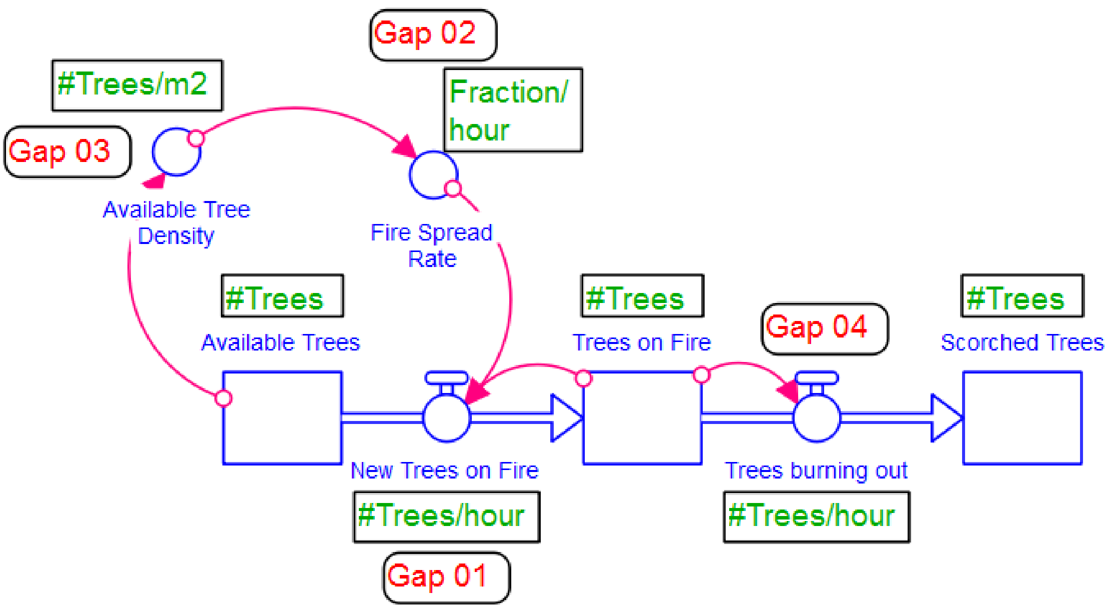


Figure 10.35: Dimension gaps between variables

The following Gaps are thus identified:

1) *New trees on fire* (#Trees/h) is a function of *Trees on Fire* (#Trees) and *Fire spread rate* (fraction/h). What should the equation be?
2) *Fire Spread rate* (fraction/h) is a function of *Available Tree Density* (#Trees/m2) which is completely different units
3) *Available tree density* (#Trees/m2) is a function of *Available Trees* (#Trees) only.
4) *Trees burning out* (#Trees/h) is a function of only *Trees on Fires* (#Trees)

10.1.17 Step 6: Mathematical formulation

10.1.17.1 <u>Missing Variables (6.1):</u>

1) Gap 01: New Trees on fire is function of a rate and trees on fire with dimension (**trees/hour**)

2) Gap 02: A missing conversion (effect) between density and fire spread rate. In order to use effect variables, the rate needs a maximum variable to transform it into a dimensionless effect. The Maximum fire spread rate is thus needed here (**fraction per hour**)

3) Gap 03: Available tree density needs the area in order to determine density **(trees/m^2**)

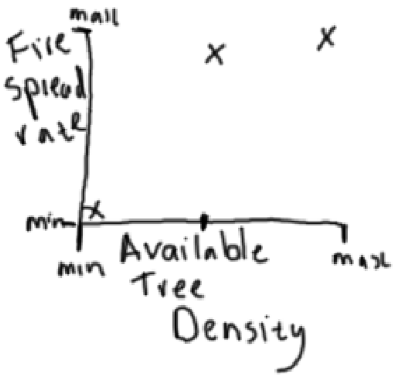
4) Gap 04: Trees burning out needs a division of time , which will be the duration (hours) that the average tree remains on fire (**trees/hour**).

10.1.17.2 <u>Effect Variables (6.2):</u>

Using appendix A (Equations) the following equations are formulated. Every *E#* references the equations in *Appendix A*. Like *E6* is the rate equation of *normal rate X effect multiplier* seen in Appendix A.

1) The first is an example of a normal rate increase like **E6**. Thus it is only the rate multiplied by the effect multiplier.
2) The *available tree density* has an effect on the *fire spread rate* that has <u>not been defined yet</u>. In this case, the definition needs to be made.
    a. Draw a **X/Y coordinate** with the *available tree density* as the x and the *fire spread rate* as the y:

3) Define **three points** on the graph:
    i. When available tree density is at its **max**
    ii. When available tree density is at its **min**
    iii. When available tree density is **halfway** between max and min



4) Connect the points in a **continuous function**:

5) Minimum and maximum values:
    a. Available tree density: Min = 0; Max = 1
    b. Fire Spread rate: Min = 0; Max = 2 per hour (It can triple the number of trees on fire within one hour)

10.1.17.3 <u>Equation Formulations (6.3):</u>

1) $New\ Trees\ on\ Fire = Fire\ spread\ rate\ \times Trees\ on\ Fire$
2) $Effect\ of\ density\ on\ fire\ rate = f(\frac{Available\ Tree\ Density}{Max\ Tree\ Density})$

3) $Fire\ Spread\ Rate = Effect\ of\ Density\ on\ Rate\ \times Max\ Fire\ Spread\ Rate$
4) $Available\ Tree\ Density = \frac{Available\ Trees}{Forest\ Area}$
5) $Trees\ Burning\ Out = \frac{Trees\ on\ Fire}{Tree\ Burning\ Duration}$

10.1.17.4 Stock Stages / Aging chains (6.4):

There inherently exists stages between the stocks and of the transitions in the stages has a time variable: New Trees on Fire has the maximum fraction of trees per hour, while trees burning out has the duration that the tree remains on fire.

10.1.17.5 Final Dimension Checks and Multipliers (6.5):

Additional equations that are simple arithmetic relationships:

5) The effect variable is **non dimensional** and thus the input (density) needs to be **normalized** by the division of the *maximum tree density* that is possible in the forest. (**E7**)
6) The **output** of the effect variable is also **non-dimensional** and thus needs to be multiplied by the maximum fire spread rate possible in the forest. (**E8**)
7) The *available tree density* needs the *forest area* (m^2) to ensure that the dimensions are balanced.
8) The *Trees burning out* needs a *time delay* which can be described by (**E2**).

New Variables:

- **Max Available Tree Density:** The maximum number of trees that will grow in 1 m^2.
- **Effect of Density on Rate:** The assumed qualitative (dimensionless) relationship between the tree density and the rate at which the fire spreads.
- **Forest Area:** The total area in m^2 that is in the boundary of the Forest
- **Tree Burning Duration:** The hours taken from when the tree is lit on fire to when it is scorched.

10.1.18 Step 7: Detailed Stock and Flow Diagram

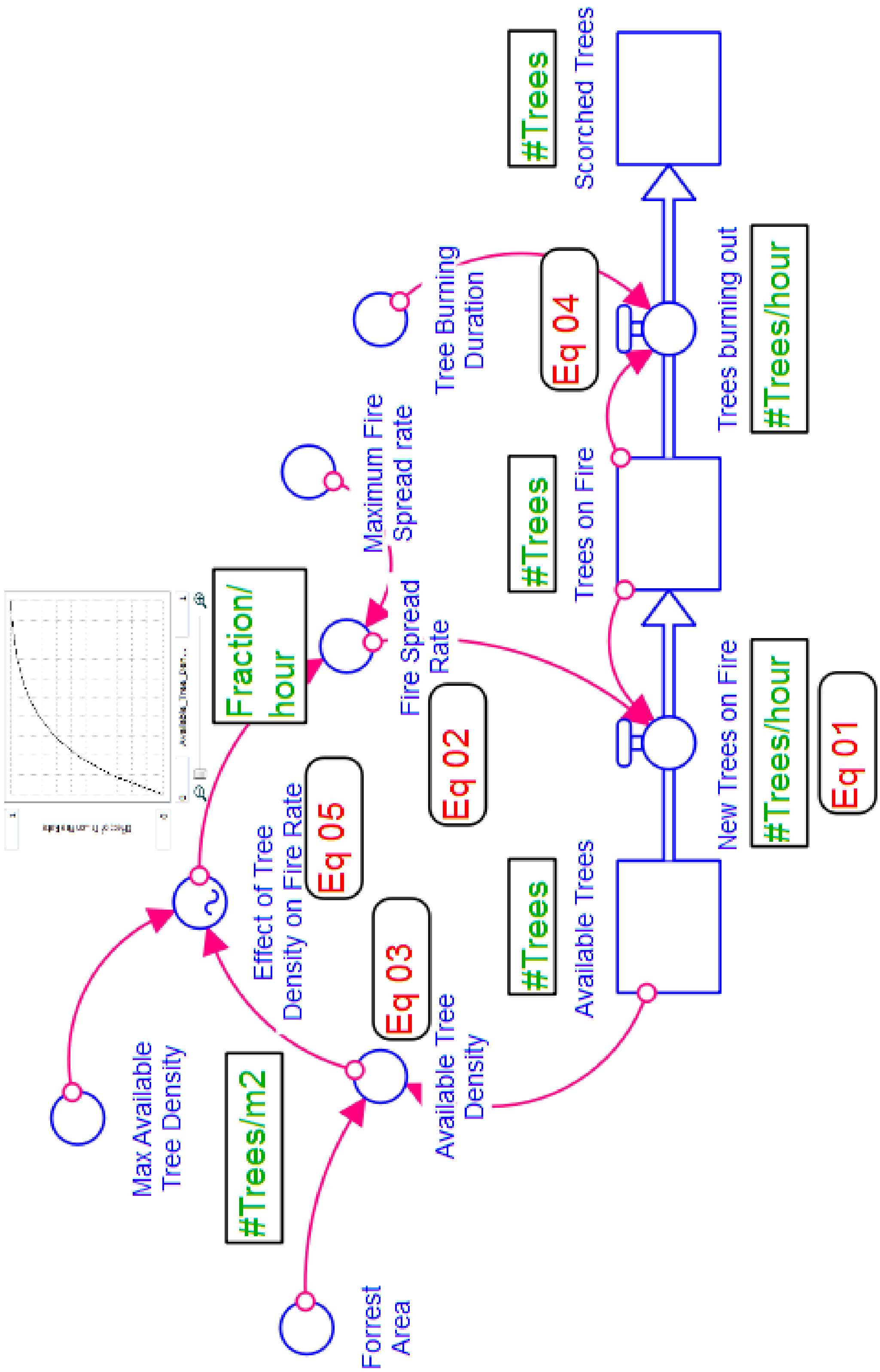


Figure 10.36: Detailed Stock and Flow Diagram of the Forest Fire Simulation

10.1.19 Step 8: Small loop models and validation

10.1.19.1 Smallest Loop (8.1):

Smallest Loop: Reinforcing Growth (R)

10.1.19.2 Construct Loop (8.2):

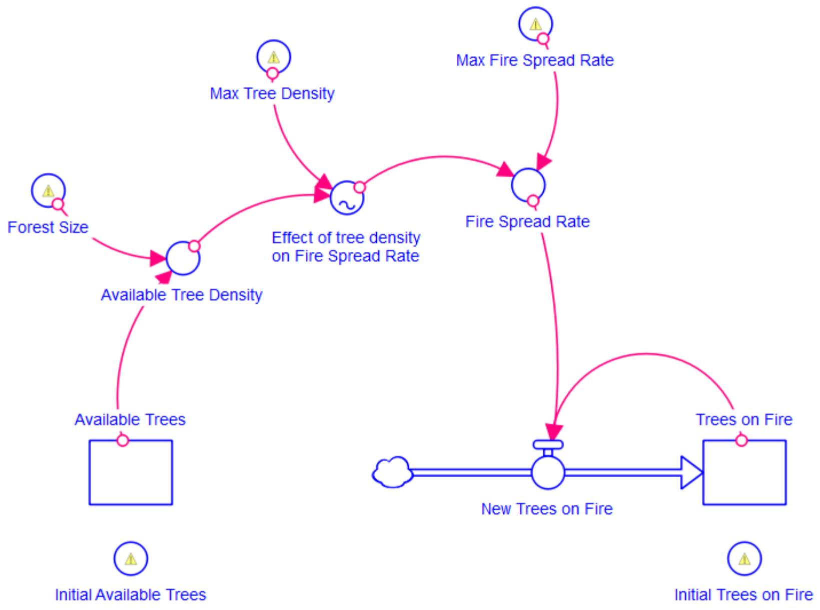


Figure 10.37: Small Loop Simulation of Reinforcing Growth

It is important to note that the Reinforcing loop does not yet reduce the available trees. As such the flow is not connected to the available trees.

10.1.19.3 Define constants (8.3):

Define the *Initial available trees* as **1 000 trees**. Assuming a *maximum tree density* of **1 tree per m2**, the *forest size* must be much larger than 1 000. It is arbitrarily chosen as **20 000 m^2**. The *maximum fire spread rate* is assumed as **2 per hour** which implies that every hour each tree can light up two trees while it is burning. *Initially* assume only ***1 tree is burning***

10.1.19.4 Test Atomic behaviours (8.4):

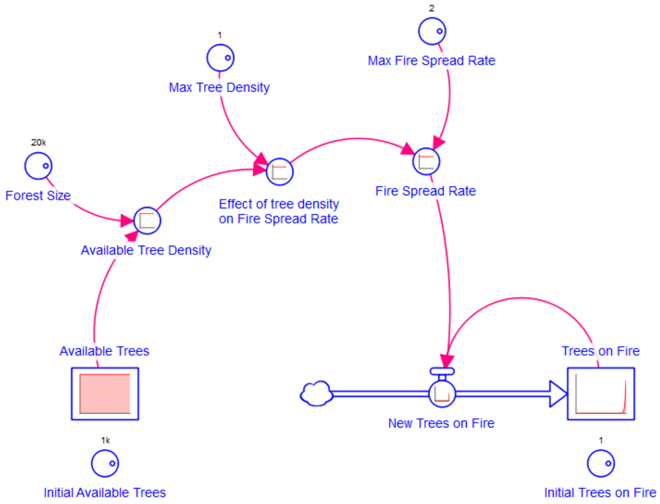


Figure 10.38: Results from running reinforcing loop simulation

The result shows that the trees on fire grow exponentially as expected and defined in step 2 for Trees on Fire (Figure 10.28). The behaviour is thus validated against step 2.

10.1.19.5 Next loop (8.5):

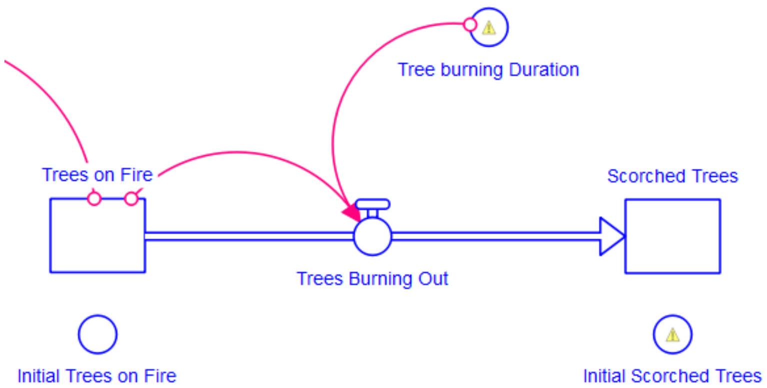


Figure 10.39: Basic construction of the Balancing Loop

The *initial value for the scorched trees* will be chosen as **0**. The *tree burning duration* is estimated at **10 hours**. This means that it takes the fire about 10 hours to burn down the tree, transformed from a healthy to a scorched tree. In this case, there has to be a larger value for the *trees on fire* to see the decay. As such the *initial trees on fire* is chosen as **100 trees**

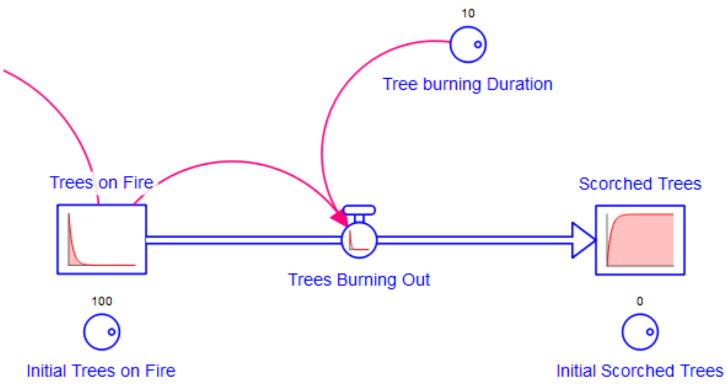


Figure 10.40: Results from running balancing loop simulation

The *trees on fire* does follow a balancing negative effect as expected from step 2 (Figure 10.29). The behaviour is thus validated against step 2.

10.1.20 Step 9: Integrated model testing and verification

10.1.20.1 <u>Integration (9.1):</u>

Connecting the flows to their appropriate stocks and resetting the *initial trees on fire* to **1** the final structure can be seen next:

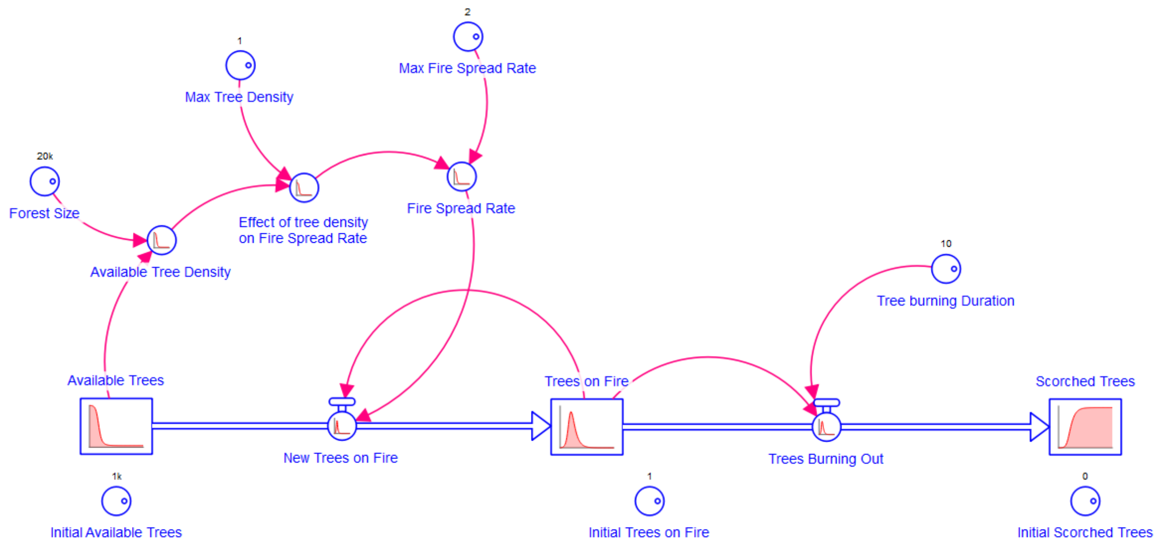


Figure 10.41: Integrated Forest Fire Simulation

The behaviour of the *Trees on fire* already shows very strong alignment to expectations of Step. In the next parts the different equilibrium tests will be conducted.

10.1.20.2 Equilibrium test (9.2):

It is expected for the system to remain **static** when there are *no initial trees on fire*. The test will be conducted by altering the *initial trees* on fire to **0**.

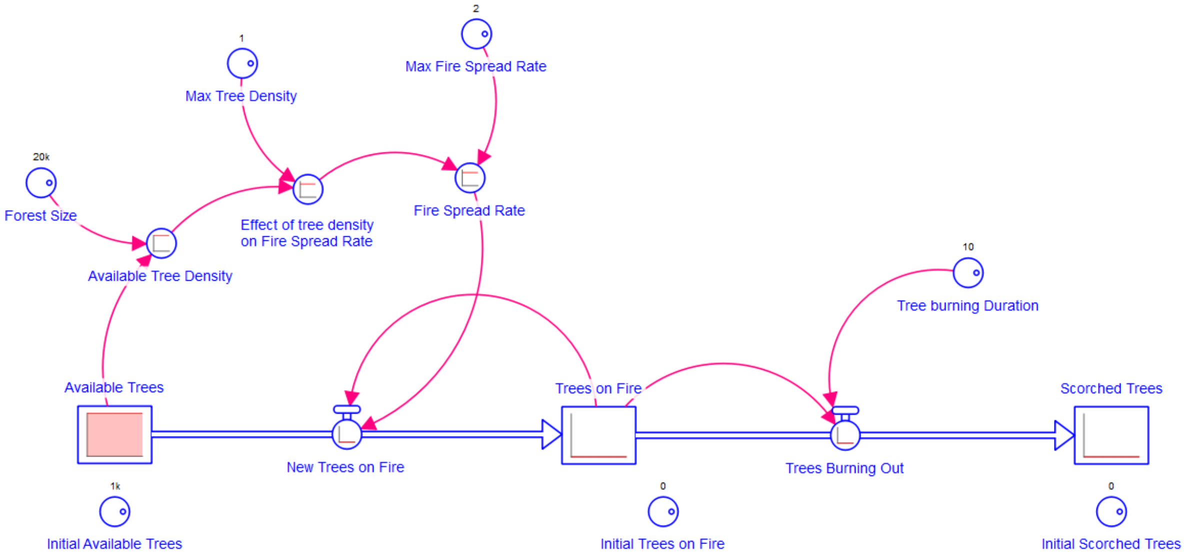


Figure 10.42: Equilibrium Condition for Forest Fire Simulation

As expected there are **no changes** in the model and all the **flows remain at zero**.

10.1.20.3 Disturbance test (9.3):

In this type of system, it is expected that the system will always end in an **equilibrium** state due to the **limited fuel** (available trees). An extreme test will thus be conducted where the *available trees* are set to **10 000**, *initial trees on fire* to **100** and *scorched trees* kept at **0**. The test is to see if the system establishes a new equilibrium point.

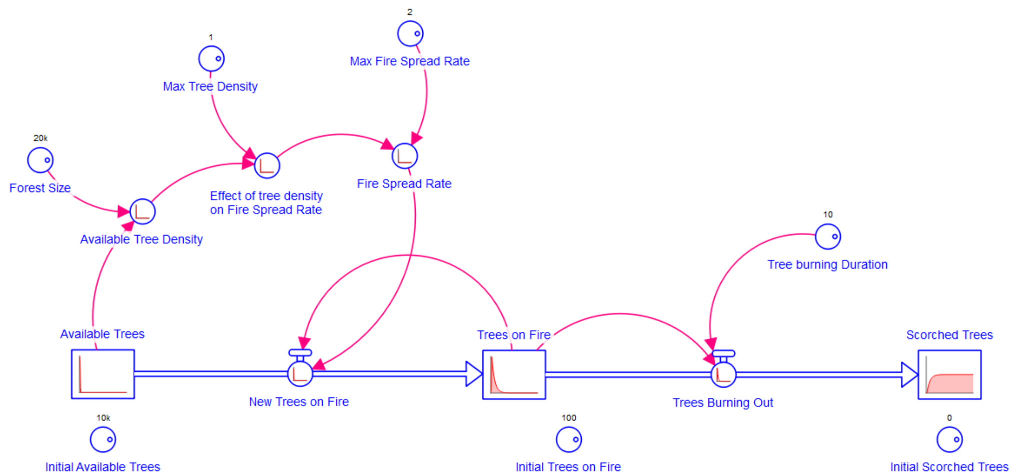


Figure 10.43: Disturbance test 1 on Forest Fire Simulation

A **new equilibrium** is **attained** but the structure reacts **too fast** under these conditions that it seems like an instant reaction. As such the *max fire spread rate* is changed from 2, to a new value of **0.33**. This means that it takes about **3 hours for a burning tree to light another tree.**

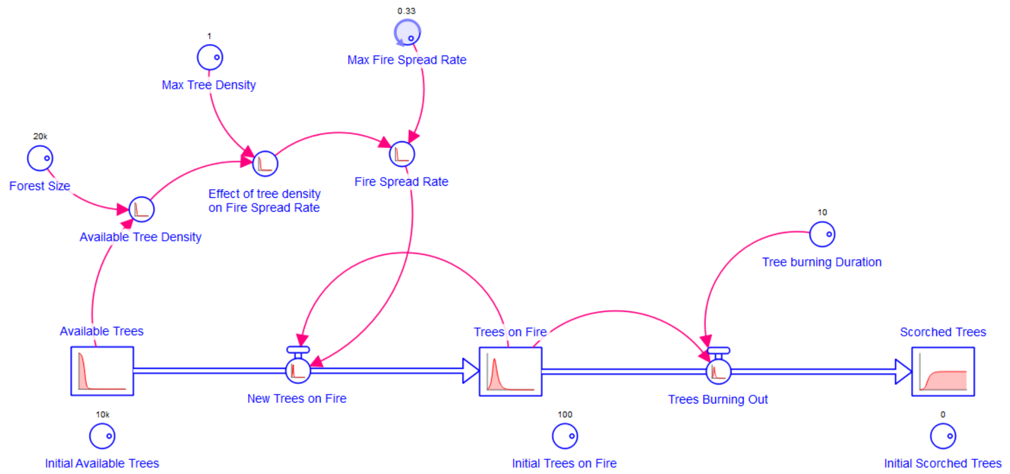


Figure 10.44: Disturbance test 2 on Forest Fire Simulation

It is already clear that the **max fire spread rate** has a **strong effect** on the rate at which the effect occurs. It is also clear that there is **a sharp exponential growth of trees on fire** which is follow by a **sharp decay as the available trees burn out**.

10.1.20.4 Reproduce Reference Mode (9.4):

In step 1 the same type of behaviour was seen as already described by 9d. A difference between these two might be the duration that the fire stays active for.

The following changes were made:

- Initial Available Trees: **4 000 trees**
- *Max Fire Spread Rate*: **0.42 fraction per hour**
- Tree Burning Duration: **5.8 days**

The result for number of trees on fire shows the same behaviour as expected in step 1.

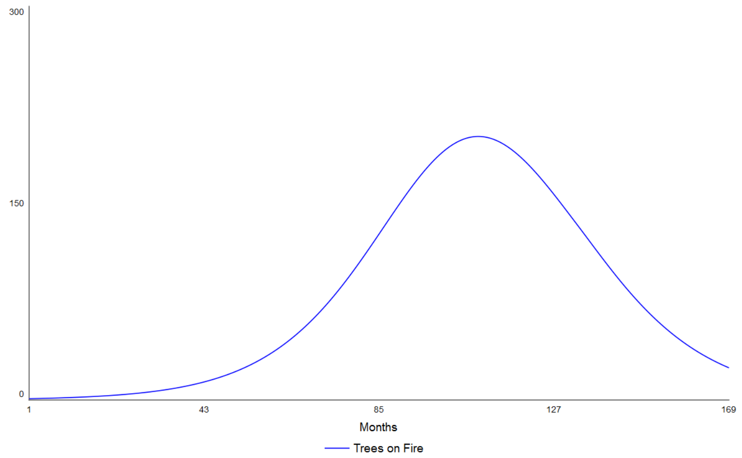


Figure 10.45: Forest Fire reproducing behaviour identified in Step 1

It is important to note that in this **boundary**, the **only fuel** source considered was the **carbon** in the **tree**. Fire also needs **Oxygen** and **Heat to continue**. Heat is available but the **oxygen** is **not simulated** in this case. This could create the secondary graphs seen in step 1.

10.1.21 Step 10: Sensitivity Analysis

10.1.21.1 Identify variables (10.1):

- Forrest Size: **20 000**
- Max Tree Density: **1**
- Max Fire Spread Rate: **0.42**
- Tree Burning Duration: **5.8**
- Initial Available Trees: **4 000**
- Initial Trees on Fire: **1**
- Initial Scorched Trees: **0**

Three chosen variables are:

1) Initial Trees on Fire – The reason this variable is chosen is because it can relate back to policies that may control the type of fires that start in the area.
2) Tree burning duration – The reason why this variable is chosen is to see the impact of different tree types when designing or altering forest areas.
3) Initial Trees available – The reason for this variable is since pro-active policies can be designed that control the amount of trees in a forest.

10.1.21.2 Sensitivity Range (10.2):

The range of sensitivity was chosen as 98% in order to test for extreme conditions like when trees only burn for 0.12 hours (7.2 minutes) before being scorched, or a very low amount of trees (only 80).

Table 10.9: Sensitivity Range of Forest Fire Simulation

Sensitivity Range of 98%			
Variable name:	Initial Value:	Min	Max
Initial Trees on Fire	1	0.020	1.980
Tree burning duration	5.8	0.116	11.484
Initial Trees available	4000	80.000	7920.000

10.1.21.3 Sensitivity Points (10.3):

The sensitivity points are calculated using the values in the sensitivity range for 5 different scenarios, progressing from the minimum to maximum values:

Table 10.10: Sensitivity Points of Forest Fire Simulation

	Sensitivity Points	Value for each run#				
Scenario	Variable name:	1	2	3	4	5
1	Initial Trees on Fire	0.02	0.51	1.00	1.49	1.98
2	Tree burning duration	0.12	2.96	5.80	8.64	11.48
3	Initial Trees available	80.0	2040.0	4000.0	5960.0	7920.0

10.1.21.4 Analysis (10.4):

Initial Trees on Fire:

The initial value for the variable was 1 and is incrementally increased from 0.02 to 1.98 in the five different scenario runs:

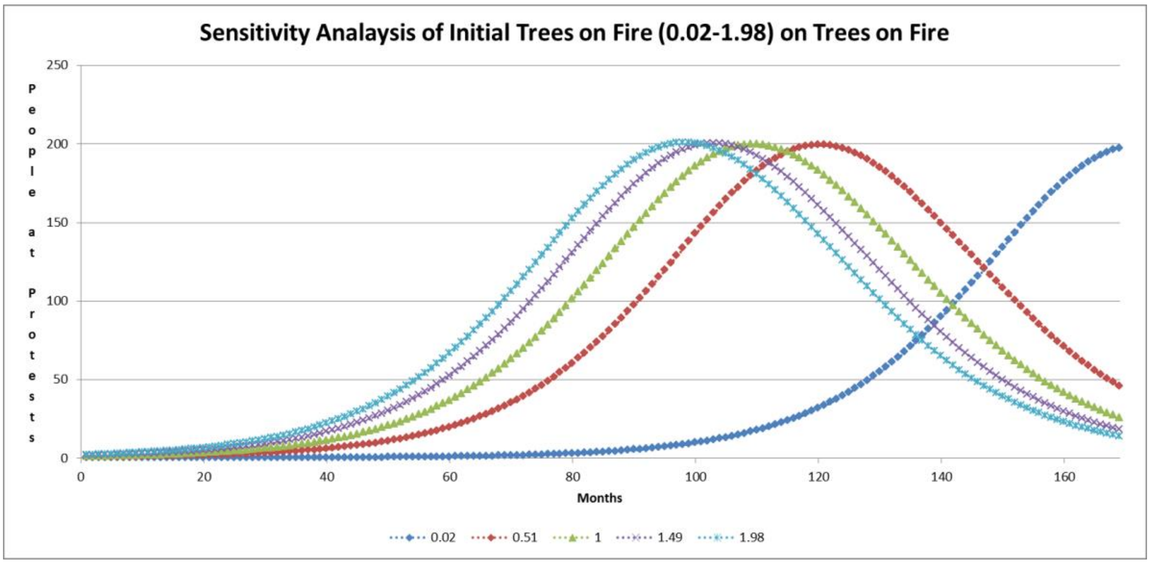


Figure 10.46: Sensitivity Analysis on Initial Trees on Fire

The interesting behaviour here is that it does not change the maximum number of trees on fire, yet it does alter when this maximum is reached. Even having an extremely small fire initially, will still trigger the forest fire to take place, it does however give the fire fighters more time to react, assuming that the forest is constantly monitored. Contextually this relates to how easy it is for a forest fire to start with seemingly insignificant sparks that can lead to massive forest fires.

The final values of each scenario does not mean much as the dynamics in the scenario is not completely finished as seen in the sensitivity scenario below:

Table 10.11: Sensitivity Table of Initial Trees on Fire

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Final Percentage effect	665%	77%	0%	-30%	-46%

The difference in the percentage effect can only be related to where the forest is in it's dynamic state. The very high percentage of 665% is an indication that there is a very large delay before the forest fire starts growing exponentially. The -46% indicates that it is much faster that the initial run. It is however notable that the minimum (-46%) has a much lower absolute change relative to the maximum (665%) which shows that the more trees are initially on fire, has a lesser and lesser effect as it increases. The opposite however is true when decreasing the initial trees on fire: The smaller the initial the event, the more time exponentially will be required before the forest fire starts growing exponentially.

Tree Burning Duration:

The initial tree burning duration was 5.8 hours which was incrementally increased from 0.12 hours to 11.48 hours in the five runs and can be seen below:

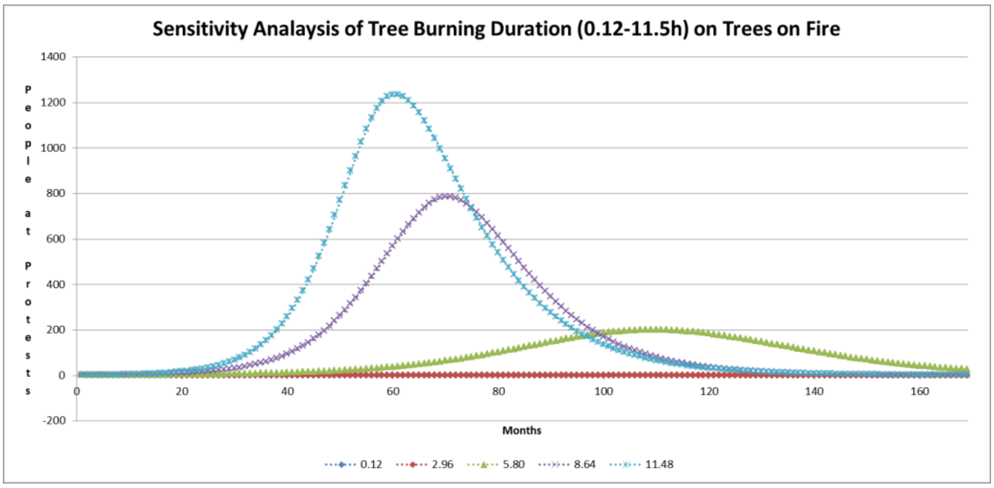


Figure 10.47: Sensitivity Analysis on Initial Tree burning Duration

The interesting behaviour seen here is that the maximum trees on fire drastically reduce as the burning duration decreases, the time taken to reach the amplitude is increased as the duration decreases. There is a very large decrease when the duration goes below 5.8 hours, while the larger the duration becomes the maximum also increases, yet the increases become smaller: Observe the change in maximum from 5.8 to 8.64 is larger than the change in maximum from 8.64 to 11.48. The sensitivity results are shown next:

Table 10.12: Sensitivity Table of Tree Burning Duration

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Final Percentage effect	-100%	-100%	0%	-97%	-97%

Since the sensitivity percentage effect is based on the final values at 169 hours, the results do not mean much, since the final number of trees on fire do not change much between the runs. Instead, the sensitivity was then based on the maximum number of trees and the following can be seen:

Table 10.13: Sensitivity Table 2 of Tree Burning Duration

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Maximum Percentage effect	-99%	-99%	0%	293%	518%

Observing the maximum percentage effect (maximum number of trees in each scenario relative to the base scenario 3 run), it is seen that Run 1 and 2 have very similar results with 99% less maximum trees. The larger the duration however becomes, the maximums increases to 293% and 518%. The observation made above can be seen here again, where the percentage change from run 3 to 4 is 293% while the percentage change from run 4 to 5 is 225%, which is less than the previous change. It is thus assumed that as the duration increases, the effect will become less.

Initial Available Trees

The initial available trees are 4 000 which is altered to incrementally increase from 80 to 7920 in the 5 scenario runs seen below:

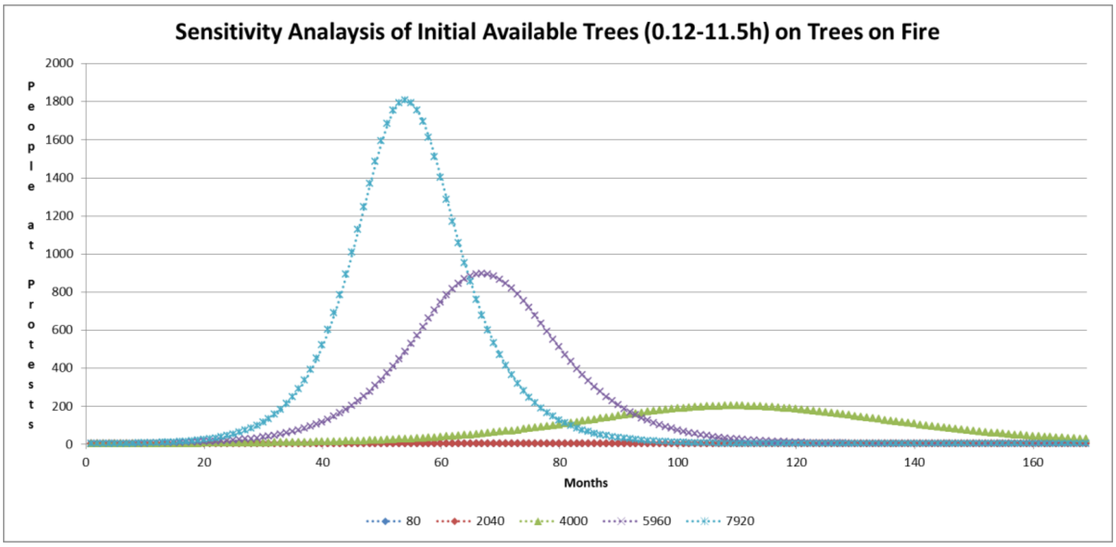


Figure 10.48: Sensitivity Analysis on Initial Available Trees

The initial available trees relate directly to the tree density and the tree density is the driving force for how fast the fire spreads (fire spread rate). As the number thus increases, the higher the density becomes and the faster the fire spreads. The behaviour seen here is very similar to the fire burning duration where as the number increases, the higher the maximum and the faster the maximum is reached.

In a similar way, the final trees on fire does not reveal as much about the system than the maximum number of trees on fire would. The maximum percentage effect is thus chosen as the sensitivity percentage evaluations:

Table 10.14: Sensitivity Table of Initial Available Trees

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Max Percentage effect	-99%	-99%	0%	347%	804%

The first and second run has almost exactly the same behaviour as seen in the previous scenario. Run 4 and 5 seem similar at a quick glance, yet looking a bit closer there is an interesting difference. The first difference is that the percentages are higher at 347% (293% before) and 804% (518%). The second difference is that the effect seems to become stronger as the initial trees increases with a first difference from run 3 to 4 of 347% and a second difference from run 4 to 5 of 456%. This clearly shows that the initial trees available has the strongest effect on the forest fire simulation relative to the other two chosen ones.

10.1.21.5 Ranked Leverage Points (10.5):

A) The highest leverage is the **initial number of trees** in the forest: The higher this number becomes, the larger the forest fire will become (exponentially). Keeping this value at a an acceptable state, allows the **tree density** to remain constant and reduce the exponential expansion rate of the forest fires.

B) The second highest is the **tree burning duration** which is a direct function of the type of tree and amount of fuel stored within it. The higher the number becomes the larger the forest fire becomes but not exponentially. Above a certain duration, the fuel in the fire plays a lesser role in the spread of the fire. It does however reveal that very low burning durations, like short dry grass, may quickly initiate a fire, but it quickly dies out and does not pose a great risk, unless the grass is connected to trees.

C) The lowest lever is the **initial number of trees on fire**. Despite the fact that often the initial spreading events cannot be controlled it does show that even small, seemingly insignificant events, like a spark, can initiate the forest fire. The very small events however are very deceptive as they have a strong delay associated with them, so by the time that the forest fire is noticed, it might be very difficult to trace the original source due to this delay.

10.1.22 Step 11: Emerging Lessons

10.1.22.1 Emerging Insights (11.1):

The modelling process started with the following sentence:

“A raging **forest fire** will continue to **expand** until it runs **out** of **fuel**”

Through the process **12 dynamic variables** were identified and simulated, of which **3** were **stocks**. **3 leverage points** (out of **8 levers**) were identified as being the **most controllable**: *Initial Trees on Fire*, *Tree Burning Duration* and the *initial trees available* in the forest. The strongest was found to be the *tree burning duration* with an increase in burning **2.3 hours longer** resulting in more than **420 higher peak** *trees on fire* and a

75% decrease in the *available trees* after the fire ends. The **second** strongest **lever** but the most available to policy is the *initial number of trees available*.

It might be **counterintuitive** but a **policy should** be **focused on reducing the available trees** in a forest **below** a certain tipping **point**. In this case the tipping point was around **4 000 trees**. Allowing trees to grow **beyond 4 800** could lead to more than **3 530 trees** to be **burnt up** (**75%** of the forest). **Decreasing** the *initial number of trees* to around **3 200**, only about **326 trees** (**10%** of the forest) is **damaged**. The **10%** can be regenerated through **growth** in a short time but the **75%** destruction will take **significant time to regenerate** and then it is only referencing the trees, not the **biodiversity** that is **lost**. The base scenario case of the simulation can be seen next, access to this simulation is found at the end of this step.

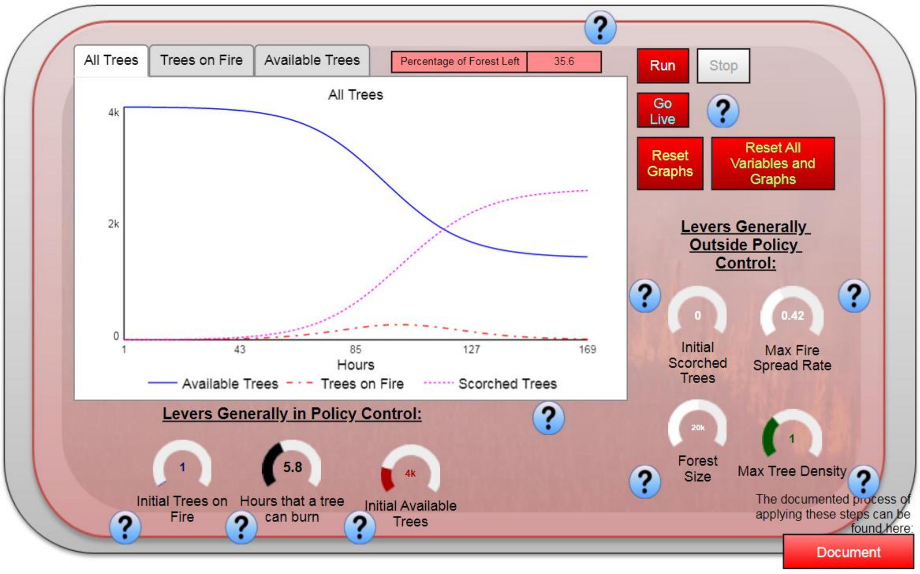


Figure 10.49: Simulation Interface of the Forest Fire Simulation

The following is from USGCRP (The United States Global Change Research Program) and aligns findings from exploring the deeper structure of the applied model to a **real world example** of **applying** and **not applying** the *purposeful reduction in available trees* (Global Change, 2020):

“Forest management that selectively removes trees to reduce fire risk, among other objectives (a practice referred to as “fuel treatments”), can maintain uneven-aged forest structure and create small openings in the forest. Under some conditions, this practice can help prevent large wildfires from spreading. Photo shows the effectiveness of fuel treatments in Arizona’s 2002 Rodeo-Chediski fire, which burned more than 400 square miles – at the time the worst fire in state history. Unburned area (left) had been managed with a treatment that removed commercial timber, thinned non-commercialsized trees, and followed with prescribed fire in 1999. The right side of the photo shows burned area on the untreated slope below Limestone Ridge."

Figure 10.50: Managed Forest (left) and unmanaged Forest (right) (Photo Credit: Jim Youtz, U.S. Forest Service)

10.1.22.2 System Leverage Points (11.2):

The main leverage point is ensuring that the number of trees in the forest remain under a specific tree density, as this will prevent a high fire spread rate. The second leverage point is to make sure that the forest management agency understands the type of trees and the amount of fuel inside of them that will give an indication of the duration that the trees will burn. If a forest is being designed, the density of the trees needs to be calibrated to the amount of fuel inside of the trees (more fuel, reduce the allowable tree density, which means reducing the maximum allowable trees in the forest). Finally the lowest lever is the intial trees on fire, which is not technically a lever yet it does reveal that seemingly insignificant sparks, glass or matches can initiate the destructive forest fire and as such should be regulated by the forest management.

10.1.22.3 List of Variables (11.3):

Table 10.15: Final list of variables and definitions for the Forest Fire Simulation

Variable Name	Variable Meaning	Unit
Available Trees	The number of trees in the forest that are not on fire but can catch fire.	Number of Trees
Trees on Fire	The trees that are currently burning and that will burn out after some time.	Number of Trees
Scorched Trees	Trees that have completely burnt out and have no more fuel left to burn	Number of Trees
New Trees on Fire	The trees that has caught fire in the last hour.	Trees per hour
Trees Burning out	Time taken for the fuel in one burning tree to completely be used up by the fire.	Trees per hour
Tree Burning Duration	The hours taken from when the tree is lit on fire to when it is scorched.	Hours
Fire Spread Rate	The fraction of the current trees on fire that spread fire to new trees every hour	Fraction per hour
Max Fire Spread Rate	The maximum fire spread rate of that tree type	Fraction per hour
Forest Size	The total area in m^2 that is in the boundary of the Forest	Square meters
Available Tree Density	The number of available trees over the forest area.	Trees per square meter
Max Tree Density	The maximum number of trees that will grow in 1 m^2.	Trees per square meter
Effect of Tree Density on Fire Spread Rate	The assumed qualitative (dimensionless) relationship between the tree density and the rate at which the fire spreads.	Dimensionless

Online link to the Forest Fire Simulation:

https://exchange.iseesystems.com/public/corne/forest-fires-limits-to-growth-archetype/index.html#page1

Appendix 2-C: Eroding Goals Simulation Development

In this section, the LST method explained in Chapter 4 is applied to the Eroding Goals archetype. The general system archetype is applied to the South African education system. The system archetype for Eroding Goals and Escalation are larger than the first two, which also leads to a larger simulation structure.

10.1.23 Step 1: Problem Description

10.1.23.1 Word Model (1.1):

The South African Education system, like many other systems in South Africa, was in desperate need for transformation in 1994 (Driekie & Mabokeng, 2009). The average matric pass rate was just above 50% in 1995 and imperative to rise this value. Mainly two mechanisms exist to improve the pass rate, the first requires long term and large investments into the education system which will improve the quality of education throughout the country while the other mechanism would be to lower the difficulty of matric question papers in order to improve the pass mark. The second mechanism takes much less investment and time, with quick results yet the actual quality of education is not improved, only the appearance.

10.1.23.2 Behaviour over time (1.2):

The historical South African pass rate is seen in the next figure for South Africa from 1995 to 2019 (MyBroadband, 2020).

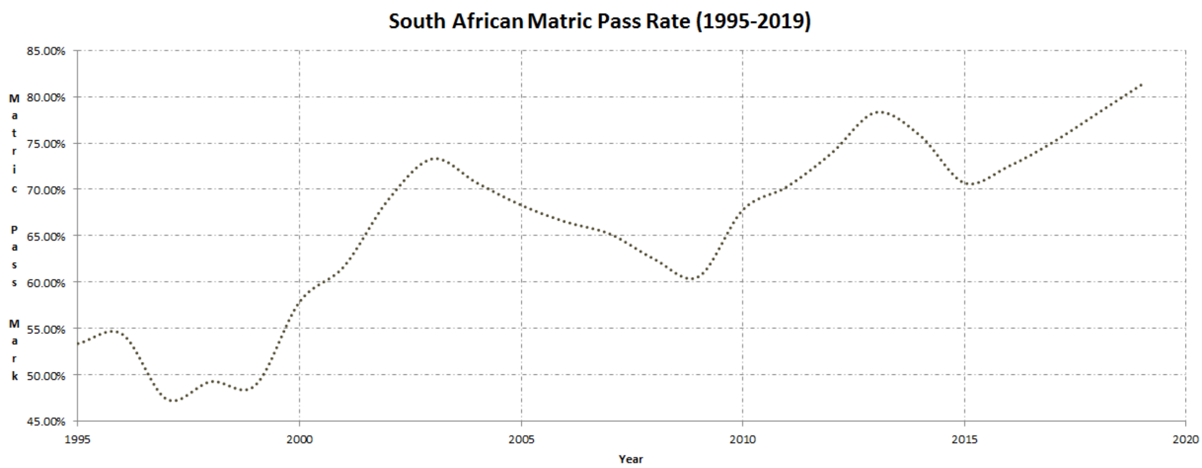


Figure 10.51: South African Matric Pass Rate (MyBroadband, 2020)

The results show that after the Apartheid regime ended in 1994, the pass rates of the country took a dip in the first few years after. The pass mark however started increasing drastically over the 25 years, ending with the highest pass mark at 81.3%, which is a massive improvement of almost 28% in 25 years.

Although this pass mark improvement is incredible, in 2018 it was found that only 172 043 students (33.6%) of grade 12 students managed to pass bachelor level education against the Medium Term Strategic Framework target of South Africa set at 255 000 (BusinessTech, 2020). The pass mark for mathematics in 1994 was 18%, while in 2018 there was still only 21.7% of students passing mathematics at 50% (BusinessTech, 2020). The general mathematical skills of students have slightly improved, yet not nearly as the matric pass mark would indicate.

In summary the matric pass rates goals are achieved more and more, yet it seems like there are still a large problem in the mathematical skills (21.7%) and overall university bachelor's completions of (34%). The lower goals set for matric pass rate has drastically increased the perceived performance of the South African education system, yet the actual skills improvements of students are questionable, or at least not as good as matric pass rates seem to convey. The SA result stands in stark contrast to the Finland's education system whom kept strict governance of their goals, which required 50 years of investment to reach, yet it has surely paid off. This is from the Finnish government statistics:

"The continuously improving level of education of the population has contributed to the rise in the productivity of labor and, consequently, rapid economic and social development." (Statistics Finland, 2020)

10.1.23.3 <u>Purpose (1.3):</u>

The purpose of the model is to use the LST methodology to transform the general eroding goals archetype into a mathematical simulation of the matriculate pass rate eroding goals, in order to test the methodology and derive more insights.

10.1.23.4 <u>Core Variables (1.4):</u>

4) Goal skill requirement (**Skill level**)
5) Average student abilities (**Skill level**)
6) Quality of Education system (**Qualitative**)
7) Matric Pass Rate (**Percentage**)
8) Pressure to improve pass rates (**Qualitative**)

10.1.23.5 Time Frame (1.5):

A 20 year time frame at the resolution of years

10.1.24 Step 2: Causal Loop Diagram

10.1.24.1 Core Story (2.1):

The core story being told is where goals are compromised in the long run in order to meet the goals in the short run. The education system in South Africa required drastic intervention and improvement after the Apartheid Regime ended. One of the big education performance targets are the matriculation rate (percentage of students passing their last year of school). There exist two main mechanisms: improve the education system infrastructure or alter the student difficulty level. The first mechanism would be ideal, yet there is a large delay in investments, implementation construction and optimization that is needed before the student skills start improving. The pressure to achieve the target matriculation rate increases as more students start accumulating in the education system after failing. As such, the alternative mechanism is consulted which takes much less time and resources to achieve. The matriculation rate then increases and decreases the need for fundamental education investments even though the actual skills are not improving as desired, stagnating or even decreasing over time.

10.1.24.2 Create Causal Loop Diagram (2.2):

The eroding goals system archetype has two competing balancing loops. The bottom loop is the structural solution that will improve the fundamental skills and reach the target, yet there are significant delays in achieving the improvement. The top balancing loop is an alternative way to reach the goal, by lowering the difficulty of the goal. The top loop is easier and faster to change and thus people often fall trap to lowering the goal. The end result is that the actual performance reaches a plateau even though it seems like the performance is improving due to the goal achievement.

The application of the system archetype to the matriculated pass rate is seen below:

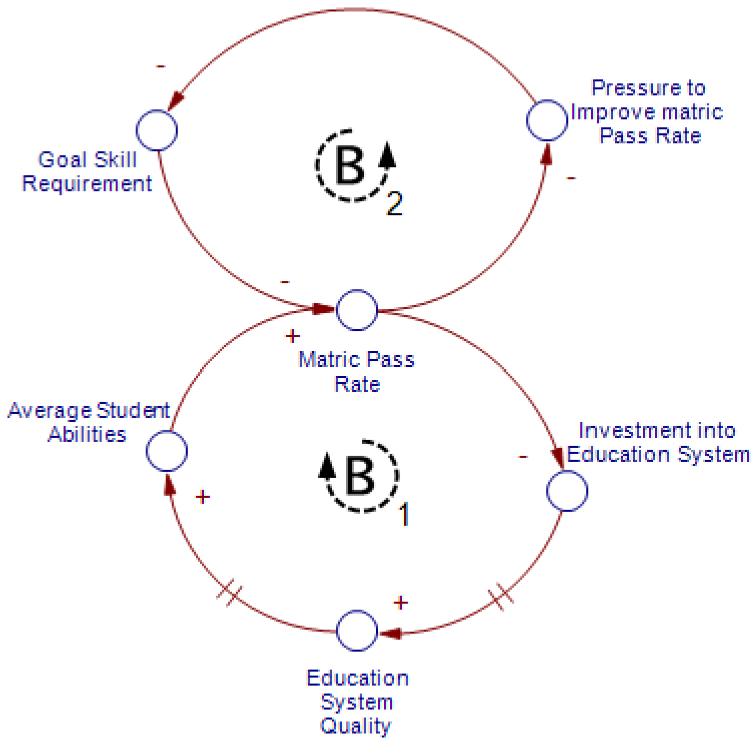


Figure 10.52: South African Matric Pass Rate (MyBroadband, 2020)

Two balancing loops are created and explained in the next section.

10.1.24.3 Atomic Loop Behaviours (2.3):

3) **Loop B1 – Long Term Investment**: When the matric pass rate is low, the government would invest into the education system (-). The greater investments into the education system will improve the education system quality after some time (+). The improvement in education quality will also take time to improve the student's abilities during the 12 years of schooling (+). The improvement in school abilities will improve the average matric pass rate (+). This finally leads to the balancing (B+) loop as there is only one negative, yet this loop has significant delays.
4) **Loop B2 – Lower Targets**: The alternative is that when matric pass rate is low, the pressure to improve matric pass rate on the government increases (-). The large pressure leads to the government lowering the goal skill requirements (-) to pass. As a result the matric pass rate increases (+). The ability, speed and low investment requirement for this loop, makes it more attractive than Loop B1. The final loop is balancing (B-) since there are an unequal number of negatives.

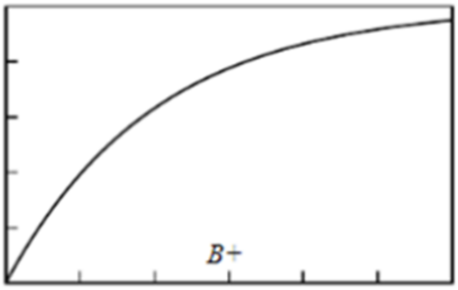


Figure 10.53: Expected Loop Behaviour for the Long term Investment

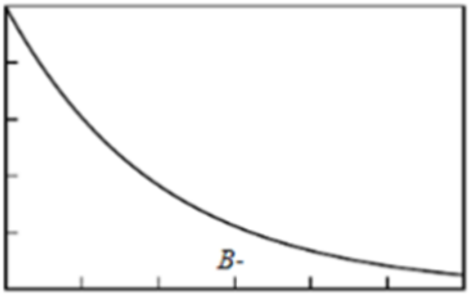


Figure 10.54: Expected Loop Behaviour for Lower Targets loop

The two loops are thus in direct competition with each other on the same variables. The final behaviour of the system archetype is not known until the simulation is constructed and the behaviour emerges, yet we can expect that these two loops will be in competition with each other.

10.1.25 Step 3: Stocks and Flows

10.1.25.1 <u>Snapshot test (3.1):</u>

When time freezes all the variables listed in the CLD above will remain: Goal Skill Requirements, number of students and education system infrastructure

10.1.25.2 <u>Test stocks for nouns (3.2):</u>

- Goal skill requirement: Goal is a common noun, with qualitative dimension ranging from 0-100.
- Education System infrastructure: Infrastructure is a collective noun and with dimensions of # Of buildings.
- Number of Students: Students are a common noun, with the dimension of # of students.

10.1.25.3 Test each loop for stocks (3.3):

- Loop B1: Goal skill requirement is the stock on Loop B1
- Loop B2: Number of students and education system infrastructure are both stocks in loop B2.

10.1.25.4 Identify the flows (3.4):

Three stocks exist, each with its own flows:

- Goal skill requirement:
  - Bi-Flow: Changing the goal requirement due to pressure
- Number of students:
  - Inflow: New (grade 1) students
  - Outflow: Students dropping out
  - Outflow: Students completing school
- Education infrastructure:
  - Inflow: School infrastructure investments
  - Outflow: School infrastructure depreciation

10.1.25.5 Delays and aging chains (3.5):

Number of Students: New

Number of students will surely be an aggregated stock with delays, as students cannot enter a school in grade 1 and leave the next year in grade 12, even if exceptionally smart. The simplest assumption will be made as to separate the students into two groups: Students in Grade 1 to 11 and Students in Grade 12. A detailed model can include students stocks for each year, from grade 1 to grade 12, yet in this case, the purpose of the study is not to reproduce exact reality, but rather test if the LSTs can produce useful simulation. As such the number of student stock system is split as follows:

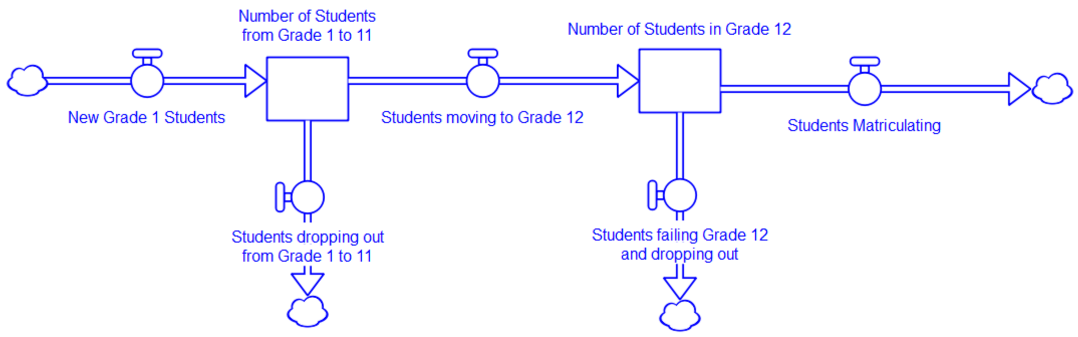


Figure 10.55: Delay chain in Students progression through Education

The flows between the two stocks are the students that are moving into the matriculation space. Each of the stocks can have students dropping out, yet the Grade 12 dropout students are students who fail the year and do not decide to complete their studies. The students matriculating, leaves the system in being studied.

Education Infrastructure:

The education infrastructure is thought of as the number of buildings (and their associated staff, skills) that is fully functional and equipped to deal with students. Buildings and their associated skills/tools cannot appear overnight and investment is needed, where after construction and commissioning of the building. As such the education infrastructure will have at least two staggered stocks. The first being the infrastructure investment, which is the money and resource allocations, which will then time to build and commission and become education infrastructure. This can be seen below:

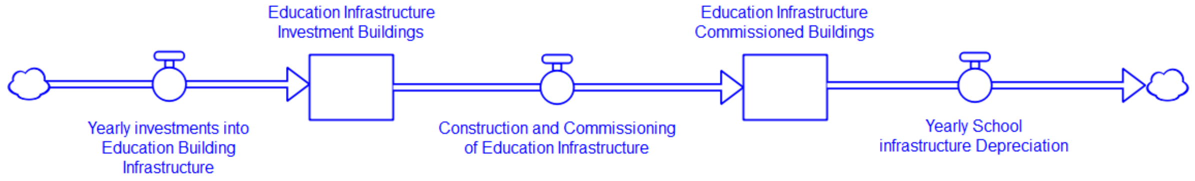


Figure 10.56: Delay chain in construction and commissioning of Education buildings

Every year the education system requires investments, which will lead to construction and commissioning. This is due to the infrastructure depreciation of building that need to be maintained.

Goal Skills to reach students:

The Goal to reach by the students, which will determine the pass rate, can be changed by the bi-flow as indicate below. Yet there is no staggered stock system as it is assumed that, relative to the other two stock systems, goals are much easier to change than the structural components.

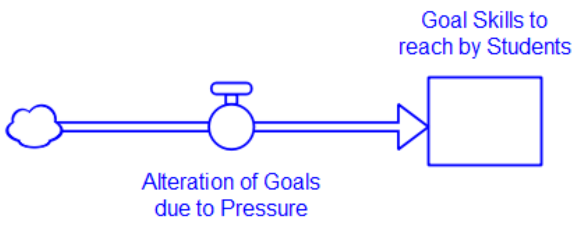


Figure 10.57: Simple Goal Skills Stock and flow

10.1.26 Step 4: Basic Stock and Flow Diagram

10.1.26.1 System Architecture Map (4.1):

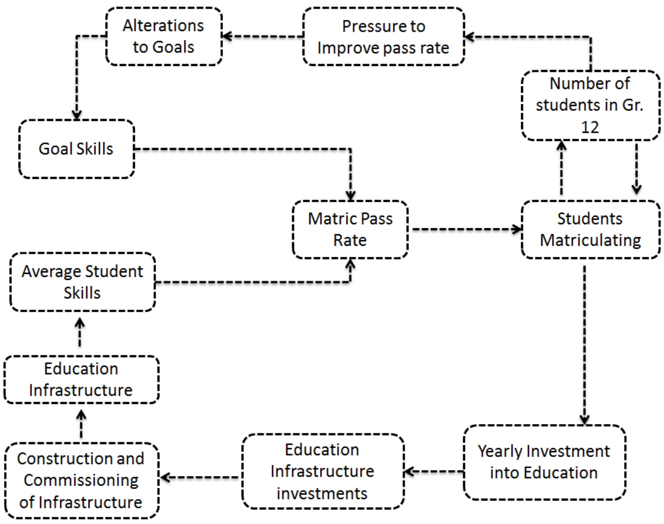


Figure 10.58: SAM of the Education Simulation

10.1.26.2 Separate Stock and Flows (4.2):

Identified in step 3.5

10.1.26.3 Merge to one Stock and Flow Diagram (4.3):

The culminated diagram is given below of the stocks and flow connections.

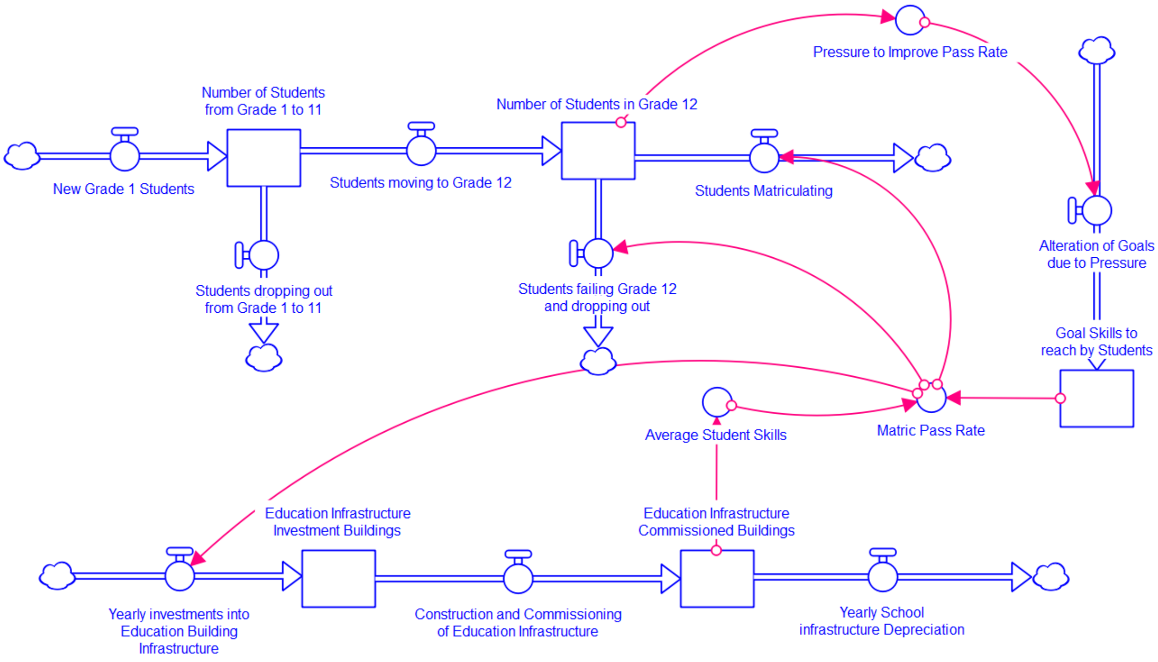


Figure 10.59: Basic Stock and Flow Diagram of Education System

10.1.27 Step 5: Dimensional Analysis

10.1.27.1 <u>Stock Dimensions (5.1):</u>

- **Number of students** allocated to Students from grade 1 to 11 and Number of students in Grade 12.
- **Number of buildings** allocated to Education infrastructure investment buildings and Education infrastructure commissioned buildings.
- **Skill Level** allocated to Goal skills to reach by students.

10.1.27.2 <u>Flow Dimensions (5.2):</u>

- **Number of students per year** allocated to new grade 1 students, students dropping out from grade 1 to 11, students moving to grade 12, students failing grade 12 and dropping out and finally the students matriculating
- **Number of buildings per year** allocated to yearly investments into education building infrastructure, construction and commissioning of education infrastructure and finally the yearly school infrastructure depreciation.
- **Skill level change per year** allocated to *alterations of goals due to pressure*.

10.1.27.3 Complete Dimensions (5.3):

- *Matric pass rate*: **Dimensionless**, as this is a division between actual and goal skills.
- *Average student skills*: **Skill Level**, same as the goal skills stock.
- *Pressure to improve pass rate*: **Pressure**, in order to change goals.

10.1.27.4 Dimensional Gaps (5.4):

All the variables have now been defined in ito their dimensions. The gaps are identified in red question marks next.

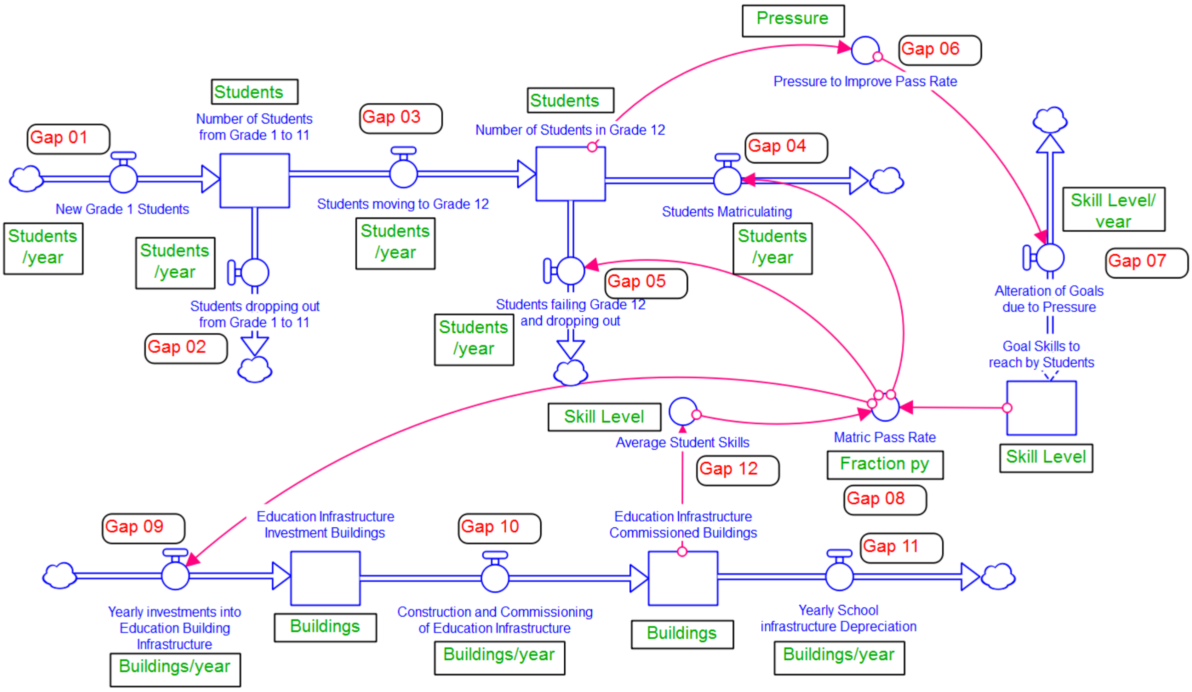


Figure 10.60: Dimensions and their gaps in the Education Simulation

The dimensional gaps are and the associated equation (Ex) from appendix A:

1) Gap 01: Missing input
2) Gap 02: Missing time fraction
3) Gap 03: Missing time
4) Gap 04: Missing time fraction
5) Gap 05: Missing time fraction
6) Gap 06: Missing conversion from students to pressure
7) Gap 07: Missing conversion from students and skills
8) Gap 08: Just a division between the average and goal skills
9) Gap 09: Conversion required between pass rate and buildings invested into per year.

10) Gap 10: Missing time
11) Gap 11: Missing time
12) Gap 12: Missing conversion between buildings and student skills

The anger per person at protest, should be a division between repressed anger and number of people at protest.

10.1.28 Step 6: Mathematical formulation

10.1.28.1 Missing Variables (6.1):

1) Gap01: **Yearly incoming grade 1 students** constant (students/year)
2) Gap 02: Normal rate required **– dropout rates in grade 1 to grade 11** (fraction per year) [Eq1]
3) Gap 03: Average years taken from Grade 1 to 12 (year) [Eq2]
4) Gap 04: Multiplying stock and converter
5) Gap 05: Matric drop out rate after failing (percentage)
6) Gap 06: Needs a **maximum student numbers** to normalize the variables into pressure and then an **effect variable** to transform pressure to skill level change. [Normalization function]
7) Gap 07: Gap variable change, so the best equation to use is [Eq3], **gap between average skills and goal skills**, as well as **years taken to adjust goals**.
8) Gap 08: No missing variables, student skills divided by goal.
9) Gap 09: **Normalizing the matric pass rate**, with a **desired pass rate** to be used in an **effect variable** to change the pass rate to educational investments.
10) Gap 10: Average years taken to build and commission buildings [Eq2]
11) Gap 11: Average life time of educational infrastructure [Eq2]
12) Gap 12: In order to identify average student's skills from the number of educational buildings, the **students per building** will be used together with the **ideal students per building to achieve 100 skill levels**. [Normalization Function]

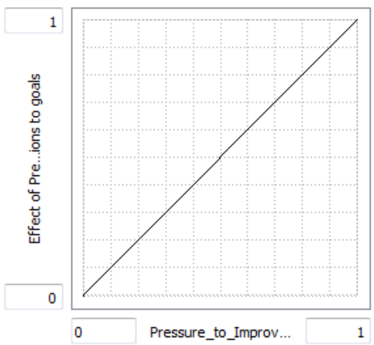
10.1.28.2 Effect Variables (6.2):

There are two effect variables identified in the system: Effect of pressure on alterations to goals AND Effect of pass rate on educational investments:

Effect of pressure on alterations to goals:

This variable captures the effect that the pressure of the matric student overcapacity will have on the change in goals.

1) The name: Effect of pressure on alterations to goals
2) The X/Y Coordinate system:
    a. X – Pressure to improve pass rate (non-dimensional)
    b. Y – Effect on alterations to goal (non-dimensional multiplier)
3) Define the three points:
    a. When pressure is 0, then effect should be 0 since there is enough space available for matric students.
    b. When pressure is at 0.5 it is assumed that people would be above halfway.
    c. When pressure is 1, then effect should be 1 as the need to release students from the schooling system is very high.
4) Connect the points to produce the final graph:



5) Define the minimum and maximum values:

Pressure:

Min = 0; Max = 1.

Effect on alterations

Min = 0; Max = 1.

Effect of pass rate on rate on Educational Investments:

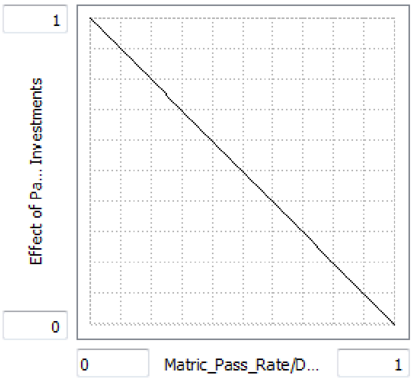
This variable captures the effect that the matric pass rate will have on the yearly educational buildings invested into.

1) The name: Effect of pass rate on educational investments
2) The X/Y Coordinate system:
    a. X – Matric Pass rate/Desired pass rate (non-dimensional)
    b. Y – Effect on educational investments (non-dimensional multiplier)

3) Define the three points:

   a. When pass rate is 0, then effect should be 1 since the need to improve education is very high.
   b. When pass rate is at 0.5 it is assumed that about half of the investments will be made.
   c. When pass rate is 1, then effect should be 0, as the lowest investments will be made since the education system does not seem to need as much attention as other areas.

4) Connect the points to produce the final graph:



5) Define the minimum and maximum values:

Matric rate:

Min = 0; Max = Ideal Pass Rate.

Building investments

Min = Minimum Yearly Building Investments; Max = Maximum Yearly Building Investments.

10.1.28.3 Equation Formulations (6.3):

1) $New\ Grade\ 1\ Students = Yearly\ Incoming\ Grade\ 1\ Students\ (constant)$
2) $Students\ dropping\ out\ from\ Grade\ 1\ to\ 11 =$
   $Drop\ Out\ Rates\ in\ Grade\ 1\ to\ 11\ \times Number\ of\ students\ from\ Grade\ 1\ to\ 11$
3) $Students\ moving\ to\ Grade\ 12 = \frac{Number\ of\ Students\ from\ Grade\ 1\ to\ 11}{Average\ Years\ taken\ from\ Grade\ 1\ to\ 12}$
4) $Students\ Matriculating =$
   $Matrix\ Pass\ Rate\ \times Number\ of\ Students\ in\ Grade\ 12$

5) $Students\ failing\ Grade\ 12\ and\ Dropping\ out = (1 - Matric\ Pass\ Rate) \times Matric\ Drop\ Out\ Rate\ after\ Failing\ \times Number\ of\ Students\ in\ Grade\ 12$

6) $Effect\ of\ Pressure\ on\ Alterations\ to\ goals = \mathrm{f}(\frac{Number\ of\ Students\ in\ Grade\ 12}{Max\ Number\ of\ Student\ in\ Grade\ 12})$

7) $Alteration\ of\ Goals\ due\ to\ Pressure = Effect\ of\ Pressure\ on\ Alterations\ to\ goals\ \times \frac{(Average\ Skills - Goal\ skills\ to\ reach)}{Years\ taken\ to\ adjust\ goals}$

8) $Matric\ Pass\ Rate = \ IF\ Average\ Student\ skills > Goal\ Skills\ to\ reach\ by\ students\ THEN\ 1\ ELSE$

$$\frac{Average\ Student\ Skills}{Goal\ Skills\ to\ reach\ by\ Students}$$

9) $Yearly\ Investments\ into\ Education\ building\ infrastructure = Minimum\ Yearly\ Building\ Investments + Effect\ of\ pass\ rate \times (Maximum\ yearly\ building\ investments - Minimum\ yearly\ building\ investments)$

10) $Construction\ and\ Commissioning\ of\ Education\ Infrastructure = \frac{Education\ Infrastruction\ Investment\ Buildings}{Average\ Years\ taken\ to\ Build\ and\ Commision\ Buildings}$

11) $Yearly\ school\ infrastructure\ depreciation = \frac{Education\ Infrastructure\ Commissioned\ Buildings}{Average\ life\ time\ of\ Educational\ Infrastructure}$

12) $Average\ Student\ Skills = (1 - \frac{Students\ per\ building}{Ideal\ Students\ per\ Building\ for\ 100\ skill\ level})$

10.1.28.4 Stock Stages / Aging chains (6.4):

The stage fractions have all been defined in equations 3, 10 and 11.

10.1.28.5 Final Dimension Checks and Multipliers (6.5):

All the dimensions were rechecked and found to be in order. No additional conversion multipliers for dimensional consistency are needed.

The final list of variables, their definitions and dimensions can be seen below.

Table 10.16: First list of Variables and their description in Education Sim

Name	Description	Dimensions
Alteration of goals due to pressure	The rate at which the goal skills are changed by the department of education	Skill level/year
Average life time of educational infrastructure	The average years taken for educational infrastructure to depreciate completely	Years
Average student skills	The average skills that the matric students have in the current year	Skill level
Average years taken from Grade 1 to 12	The average years taken for a student to move from grade 1 to 12	Years
Average years taken to build and commission buildings	The average years that is required in order to both build the new buildings as well as commission them to full functionality for students	Years
Construction and commissioning of education infrastructure	The number of buildings that are being commissioned in this year	Buildings
Drop out Rates in Grade 1 to 11	The average fraction of students that drop out of school from grade 1 to 11 every year	fraction /year
Education infrastructure investment buildings	The number of buildings that have received investments and in the process of building and commissioning	Buildings
Effect of pass rate on yearly building investments	The mathematical relationship that pass rate has on the educational investments	Dimensionless
Effect of pressure on alterations to goal	The mathematical relationship that pressure has on rate of goal changes	Dimensionless
Goal skills to reach by students	The goal set by the department for the matric students to reach	Skill level
Ideal students per building	The ideal amount of students per fully commissioned building that will allow the best education to allow students to all pass	Students/building
Matric drop out rate after failing	The fraction of students that leave school after failing their matric year and never returning	Fraction

Table 10.17: Second list of Variables and their description in Education Sim

Name	Description	Dimensions
Matric Pass rate	The fraction of students that has passed in this year	Fraction/year
Max number of students in grade 12	The maximum allowable number of students that are in matric	Students
Maximum yearly building investments	The maximum number of buildings that can be invested into in one year	Buildings
Minimum yearly building investments	The minimum number of buildings that has to be invested into every year	Buildings
Number of students from Grade 1 to 11	The total number of students that are in the schooling system in Grade 1 to 11	Students
Number of students in Grade 12	The number of students that are in matric in this year	Students
Students dropping out from Grade 1 to 11	The number of students that drop out in grade 1 to 11 in this year	Students/year
Students failing Grade 12 and dropping out	The number of matric students that has failed and will not return to school	Students/year
Students matriculating	The number of students that successfully finished their matric year	Students/year
Students moving to Grade 12	The number of students that are moving into their matric year	Students/year
Students per building	The average numbers of students per commissioned building	Students/building
Yearly Incoming Grade 1 Students	The number of students entering the schooling system as first graders	Students/year
Yearly investment into education building infrastructure	The actual number of buildings invested into in this year	Buildings/year

In the next step the detailed stock and flow diagram can be seen, which can be a blueprint for model construction.

10.1.29 Step 7: Detailed Stock and Flow Diagram

The list of equations given in step 6.3 is referenced on the final SFD here.

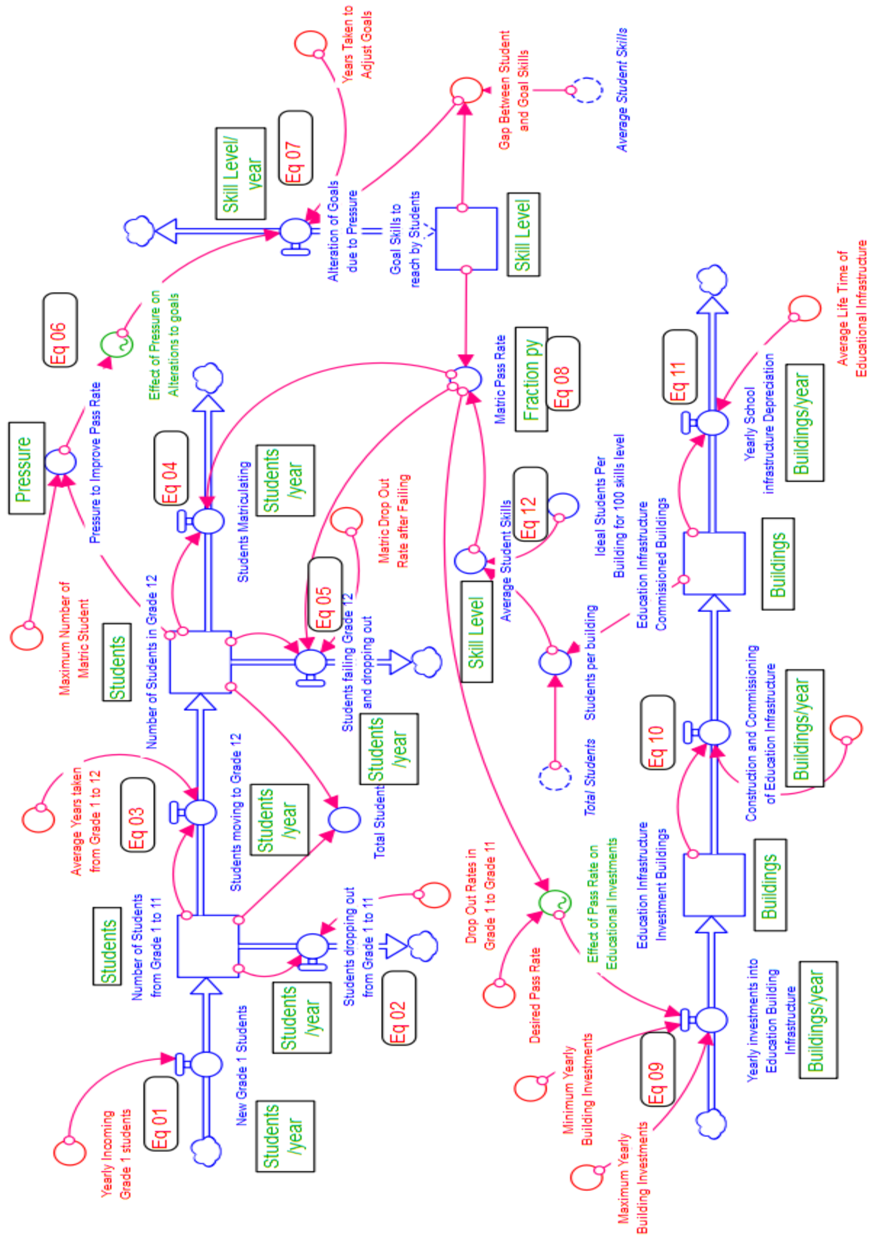


Figure 10.61: Detailed Stock and Flow Diagram of the Education Sim

Now that the blue print has been laid out, the simulation construction process can start.

10.1.30 Step 8: Small loop models and validation

10.1.30.1 <u>Smallest Loop (8.1):</u>

The smallest loop identifiable in the CLD is the Balancing loop 2: Lower the targets (B-Behaviour).

10.1.30.2 <u>Construct Loop (8.2):</u>

The three variables in the CLD involved is Goal, Pass rate and pressure. The stocks and flows associated with these variables are selected in Step 7 and built next. The associated stocks includes: Goal Skills…, Number of students in Grade 12 and Grade 1 to 11.

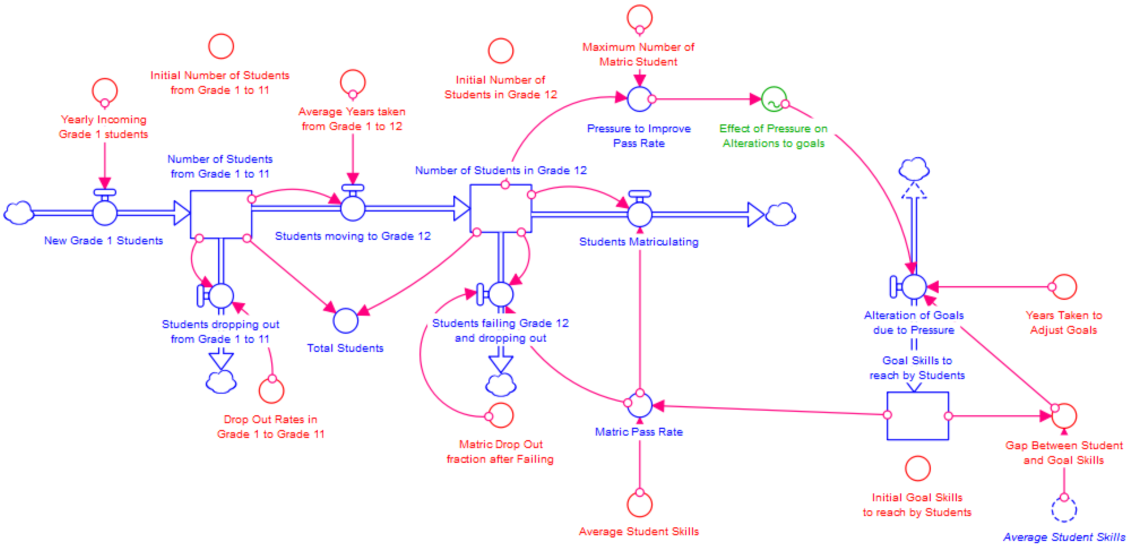


Figure 10.62: Loop Construction of Lower Targets

10.1.30.3 <u>Define constants (8.3):</u>

Stick to simple values as far as possible.

Stocks:

Initial Number of Students in Grade 12: 100

Since the rest of the schooling system needs at least 11 times more students there-in, the value was rounded up to 2 000

Initial Number of Students from Grade 1 to 11: 2 000

Initial Goal Skills to reach by Students: 0.8

Other Variables (Red):

Yearly Incoming Grade 1 students: 120

Drop out rates in Grade 1 to Grade 11: 0.01

Average years taken from grade 1 to 12: 12

Maximum number of matric students: 120

Years taken to adjust goals: 2

Average student skills (assumed constant in B2): 0.6

Matric drop out fraction after failing: 0.75

10.1.30.4 Test Atomic behaviours (8.4):

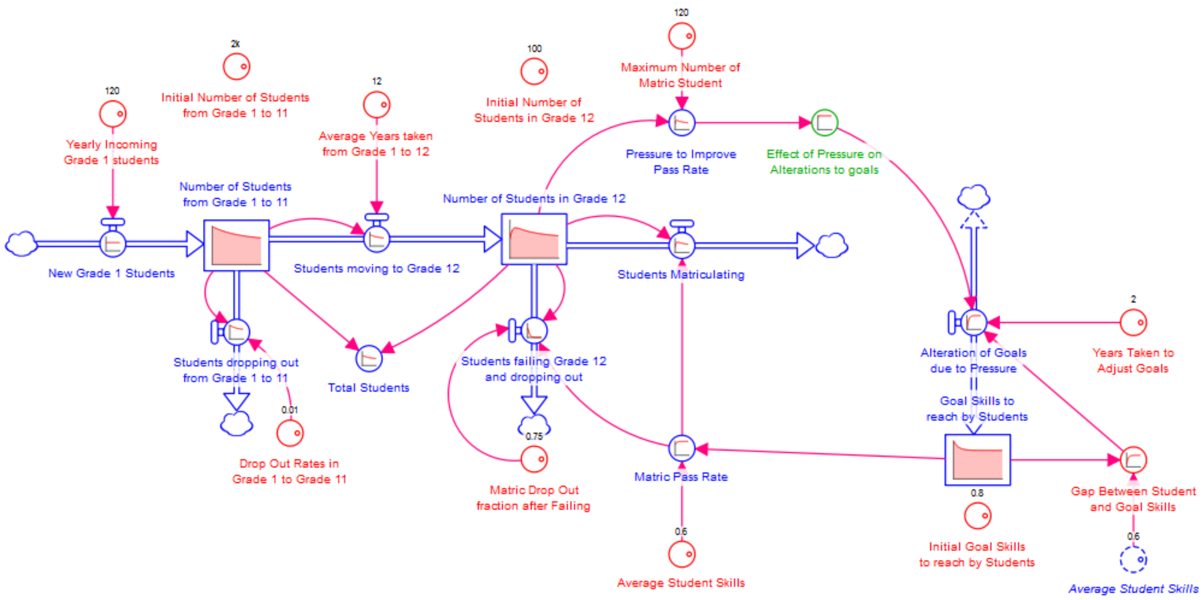


Figure 10.63: Running simulation of the Lower Targets Loop

The results for the goal, actual skills and matric pass rate are shown next.

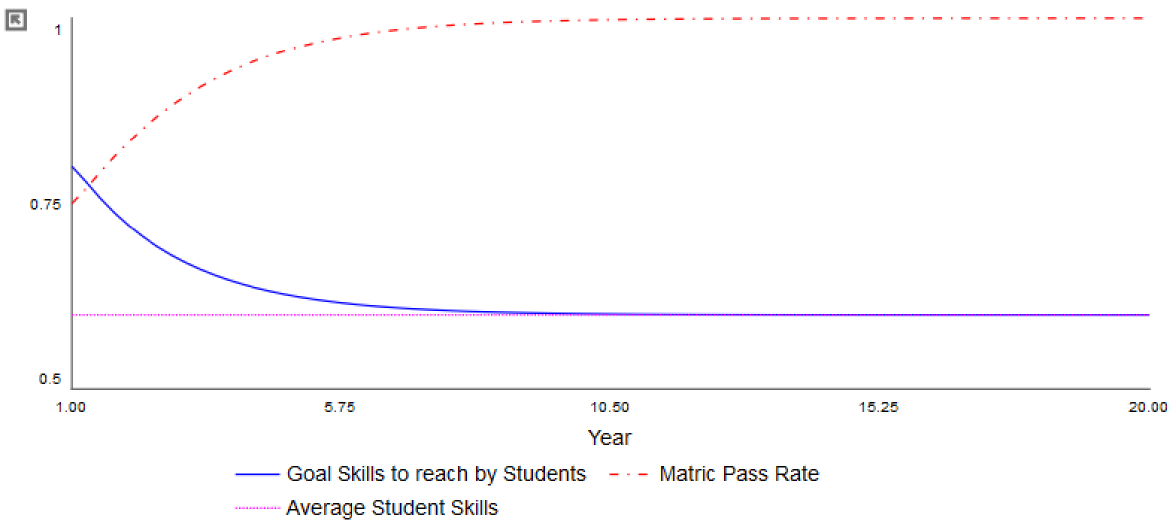


Figure 10.64: Lower target loop simulation behaviour

The goal skills show how the negative balancing loop that is represented by the Balancing loop 2: Lower the target. It clearly shows that as the target is lowered, the matric pass rate also grows. At the end the superficial result seems great, as the matriculation percentage improves significantly yet the actual skills has remained exactly the same, which creates an incorrect impression of the systemic health. As seen in Figure 10.54.

This validates the Loop identified in Step 2.4 of the balancing positive effect on the hateful ideas. The isolated loop seems to fix the problem, just like the causal loop diagram is pointing towards.

10.1.30.5 <u>Next loop (8.5):</u>

The bigger loop is the Long Term Investment Loop. The variables involved in B1: Pass rate, investments into education system, education system quality and average student abilities.

The stocks involved in this loop: Number of students in Grade 12, Number of students in grade 1 to 11, Education infrastructure Commissioned buildings, Education Infrastructure Investment Buildings.

Stocks:

The number of buildings should roughly be realistic for about 2 100 students, as such it was chosen as 25.

Initial education infrastructure investment buildings: 25

Initial education infrastructure investment buildings: 25

Other Variables (Red):

Ideal students per building for 100 skill level:	100
Desired matric pass rate:	0.8
Minimum yearly building investments:	1
Maximum yearly building investments:	50
Average years taken to build and commission:	15
Average life time of educational infrastructure:	20

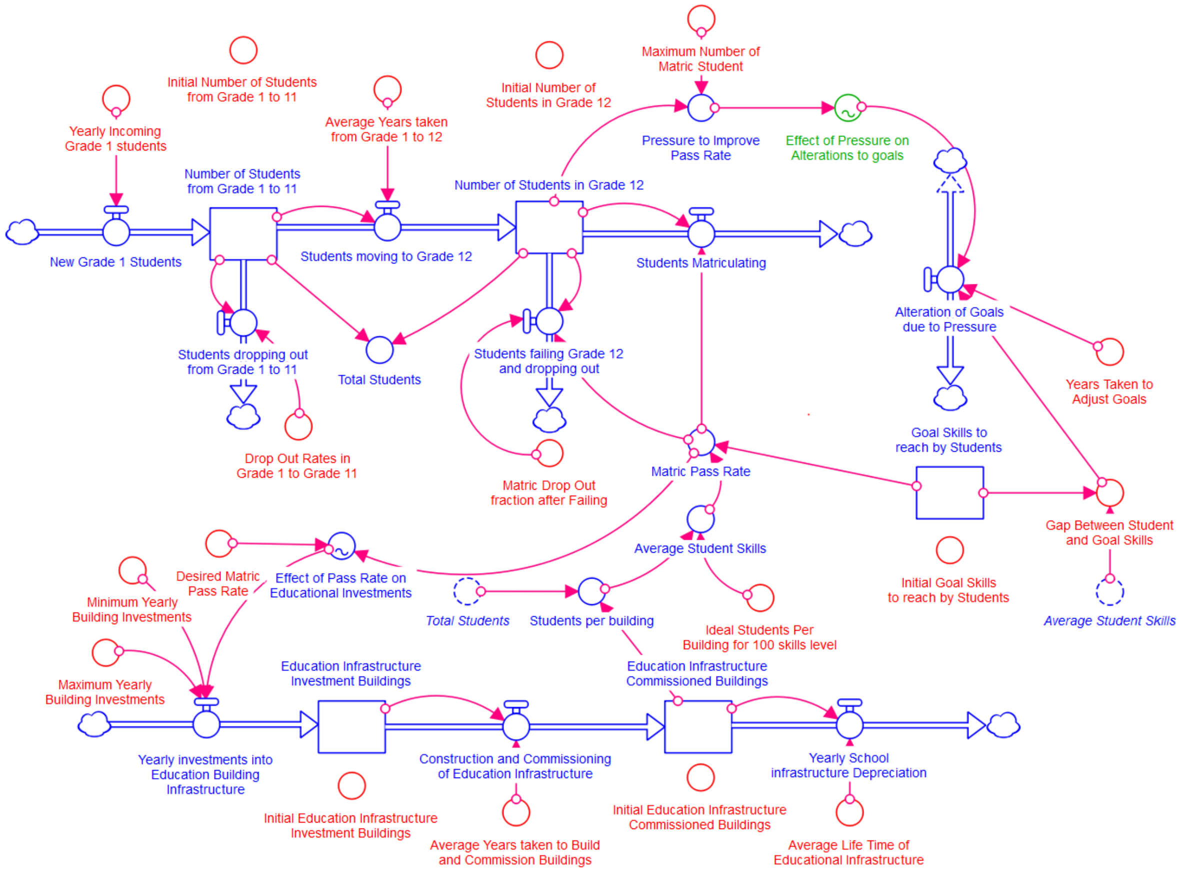


Figure 10.65: Long term Investment loop simulation

The complete structure is now built, yet some of the flows are disconnected, in order to isolate only the first balancing loop (flow of goal adjustments which is solely a part of balancing loop 2). The goal, pass rate and average student skills are seen below:

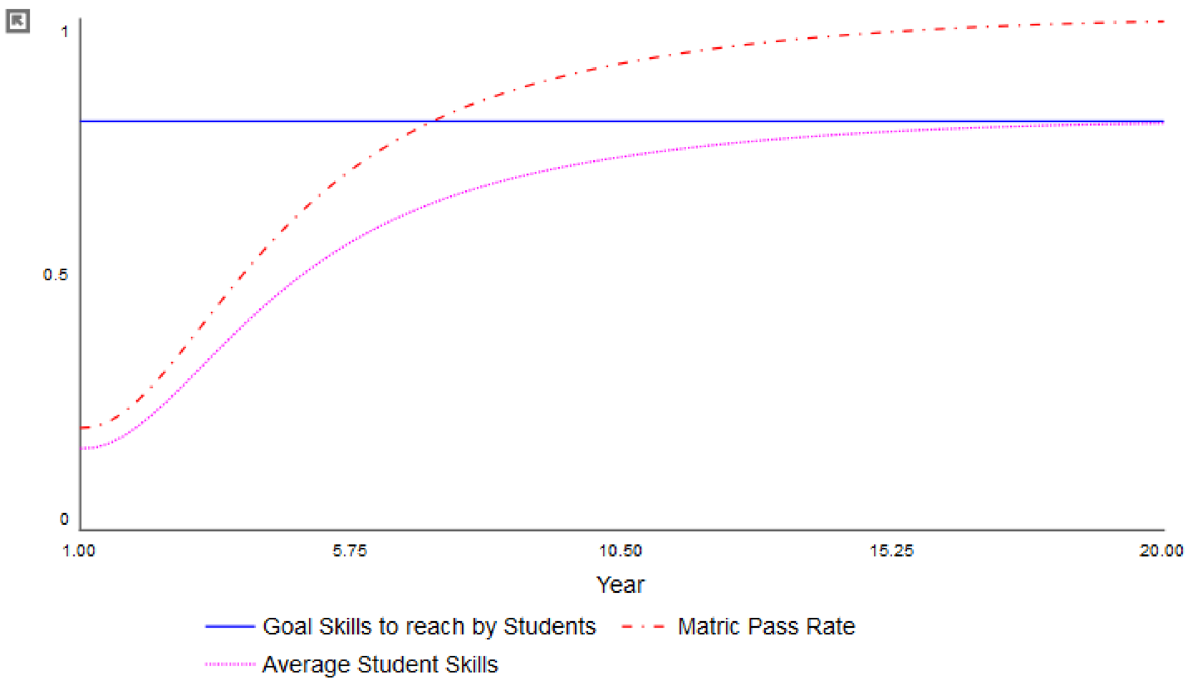


Figure 10.66: Long term Investment loop simulation result

In this case the goal is kept constant while the average student skills are improved. The student skills and matric pass rate both exhibit the B+ behaviour as identified in Step 2. The interesting observation is that both loops produce a 100% pass rate at the end, yet the balancing loop 1 achieves this through improving the student skills while balancing loop 2 achieves this much faster through altering the goals. This is also what the CLD story is telling in step 2 which validates the separate loops.

10.1.31 Step 9: Integrated model testing and verification

10.1.31.1 Integration (9.1):

Connecting the models only required the reconnection alteration of *goals due to pressure*:

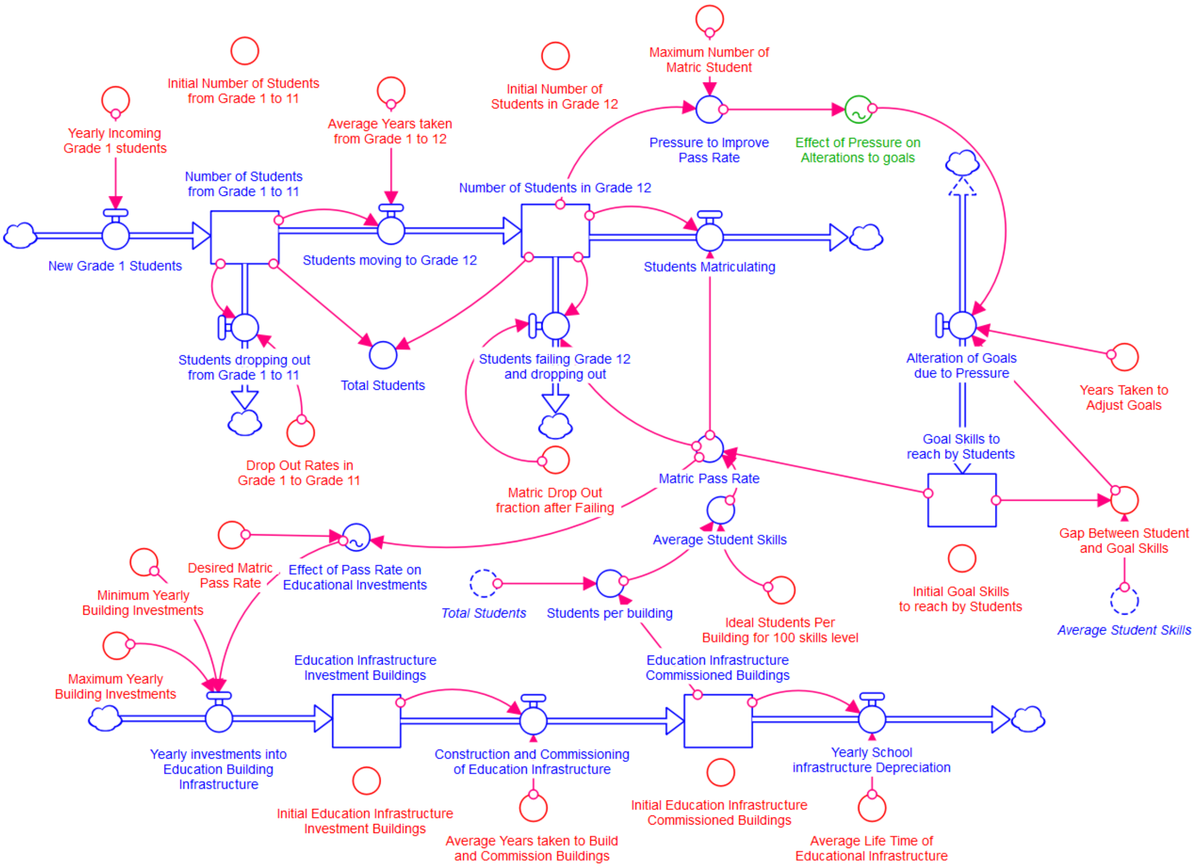


Figure 10.67: Integrated Education Simulation

10.1.31.2 Equilibrium test (9.2):

The change in the the system is driven by the difference between the goal skills and actual skills. In order to achieve some equilibrium when the initial goals and average student skills are almost the same. Since the average student skills are a function and not easily changeable, the initial goal skills are chosen as the same value of average student skills yet with the increase in initial number of buildings to 33 and 50. The initial goal is then set at 0.58 and the results shown next:

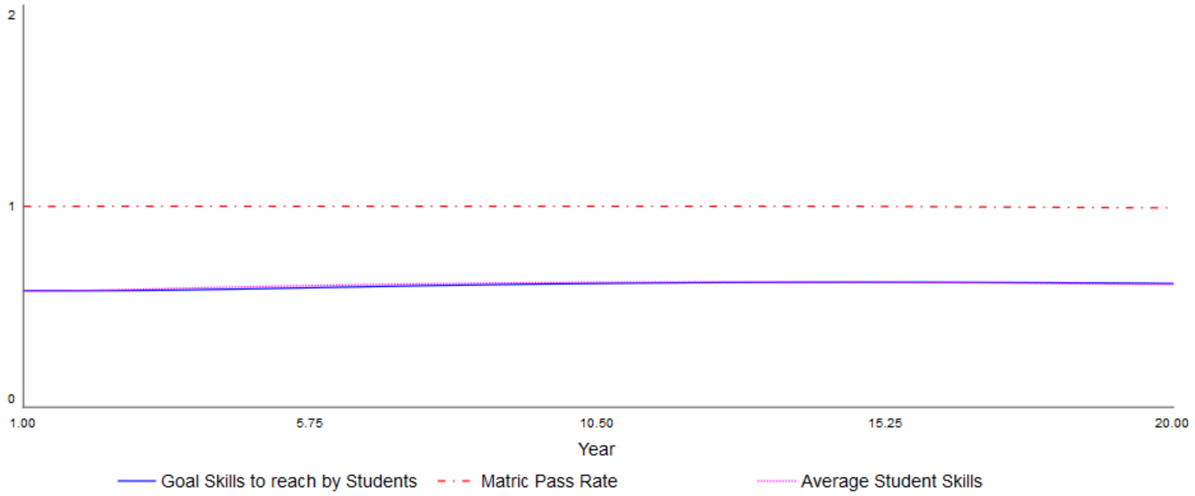


Figure 10.68: Equilibrium Test on Education Simulation

The model is not in perfect equilibrium as the buildings keep depreciating and requires constant investments which is dependant on the pass rate which is a culmination of the complexity in the system.

10.1.31.3 Disturbance test (9.3):

There is a few places in the model where a change can be introduced, in this case the change is introduced into additional investments into the educational system (buildings). The minimum yearly building investments are 1 and the maximum is 50. Constant additional building investments of 10 buildings per year are added since the 10th years of the simulation.

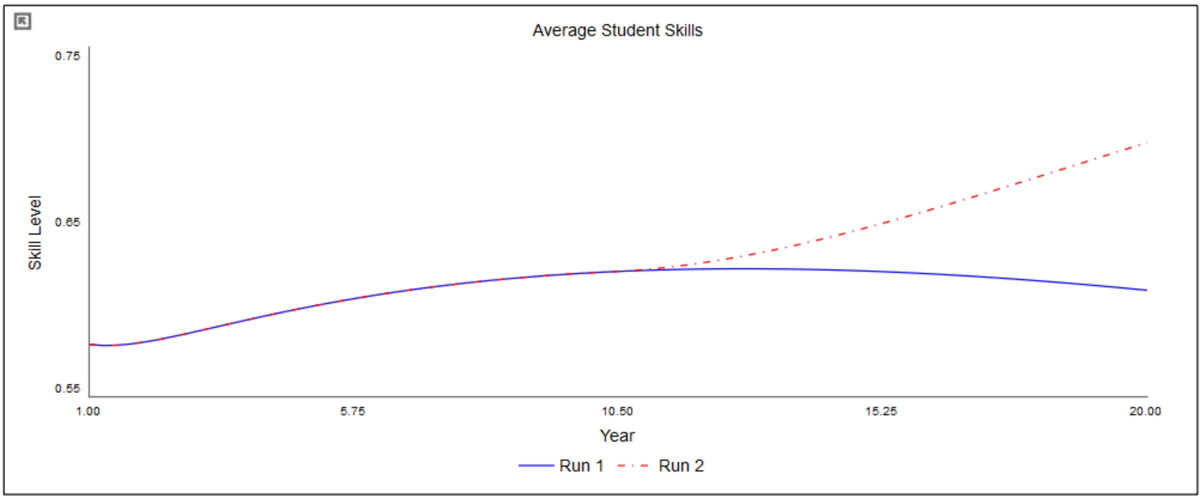


Figure 10.69: Disturbance to Equilibrium Test on Education Simulation

The results show that the constant investment in buildings only starts increasing student performance after 2 years of constant investments. The impact however after 10 years of constant investment is 8%.

10.1.31.4 Reproduce Reference Mode (9.4):

In order to reproduce the behaviour in step 1, more historical context is required. In the transition to the post-apartheid system, the public school system was opened to all races which meant that the public schooling system starting taking in a much larger amount of students every year. It also lead to a pulse of new students into the education system, assumed in this case to be 1000 to the grade 1 to 11 and a pulse of 50 to the grade 12 groups (about half of the original stock pulsed).

The model was adjusted by adding an influx in students of an additional 50 per year from year 5 onwards. Another change that was made to the model inputs was that the years taken to adjust the educational goals, was increased from 2 to 10 years. The post-apartheid government also had many injustices to restore and thus the maximum budget towards education was reduced to 10 buildings per year.

The initial goal skill level that was required in the system was very high, due to the success to the successful archetype that strengthened only the dominant race's abilities. This value was thus changed to 0.981.

The results of the narrative sketched above can be seen in the simulation results:

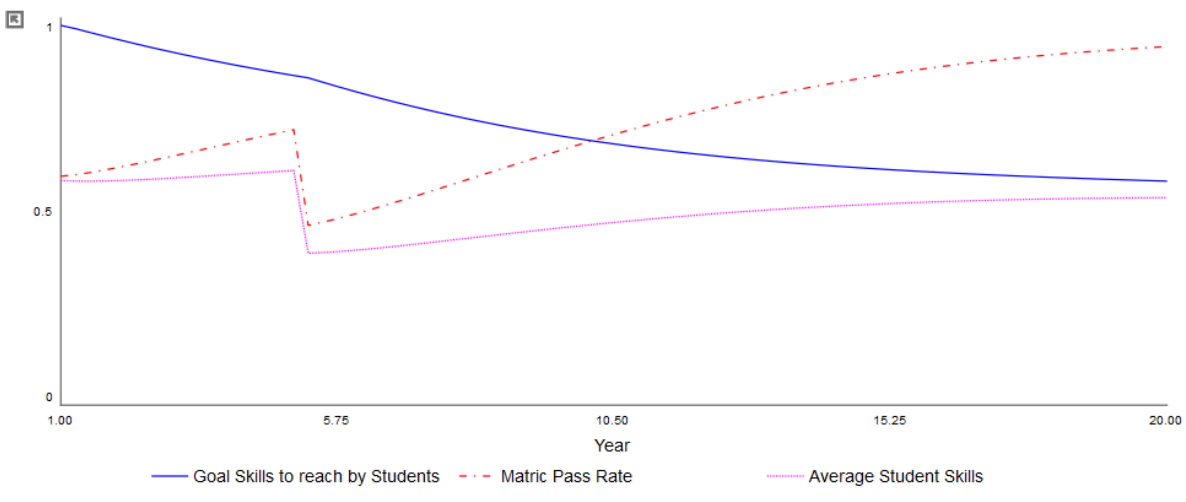


Figure 10.70: Education Simulation Reproduction of Reference Mode

Similarly in the results of step 1, there was an initial decrease in the matric pass rate as the apartheid regime ended. The schooling systems were not designed to handle the additional flow of students and this had strong impacts the matriculation pass rates. The matric pass rate however does start to gradually increase over time, just like the pass rates increase over time in the historical graph of South Africa. The real data however has many more fluctuations in the matric pass rate which could be due to all the excluded complexity that is not modelled by the simplified simulation.

The eroding goals archetype simulation applied to the education system does however reveal that even though the pass rate is increasing, the actual skills are not increasing as significantly, just like indicated in step 1 (Figure 10.51) with the actual historically referenced data/impressions of the system.

10.1.32 Step 10: Sensitivity Analysis

10.1.32.1 Identify variables (10.1):

The list of all the externally driven variables is given below. Each was tested and three variables were identified and explained why these were chosen:

Table 10.18: All external variables in the Education Simulation

Name	Value	Units	Chosen	Reason
Average life time of educational infrastructure	20	Years	No	
Average years taken from Grade 1 to 12	12	Years	No	
Average years taken to build and commission buildings	15	Years	Yes	The impact in building and commisioning new schools
Drop out Rates in Grade 1 to 11	0.01	fraction /year	No	
Desired Matric Pass Rate	0.8	fraction	Yes	The drive for the government to take action against a poort education quality
Ideal students per building	100	Students/building	No	
initial educational buildings commissioned	50	Buildings	No	
Initial educational buildings invested into	33	Buildings	No	
initial goal skills to reach	0.981	Skill Level	No	
Initial students in grade 1 to 11	2000	Students	No	
Initial students in grade 12	100	Students	No	
Matric drop out rate after failing	0.75	Fraction	No	
Max number of students in grade 12	120	Students	No	
Maximum yearly building investments	10	Buildings	No	
Minimum yearly building investments	1	Buildings	No	
Yearly Incoming Grade 1 Students	120	Students/year	No	
Years taken to adjust goals	10	Years	Yes	This can be a policy lever where law would allow

The three variables are thus:

1) Average years taken to build and commission buildings
2) Desired matric pass rate
3) Years taken to adjust goals

10.1.32.2 Sensitivity Range (10.2):

The sensitivity range is selected at 98% lower and higher. The basic value, minimum and maximum is shown in the table below:

Table 10.19: Sensitivity Range of Education Simulation

Sensitivity Range of 98%			
Variable name:	Initial Value:	Min	Max
Average years taken to build and commission buildings	15	0.300	29.700
Desired Matric Pass Rate	0.8	0.016	1.584
Years taken to adjust goals	10	0.200	19.800

10.1.32.3 Sensitivity Points (10.3):

The run values are determined by using the max and min values divided by the number of runs -1. In this case the number of runs was arbitrarily chosen as 5. The values for each of the three scenarios and their run values can be seen in the table below.

Table 10.20: Sensitivity Points of Education Simulation

	Sensitivity Points	Value for each run#				
Scenario	Variable name:	1	2	3	4	5
1	Average years taken to build and commission buildings	0.300	7.650	15.000	22.350	29.700
2	Desired Matric Pass Rate	0.010	0.255	0.500	0.745	0.990
3	Years taken to adjust goals	0.200	5.100	10.000	14.900	19.800

Each of the scenarios is referred to shortened names:

1) Build time: Average years taken to build and commission
2) Desired Pass Rate: Desired matric pass rate
3) Goal Adjustment time: Years taken to adjust goals

10.1.32.4 Analysis (10.4):

Build Time

The initial years taken to build and commission buildings are 15 years. The values for the sensitivity are then incrementally increased from 0.3 years to 29.7 years in five different runs. The impact of these changes on the yearly matriculation rate can be seen in the scenarios below:

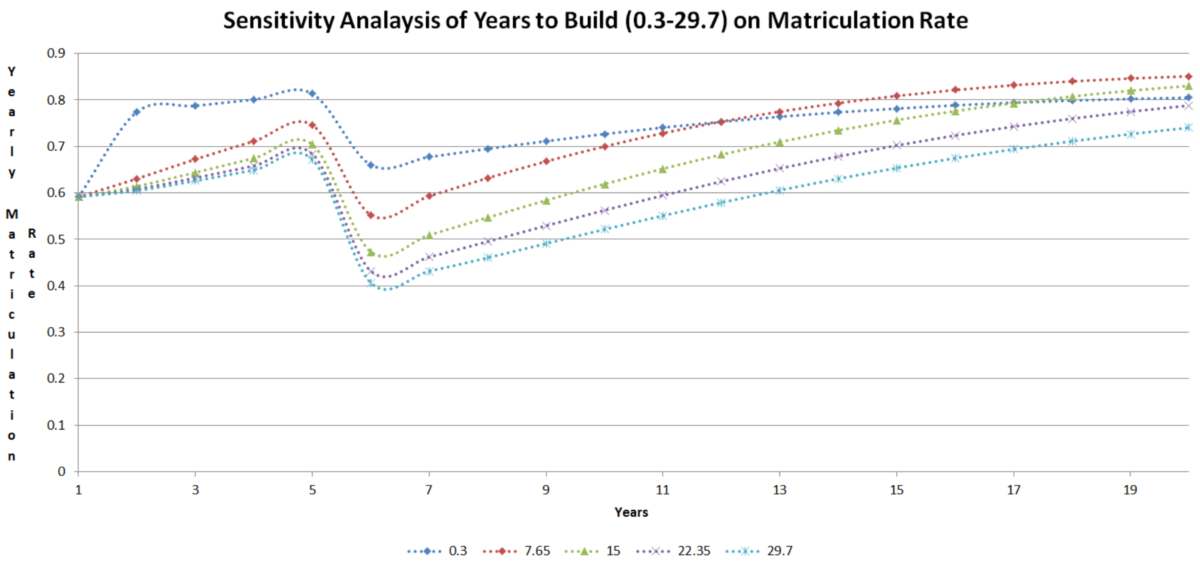


Figure 10.71: Sensitivity analysis on Years to Build and Commission

The very small build and commissioning time of 0.3 years is very unrealistic since it says that a new building can be built and fully commissioned in a third of a year and can function as an extreme condition test. The result shows that if the delay for building and commissioning could ever be this small, then the reduction in delay prevents the goals from eroding, yet it is also an unrealistic value. The more realistic (but still small) delay of 7.65 years shows the best performing scenario with the highest matriculation rate after 20 years. The longer delays of 22 and 30 years show an exponentially increasing trend of poor matriculation. The 30 year is most likely also the extreme condition on the other side of the scale which strengthens the eroding goals archetype.

The sensitivity table below shows a more realistic reduction in years taken to build and commission educational infrastructure would improve the final matriculation rate, albeit small.

Table 10.21: Sensitivity Table of Years to Build and Commission

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Final Percentage effect	-3%	2%	0%	-5%	-11%

The larger the increase in build time the greater the deterioration in the final matriculation rates, with an 11% decrease in matriculation rate with a 98% increase in build time.

Desired Pass Rate:

The initial desired pass rate was defined as 0.5 (50% pass rate). The rate was changed to a very low (extreme condition) test value of 0.01 which is completely unrealistic as the government would (hopefully) never be satisfied with a 1% pass rate. The values were then increased to 0.255, 0.5, 0.745 and 0.99. The last 99% pass rate is also idealistic and probably unachievable. The different set ideal pass rate effects on the yearly matriculation rate can be seen below.

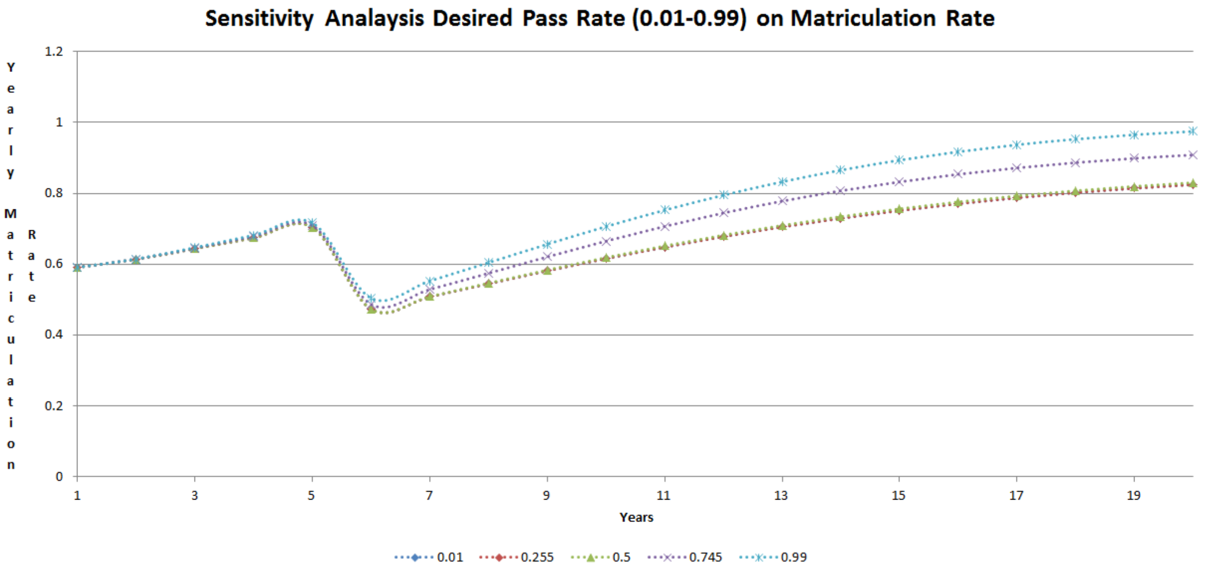


Figure 10.72: Sensitivity analysis on Desired Pass Rate

The interesting aspect in this graph is that the three set points of 0.01, 0.255 and 0.5 have almost exactly the same end result, which shows that if little to no priority is given to reach an high matriculation rate, that the matriculation rate would remain uninfluenced by this variable. Increasing the desired matriculation rate above 0.5 to 0.74 and 0.99, the long term matriculation pass rate does improve. The differences however are quite small in the first 10 years due to the link to the educational investments which inherently have a 15 year delay. The sensitivity analysis for the different scenarios and their effects can be seen below:

Table 10.22: Sensitivity Table of Desired Pass Rate

Sensitivity Table Scenario 2	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Final Percentage effect	-1%	-1%	0%	9%	17%

The a decrease in the desired pass rate has no effect on the final matriculation rate (starting at 50% matriculation rate) yet the almost doubling in the value to close to 100%, does improve the final matriculation rate by 17% in 20 years.

This clearly shows the importance of the government to desire high matriculation rates. If the drive does not exist for high matriculation rates, the education system will not be enhanced. Education appreciation is thus an important soft variable in this system.

Goal Adjustment Time:

The initial skill goal adjustment time was defined as 10 years. This would mean that it would take 10 years to bridge the gap between the actual level and goal level, by changing of educational goal, mainly by exam paper difficulty. The extreme conditions of 0.2 years (about 2 months) and 20 years are used in the scenario analysis. The 2 month delay exhibits an education system that can alter the final year matriculation paper difficulty can be changed almost instantaneously. In this extreme condition it shows that the matriculation rate can be improved from 0.6 to 1 within one year. In reality this is not possible since a 2 month delay is impossible. On the other side of the extreme condition, is the 20 year delay time. The final matriculation value is 67% which is only slightly above the initial 60%. In this case it shows that the matriculation rate changes extremely slow since the goal level is changing very slowly. This is one way to ensure that the system archetype does not take hold of the system, yet it also shows that preventing it also leads to a very slow growth towards the goal. The scenario analysis is seen below:

Table 10.23: Sensitivity Table of Goal Adjustment Time

Sensitivity Table Scenario 3	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage change	-98%	-49%	0%	49%	98%
Final Percentage effect	20%	16%	0%	-12%	-19%

The goal adjustment time has the largest effect on the final matriculation rate in the opposite direction, meaning the smaller the adjustment time, the larger the matriculation rate. This is expected as the smaller the value, the faster the goals can be altered. The side effect of this however cannot be seen in the matriculation rate, but it is visible when observing the actual level for the different scenarios, shown below.

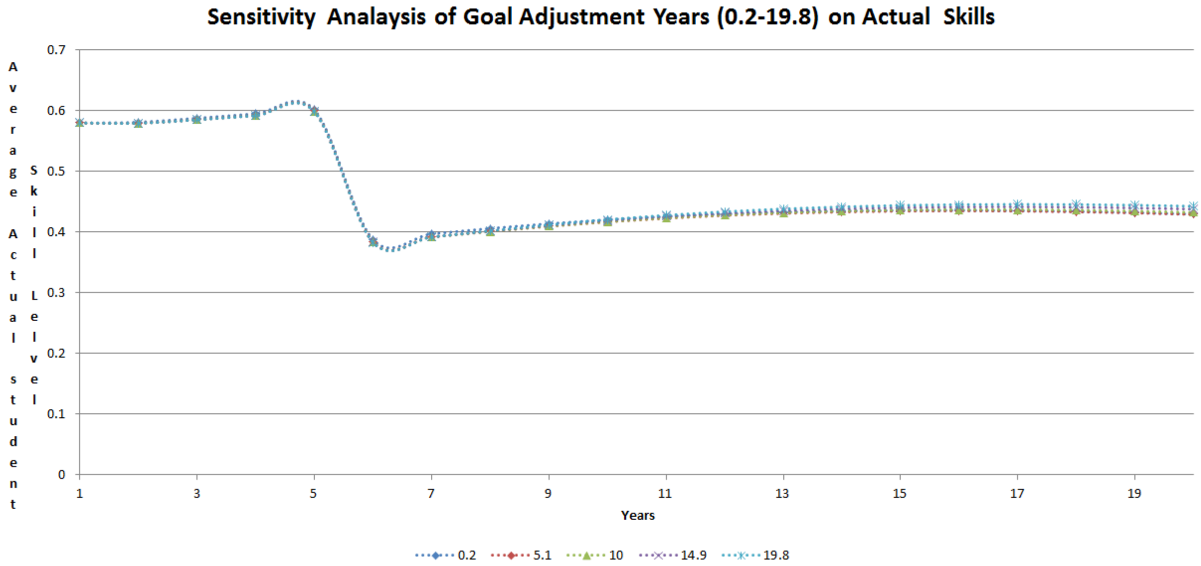


Figure 10.73: Sensitivity analysis on Goal Adjustment Time

The matriculation rate increases drastically with the 0.2 and 5.1 year adjustment time, yet for both of the low years scenarios, the actual skill level is 1% less than the original scenario. When the delay is increased to 15 and 20 years the actual skill level improved by 1% and 2% respectively this is in contrast to the matriculation rate that reduced to 12% and 19% respectively for the same years.

The scenario reveals that the matriculation rates can improve significantly yet it may only be an appearance of improvement as the actual skills only slightly improved, remained the same or even reduced.

10.1.32.5 <u>Ranked Leverage Points (10.5):</u>

In the simulation, the leverage rankings of the variables investigated are in order from strongest to weakest lever:

1) Goal Adjustment Delay – The ability to change the educational skill level required to pass matric is the most influential variable. The danger in this lever is that it creates an impression of good performance while the actual skill levels are lagging far behind, stagnate or even decrease. The lever works in a counter-intuitive fashion with actual skills. If the actual skills required improvement, the delay time should be increased which will decrease the matriculation pass rate but the long term skill level will improve.
2) Desired Pass Rate – The lever is the second strongest of the levers that were investigated and reveals that average and lower desired pass rates have almost no effect on the system. The lever however becomes strong when there exists an above average or even excellent desired pass rate (>80%). The scenario

thus reveals the importance of cultivating an appreciation for good education and the value thereof. Without this appreciation, the system struggles to improve in the fundamental skill areas.

3) Build time – The time taken to build and commission the educational infrastructure has the lowest lever on the matriculation rate, yet it does not mean least important. The lowest lever is due to the constant and long term investments that it requires in order to improve the matriculation results. The changes to the goals are much faster and thus stronger levers on the matriculation results. The build time however could improve the skill level of students significantly yet it is rather unseen as the matriculation rates are conventionally used to convey success or failure.

10.1.33 Step 11: Emerging Lessons

The simulation was kept at the initial values for the sensitivity analysis seen Step 10 above. The simulation interface was built on iSee Stella Architect with the main elements in this development document covered there. The additional inflow of students in the 5th year of the simulation is kept in order to observe the influx of new students on the education system.

10.1.33.1 <u>Emerging Insights (11.1):</u>

The simulation model reveals the following interesting scenarios:

- Desire for Good Education: The first simulation investigated was on the combined effect of desired pass rate with other variables. It was clear that the desired pass rate needs to be relatively high (>80%) before the student skills started improving. The improvement however heavily relies on the available resources allocated to the educational infrastructure. If very little resources are available the desire might be very high yet no skills improvement will be seen.
- Strong unwavering goals: Just like Meadows (2009) indicates, as well as Forrester (1999), the more difficult it is to change the goal, the less this archetype will affect the system. It was seen through the simulation evaluation that a very small delay can increase the matriculation rate very quickly while reducing the average student skills simultaneously. In order to improve the average student skills, the delay in goal adjustments needs to be very high.
- Education infrastructure: The last scenario discussed here is based on the educational infrastructure delays. The time taken to invest, build and operate educational infrastructure successfully is shortened to the build time. All educational buildings are assumed to slowly degrade as they age which requires re-investment to maintain. It was seen that if the build time can be reduced, it could make a large improvement on education levels if the desired pass rate remains high. It was also seen that the moment that the average education infrastructure lifetime becomes 10 years or less, the education system becomes chaotic. It shows the importance of educational investments as well as maintenance to sustain the current infrastructure.
- Overall analysis: According to Meadows (2008) one of the best ways to face the eroding goals is to make the goals very difficult to change (increasing goal adjustment delay to 20 years). Another strong mechanism is to ensure that there is high educational investments taking place (min of 10 buildings per year, max of 80 buildings per year) combined with a high desired pass rate. When these changes are made to the model, the following results are obtained:

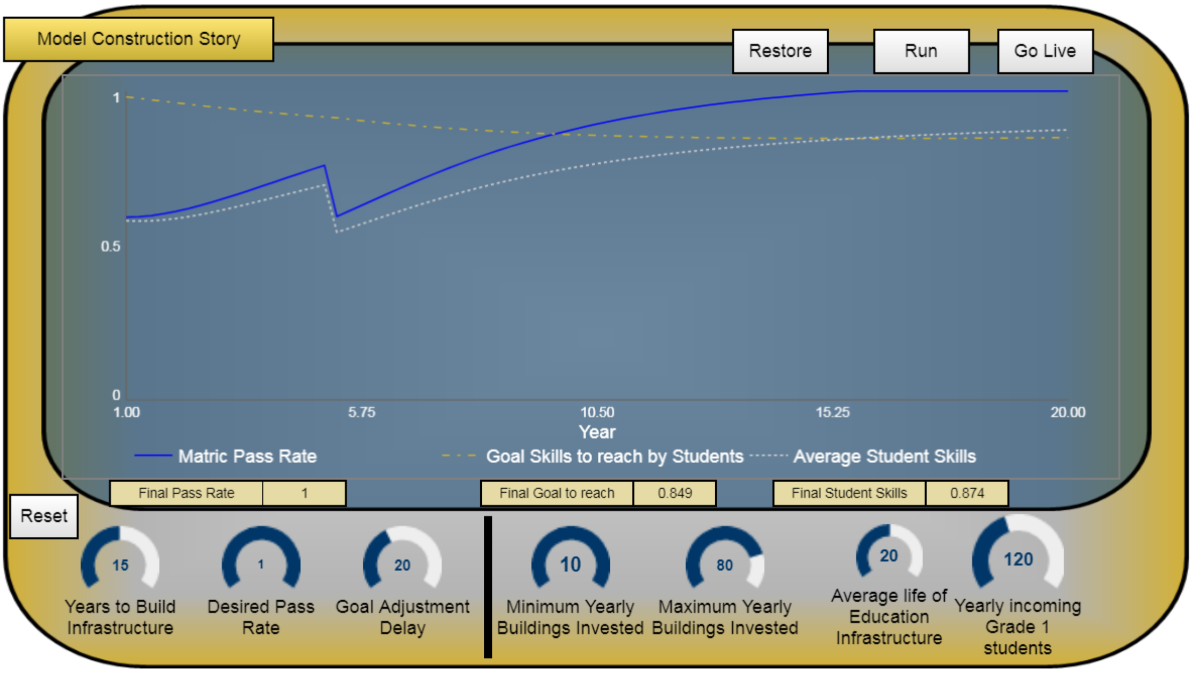


Figure 10.74: Final Simulation Interface for the Education System

It is interesting to see that the final student skills are almost 90% and still slowly improving even though the matriculation rate is already 100%. This is due to the large investments, even at a minimum of 10 buildings per year that keep fueling the student skills growth. The goal skills are also changing very slowly which allows the skills to improve. The final interesting note is that in this last scenario, in the last few years, the goal skill is increasing as the average student skills exceed the goal skills.

10.1.33.2 <u>System Leverage Points (11.2):</u>

After creating the simulation interface and engaging with the model several times, two strong leverage points emerged:

1) **Goal Adjustment Delay:** As explained in 11.1, the bigger the delay becomes the better the educational performance in the system in the long run. This does however mean that the matric pass rates will be very low for multiple years initially which creates more pressures. A long term vision is required to sustain this delay that is shared with successive leaders and their strategies. The very high delay is in a sense validated by the Finnish Education system that required 50 years of unaltered commitment.
2) **Minimum Yearly Education Investments:** The minimum yearly education should be as high as possible. The investments in education will take time to bear fruit but ultimately it is worth it in the long run. The reduction in the yearly educational investments is a very bad sign that the future is being compromised for the present and has detrimental effect many years after the decision. The

assumption here is that the investments do reach the education infrastructure and are put to good use, while this might not be true in the South African context where corruption has surfaced. Corruption however is a whole simulation on its own.

10.1.33.3 List of Variables (11.3):

A full list of all the variables with their definitions for the Education Simulation can be seen in Table 10.16 and Table 10.17 (Step 6.5)

Link to online simulation:

https://exchange.iseesystems.com/public/corne/eroding-goals---south-african-education-system

APPENDIX 2-D: ESCALATION SIMULATION DEVELOPMENT

In this section, the LST method explained in Chapter 4 is applied to the Escalation archetype. The general system archetype is specialized to polarization through social media phenomena.

10.1.34 Step 1: Problem Description

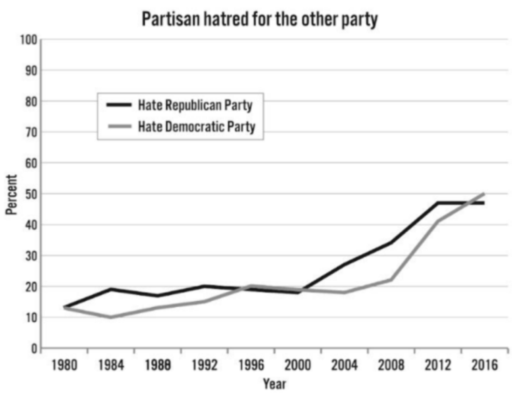
10.1.34.1 <u>Word Model (1.1):</u>

The racial tensions in South Africa experiences regular spikes on both sides when media covers racists remarks and actions. The racist remarks are shared over media so quickly that it sparks an emotional response from the opposite race. The extremists in the opposite side's race would splur racists hate speech back. When this reaches the media, it spreads like wildfire again and the first race feels threatened and the same cycle keeps taking place.

10.1.34.2 <u>Behaviour over time (1.2):</u>

Media focus on racial crimes of race A on B as well as racial crimes of race B on A over time. Both are increasing exponentially. In America the following graph shows the hatred between republican and democratic parties, which are not race based, but rather differences in fundamental beliefs:

Figure 10.75: Partisan Hatred between Republican and Democratic Parties



In South Africa there are many parties yet the ANC party has been reigning supreme since 1994, after the racial divide of the 'Apartheid-Era'. There has however been some indication of polarization in the past three elections. In 2009 the ANC party had 65.9% votes (IEC, 2019).

After the election a right wing party was established called the EFF whom leader was the ANC's previous youth leader. A few of the party's views are extremist values like singing the song 'Kill the boer, kill the farmer' which was publicly sung at some events. At the same time, there exists an alternate party called the VF Plus who associates themselves with artists like extremist 'Steve Hoffmeyer' (News24, 2019) who has made public outcries for white genocide in South Africa, classified the black economic empowerment movement as destructive and other ideas which can easily be interpreted as white supremacy. Movements like creating awareness for farm murders also run all over media like the cross for every farm murder (Twitter: Jerm, 2020).

In the next election, 2014, the ANC party's votes dropped to 62.15%. The VF Plus grew from 0.83% to 0.9% while the EFF grew from nothing to 6.35%. In the last election in 2019, the ANC dropped further to 57.5%, while the EFF party grew to 10.8%. The VF plus also grew from 0.9 to 2.38%. It should be noted that the racial distribution of South Africa in mid 2019 was about 80.7% Black African, 8.8% Colored, 2.6% Indian/Asian and 7.9% white that drastically affect the number of votes when racial tension is used as a political card. (StatsSA, 2019)

It seems like the extremist parties in South Africa are growing. Although there is no clear evidence of the link to social media in South Africa, every time that a racist remark is made, the social media platforms pulsate with the sharing of videos, aggressive debates and sometimes even physical damage to property. The latest version of this is in September 2020 where the retail company "Clicks" placed an advert on hair products that can be interpreted as conveying racial discrimination, which was met with an aggressive backlash by the EFF party on 'Clicks'. There was also the story on Vicky Momberg who used a derogatory word against a black police officer 48 times and thereafter jailed for 3 years as racist abuse (BBC News, 2018). The social media was full of outrage on these events, outage from the political parties, outrage on the outrage from other people but also 'comedic' memes that are made out of the ordeal, spreading like fire over many social media platforms. Most people receive their news from these social media outlets being shared by friends, family and people with similar ideas to them (Chaffey, 2020). By the time that the official balanced news story is created, there already exists a biased towards some polarized view.

Social media has the ability to give user's more of what they want to see and less of a balanced view of reality. Considering the racism problem, every one of the races will generally see more of their own race being discriminated against than reality, which creates the impression that other's reality must be false and leading to more extremist belief systems. The same is true for the political parties in America where there is a strong allegation that Facebook affected the 2016 voting preferences of the social media platform (Brand, 2016). These extremist belief systems often use hate towards the other (or even political party) as a fuel source to drive their movement forward.

10.1.34.3 Purpose (1.3):

The purpose of the model is to apply the LSTs on the Racial Tension Escalation Archetype in order to evaluate if the final simulation can be produced using the method and if the simulation is valuable.

10.1.34.4 Core Variables (1.4):

1) Media coverage on races - **# media stories per month**
2) Hate speech from races - #qualitative hate per month
3) Perceived hatred of races - **# qualitative hate per month**
4) Threats to races - #Number of incidents/crimes per month

10.1.34.5 Time Frame (1.5):

A 20 year time frame at the resolution of months

10.1.35 Step 2: Causal Loop Diagram

10.1.35.1 Core Story (2.1):

When race A makes a hate speech remark on race B, the media focuses on the story due to the high emotional response and interest gained form the public. This creates a perceived threat to race B. The threat/fear drives people in race group B to share/talk and polarize against race A. Given enough fear in the group, some extremist member in race B releases a racial hate speech remark against race A. This triggers the media covers and creates a threat for race A which perpetuates the cycle.

10.1.35.2 Create Causal Loop Diagram (2.2):

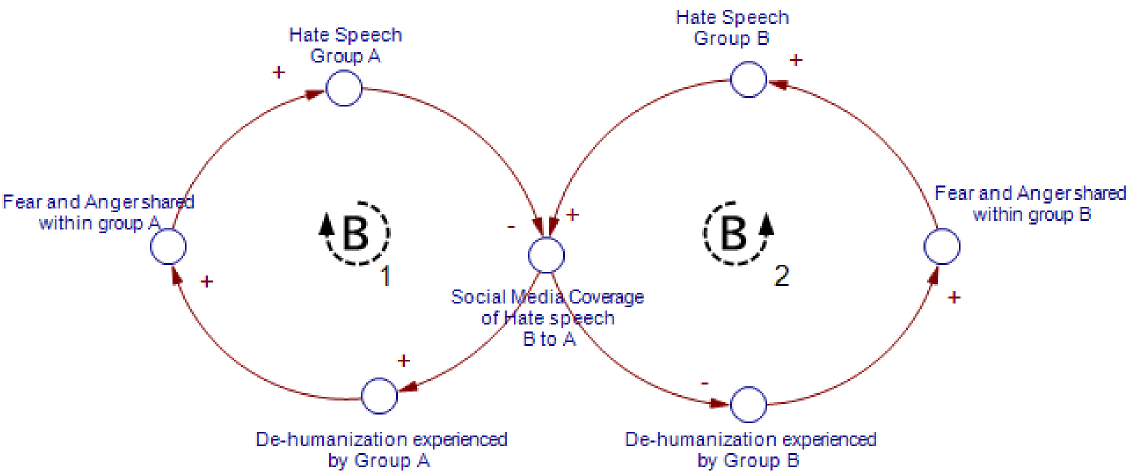


Figure 10.76: Causal Loop Diagram of Social Media Polarization

10.1.35.3 Atomic Loop Behaviours (2.3):

1) **Loop B1 – Group A Eye for an Eye:** Fear created in media for race B will increase and stabilize when the loop works in isolation, as the retaliation against group A should reduce group A's ability to threaten group B. B+ on Hate Speech Group A

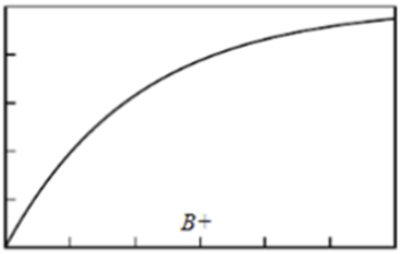


Figure 10.77: Expected Behaviour of Loop B1

2) **Loop B2 – Group B Eye for an Eye:** The same behaviour for the same reason. B+ on Hate Speech Group B.

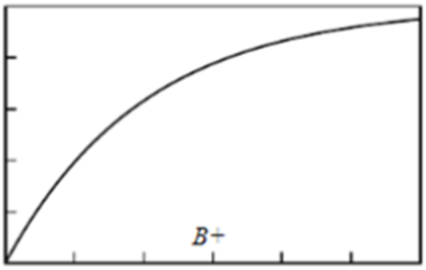


Figure 10.78: Expected Behaviour of Loop B2

3) **Loop R – You will not have the last say:** When loop B1 and B2 start working together, an unseen loop emerges which resembled the paradigm of 'An eye for an eye', which triggers another 'eye for an eye' and the fighting never ends, leading to an R+

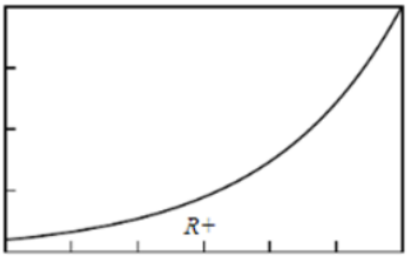


Figure 10.79: Expected Behaviour of integrated loop R

It is interesting to note that Loop R in Escalation is the only system archetype simulations where the emergent phenomena of two loops can be identified in step 2 already.

10.1.36 Step 3: Stocks and Flows

10.1.36.1 <u>Snapshot test (3.1):</u>

When time freezes threats will disappear as would the media coverage. The hate speech itself will also fade away but the hateful ideas stored in the minds of people might remain. The ideas are obtained from social media, talking, discussion racially fueled incidents and the ideas slowly dissipate with time.

10.1.36.2 <u>Test stocks for nouns (3.2):</u>

- Hateful Ideas in race group A towards race B (Dimension - Qualitative: Percentage of hateful ideas in population)- qualitative noun.
- Hateful ideas in race group B towards race A (Dimension - Qualitative: Percentage of hateful ideas in population) – qualitative noun.

Ideas can flow and become hateful. The question is where are those ideas flowing from. In the simulation it is assumed that neutral ideas are converted to hateful and hateful can be converted back to neutral. Creating two more stocks:

- Neutral ideas in race group A toward race B – countable qualitative noun.
- Neutral ideas in race group B towards race A – countable qualitative noun.

10.1.36.3 Test each loop for stocks (3.3):

- Loop B1: Hateful ideas of race group A towards race B
- Loop B2: Hateful ideas of race group B towards race A

10.1.36.4 Identify the flows (3.4):

How can these stocks change? What can change them?Both stocks function in a similar way, as such, only one will be examined:

- Inflow: Discussion/talking/sharing of hateful ideas over media
- Outflow: Natural dissipation of ideas
- Outflow: Balanced opinions from trusted news sources
- Inflow: Experiencing racism

10.1.36.5 Delays and aging chains (3.5):

Test: Can hateful ideas enter into the mind and leave the mind within one month? Yes, and thus no aggregated stocks are currently required. The percentage of hateful ideas come from the percentage of neutral ideas percentage that is converted to hate. The hate can be taken back to neutral as well.

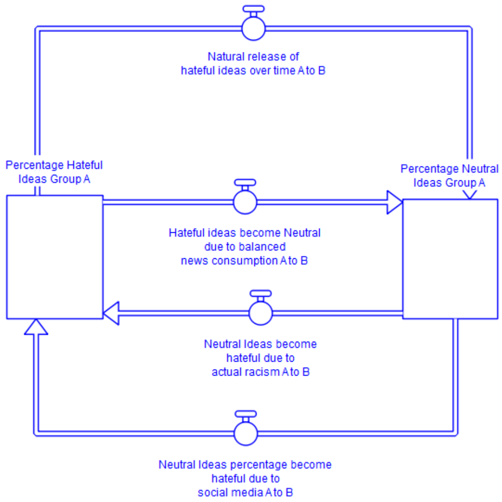


Figure 10.80: Structure of Ideas Becoming Neutral and Hateful

10.1.37 Step 4: Basic Stock and Flow Diagram

10.1.37.1 System Architecture Map (4.1):

In this case, the structure is already found in step 3 and no additional SAM is created.

10.1.37.2 Separate Stock and Flows (4.2):

As seen in Step 3.5, the stocks and flows are defined for one group and will be a duplicate for the other group

10.1.37.3 Merge to one Stock and Flow Diagram (4.3):

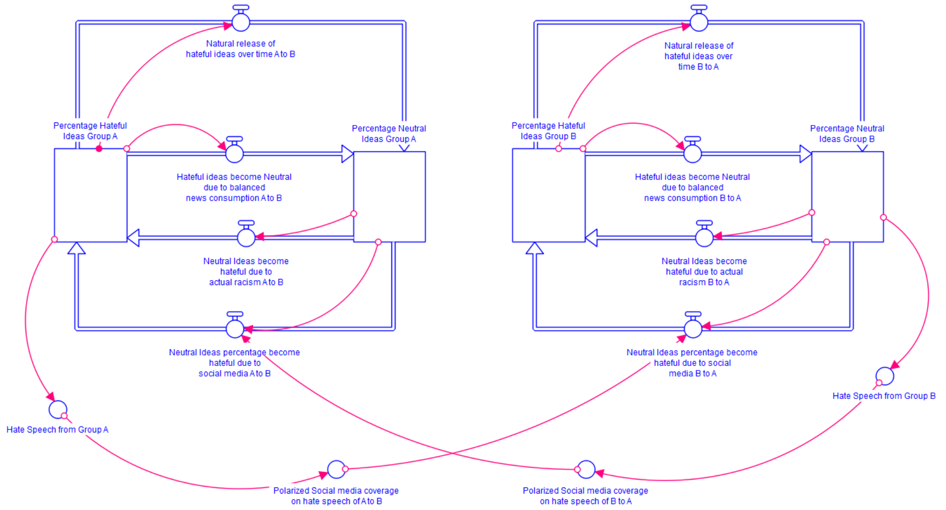


Figure 10.81: Basic Stock and Flow Diagram of Media Polarization Sim

10.1.38 Step 5: Dimensional Analysis

10.1.38.1 Stock Dimensions (5.1):

- All the stocks have a dimension of %

10.1.38.2 Flow Dimensions (5.2):

- All flows then have a dimension of % per month

10.1.38.3 Complete Dimensions (5.3):

- Hate speech variables should have the dimension of events/month
- Polarized social media coverage is also events/month

10.1.38.4 Dimensional Gaps (5.4):

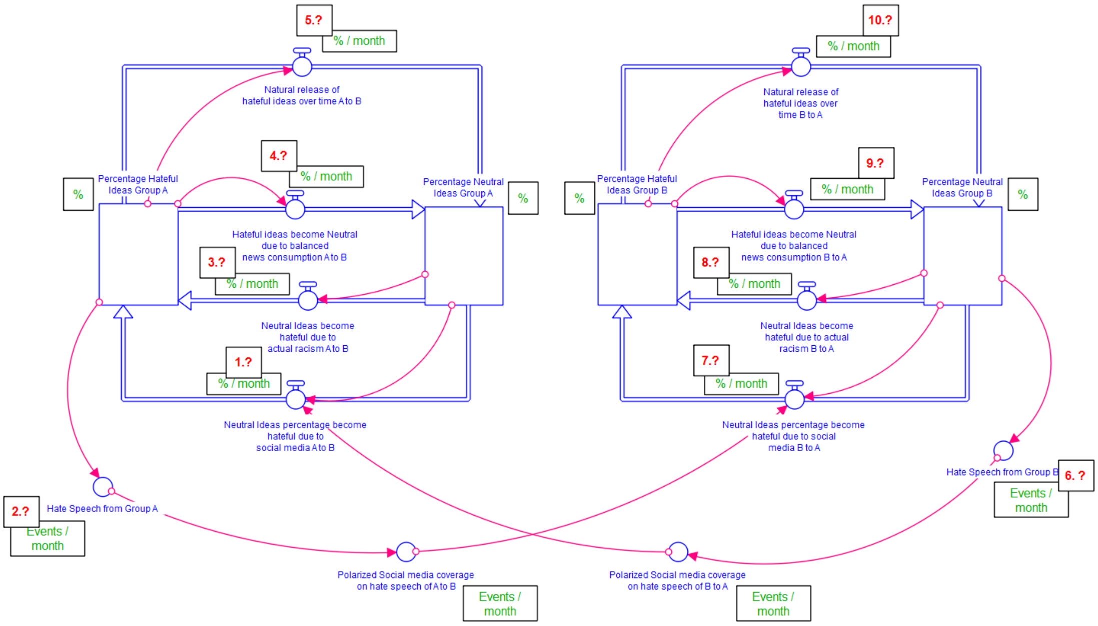


Figure 10.82: Dimension Gaps in Media Polarization Sim

The dimensional gaps are:

1) Neutral ideas (%) and polarized media coverage (events/month) -> Hateful idea generation due to social media influence (%/month). **A division is needed for events.**
2) Hateful ideas (%) -> Hate speech (Events/month). A conversion is needed between percentage hateful ideas and the number of hate speech events.
3) Neutral ideas (%) -> Hateful ideas generation due to actual racism (%/month). **A probability fraction is needed on race group A experiencing actual racism.**
4) Hateful ideas (%) -> Release of hateful ideas due to balanced news consumption (%/month). **A probability fraction of people relying on balanced news sources for facts.**
5) Hateful ideas (%) -> Natural release of hateful ideas (%/month). A Time component is needed for the average time that the group holds on to hateful ideas.

The gaps 6 to 10 are exactly the same as 1 to 5, only for the other race group.

10.1.39 Step 6: Mathematical formulation

10.1.39.1 Missing Variables (6.1):

1) A variable that is defined as **fraction per event**. In this case it could be the **fraction of people using social media as their source of news** and seeing the event (fraction per event). There also needs to be a division by events, so divide by **Maximum Events**. *Rate equation 1.*
2) This is a non-linear relationship (effect variable). No clear relation exists between the two variables. *Effect variable definition.*
3) A fractional probability is required (fraction per month). This could be the **fraction of people personally experiencing racism per month.** *Rate equation 1.*
4) Another fractional probability is required (fraction per month). This could be the **fraction of people relying on balanced news consumption per month**. *Rate equation 1.*
5) The average residence time component is required here. In this case it could be the **time (months) taken for the group to release hateful ideas**. *Rate equation 2.*

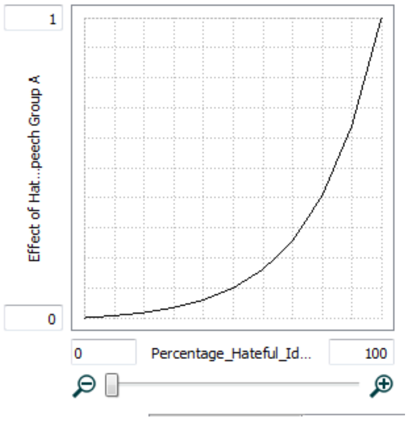
The same missing factors can be identified in 6 to 10, for the other race group.

10.1.39.2 Effect Variables (6.2):

It is only missing component 2 and 6 that needs an effect variable. Using Appendix E, the effect variable is Generated:

1) The name: The effect of % hateful ideas on the hate speech events per month
2) The X/Y Coordinate system:
3) Define the three points:

   a. When % hateful ideas are at a 0%, there are no hate speech events
   b. When % hateful ideas are at 50%. Thoughts take time to lead to action and thus there is a delayed response. Once however a certain point is reached, the hateful ideas leads to exponential acts of hate. As such at 50%, the hate speech is probably around 10% of the maximum value of events per month.
   c. When % hateful ideas are at 100%, there are max hate speech events.
4) Connect the points to produce the final graph:



5) Define the minimum and maximum values:

Percentage hateful:

Min = 0; Max = 100%

Events per month:

Min = 0; Max = Create a variable called Maximum hate speech events per month.

10.1.39.3 Equation Formulations (6.3):

1) $Neutral\ ideas\ become\ hateful\ due\ to\ social\ media =$
$Fraction\ of\ people\ relying\ on\ social\ media\ for\ news\ events\ \times$
$Polarized\ media\ coverage\ on\ hate\ speech\ of\ opposite\ group\ \times$
$Percentage\ of\ Neutral\ Ideas\ \div Maximum\ Hate\ Speech$
2) $Effect\ Variable{:}\ Hate\ Speech = Effect\ of\ Hateful\ ideas\ \times Max\ Hate\ speech$
3) $Idea\ conversion\ due\ to\ atual\ racism =$
$Fraction\ of\ people\ experiencing\ actual\ racism\ \times Neutral\ ideas\ from\ group$
4) $Idea\ conversion\ due\ to\ balanced\ news\ consumption =$
$Fraction\ of\ people\ per\ month\ relying\ on\ balanced\ news\ per\ month\ \times$
$Percentage\ of\ hateful\ ideas$
5) $Natural\ release\ of\ hateful\ ideas = \frac{Percentage\ of\ Hateful\ ideas\ in\ group}{Average\ months\ taken\ from\ group\ to\ release\ ideas}$

The same equations can be defined for equation 6 to 10, for the other group.

10.1.39.4 Stock Stages / Aging chains (6.4):

No stage fractions exist as it is assumed that ideas can spread within one month.

10.1.39.5 Final Dimension Checks and Multipliers (6.5):

There is one missing component between hate speech and social media coverage. Both have similar dimensions yet one refers to the hate speech and the other on coverage of the hate speech. A conversion multiplier is needed between each. A multiplier of 1 means that the media covers theFra exact number of media events. In reality social media algorithms amplifies the sensational events to gain more views. The multiplier would thus be larger than 1. The variable is defined as **Social media amplification multiplier**.

The final list of variables, their definitions and dimensions can be seen below.

Table 10.24: List of variables and descriptions for the Media Polarization Sim

#	Variable Name	Description	Dimension
1	Percentage Hateful Ideas	The percentage of the group that has hateful ideas about the other group	Percentage
2	Percentage Neutral Ideas	The percentage of the group that has neutral/equality ideas about the other group	Percentage
3	Fraction of people relying on balanced news	The fraction of the group that uses reliable news sources to base their views on	Fraction
4	Fraction of people relying on social media news	The fraction of the group that uses social media as the main source of forming their viewpoints	Fraction
5	Fraction of people experiencing racism directly	The fraction of people actually experiencing racism tangibly that will form hateful ideas due to the racism	Fraction
6	Average months taken to release hate ideas	The time taken for the group to forgive, release hateful views on the other group	Months
7	Effect of Hateful ideas on hate speech	The relationship between the thoughts and actions of the hatred, leading to hate speech	Dimensionless (Effect)
8	Hate speech from Group	The number of events that hate speech is actually taking place	Events
9	Total social media coverage	Social media spreading the hateful message	Events
10	Polarized social media coverage on hate speech of A to B	The percentage of social media directed at the hate of group A on B.	Percentage

In the next step the detailed stock and flow diagram can be seen, which can be a blueprint for model construction.

10.1.40 Step 7: Detailed Stock and Flow Diagram

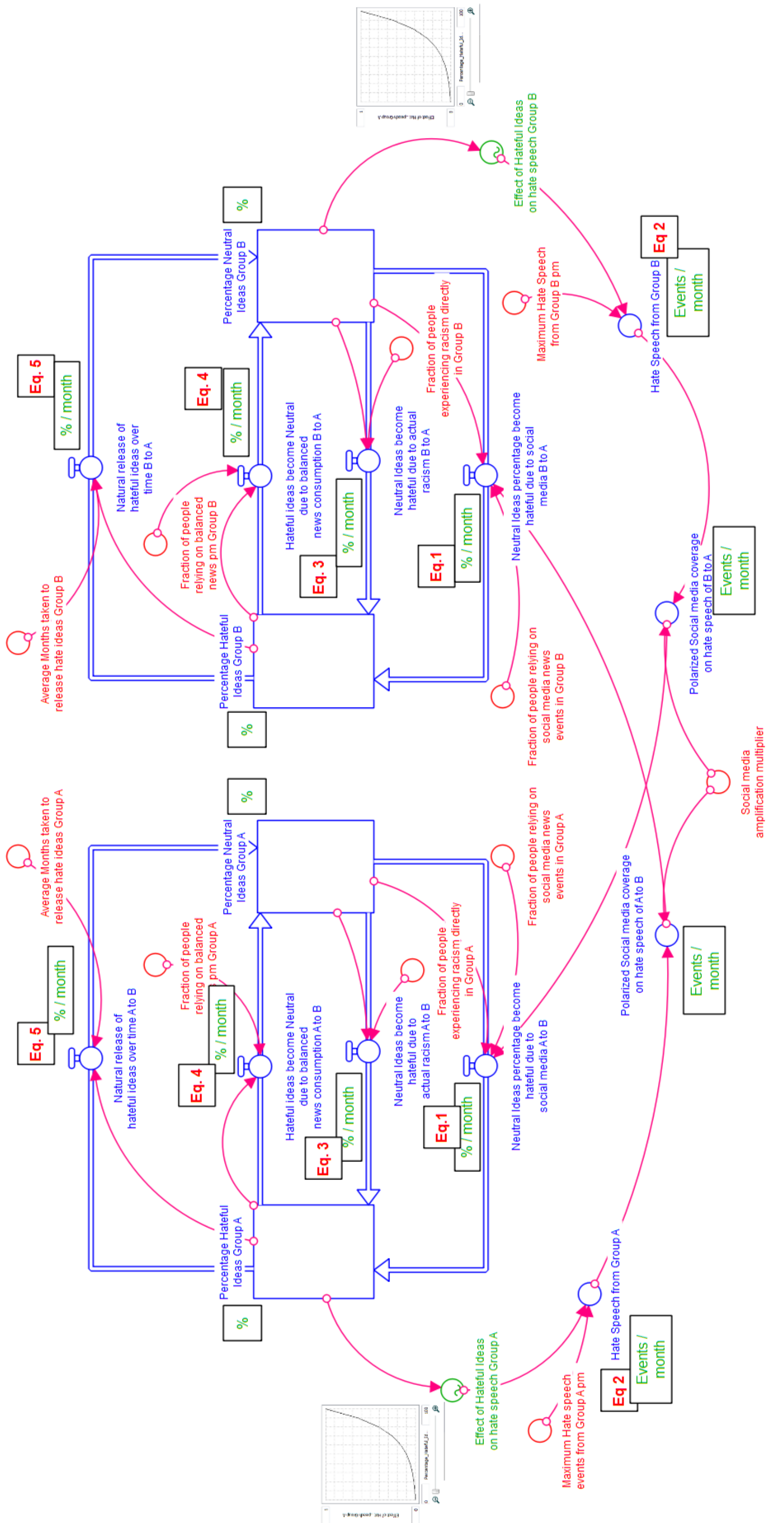


Figure 10.83: Detailed Stock and Flow Diagram of the Media Polarization Sim

10.1.41 Step 8: Small loop models and validation

10.1.41.1 Smallest Loop (8.1):

In this case there are only two loops and both having the same size. As such Group A will be chosen first.

10.1.41.2 Construct Loop (8.2):

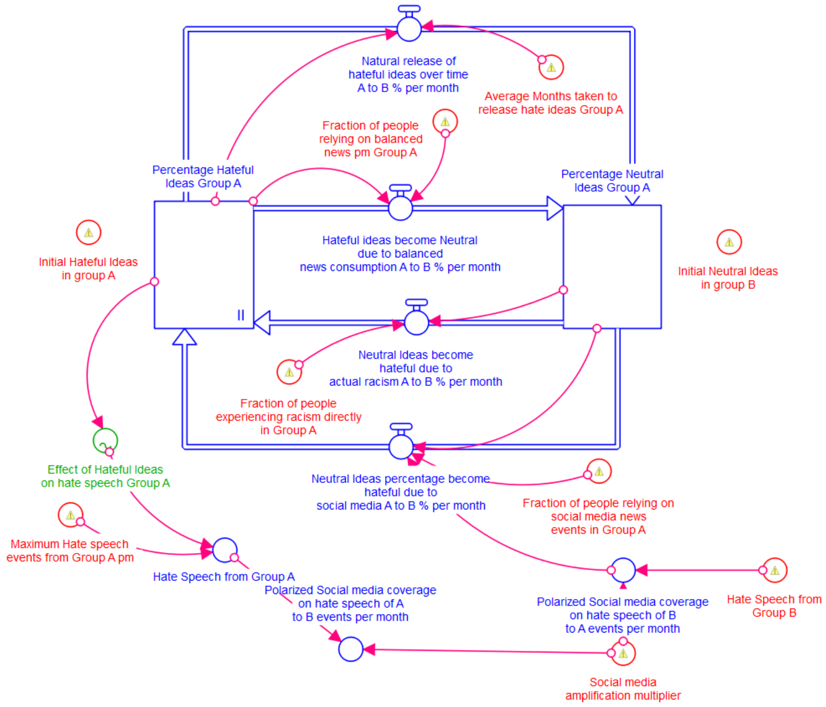


Figure 10.84: Loop B1 Simulation Construction

10.1.41.3 Define constants (8.3):

Stick to easy values like 0,1, 100 where possible.

Stocks:

Neutral Stock – 100

Hateful ideas – 0

Multipliers in flows:

Firstly define these per the CLD, the first three does not exist in the CLD and thus are made to have no impact on the small model:

Fraction of people relying on balanced news – 0

Fraction of people experiencing actual racism – 0

Average months taken to release hate ideas – 999999999 (never)

Fraction of people relying on social media news events in Group A – 1

Maximum Hate Speech events from group A: 1000

Hate speech from Group B: 100

Social Media amplification Multiplier: 2 (meaning that they are doubling the visibility of hate speech)

10.1.41.4 Test Atomic behaviours (8.4):

The results for the Percentage of Hateful Ideas are seen in the next graph:

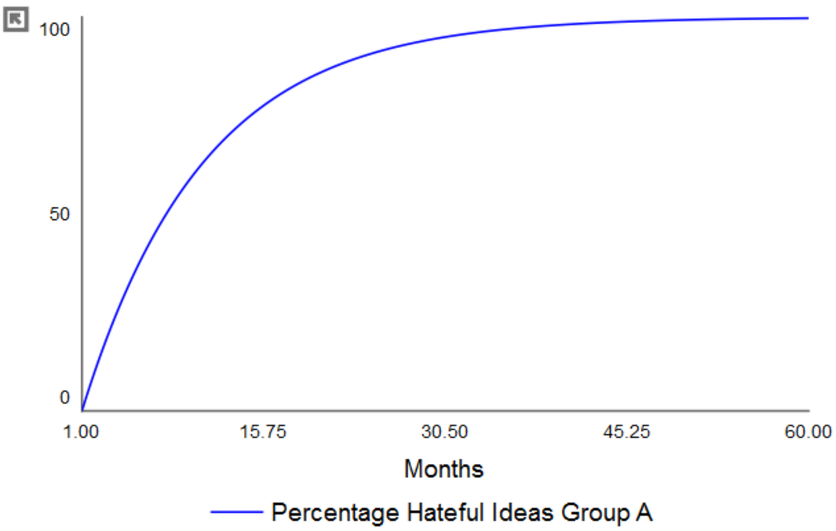
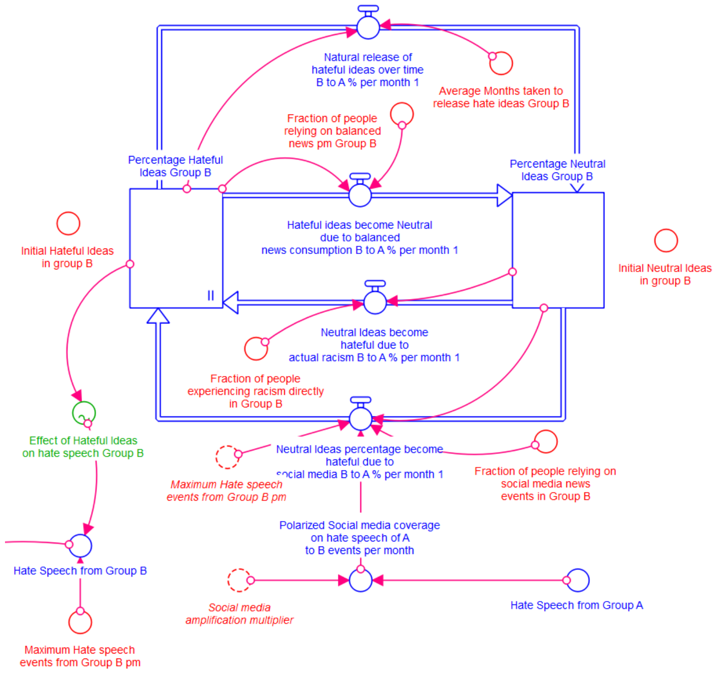


Figure 10.85: Loop B1 Simulation Behaviour

The Behaviour fits the exact behaviour of B+ as seen in the Loop Dominance Graphs in Appendix D and in Figure 10.77. This validates the Loop identified in step 2.4 of the balancing positive effect on the hateful ideas.

10.1.41.5 Next loop (8.5):

The second loop has exactly the same structure and thus chosen with the same conditions, constructed and tested below.



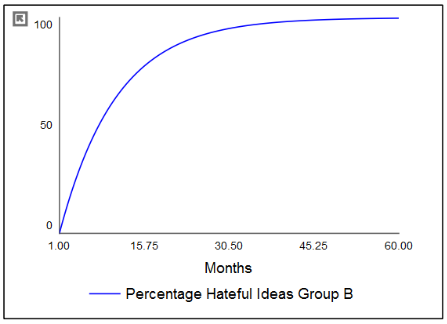


Figure 10.86: Loop B2 Simulation

The same result is obtained with a balancing loop behaviour. The true test would be to see when there was no limit on the percentage of hateful ideas, if there will still be a balancing effect (true to the CLD). (Extreme condition test)

By testing this assumption, it is found that the polarized social media coverage needs to be divided by the total social media coverage in order.

This change was made and the new results can be seen below

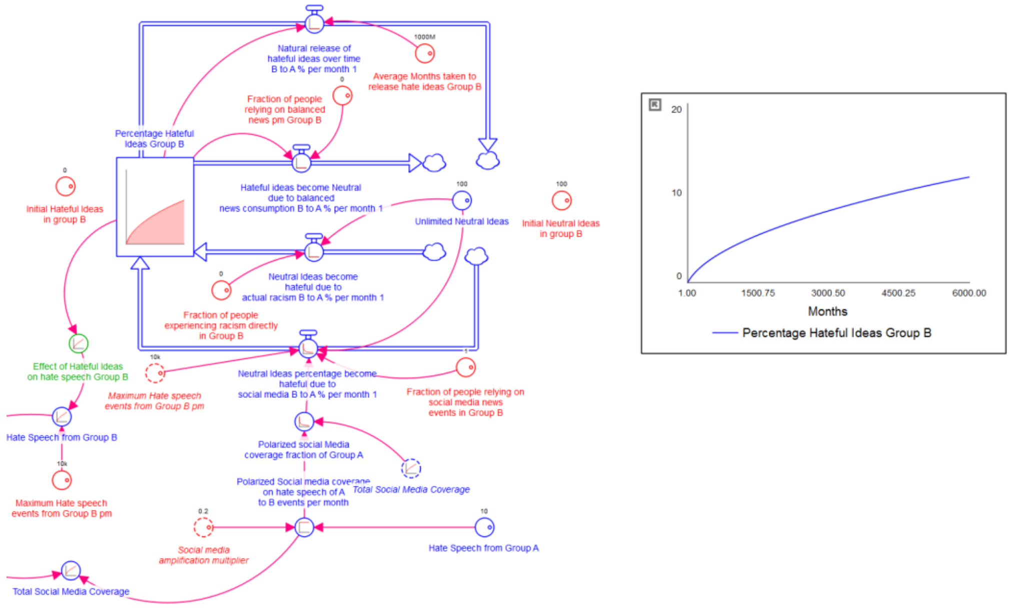


Figure 10.87: Loop B2 Simulation Behaviour

The new results show that the change is slowing down even though the amount of neutral ideas remains unlimited at 100. This assumption was to test the behaviour yet in reality there is not an unlimited supply of neutral ideas, as they are exchanged with hateful ideas. The stock is thus returned to the structure and re-run. The final results are then seen in the graph below:

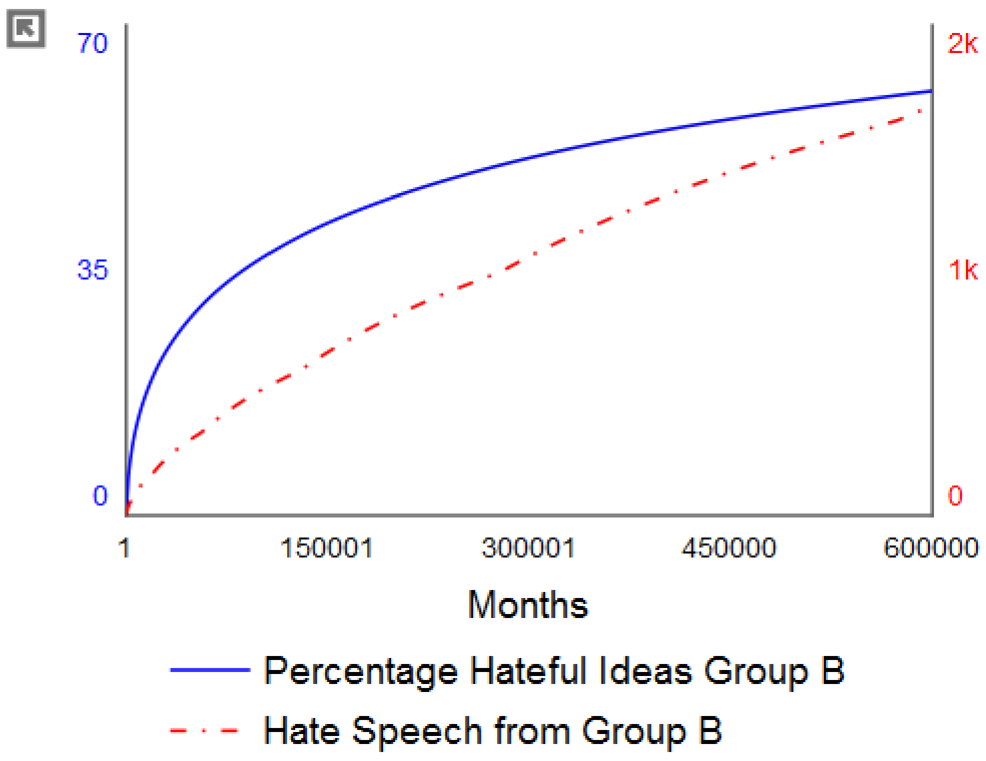


Figure 10.88: Final Results of Group B Behaviour

The Hate speech from group A was changed to 10, maximum hate speech events changed to 10 000. Initially there was no hate in group B but with the constant Hate speech of 10 from group A, the hate in group B started growing above 10 as the social media amplifies the effect together with the non-linear relationship between hateful ideas and hate speech. The hateful behaviour slows down however and is growing towards an asymptote value.

After 600 000 months or 50 000 years (extreme condition test), the equilibrium value has not been reach yet the monthly change is 0.0000234 OR 2.34 x 10^{6} %, which is extremely small, and a rounded value will be zero. This extreme condition test shows that the accumulation slows down sufficiently enough to be seen as zero.

10.1.42 Step 9: Integrated model testing and verification

10.1.42.1 Integration (9.1):

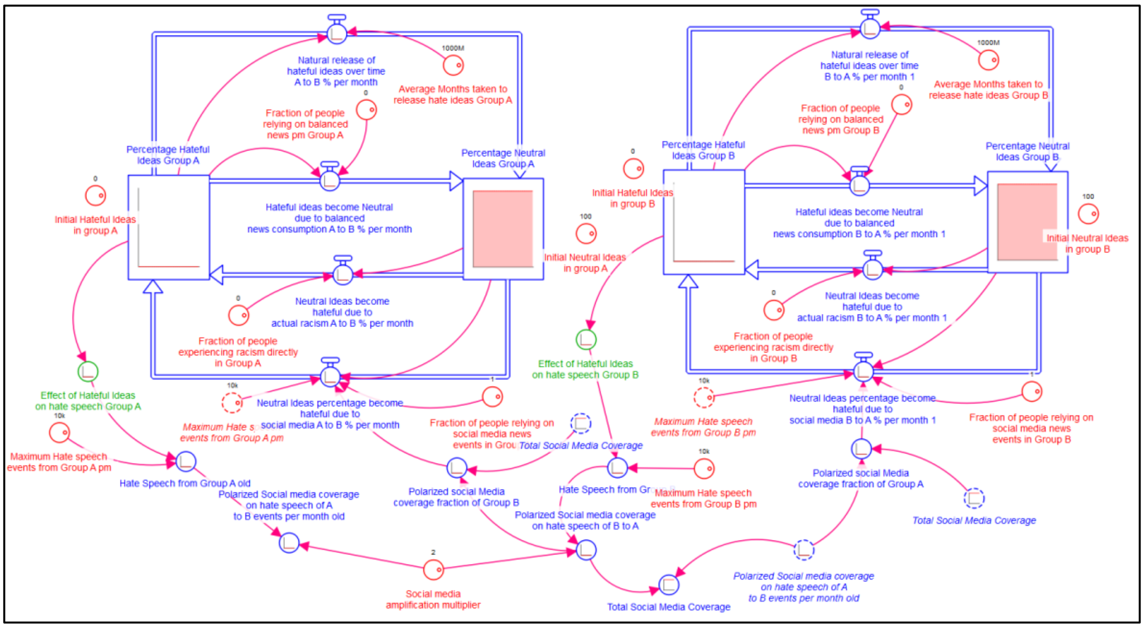


Figure 10.89: Integrated Simulation of Media Polarization Sim

10.1.42.2 Equilibrium test (9.2):

Running the simulation as is from step 8, shows the static equilibrium results seen below. The initial values assume that there is no initial hate between the group and that no group is experiencing racism. As such, the two group's ideas remain neutral.

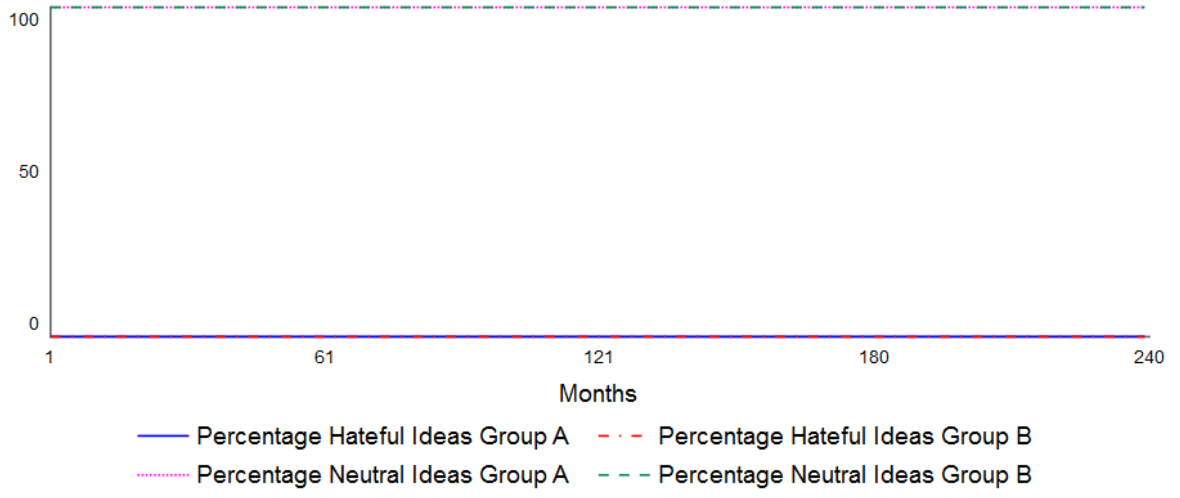


Figure 10.90: Equilibrium test on Media Polarization Simulation

10.1.42.3 Disturbance test (9.3):

A hypothesis test will be conducted on one of the groups. The test will be to observe if there is a pulse sent through fraction of people experiencing racism directly in Group B, how the system will respond.

The pulse is started at year 2 (24 months) for 1 month at a fraction of 0.25, whereafter it returns to 0. The results can be seen below.

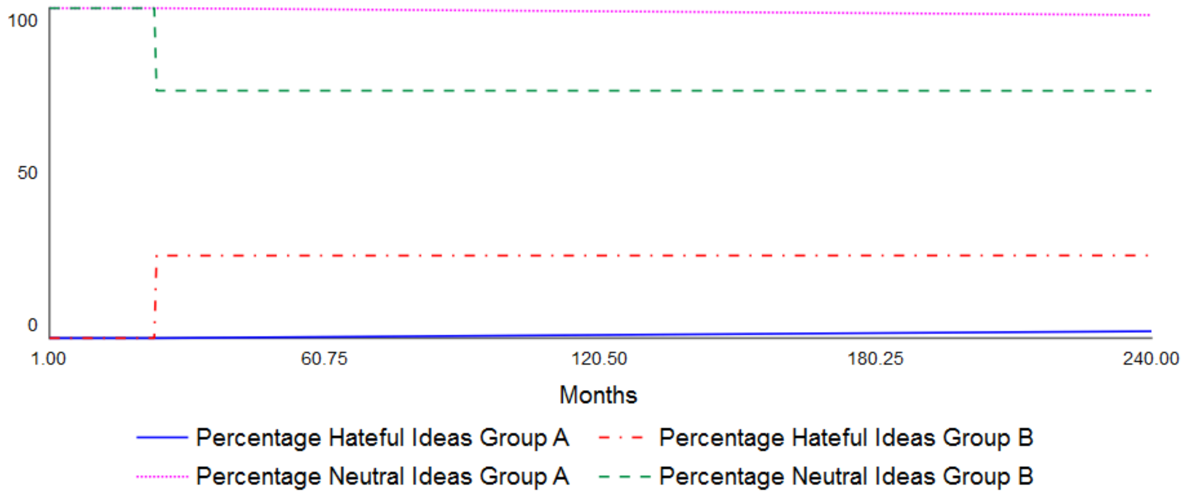


Figure 10.91: Disturbance test 1 on Media Polarization Simulation

The change is seen in the stocks which shows the pulse is working. The behaviour however shows that the feedback is too weak. After assessing the structure, the increase in maximum monthly hate speech events seems to be the problem. The value is changed back from 10 000 to 100. The new results show the impact of such a pulse event:

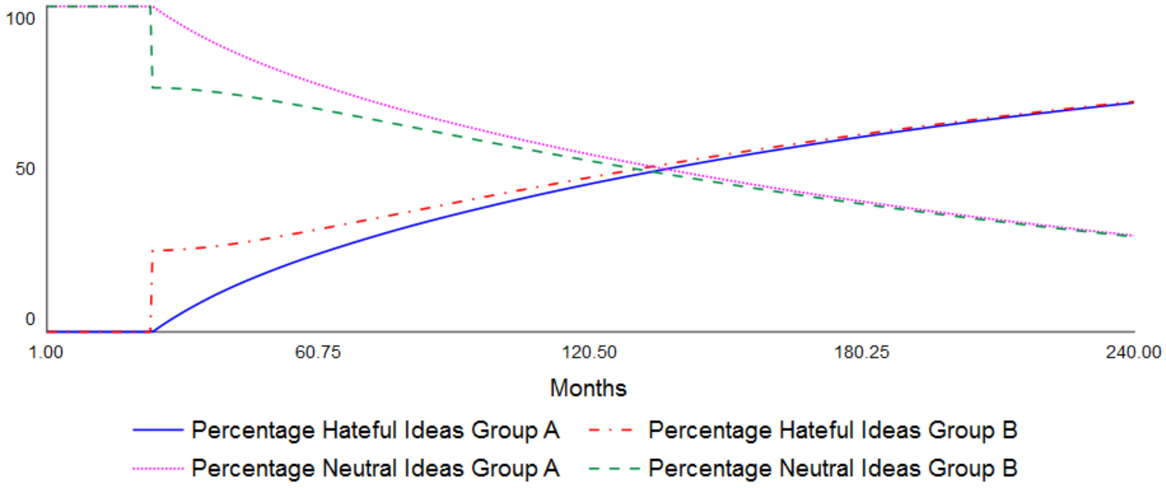


Figure 10.92: Disturbance test 2 on Media Polarization Simulation

The pulse in racism towards group B, which moves 25% of the neutral ideas to hateful ideas, starts a chain reaction. After the 20 year period, the hateful ideas in group A and B are both about 70%. The escalation behaviour can be seen just after the racism event starts where group B starts retaliating with hate speech and triggers more hate speech from group A. This creates the initial exponential growth in hate. The only reason why the hate spreading is slowing down is due to the lesser amount of people available to convert to hateful ideas.

10.1.42.4 Reproduce Reference Mode (9.4):

An essential part of the simulation basis is that the world has been increasing reliant on social media for their daily news intake. The fraction of people relying on social media news events are thus altered to become a function of time. Initially the value is 0 and as the 20 years progresses, the value increases linearly to 1, as seen below:

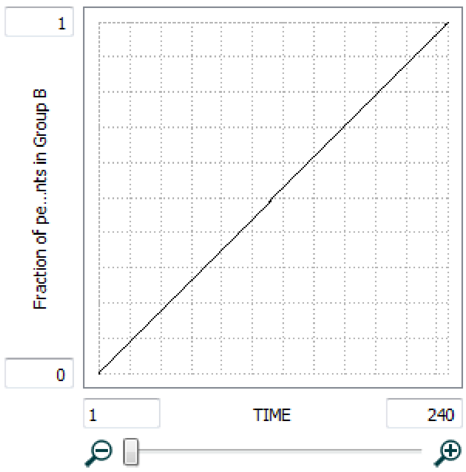


Figure 10.93: External time driver to fraction of people relying on social media

There are always extremist individuals in any group and in this case the assumption is that about 1 percent of each group initially has hateful ideas towards the other group. Running the simulation reveals an interesting scenario, seen below.

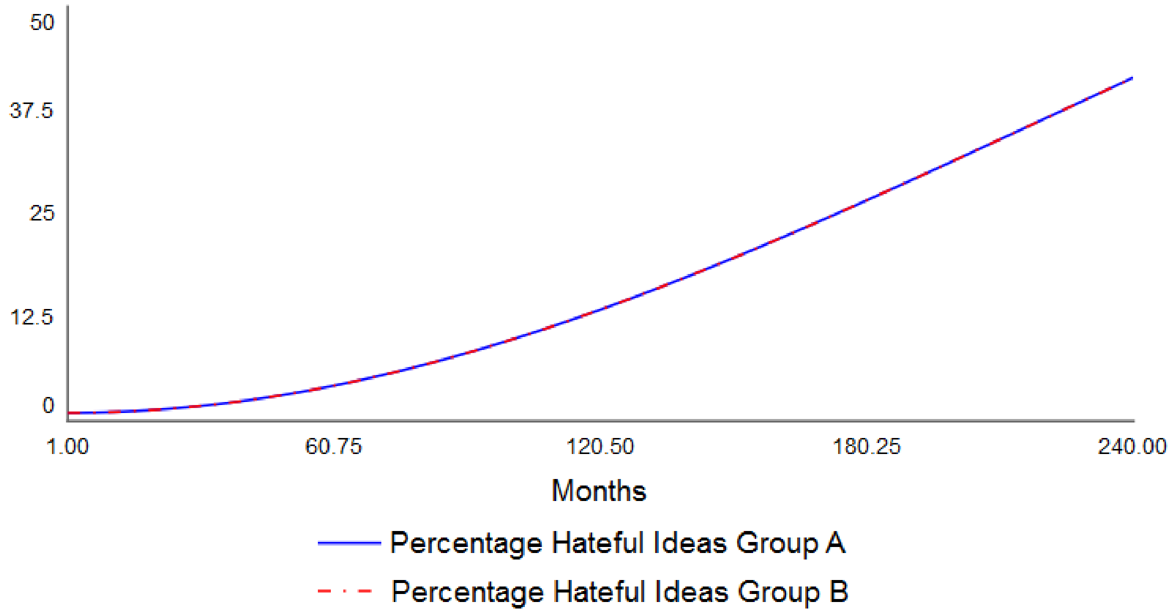


Figure 10.94: Replication attempt on Media Polarization sim

Initially when the reliance of news on social media is quite small, the growth from 1 to 2% of hateful ideas take about 35 months. After another 35 months, the hateful percentage has grown to 5.4% which shows the reinforcing archetype effect of escalation within the social media and racism combination. After 20 years, the initial 1% of the population has grown to staggering 41.5% hateful ideas on both sides of the parties, showing the polarization that has taken place.

The behaviour is seen in the political hatred between the democrats and republicans in America. A similar trend is visible in the South African extremist parties. The structure of escalation within the social media platforms may be one of the core structures which are leading to more polarization across the globe. Polarization is not restricted to race, it includes any binary believe system where there the answer is to classify one group in society as right and the other group wrong. Uplifting the one group's ideals and values and vilifying the other group. Social media is not intentionally fueling the polarization; it is due to the human nature (structure) of being ignorant and living with an 'eye for an eye' paradigm. Social media makes the most money by utilizing these weak points of humanity, which the escalation archetype shows why -> Social media usage skyrockets as along with the hatred [The social Dilema – Netflix (McDavid, 2020)].

10.1.43 Step 10: Sensitivity Analysis

10.1.43.1 Identify variables (10.1):

Two more assumptions are made to integrate some of the equations:

1) The hateful and neutral ideas should always be 100 together. As such, the initial neutral ideas = 100-initial hateful ideas
2) People either rely on balanced news or social media news. As such the fraction relying on balanced news = 1 – fraction relying on social media news.

The variables chosen for sensitivity are those that relate to the purpose and problem statement defined in step 1. The main concepts needed are the influence of social media and the initial hate percentage.

Table 10.25: List of External Variables for Sensitivity Analysis

Name	Value	Units	Chosen	Reason
Group A - Variables				
Initial Hateful ideas in group A	25	Percentage	y	Harmful ideas are part of the purpose
Average months taken to release hate ideas group A	999999999	months	n	
Fraction of people experiencing racism directly in group A	0	fraction	n	
Maximum hate speech events from group A pm	100	events	n	
Fraction of people relying on social media events in group A	0.5	fraction	y	The relying on social media for news is part of the purpose
Group B -Variables				
Initial Hateful ideas in group B	10	Percentage	y	Harmful ideas are part of the purpose
Average months taken to release hate ideas group B	999999999	months	n	
Fraction of people experiencing racism directly in group B	0	fraction	n	
Maximum hate speech events from group B pm	100	events	n	
Fraction of people relying on social media events in group B	0.5	fraction	y	The relying on social media for news is part of the purpose
Global Variables				
Social media amplification multiplier	2	unitless	y	The ability of social media to amplify harmful ideas are important

10.1.43.2 Sensitivity Range (10.2):

The sensitivity range is selected at 33% lower and higher. The basic value, minimum and maximum is shown in the table below

Table 10.26: Sensitivity Range of Media Polarization Sim

Sensitivity Range of 33.3%

Variable Name:	Basic Value	min	max
Initial Hateful ideas in group	25	16.7	33.3
Fraction of people relying on social media events in group	0.75	0.50	1.00
Social media amplification multiplier	2	1.33	2.67

10.1.43.3 <u>Sensitivity Points (10.3):</u>

The run values are determined by using the max and min values divided by the number of runs -1. In this case the number of runs was arbitrarily chosen as 5. The values for each of the three scenarios and their run values can be seen in the table below.

Table 10.27: Sensitivity Points of Media Polarization Sim

	Sensitivity Range of 33.3%	*Value of each run#*				
Scenario	Variable Changing	1	2	3	4	5
1	Initial Hateful ideas in group	16.67	20.83	25.00	29.17	33.33
2	Fraction of people relying on social media events in group	0.50	0.63	0.75	0.88	1.00
3	Social media amplification multiplier	1.33	1.67	2.00	2.33	2.67

10.1.43.4 <u>Analysis (10.4):</u>

Initial Hate

The initial hate in both groups are changed from 16.67% to 33.34%. The results are seen below.

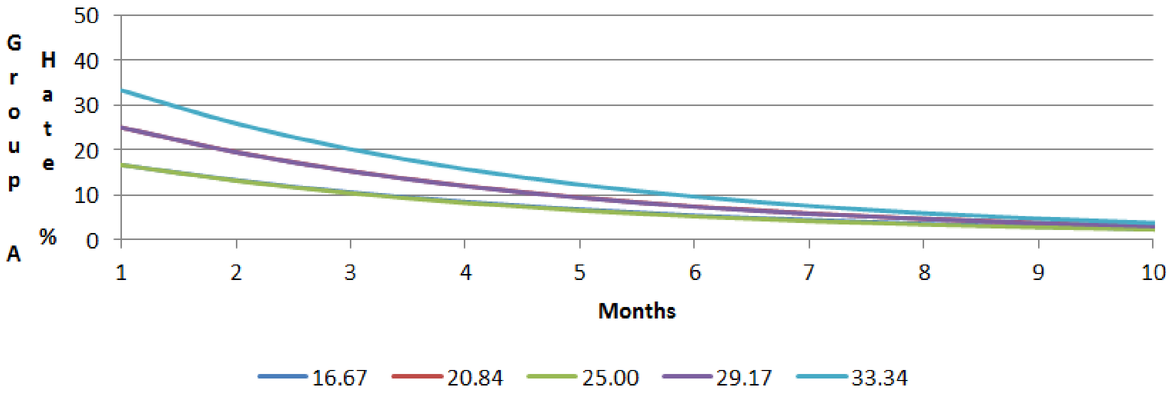


Figure 10.95: Sensitivity Analysis Results on Initial Hate

The interesting phenomena here is that with the current setup, the initial hate in both groups and all 5 scenarios decrease. The sensitivity analysis table for the first scenario after 10 months is seen below.

Table 10.28: Sensitivity Table for Initial Hate

Sensitivity Table Scenario 1	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage Changes	-0.33	-0.17	0.00	0.17	0.33
Percentage Effects	-0.16	-1.89	0.00	1.80	1.88

The table reveals that the variable affects the system in the same direction (increase leads to an increase and vice versa). It als shows that the larger the initial value is, the larger the effect becomes, although the affect is quite small at about 0.05%.

The major deduction here is that the initial hate between the groups is not a tipping point in the simulation.

Fraction of people using social media as news

The results for the scenario of fraction of people using social media are seen below where the fraction is changed from 0.5 to 1 through 5 different runs.

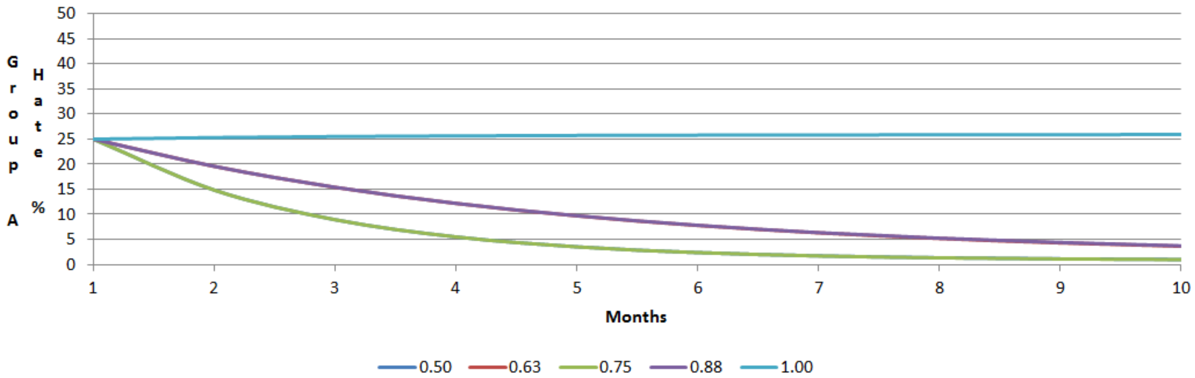


Figure 10.96: Sensitivity Analysis Results on Fraction of People reliant on social media

The interesting observation here is that the first three scenarios almost produce exactly the same results, while the last 2 (especially the last) reveals very different behaviour. The sensitivity table for scenario 2 is seen below.

Table 10.29: Sensitivity Table for fraction of people reliant on social media

Sensitivity Table Scenario 2	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage Changes	-0.33	-0.17	0.00	0.17	0.33
Percentage Effects	-0.05	-7.48	0.00	7.96	123.14

The same directional effect is observed (increase leads to increase vice versa), yet the effects are much stronger at about 1% between run 1 and 2. The strength of the effect starts increasing rapidly the closer the fraction comes to the value of 1.

The major deduction is that the tipping points will lie in the fraction range of 0.88 and 1.0. The fraction of people using social media has a very large effect on the system as it gets closer to 1, yet the system behaves almost unaltered below the values of 0.75.

Multiplier effect of Social Media

The change of only the multiplier effect of social media from 1.33 to 2.66 is seen in the graph below. The variable's meaning is related to the ability that social media has in highlighting only certain events (especially hate speech events) to the social media users. This amplifies the number of times that the same event is seen by the same user.

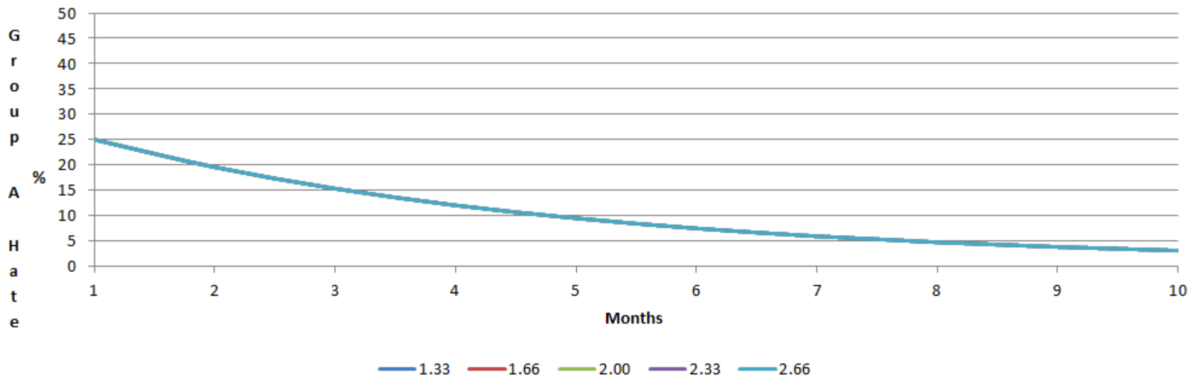


Figure 10.97: Sensitivity Analysis Results on Social Media Multiplier

It is quite apparent that there seems to be no difference between the different runs of this scenario. The sensitivity table for the scenario is seen next.

Table 10.30: Sensitivity Table for Social Media Multiplier

Sensitivity Table Scenario 3	Run 1	Run 2	Run 3	Run 4	Run 5
Percentage Changes	-0.33	-0.17	0.00	0.17	0.33
Percentage Effects	0.00	0.00	0.00	0.00	0.00

The table confirms that there is no measurable change in the effect of the multiplier. This is an interesting observation which shows that the simulation bears no relation to the change in the multiplier and results in the given circumstances. There might be 2 reasons for these:

1) The value of 2 is far too small and that in a more realistic representation, the value should be much larger. This idea is however proven false by using the simulation and changing it to 6000, where no values are still observed
2) The second idea is that the system must be in a state where enough people are using social media to trigger the archetype. This was also tested on the

simulation and the results showed that this hypothesis is also incorrect as the values remained the same.

The conclusion was then seen as the multiplier effects the populations the same since the same multiplier is used in both groups. The effect of the multiplier would only be seen when the group's work on different social media platforms, which is outside the boundary of the simulation. Thus this variable is the least effective in the simulation.

10.1.43.5 Ranked Leverage Points (10.5):

In the simulation, the leverage rankings of the varialbes become:

1) Fraction of people using social media as news source has the largest effect when the variable is between the values of 0.9 and 1.
2) Initial hate between the groups makes a small difference, when the initial hate is quite high.
3) The multiplier effect of social media has no effect on the simulation and may be excluded from the final interface.

10.1.44 Step 11: Emerging Lessons

10.1.44.1 Emerging Insights (11.1):

The simulation model reveals the following interesting scenarios:

- The escalation on both groups only takes hold when both of the groups start using social media extensively. The lesson taken here is that when social media usage spreads throughout a community, it will start having the escalation effect only when the majority of people start using the platform. Since the business model of social media is to spread to as many users as possible, given some time, most of the community does get involved in social media.
- One of the big assumptions in this model is that if you do not use a balanced source of news, that you will rely on social media to inform you about the real world news. Society starts breaking down into reinforcing cycles when most people start relying on social media for news. The lack of a balanced and trusted news/journalism is a large contributor to the social media news consumption.
- It also shows that if both groups solely rely on social media for news, that a 1 percent initial hate in just one group can initiate a spiral of hatred in both groups and after 20 years, 70% of both groups hate each other.

- Finally it shows that if one group takes much longer to forgive/release hatred than the other, it reduces both groups' hatred levels, yet the more unforgiving group retains much more hatred even though the forgiving group is being harmed more. This could be analogous to a political system that practices racial discrimination. The person discriminating often holds more hatred against the victim and may also be linked to the concept of aggrieved entitlement.

10.1.44.2 System Leverage Points (11.2):

In the escalation system there seems to be two major leverage points. The first being that the society as a whole (all groups) need to rely on balanced objective journalism for news sources. A **policy** that **promotes objective news agencies** will reduce the reliance on social media for 'facts' and reduce the spread of hateful ideas. This could of course be done by incentivizing social media to promote objective news more than general opinions, yet the current business models of social media does not afford that goal (See the Social Dilema).

The second leverage point is a shift in the mental models of responding to hate speech. Hate speech and especially hate crimes should never be ignored, it should be put into the open through objective news agencies. These events should be discussed by the community as a whole yet the ability to forgive would structurally weaken the effect of the archetype. **Policies** that **promote influencers** who **forgive** will make a big impact on the type of ideas people allow to grow inside themselves.

In South Africa, maybe even world wide, the most prevalent example of such a person, is Nelson Mandela. He was imprisoned for 27 years after standing up against the racist 'Apartheid' regime, he said the following (Yarali, 2019): "As I walked out the door toward the gate that would lead to my freedom, I knew if I didn't leave my bitterness and hatred behind, I'd still be in prison." Some believe that this one man's life of forgiveness prevented the outbreak of a racial war and it truly shows the power of forgiveness, especially in the hatred escalation archetype. This is what Nelson Mandela said about the concept of forgiveness which the simulation archetype confirms:

"Forgiveness liberates the soul, it removes fear. That's why it's such a powerful weapon."

–Nelson Mandela

10.1.44.3 List of Variables (11.3):

The following are variables/concepts that emerged through the modelling process

- **Neutral Ideas:** Hateful ideas, do not come from a cloud, but are neutral ideas that are transformed into hateful ideas due to some action experienced or seen that changes the idea in the human mind. As such there is a movement between neutral and hateful ideas depending on the groups' exposure and focus.
- **Average months taken to release hate:** It is not only social media that influences the movement between the groups even though the simulation is mainly focused on that boundary. Some groups also have the ability to forgive and release the hate. The ability to forgive as a group is a critical factor in fueling this escalation application.
- **Balanced news Consumption:** Any community is constantly consuming information about the world. The assumption is that social media has become the news source for many people in a community. The alternative is that people use balanced news sources to inform their world view. A study conducted by Swartz et al. (2020) on a racial derogative statement in South Africa, showed that in reality only about 2% of people agreed with the derogative statement while the rest of the participants said that they do not agree with the statement. In such a balanced investigation, the reality becomes clear that it is an extremist idea yet in social media, if the person only sees their own posts and ideas, the idea might be created that most of the other group of people are like that and start hateful ideas back at them.
- **Actual Racism:** The simulation allows for actual racism/hate crimes against the other group yet this quickly escalates the situation. It is clear that if these crimes do take place, that they need to be stopped otherwise it can through the complete system into discourse. It could be the reason why human communities often end up in the escalation archetype. The archetype quickly affords everyone in the community to become aware of the injustice and act on it, in order to prevent it from taking place again. The problem however is that when the same mechanism (albeit violence, destruction or hate speech) is used to protect the group, it starts a vicious cycle of hate as seen in the simulation.

Link to online simulation:

https://exchange.iseesystems.com/public/corne/escalation-polarization-through-social-media/index.html#page1