4 RESEARCH DESIGN AND METHODOLOGY

4.1 Purpose and Outline of the Chapter

The purpose of this chapter is to explain and document the research methodology and testing strategy followed in the research project.

Although the primary data gathering methodology is introduced, the documentation process thereof is not recorded in this chapter. Please refer to Chapter 6 for a detailed account of the Delphi study performed.

The chapter discusses and describes the research design, after which background information and the origins of the system dynamics methodology are provided. A section is allocated to a detailed description of the methodology. The most important strengths and weaknesses of the system dynamics methodology are explored and its particular suitability for this research project is discussed.

This chapter also analyses the model building process as well as the testing and validation strategy followed.

4.2 Research Design

4.2.1 Design description

The type of research undertaken in this project is a theory/model building study. Mouton (2001:176) describes such a study as "Studies aimed at developing new models and theories to explain particular phenomena."

Scientists employ models and theories in an attempt to explain observed phenomena in the world. Science can simply not progress without these models and theories. A model is a set of statements aiming to represent a phenomenon or set of phenomenon as accurately as possible. Good theories and models (Mouton, 2001:176):

- provide causal accounts for the world
- allow us to make predictive claims under certain conditions
- bring conceptual coherence to a domain of science; and
- simplify our understanding of the world.

This research project proposes a dynamic model for R&D in the NSI. The applicability and validity of this model depends on the quality of causal assumptions made and the accuracy of the structure of the model.

4.2.2 Design classification

The study is empirical in nature. Secondary numerical and textual data is thus used in developing the model. In some instances, databases were analysed and data was extracted.

The structure of the model is derived from secondary textual data. The method followed in deriving the model for this study is therefore chosen to be deductive reasoning, one of the most powerful methods of deriving models and new theories.

One of the main problems usually encountered with the development of system dynamics models is the availability of reliable time series data. This study is certainly no exception. The author did however go to exceptional lengths to ensure that the most accurate and reliable data was used for the empirical testing and ultimately for underpinning of the model.

Primary data was gathered by means of a Delphi study, a study employed to gather data and opinions on the following issues:

- appropriateness of indicators used to measure R&D output in the study
- alternative indicators to measure R&D output in South Africa; and
- the main issues that will threaten the South African R&D capacity in the following 20 years (future trends).

The Delphi study is discussed in detail in Chapter 6.

The following section describes the modelling methodology followed in the thesis in greater detail.

4.3 The System Dynamics Methodology

The system dynamics methodology aims to analyse complex systems and problems, using computer simulation software. System dynamics originates from the 1960s, when Jay Forrester created a methodology for analysing complex systems to aid and improve decision-making and policy formation (Meadows et al, 1974). This methodology could also be used to include relevant cause-effect relationships, delays and feedback loops in complex system to account for their unexpected behaviour.

In July 1970, the executive committee of the Club of Rome attended a seminar presented by members of the System Dynamics Group at MIT. The committee was tasked with determining whether the system analysis techniques developed at MIT could provide new perspectives on the interlocking complexity of costs and benefits inherent in continued physical growth on a finite planet. Forrester introduced a preliminary computer simulation model known as World2 at The Club of Rome meeting. The model specified important relationships among population economic output and environmental constraints (Meadows et al, 1974).

Using system dynamics modelling, Forrester demonstrated how simple solutions often had unplanned and unwanted effects. He used the methodology to emphasise the importance of clarity of purpose before intervening in a system to correct a defined problem, issue or undesirable effect. Forrester ultimately contributed a method through which problems can be solved with more sophisticated levels of analysis (Forrester, 1961).

The four grandparents of the system dynamics methodology are computer technology, computer simulation, strategic decision-making and feedback thinking. It is indeed a fortuitous mix, especially since an engineer's notion of feedback connects seamlessly with the circular causal complexity that strategic thinkers encounter (Coyle, 2000).

In a 1956 paper, which is known today as one of the definitive paper of the field, Forrester (2003) describes the new developments that ultimately enabled him to develop the system dynamics methodology:

- the use of servo-mechanisms and their extensions into complex military weapons systems gave an impression of the importance of inertia, elasticity, storage and delays in determining the stability of complex systems
- the use of differential equations by engineers to describe time dependent systems. The use of differential equations in closed-cycle systems was extended to the theory of sampled data systems
- electronic digital computers developed to a stage where routine processing of numbers were cheaper than doing it by hand; and
- the art of computer simulation models were developed to model systems at an accelerated time scale.

Forrester envisioned an enhanced modelling methodology, one that would enable modellers to model complex systems, such as national economies and industrial firms, more accurately:

> "*I am very certain that the model that now become possible will be effective and of great importance in understanding and managing the individual industrial firm. With respect to the national economy as a whole, I expect the model that can be constructed in the next five years to be many times better than those of the past.*" (Forrester, 1956)

Roberts (1978:1) defines system dynamics as the application of feedback control systems principles and techniques to managerial, organisational and socio-economic problems.

System dynamic models are essentially simplifications of reality based on the analyst's understanding of the system and assumptions made regarding expected behaviour. System dynamic modelling in management sciences proves to be an extremely useful tool. The approach indeed proves an excellent tool to assess a system's ability to adjust to change and to test new decisions that have to be taken. System dynamics modelling does however not guarantee accurate prediction of future behaviour. Instead, it is more powerful in increasing the understanding of behaviour and identifying expected trends related to changes in the system (Botha, 1997).

Coyle (1996:10) documented the following thorough description of system dynamics:

> "*System dynamics deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation*".

System dynamic models are mainly used for:

- policy testing (Forrester, 1961)
- what-if scenarios (Morecroft, 1988); and
- policy optimisation (Kleijnen, 1995).

Forrester provides an explanation of his intentions with the methodology as well as how it will enhance modelling techniques when compared to other economic models (Forrester, 1956, 2003). The following section thus summarises a number of the distinct advantages of using the system dynamics methodology as stated in Forrester's paper of 1956. The majority of these advantages are still applicable today.

4.3.1 Arguments for using the System Dynamics methodology

Dynamics structure: system dynamics allows modellers to include sequence of events in the model structure.

Time delays can be incorporated in the simulation of the system. These do however not refer to the occasional time-shift incorporated in some economic models to obtain a 'lagged' variable for correlation purposes. Instead, these delays refer to an organic delay in one of the flow channels in the model, e.g. the time required for processing an order for goods.

System dynamics also allows the modeller to include reservoir effects into the model. A reservoir effect can be explained as the build up of a level of which the effect is only seen later, e.g. the level of interval between an innovation being considered a luxury versus a necessity.

Lastly, system dynamics allows the modeller to connect the flow of different resources to each other, e.g. the flow of human resources into and out of the system is connected to the flow of tacit knowledge and skills through the system.

Information flows and decision criteria: explicit recognition of information flow channels and information transformation is possible. Many economic models are constructed on the economy's external symptoms. System dynamics however allow models to be constructed on the basic processes included in the system. The modelling methodology also allows for the inclusion of the system's extended history as well as how people might have been conditioned by it.

Differential equations seem to be better suited to describe an economic system's behaviour than the algebraic equations often used in economics. Delays, momentum, elasticity, reservoirs and acceleration are the fundamental quantities differential equations have been developed to describe.

System dynamics allows models of ***much greater complexity and completeness*** than many economic models. A multitude of variables can be included in models with much more ease. The labour involved in the step-by-step solution of differential equations for one single solution is much less than solving a set of algebraic equations in the corresponding set of variables.

Forrester (1968) believes that "most dynamics behaviour, especially in social systems, can be represented by models that are non-linear and so complex that analytical mathematical solutions are either impossible or extremely complex to develop. For such systems, the simulation process of using step-by-step numerical solutions is available."

Empirical solutions: explicit solutions are impossible with the system dynamics approach. Solutions are generated through various assumptions about the model behaviour to changes in constants, individual values of variables.

Simulation modelling is therefore not a general solution. It also does not provide all possible behaviour patterns. Simulation modelling does however provide the time history of system behaviour corresponding to the coefficients and initial conditions whose numerical values were selected. Different conditions in a system can be tested by repeating full step-by-step computation of a system's time response.

The above section therefore concludes that the systems dynamics methodology is a suitable tool for modelling complex systems and systems with feedback complexity.

The following section provides more insight into the methodology itself as well as the different stages and steps of modelling systems.

4.4 The Modelling Process

4.4.1 Background on the modelling process

Rubinstein and Firstenberg (1995:161) defined a process for the development of a model. To achieve a simple high level of abstraction, the following fundamental steps must be followed:

1. establish the purpose of the model;
2. list the possible elements, i.e. observations, measurements and ideas, however remote, that may relate to the purpose;
3. select those elements listed in step 2 that are relevant to the purpose of step 1;
4. aggregate elements that can be chunked together by virtue of their strong structural, functional or inactive connections between them. This can be described as a process of classification; and
5. repeat step 4 several times until a model consisting of seven elements, aggregated into approximately two chunks emerges;

This process can be repeated by sub-aggregation of each chunk in step 5.

The generic process discussed above is also used when developing a system dynamics model. The development of the system dynamics model is an iterative process ((Coyle, 1996), (Sterman, 2000)). The modelling process, which is also followed in this study, is a continual process of formulating hypothesis, testing and evaluating formal and mental models.

Various researchers have aimed to organise the modelling activities, varying from three to seven different stages, each using a different set of arguments:

Table 4-1: Steps and Stages in the System Dynamics Modelling Process

Meadows and Behrens (1974:5)	Roberts (1983)	Sterman (2000)
General description of the problem observed	Problem definition	Problem articulation
Precise specification of model's purpose		
Definition of time horizon		
Identification of major elements to be included	System conceptualisation	Dynamic hypothesis
Postulation of model structure	Model representation	Formulation
Estimation of parameters		
Evaluation of model sensitivity	Model behaviour	Testing
	Model evaluation	
Experimentation and simulation	Policy analysis and model use	Policy formulation and evaluation

Although the way in which researchers group the main activities of developing a system dynamics model differs, the researchers remain consistent on the activities considered important in the process.

4.4.2 Modelling steps followed in this thesis

This research project followed the iterative steps as described by Sterman (2000) in his book, entitled Business Dynamics.

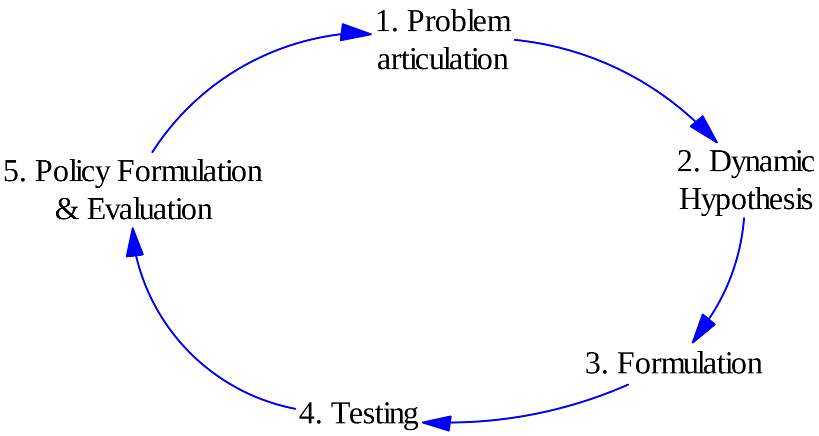


Figure 4-1: The Modelling Process is Iterative (Sterman, 2000)

The following sections depict a modified version of the five steps applied in the development of the system dynamics model of R&D activities in the South African NSI. Although the process was very much an iterative one, only the final outcome of each stage is documented. The sections also describe the methodological steps followed in the thesis as well as the chapters in which the phases are documented in the thesis structure.

4.4.3 Problem articulation

Background of system: What is the background of the development of the R&D system in South African?
Research problem: What is the problem researched in the thesis and why is it a problem?

This study acknowledges the problem articulation as the foremost step in the modelling process. A clear purpose for the model is therefore the vital ingredient for a successful modelling study. To ensure that the model developed is useful, a specific problem should be addressed. All useful models have one common characteristic: it simplifies reality, thereby easing comprehension. A clear purpose therefore goes a long way in clarifying the elements that should be included in the model. The art of model building lies in the knowledge of what to include, and more importantly, what to exclude. The purpose of the model acts as the logical knife.

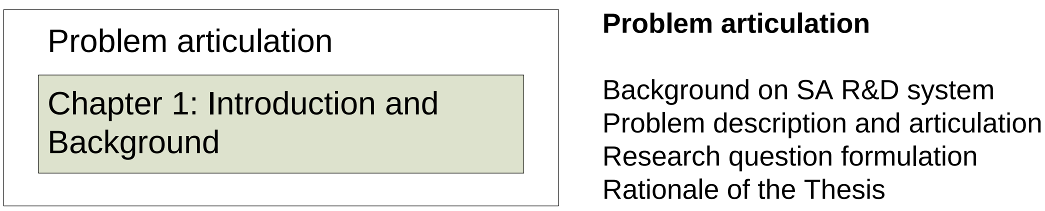


Figure 4-2 Problem Articulation

The model's problem articulation is documented in Chapter 1. A brief history of the development of the South African R&D system is also discussed. The chapter illustrated that the system has been developed over decades up to the point where it emerged as the relatively sophisticated R&D system it is today.

4.4.4 Formulation of the dynamic hypothesis

Key variables: What are the key variables and concepts to be considered in developing a conceptual model of an R&D sector?
Initial hypothesis generation: Which current theories around generating and creating knowledge and dynamics are included in R&D and innovation systems?
Endogenous focus: Formulate a dynamic hypothesis that explains the dynamics as endogenous consequences of the feedback structure.
Mapping: Develop maps of causal structure based on initial hypotheses and the elements important for developing an R&D system's dynamic behaviour.

The dynamics hypothesis is a theory that explains how the system developed its current observed behaviour. The hypothesis is dynamic, since it provides an explanation of the dynamics characterising the system in terms of the underlying feedback as well as the system's stock and flow structure.

A thorough literature study was conducted to scrutinise the existing body of knowledge and to identify the vital elements for inclusion in an R&D system model.

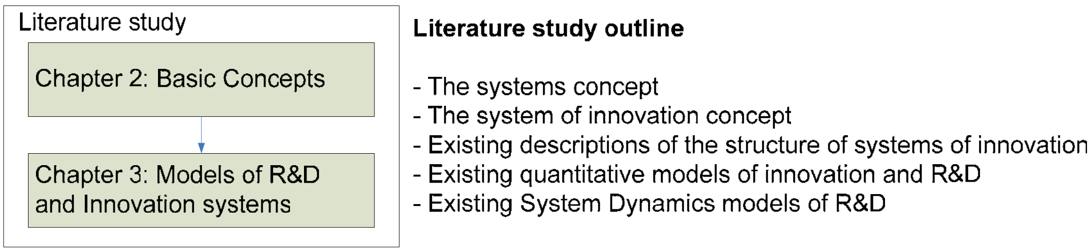


Figure 4-3 Research on Current Theories of R&D and Knowledge Creation

The structure and important elements for inclusion in a model was researched and documented in Chapters 2 and Chapters 3. The knowledge obtained in the literature study was applied in developing the system dynamics model. During this development phase of the model building study, an endogenous explanation is provided to explain the dynamics of the system generated as a result of interactions of the elements important for inclusion in the model.

To simplify the task of developing a model for the South African R&D system, a basic building block or a generic model of an R&D sector was defined and developed. The approach followed was aimed at creating a generic model of an R&D performing sector, based on the theoretical principles of the performance of R&D, i.e. the creation of knowledge.

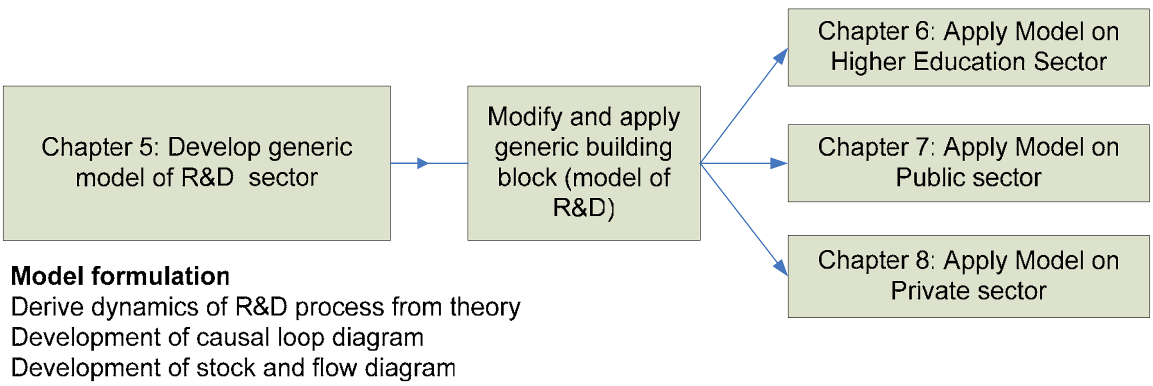


Figure 4-4: Application of the Generic Model on R&D Performing Sectors in SA

Although there are some similarities in the development of new knowledge and the specific types of resources in R&D performing sectors, they are also unique in many ways. The generic model was therefore modified to suit the specific and unique structures of different R&D performing sectors within the HES as well as public and business R&D sectors of the South African NSI.

In aid of the communication and documentation of the model boundary and structure, causal loop diagrams as well as stock and flows structures were developed to map the causal links between variables.

4.4.5 Model validation and evaluation

Formulation of the simulation model

Specification of structure and decision rules
Estimation of parameters, behavioural relationships and initial conditions
Tests for consistency with the purpose and boundary

After the dynamic hypothesis was developed, it was applied to the three R&D sectors in the South African system of innovation. The application of the generic model on the three sectors generated a wealth of insights.

The data gathering is documented in these chapters. The trends observed from the data gathered, resulted in the model being modified accordingly. While the basic feedback structure remains, the indicators used and the specific policies in the sector contribute to some structural changes in the model.

Testing

Comparison to reference modes: Does the model reproduce the problem behaviour adequately for your purpose?
Robustness under extreme conditions: Does the model behave realistically when stressed by extreme conditions?
Sensitivity: How does the model behave when given uncertainty in parameters, initial conditions, model boundary and aggregation?

See Section 4.7 for a detailed discussion on the testing strategy followed in this research project.

Testing the model comprises much more than only a simple replication of historical data. Tests were conducted on the model to ensure dimensional consistency, sensitivity of the model in terms of policy recommendations as well as uncertainty in assumptions.

The model was also tested for extreme conditions that might not even occur in the real world. These tests are vital tools for identifying flaws in the model.

Policy Design and Evaluation

Scenario specification: What environment conditions might arise?
Policy design: What new decision rules, strategies and structures might be tried in the real world?
"What if…." analysis: What are the effects of these policies?
Sensitivity analysis: How robust are the policy recommendations under different scenarios and given uncertainties?

Interactions of policies: Do the policies interact? Are there synergies or compensatory responses?

These model development phases have been documented in the following chapters:

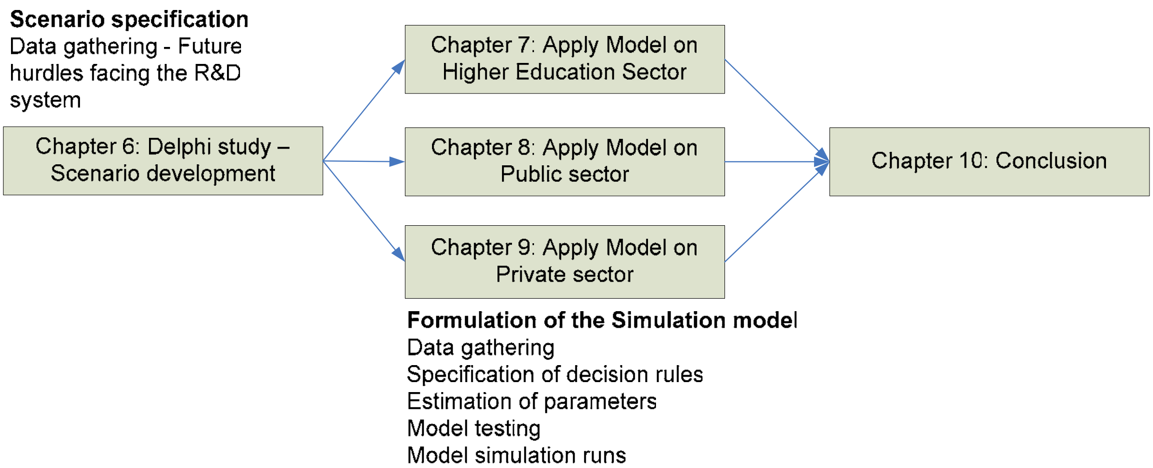


Figure 4-5: Structure for the Documentation for Model Validation and Evaluation

Conclusions drawn from the Delphi study was used to develop a selection of scenario tests that, in turn, were run on the system models developed in Chapters 7 to 9.

As a reasonable measure of confidence was developed in both the model's structure and behaviour, it was used to design and evaluate policies for improvement. In some instances during the policy design phase, the process entailed far more than simply shifting parameter values. The model structure was changed accordingly or some extra dynamics were included to test the effect of these structures against the predicted output of the model.

The outcome of the model testing phase is discussed in the concluding chapter, i.e. Chapter 10. The discussion on the test results is combined with the evaluation and discussion on shortcomings in the models.

Before a discussion on the actual development of the conceptual model, the tools used to develop the dynamic model are discussed briefly.

4.5 System Dynamics Tools

This section describes the system dynamics tools employed in this thesis. The two sub-sections describe, introduce and explain the concepts of causal loop diagrams as well as stock and flow diagrams.

4.5.1 Causal loop diagrams

Causal Loop Diagrams (CLD) is an important tool to represent a system's feedback structure. CLDs are especially beneficial for (Sterman, 2000, 139):

- quickly capturing hypotheses about causes of dynamics
- eliciting and capturing mental models of individuals or teams; and
- communicating important feedbacks believed to be responsible for the system's behaviour.

Causal diagrams consist of variables connected by arrows that denote causal influences among the variables. Important feedback loops are also identified in the diagram. The following figure explains the notation used in these diagrams.

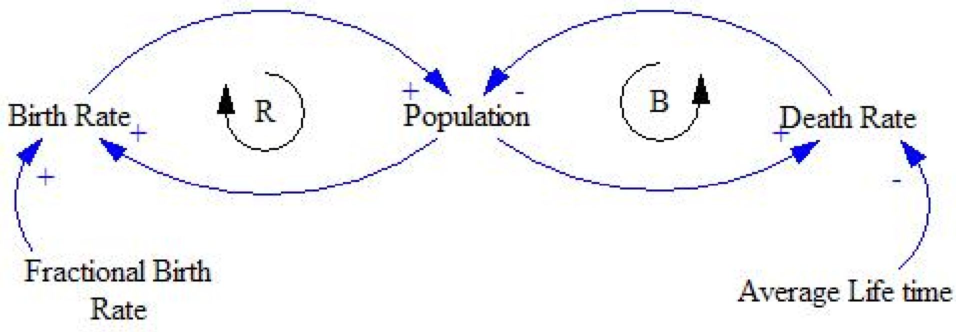


Figure 4-6: Causal loop Diagram Notation Example

Casual links are the lines with arrowheads that connect variables in a causal diagram, e.g. birth rate and population is connected with a causal link with polarity +. Link polarities are indicated at the arrowheads. Positive/reinforcing loops are indicated with an 'R' and negative/balancing loops are indicated with a 'B'. There are two polarities, namely a positive and a negative polarity.

A positive link, as shown between birth rate and population, indicates that where a change occurs in the controlling variable, the controlled variable will change in the same direction. To illustrate this point more clearly:

- should the controlling variable, *birth rate*, increase, the controlled variable, *population*, will increase to above the level it would have been; and
- should the controlling variable, *birth rate*, decrease, the controlled variable, *population*, will decrease to below the level it would have been. This is also known as a *positive or reinforcing feedback loop.*

A negative link indicates that a change in the effect will also result in a change in the opposite direction to the cause. To illustrate this point more clearly:

- should the controlling variable, *average life time*, increase, the controlled variable, *death rate*, will decrease to below the level it would have been; and
- should the controlling variable, *average life time*, decrease, the controlled variable, *death rate*, will increase to above the level it would have been.

Time delays can also be indicated in causal loop diagrams. The following figure depicts the causal relationship between road construction and the road's traffic capacity.

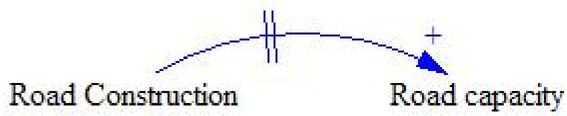


Figure 4-7: Causal Indicator with a Delay Marking

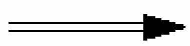
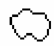
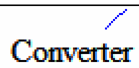
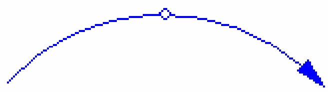
This section shortly described some concepts in the documentation of CLDs. In following sections, these diagrams will be used to convey important feedback loops and causal relationships between elements in a system.

CLDs do however suffer from a number of limitations, the most important of these its failure to capture what is actually happening in the system but only what would happen should something change. CLDs thus fail to capture the stock and flows structure of a system (Sterman, 2000). The following section describes stocks and flows in more detail.

4.5.2 Stocks and flows

Along with feedback, stocks and flows are the two central concepts of dynamic system theory.

Table 4-2: Building Blocks of the Stock and Flow Diagrams

Stocks represent entities in the system where contents and levels can fluctuate during the period of simulation. Content of levels is cumulative of behaviour in previous time intervals.	
Flows represent movements of entities in the system. Equations governing flow provides the rate of the flows. Flows can be physical or abstract	
Valves control flows	
Sources and sinks are indicated with clouds. A source represents the stock from which a flow originate outside the boundary of the model arises. Sinks represent sinks into which flows leaving the model drain.	
Converters represent variables influencing behaviour of stocks and flows, e.g. the gravity constant will be defined by a converter.	
Connectors represent linkages between various elements in the system	

The stock and flow diagram for the population causal loop depicted in Figure 4-6 will take on the following form:

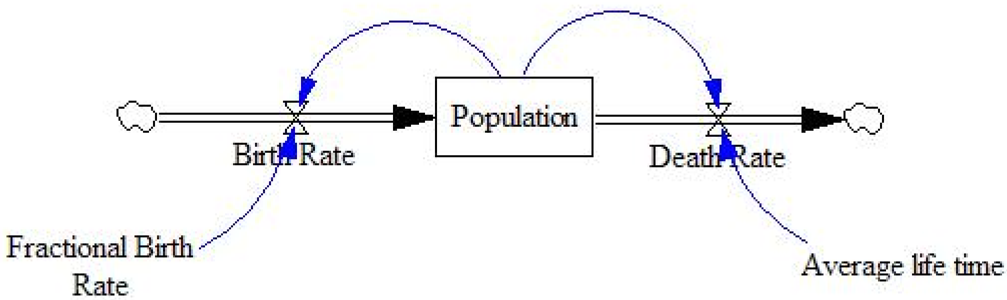


Figure 4-8: Stock and Flow diagram of a Population Model

Stocks make a very important contribution to dynamics (Sterman, 2000):

- characterises the state of the system and provides the basis for actions
- provides systems with inertia and memory. Stocks accumulate past events, as its content

can only change with an inflow or outflow
- forms the sources of delays. Differences between inputs and outputs accumulate in a stock of material in process; and
- decouples rates of flow and create disequilibrium dynamics. The differences between inflows and outflows are absorbed by stocks, allowing the inflow and outflow process to differ.

A major strength in the stock and flow representation is the clear distinction between physical flows through the stock and flow network and the information feedback loops that close the loops in the system. Stocks are reserved in the system because if stocks flow from one to the other, the first stock loses exactly as much as the other gains.

4.6 Mathematical Representations of Stocks and Flows

Sterman (2000) states that the stock and flow diagramming convention is based on the hydraulic metaphor, i.e. the flow of water in and out of reservoirs. The quantity of material in any stock is the accumulation of material into the stock minus the flow of material out of the stock. Stocks accumulate or integrate their flows. The net flow into the stock is therefore the rate of change of the stock.

$$Stock(t) = \int_{t_0}^{t} Inflow(s) - Outflow(s)ds + Stock(t_0) \qquad \textbf{4-1}$$

$Inflow(s)$ represents the value of the inflow at any time between the initial time t_0 and the current time t. $Outflow(s)$ represents the value of the outflow at any time s between the initial time t_0 and the current time t. The net rate of change of any stock, i.e. its derivative, is the inflow less the outflow, which defines the following differential equation:

$$d(Stock)/dt = Inflow(t) - Outlfow(t) \qquad \textbf{4-2}$$

In general, the flows can be described as functions of the stocks as well as other state variables and parameters.

In this thesis, the INTEGRAL() function will be used when referring to the accumulation of a stock:

Stock = Integral **(Inflow-Outflow) + Stock value at** t_0 **4-3**

4.6.1 Simulation software

The software package chosen for the development of the simulation model is Stella™ version 8.

Stella™ is a visual modelling tool that allows system modellers to conceptualise, document, simulate, analyse and optimise models of dynamic systems. Stella provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams. The following is a screen shot of a simple stock and flow diagram in Stella:

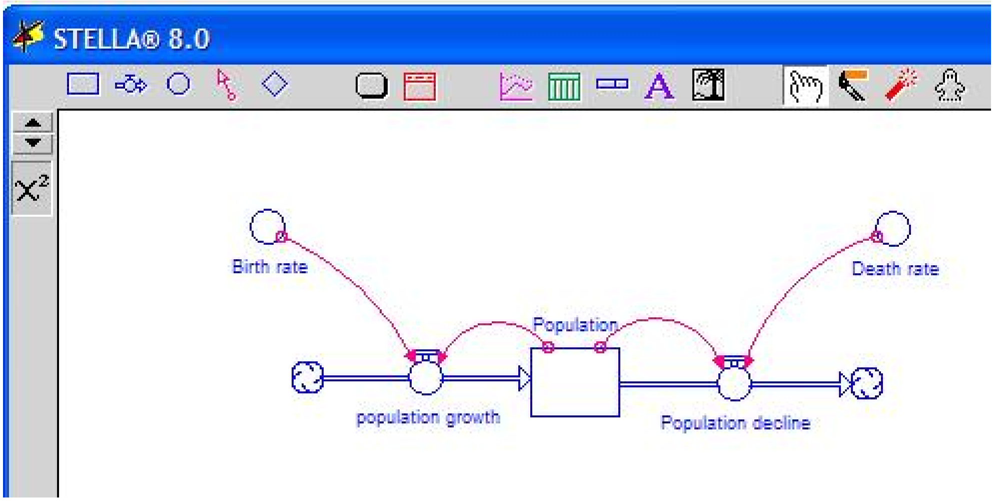


Figure 4-9: Stock and Flow Diagram in Stella 8.

The software package generates differential equations graphically as the analyst creates a model of a system graphically. The following is a screen shot of the system of differential equations developed by the software:

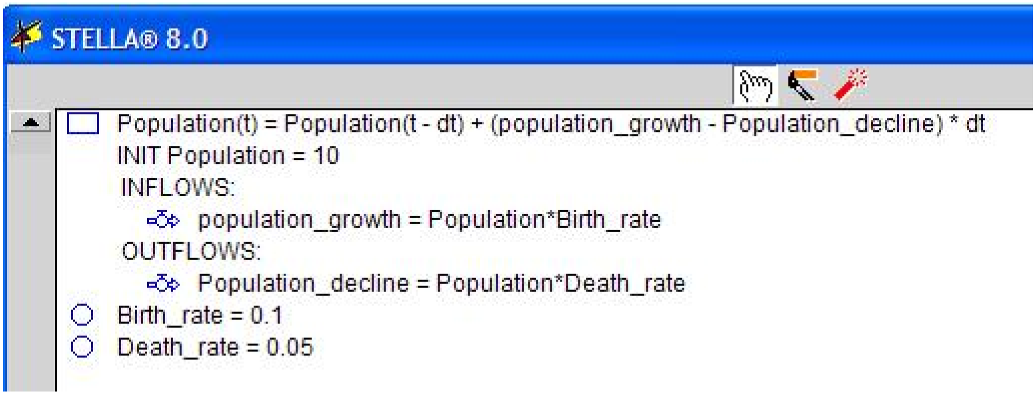


Figure 4-10: System of Differential Equations Developed by the Software

It is essential to test the model thoroughly to ensure that it captures the most important aspects of the system it represents. The following section discusses the model testing and validation strategy followed in this thesis.

4.7 Dynamic Hypothesis Testing and Validation Strategy

> *"Many modellers speak of model validation" or claim to have 'verified' a model. In fact validation and verification of models is impossible….no model can ever be verified or validated. Why? Because all models are wrong…all models, mental or formal are limited, simplified representations of the real world. They differ from reality in ways large and small, infinite in number.*
>
> *If validation is impossible and all models are wrong, why do we bother to build them? It is the modeler's responsibility to make sure that the best model is used. Instead of seeking a single test of validity model either pass or fail, good modelers seek multiple points of contact between the model and reality by drawing on many sources of data and a wide range of tests.*" (Sterman, 2000)

Sterman (2000:846) stresses the importance of testing the model. He also emphasises that the modeller refrain from focussing only on the recreation of historical data, but to also consider the underlying assumptions, robustness, and the sensitivity of results to assumptions. He presents a detailed description of the different tests that should be performed on the model.

The tables in each one of the following subsections include the questions asked to test the model developed in this research project. These tables are abstractions from Sterman (2000), which is a summation of work done by Forrester (1973), Forrester and Senge (1980) and Barlas (1989, 1990, and 1996).

4.7.1 Dimensional consistency test

The dimensional consistency test was among one of the very first tests executed on the models. Instead of specifying the units of measure after the model is developed, specification should take place as the model is developed. This test was conducted to ensure that all equations are dimensionally consistent without the inclusion of arbitrary scaling factors that have no real world meaning.

Purpose of the Test	Tools and Procedures
Is each equation dimensionally consistent without the use of parameters with no real world meaning?	• Use dimensional analysis software. • Inspect mode equations for suspect parameters.

4.7.2 Boundary adequacy test

The boundary adequacy test assesses the appropriateness of the model boundary for the specific model purpose. The following table summarises the tools used to determine the adequacy of the model boundary:

Purpose of the test	Tools and Procedures
• Are the important concepts for addressing the problem endogenous to the model? • Does the model's behaviour change significantly when boundary assumptions are relaxed? • Do the policy recommendations change when the model boundary is extended?	• Model boundary charts, subsystem diagrams, stock and flow maps as well as and direct inspection of model equations. • Use interviews and workshops to solicit expert opinion, archival materials, review of literature and direct inspection/participation in system processes. • Modify the model to include plausible additional structure. Make constants and exogenous variables endogenous before repeating sensitivity and policy analysis.

4.7.3 Structure assessment test

The structure assessment test is performed to determine whether the model is consistent with the real system when keeping the purpose of the model in mind. This test aims to identify 'free lunches', inconsistencies and inappropriate assumptions. Violations of physical laws can be attributable to either inappropriate assumptions or the model's inability to capture the stock and flow structure of the real system adequately. 'Free lunches' can be described as activities that are assumed to occur, yet the occurrence is not backed by the important resources that it needs to occur in the real world.

Purpose of the Test	Tools and Procedures
• Is the model structure consistent with the system's relevant descriptive knowledge? • Is the level of aggregation	• Use policy structure diagrams, causal diagrams, stock flow diagrams and direct inspection of the model. • Use interviews and workshops to solicit expert opinions, archival materials, direct inspection or participation in the

appropriate? • Does the model conform to basic physical laws, such as conservation laws?	system processes. • Conduct partial model test on the intended rationality of the decision rules. • Develop disaggregated sub models and compare behaviour to aggregate formulations. • Disaggregate suspect structures before repeating sensitivity and policy analysis.

4.7.4 Parameter assessment test

Before estimating parameters, the author ensured each variable had a real world meaning. The next step was to devise a plan on how the parameters would be estimated. Basic choices included formal statistical estimation or judgemental estimations. In the end, a combination of these two options was followed.

Throughout the formulation of the stock and flows structure, numerous parameters were estimated from either literature or judgement. These estimations are discussed in more detail in Chapters 7 to 9.

The thesis follows a statistical estimation of the parameters included in the knowledge production functions, while linear regression techniques are applied to the parameter estimation. The estimated models were tested for co-linearity, autocorrelation and heteroscedasticity. Stationarity tests conducted on the models tested the spuriousness of the modelled relationships.

Purpose of the Test	Tools and Procedures
• Are the parameter values consistent with relevant descriptive and numerical knowledge of the system? • Do all parameters have real world counterparts?	• Use statistical methods to estimate parameters (wide range of methods available). • Use partial model tests to calibrate subsystems. • Use judgement methods based on interviews, expert opinion, focus groups, archival materials, direct experience, etc. • Develop disaggregate sub models to estimate relationships for use in more aggregate models.

4.7.5 Extreme conditions test

For the purposes of this research project, the model was tested for robustness in extreme conditions. To pass this test, the model must behave realistically no matter how extreme the inputs or policies imposed on it. The methods used to ensure the above included both direct inspection of the equations as well as simulation.

An example of such a test performed on the system was gauging the model's reaction if the amount of human resources performing R&D was reduced to zero. A realistic reaction to the above situation would be for the entire system's R&D production to drop to zero as well.

During the modelling study, the author took great care to ensure that any implausible behaviour caused by extreme conditions would be examined in detail to identify the precise source of the flaw.

Purpose of the Test	Tools and Procedures
• Does each equation make sense, even when its inputs take on extreme values? • Does the model respond plausible when subjected to extreme policies,	• Inspect each equation. • Test response to extreme values of each input, alone and in combination. • Subject the model to large shocks and extreme conditions. Implement tests that examine conformance to basic physical

shocks and parameters?	laws, e.g. no inventory, no shipments, no labour and no production.

4.7.6 Integration error test

System dynamics models are formulated in continuous time and solved by numerical integration. The integration method (Euler's method) as well as the time step (0.125 year) was selected with utmost care to ensure accuracy for the purpose of the model.

Tests were executed to gauge model sensitivity regarding these two issues.

Purpose of the Test	Tools and Procedures
Are the results sensitive to the choice of time step of numerical integration method?	Cut the time step in half and test for changes in behaviour. Use different integration methods and test for changes in behaviour.

4.7.7 Behaviour reproduction test

Numerous tools are available to assess the model's ability to recreate and reproduce the system's behaviour. It is imperative to understand both the source and the size of the error. Plotting the simulated and actual output together is a powerful way of assessing the main trends that the model follows as well as pinpointing where it fails to follow the most important trends.

A statistical method is employed to calculate the coefficient of determination (R^2) to find an expression of the fraction of the variance explained by the model.

Purpose of the Test	Tools and Procedures
• Does the model reproduce the behaviour of interest in the system both qualitative and quantitatively? • Does it generate the symptoms of difficulty motivating the study? • Does the model generate the various modes of behaviour observed in the real study? • Do the frequencies and phase relationships among the variable match the data?	• Compute statistical measures of correspondence between model and data: descriptive statistics (R^2, MAE), time domain methods, e.g. autocorrelation functions, frequency domain methods, e.g. spectral analysis, etc, • Compare model output and data qualitatively, including modes of behaviour, shape of variables, asymmetries, relative amplitudes and phasing, unusual events. • Examine response of model to test inputs, shocks and noise.

4.7.8 Behaviour anomaly test

The behaviour anomaly test examines the importance and strength of relationships within the model by scrutinising the alteration in output where a specific structure is left out or changed. This is also referred to as 'loop knock out analyses.

A loop knockout analysis was performed on the simulation model to determine the importance of a number of variables in the system.

Purpose of the Test	Tools and Procedures
Does anomalous behaviour result when assumptions of the model are changed or deleted?	• Zero out key effect (loop knockout analysis). • Replace equilibrium assumptions with disequilibrium structures.

4.7.9 Family member test

This test questions the model's ability to generate output for real life systems belonging to the same class the system is meant to mimic. The more different instances the model is able to represent, the more general the theory becomes. This test is particularly useful where the class that the model belongs to include a wide variety of behaviours.

The conceptual model of an R&D subsystem developed in this study was applied to three R&D performing sectors in the South African NSI. This application also tests the generality of the formulation of the conceptual R&D sector model developed in this thesis.

Purpose of the Test	Tools and Procedures
Can the model generate the behaviour observed in other instances of the same system?	Calibrate the model to the widest possible range of related systems.

4.7.10 Surprise behaviour test

Discrepancies between the model's output and the actual historical data indicate that the model is flawed. This flaw can lurk in either the mental or the formal model or both. Since the problem of reliable time series data is a well-known dilemma, the actual data was also examined as a possible source of the problem.

Surprise behaviour occurs when a model generates a previously unrecognised behaviour, one that actually occurs in the system. To ensure the test's effectiveness, the model behaviour was analysed closely.

Purpose of the Test	Tools and Procedures
Does the model generate previously unobserved or unrecognised behaviour?	• Keep accurate, compete, and dated records of model simulations. Use the model to simulate likely future behaviour of the system. • Resolve all discrepancies between model behaviour and your understanding of the real system. • Document participant and client mental models before starting the modelling effort.

4.7.11 Sensitivity analysis test

Since all models are simplifications of reality, the robustness of the model was tested through uncertainty in the assumptions. Sensitivity analysis questions whether the conclusions change in ways that are important to the purpose of the model where assumptions are varied over plausible ranges of uncertainty. The type of sensitivity of concern in any project depends on the purpose of the model. The three types of certainty tested for are described in the following table:

Purpose of the test	Tools and Procedures
• *Numerical Sensitivity:* Do the numerical values change significantly? • *Behaviour sensitivity:* Do the modes of behaviour generated by the model change significantly? • *Policy sensitivity:* Do the policy implications change significantly when assumptions about parameters, boundary and aggregate are varied over the plausible range of uncertainty?	• Perform univariate and multivariate sensitivity analysis. • Use analytic methods, i.e. linearisation, local and global stability analysis, etc. • Conduct model boundary and aggregation tests. • Use optimisation methods to find parameter combinations that generate implausible results or reverse policy outcomes.

4.7.12 System improvement test

System improvement test questions whether the modelling process has succeeded in enhancing the system. To pass this test, policies aimed at an improvement of system performance were designed. Once implemented, the effect on the model was tested to see if it predicts an improvement in system performance.

In essence, it is extremely difficult to determine improvement in a system regarding changes. Rigorous follow up research is therefore imperative to determine the success of the policy recommendations.

Purpose of the Test	Tools and Procedures
Did the modelling process help change the system for the better?	• Design instruments - advance to assess the impact of the modelling process on mental models, behaviour and outcomes. • Design controlled experiments with treatment and control groups, random assignment, pre-invention and post-intervention assessment, etc.

4.8 Chapter Summary

This research project is a model or theory building study. Models can be defined as a simplified representation of more complex forms, processes and functions of physical phenomena or ideas. Scientists use models and theories in an attempt to explain phenomena in the world. Models allow predictive claims under certain conditions (Mouton, 2001:176).

The human mind is well adapted to building models of objects in space as well as models associating words and ideas. The human mind is however inadequate to construct and interpret dynamic models that represent change in time in complex systems (Forrester, 1968). It can therefore become extremely complex to develop analytical mathematical models when the system understudy exhibits non-linear behaviour. For such systems, the simulation process of using step-by-step numerical solutions is available.

In this project, secondary textual data is used through deductive reasoning to arrive at the conceptual model structure, after which the model structure will be tested, changed and modified. Since the model is only a simplified representation of reality, a number of misfits might occur between model behaviour and reality. As the success of a modelling study lies in the usefulness of the model developed, the model's accuracy and detail level must be appropriate for the purpose of the model.

The system dynamics methodology was followed to develop a model of the dynamic behaviour of R&D in the NSI. Numerous tests were conducted to ensure that the model building research is rigorous and accurate.

The following chapter documents the development of the conceptual model of R&D in the South African system of innovation.

5 CONCEPTUAL MODEL

5.1 Purpose and Outline of the Chapter

Following Forrester's (1973, 4) reasoning, the formulation of a system model must start with identifying the smallest number of components within which the dynamic behaviour understudy will be generated.

This chapter documents the development of a conceptual system dynamics model of R&D in the NSI. The following section derives major elements and concepts from the literature and theory review performed in previous chapters.

5.2 R&D Performing Sectors in the Model

This study draws heavily on existing data sources. Examples of information sources include the Frascati R&D surveys, the Department of Education, science council and university year reports as well as the innovation survey performed by the University of Pretoria in 2001.

The Frascati manual is used as a reference for developing the model structure as this document aims to standardise the collection of national R&D information. Such standardisation facilitates comparisons between country data as well as time series data. South Africa is also fully committed to follow this approach. It is therefore simply a sensible option to both acknowledge and use the same breakdown structure used in the survey instrument.

The Frascati manual prescribes the following breakdown structure for the collection of R&D data (OECD, 2002c: 54-74):

- business enterprise
- government
- private non-profit
- higher education; and
- abroad

As the private non-profit sector plays only a very small role in the South African R&D system, it is not analysed further in this study.

The model attempts to include the performance of R&D activities for the higher education, public and business sectors in South Africa. This sector breakdown is also directly in line with the breakdown identified for the NSI by Galli and Teubal (1997) in Chapter 2.

The abroad sector is not analysed explicitly as an R&D performing sector. Its influence and exchanges of resources is however implied in the endogenous R&D performing sector models.

Chapter 2 stated that no system could exist completely isolated from its environment. This is also evident from Freeman's (1987) definition of the NSI: "the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies".

This aspect is incorporated to include the flows of resources between R&D performing sectors within South Africa as well as external R&D systems.

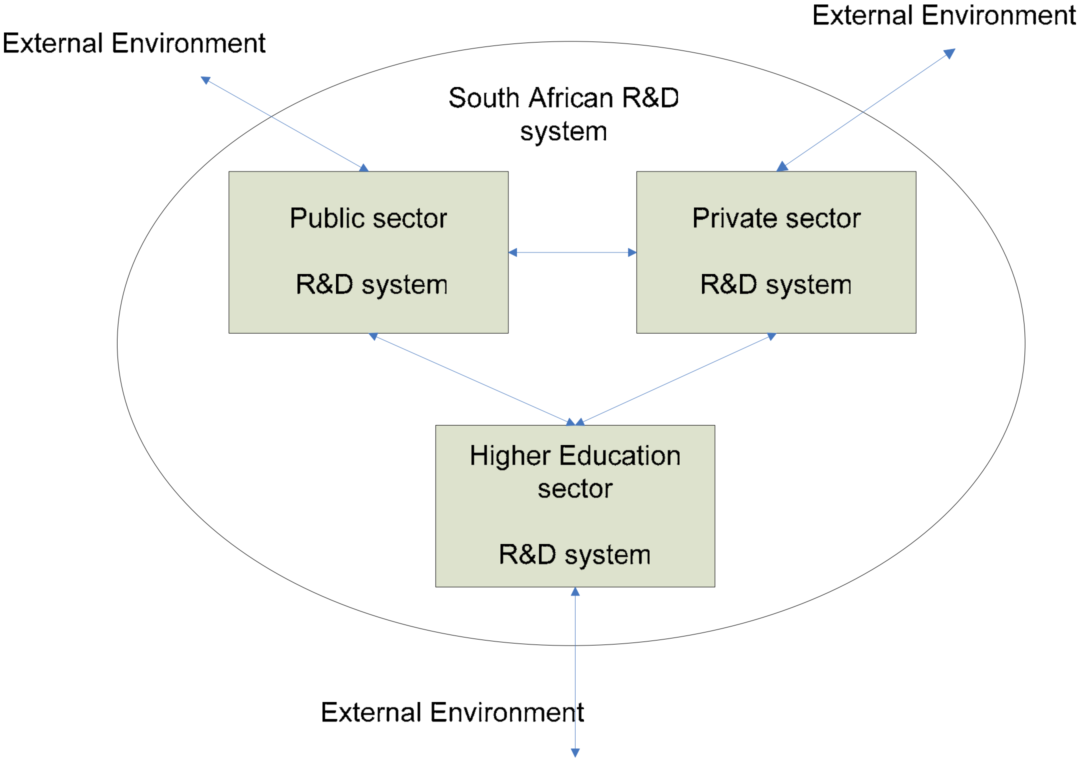


Figure 5-1: Interaction and Flows between R&D Sector Models

Figure 5-1 portrays a high-level view of interactions and flows between the major R&D performing sectors in the South African R&D system. Interactions and flows of resources occur across the system boundary to the exogenous environment. These flows and interactions also occur between R&D performing systems endogenous to the South African system, i.e. the higher education, business and public sectors.

This section emphasises that the South African R&D system does not exist in isolation, as flows exist between the South African and foreign R&D systems. Given the flow of knowledge and resource between them, the above is also true for the R&D performing sectors in the South African R&D system.

To both reach a clearer understanding of the important variables in the model and to glean a dynamic hypothesis, the basic structure of an R&D sector is derived from theory.

5.3 Generic Model for a Sectoral R&D System

This chapter focuses on developing a conceptual model of R&D in the South African system of innovation. The approach followed (see Figure 5-2) entails creating a generic model of an R&D performing sector. Numerous aspects and theoretical principles surrounding the performance of R&D are similar across different R&D sectors in a country. In an attempt to simplify the task of developing a model for the South African R&D system, the basic building block for the development is defined and derived first.

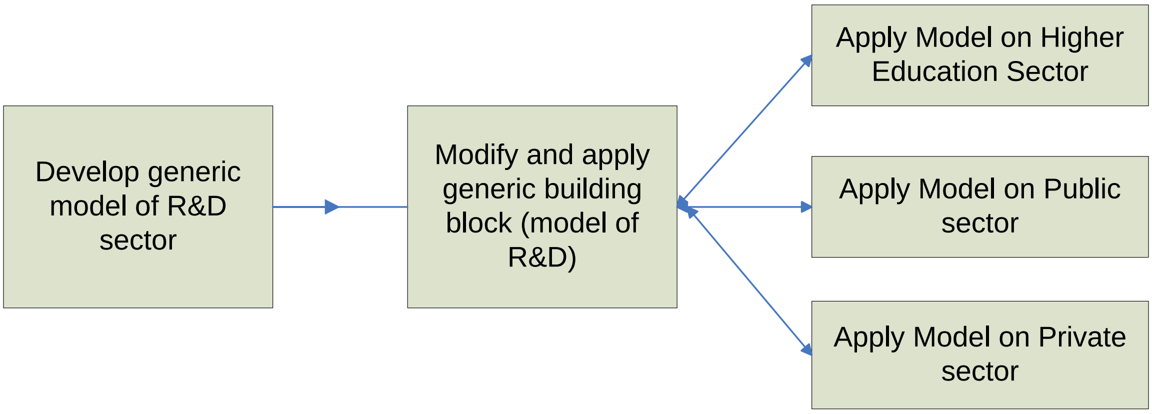


Figure 5-2: The Application of the Generic Model on R&D Performing Sectors in SA.

Although there are a number of similarities in the development of new knowledge on the one hand and the specific types of resources in R&D performing sectors on the other, they are unique in many ways. The conceptual model developed in this chapter is therefore applied and modified to suit the unique structure of the three R&D sectors that the model is applied to in Chapters 7 to 9.

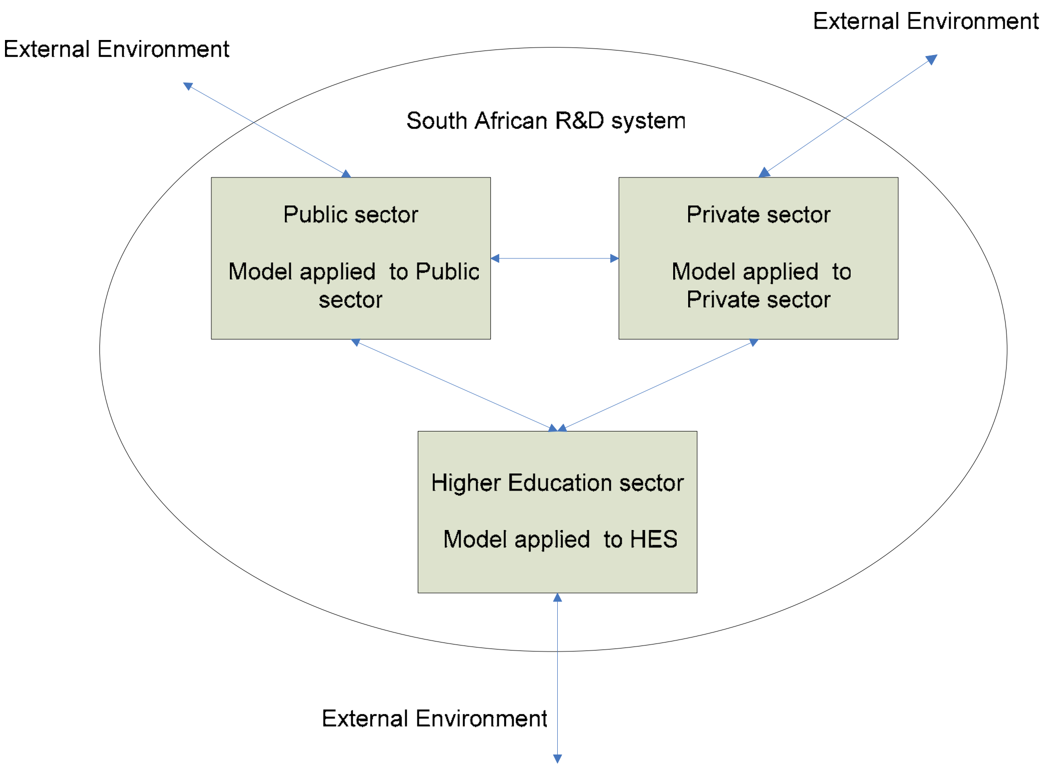


Figure 5-3: High-level view of the Model Structure

Figure 5-3 depicts a high-level view of the model structure indicating the three subsystem models. The reason for taking this approach is that it saves space and minimises rework in the formulation of dynamic hypotheses for the respective R&D performing sectors.

The next step is however to formulate and define the basic structure of an R&D performing sector model. The following section documents the derivation of the model structure from theory.

5.4 Theoretical Underpinning of the Dynamic Hypothesis

Freeman (1992:170) believes that although R&D is not the only source of technical change, it remains one of the main points of entry for new scientific development as well as the main focus for the development of new products and processes in most branches of industry.

It is crucial for any nation to develop an R&D capacity. The literature study concluded that an R&D investment aimed at developing an R&D capacity to create new knowledge as well as the ability to absorb new knowledge is important for a country's economical development ((Jones, 1995), Du Toit (2004)). Naturally, this also holds true for South Africa.

History plays an imperative role in the level of a system's development (Edquist, 1997). Within a complex system, events and developments are path dependent and take place over time. Small events are reinforced through positive feedback loops and become crucially important. The model developed in this section acknowledges the important role that the accumulation of *knowledge* and *skills* play in the development of an R&D system.

Romer (1990), Porter (1990), Lundvall (1992) and Johnson (1992), Niosi (2002), Nasierowski and Arcelus (1999) agree on the presence of human resources as an important input to the performance of R&D. Human resources engaged in R&D activities over a period of time, resulting in both the human resources building up and encapsulating tacit knowledge, know-how and skills. All the above are developed through experience. Non-codifiable knowledge or tacit knowledge encompasses the following:

- 'learning by doing' (Arrow, 1962)
- 'learning by using' (Rosenberg); and
- 'learning by interacting' (Lundvall, 1992b).

Lundval and Johnson's (1992) theory of interactive learning provides for the deterioration of knowledge, as it falls out of use or is replaced by new knowledge. Since R&D is performed in the system, the knowledge created can be expected to remain current and relevant for only a period of time after which it becomes obsolete.

The above section therefore concludes that human resources play a crucial part in the development of new knowledge. The development of new knowledge also results in human resources gaining insight and skills, referred to as tacit knowledge. The following sections deal with the dynamic human resources processes engaged in learning and the development of new knowledge.

5.4.1 The internal generation of new knowledge

The definition of R&D as documented in the Frascati manual states that R&D comprises the creation of knowledge, including knowledge of man, culture and society through the use of the stock of knowledge to devise new solutions (OECD, 2002c: 30). This definition highlights the central role that knowledge plays in generating new knowledge. Romer (1990), Lundvall (1992) and Rosenberg (2000) also support this view in their work.

The literature also acknowledges the role of capital resources (Christensen, 1992: 147) and capital assets as an important input to the R&D process ((OECD , 2002), (Porter, 1990). In the formulation of the model, capital assets stock is modelled as an aggregate stock of previous investment in equipment, land and buildings used by human resources to perform R&D.

The following figure captures this dynamic hypothesis:

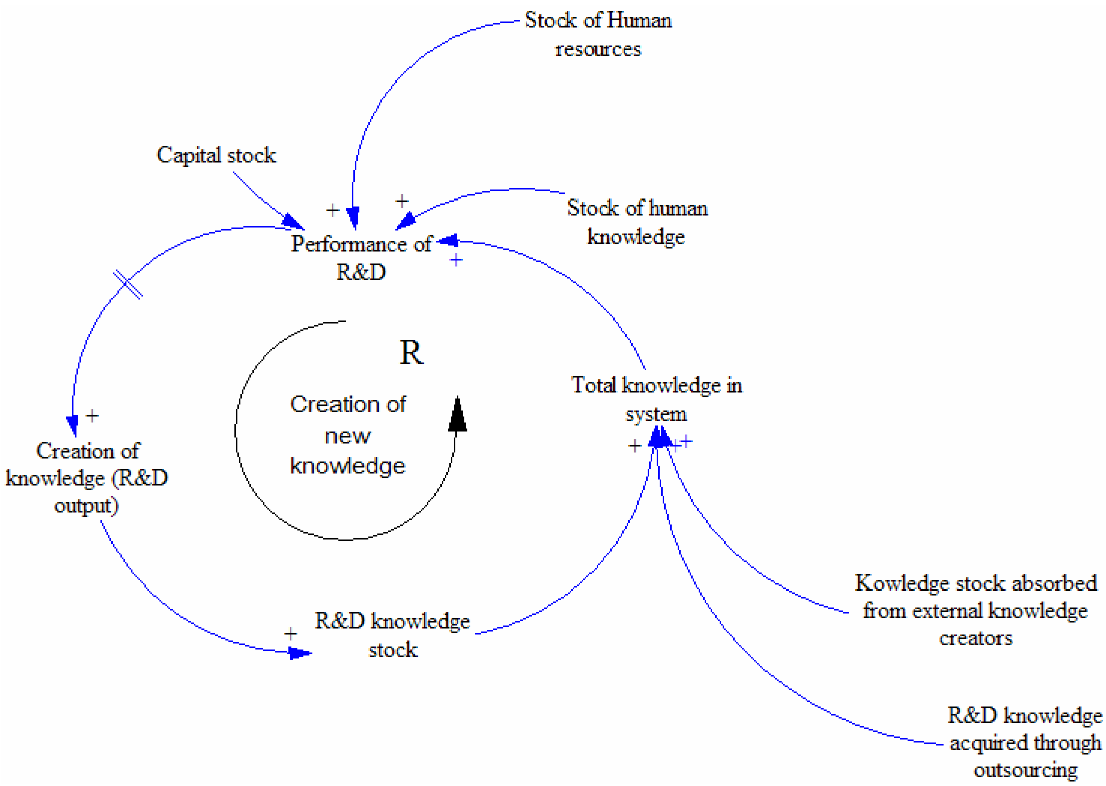


Figure 5-4: The creation of knowledge by utilising existing knowledge

The dynamic hypothesis aims to capture the process of R&D performance. The diagram captures a reinforcing loop. Human resources in an R&D system draw on capital stock, i.e. buildings, land and equipment, knowledge within the system as well as their own expertise and experience to perform R&D activities. Human resources also gain experience by performing R&D activities, resulting in a higher level of experience and expertise. Performing R&D activities result in new knowledge being created and ultimately in more knowledge being added to the 'R&D knowledge stock'.

Apart from the R&D knowledge stock and tacit knowledge of researchers, an additional knowledge stock can be identified. This is the absorbed knowledge stock. The following section describes the accumulation of this knowledge stock in more detail.

5.4.2 The absorption and acquisition of external knowledge

Werker and Fritsch (1999) provide a detailed explanation of the factors that influence the generation of knowledge. They believe that an organisation's performance with regards to the generation of knowledge depends on its ability to combine internal knowledge and external knowledge in a new way. This thus proves that the performance of R&D is also dependent on the acquisition and absorption of knowledge from external sources. It is also a direct implication that the organisation must at least possess the ability to identify, absorb and apply new knowledge for its own means, a process commonly referred to as the 'absorptive capacity' (Cohen and Levinthal, 1990).

Fritsch and Werker (1999) state that besides the ability to absorb information, the amount of knowledge actually transferred into the organisation is also dependent on the quantity, quality and the kind of knowledge available in the external environment.

The following figure represents a dynamic hypothesis as derived from the theory:

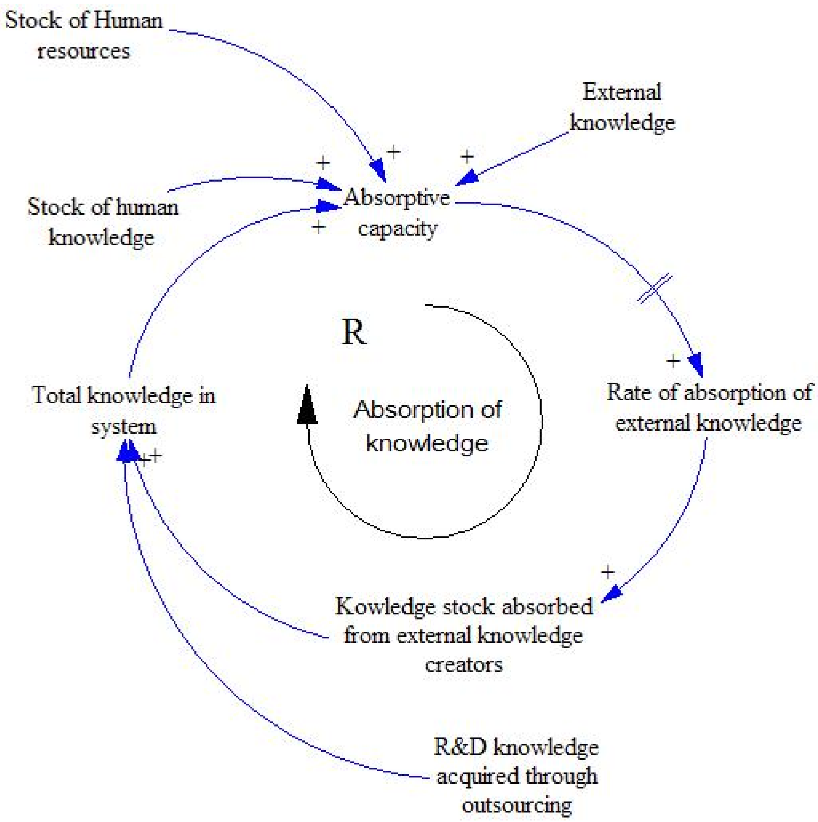


Figure 5-5: Absorption of Knowledge through Knowledge

The dynamic hypothesis displayed in Figure 5-5, represents a reinforcing loop for building system knowledge through the absorption of external knowledge. The loop displays dynamics involved in the absorption of knowledge from the external environment. This can only be achieved if the system has a level of absorptive capacity. The dynamic hypothesis assumes that the system's absorptive capacity depends on the presence of human resources, tacit knowledge and experience as well as previously generated and accumulated knowledge in the system. The absorptive capacity is also influenced by the external knowledge stock's characteristics. The system draws on its absorptive capacity to accumulate knowledge from the external environment.

As the successful performance of R&D depends on the successful integration of external and internal knowledge stocks, the following section deals with integrating the two reinforcing feedback loops that have been derived.

5.4.3 The integration of knowledge stocks

This section develops a dynamic hypothesis for the development of new knowledge. Figure 5-6 displays a dynamic hypothesis that incorporates the reinforcing loops derived from previous sections.

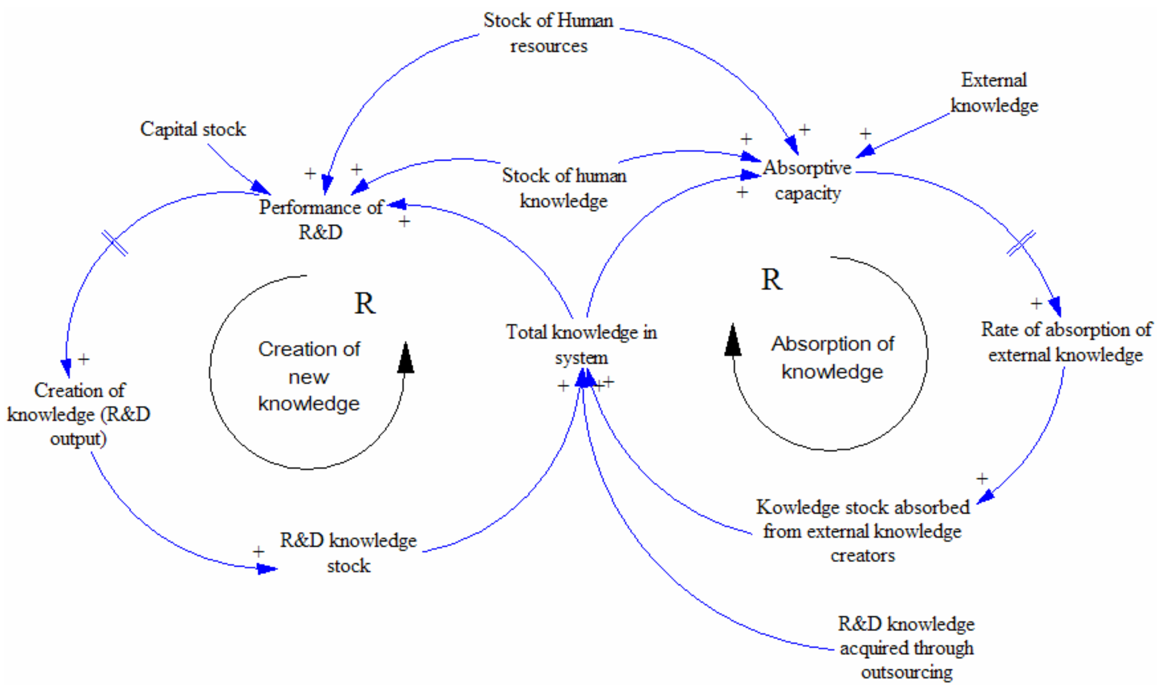


Figure 5-6: Casual loop diagram of an R&D system

Figure 5-6 depicts a CLD for integrated feedback loops of the creation of new knowledge and the absorption of knowledge. The creation of knowledge and the absorption of knowledge depend on the system's previous investment in human resources, the corresponding human knowledge stock as well as the current knowledge stock, i.e. the R&D knowledge stock and integrated external knowledge stock.

The CLD clearly depicts the relationships between variables and the system's feedback structure. CLDs however do not provide a way of communicating the model's physical structure. It also fails to capture the accumulation of goods as a result of flows in the system. The CLD developed up to this point is consequently expanded into a stock and flow diagram. The following section builds on the causal loop structure derived from theory.

5.5 Stock and Flow Diagram

Following the work of Romer (1990), Lundvall (1992) and Rosenberg (2000), the model acknowledges the central role of knowledge and the availability of human resources ((Romer, 1990), (Porter, 1990), (Lundvall and Johnson, 1992), (Niosi, 2002), (Nasierowski and Arcelus, 1999)) as inputs to system performance.

As indicated in the development of the causal loop structure, two main feedback loops can be identified within a sectoral R&D system, namely:

- an internal knowledge creation loop, i.e. an R&D performing loop; and
- absorption of external knowledge loop.

The formulation of the stock and flow diagram is based on the formulation of rate (flow) equations. Before the model is discussed in more detail, the formulation of the rate equations is explained. These rate equations involve the formulation of mathematical equations to estimate the influence that changes in stocks in the system might have on each other. To estimate the effect that a change in a stock (X_i) could have on a variable (Y), the following formulation is used:

$$\text{Change in Y because of } X_i = f(X_i / X_i^*) \quad \textbf{5-1}$$

The variable Y can either be a rate or an auxiliary that feeds into a rate. The non-linear functions are normalised by the normal or reference value of the inputs (X^*_i). The normalisation ensures that when the inputs X_i equal their reference levels, the output Y equals its reference level. Normalising means the input and output of the effect of X_i on Y are both dimensionless, allowing separation of normal values from the effects of deviation from normal.

Reference levels throughout the model formulation are chosen to be the values for the initial levels of the stocks in the model.

Throughout the model, the change in variable Y because of X_i is modelled to take a power function form of the normalised inputs:

$$\text{Change in Y because of } X_1 = \left(\frac{X_i}{X_i^*}\right)^{a_i} \quad \textbf{5-2}$$

(Where $X^*_{i\,i}$ is the reference value for stock X_i)

The first aspect of the stock and flow diagram under scrutiny is the human resources stock and their associated tacit knowledge. The following section explains this stock and flow diagram subsection in more detail.

5.5.1 Human resources

As described in the section relating to the CLD, human resource stock in an R&D performing sector contributes to the creation and development of new technologies. It is also within the human resources that the majority of the tacit knowledge is stored. The dynamics involved in the headcount of research personnel in the system uses an ageing chain dynamic. This is an extremely common formulation and has been used by numerous modellers to model ageing properties in systems[1]. An ageing chain includes a number of stocks, which can also be called cohorts.

Figure 5-7 is a graphical representation of the ageing chain dynamics employed in the model. Each cohort has an inflow $R_{\inf low}(i)$ and an outflow $R_{outflow}(i)$. Research staff moves from cohort i to cohort $i+1$ though the transition rate $R_{transition}(i,i+1)$.

[1] See Forrester (1969), Sterman (2000)

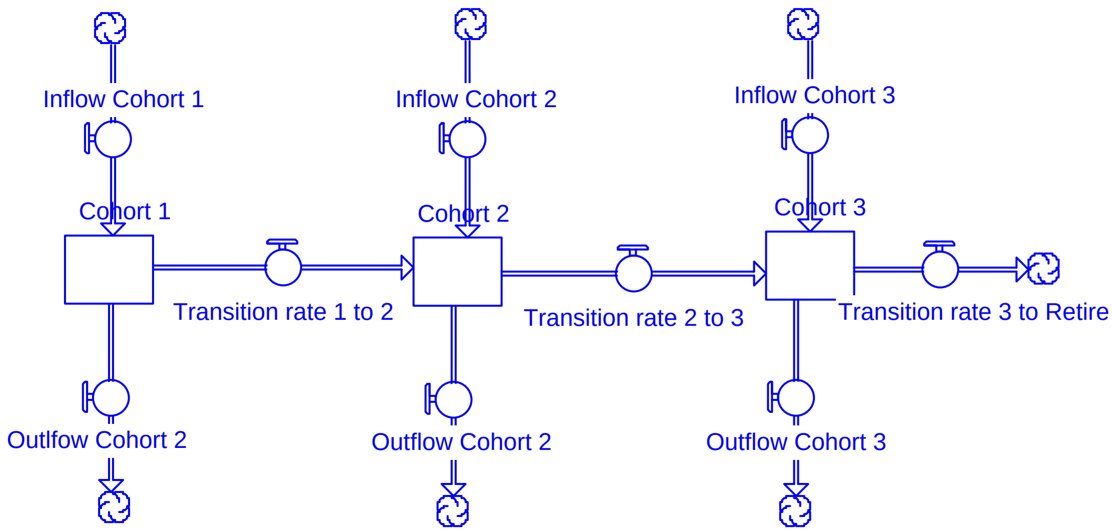


Figure 5-7: Ageing chain of Human Resources in the HES

The transition rate $R_{transition}(i,i+1)$ is modelled as a delay that takes the form of a first order process[2], $R_{transition}(i,i+1) = S_{HR}(i)/AT$,where AT denotes the average time residence before a person matures from the cohort to flow to the next.

Three stocks (cohorts) are used to capture flows of researchers of the following age groups:

- cohort 1 ($S_{HR}(1)$): young researchers aged 25-39 (AT_1 = 15)
- cohort 2 ($S_{HR}(2)$): experienced researchers aged 40-49 (AT_2 = 10); and
- cohort 3 ($S_{HR}(3)$): mature researchers aged 50 + (AT_3= 15)[3]

The following expression can thus be formulated for the cohorts:

$$S_{HR}(i) = \text{integral}\left(R_{\inf\, low}(i) - R_{outflow}(i) - R_{transition}(i,i+1), S_{HR}(i)_{t_0}\right) \qquad \textbf{5-3}$$

Where $S_{HR}(i)_{t_0}$ is the initial value of $S_{HR}(i)$.

The inflow ($R_{\inf\, low}(i)$) of new human resources becomes a necessity as older staff retires or as human resources leave the system for whatever reason ($R_{outflow}(i)$). The system employs the dynamic of a goal-seeking loop, thus comparing the current headcount in the system with the target headcount in the system.

[2] A first-order outflow from a stock implies that the stock contents are mixed perfectly. More specifically, the probability that a particular item will exit is independent on the time it entered the stock. The number of cohorts can be increased until it represents a reasonable approximation of the real system

[3] An average Retirement rate of 65 years is assumed.

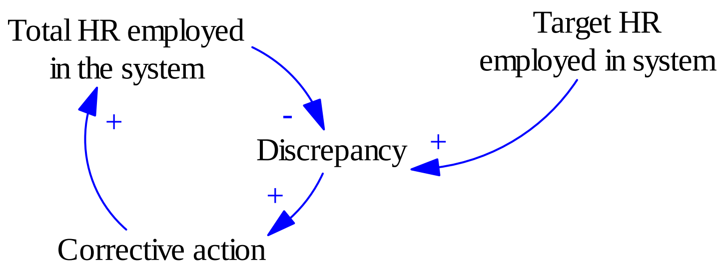


Figure 5-8 Goal Seeking Behaviour Employed in the Model

Should there be a discrepancy between the human resources employed in the system, the system will automatically take corrective action by either allowing a flow of academics into the system (hiring - $R_{\inf\ low}(i)$) or by an outflow (retrenching or firing the people - $R_{outflow}(i)$).

Discrepancy = Target Headcount – Total Headcount

The following two sections describe the detail around how $R_{outflow}(i)$ and $R_{\inf\ low}(i)$ are computed.

5.5.1.1 Inflow of human resources into the system

Where discrepancy > 0, the system employs less people than the target amount and should thus appoint new people. The decision as to which stocks the people should be assigned is made through the inflow percentage distribution parameters $A_{\inf\ low}(i)$ in the model.

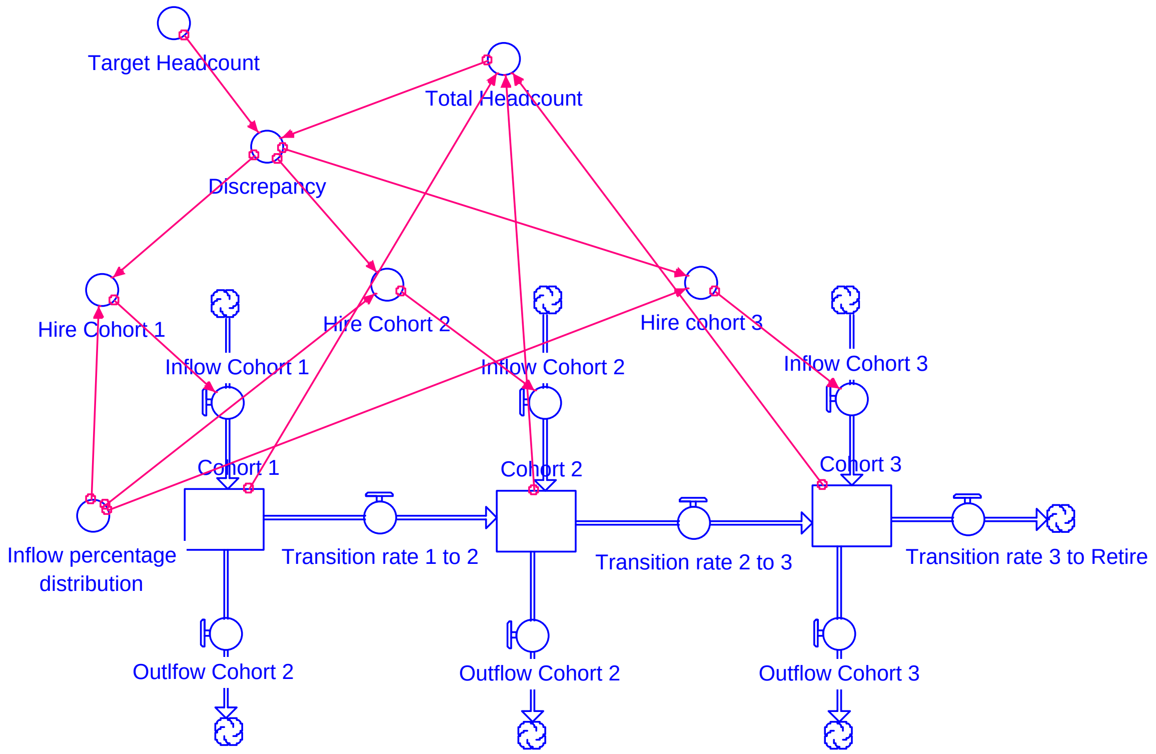


Figure 5-9 Ageing Chain Dynamic with Employment Dynamic Included

Where $Discrepancy > 0$, $R_{\inf\ low}(i) = Discrepancy * (A_{\inf\ low}(i))$ else 0

5-4

Where $A_{\inf\ low}(i)$ is the percentage distribution through which new appointments are made.

Where $\sum_{i=1}^{3} A_{\inf\ low}(i) = 1$ (These values are estimated in the model)

5.5.1.2 Outflow of human resources in the system

Where *Discrepancy* < 0, the system employs more people than the target amount and should thus allow human resources to flow from the stocks to correct for the discrepancy.

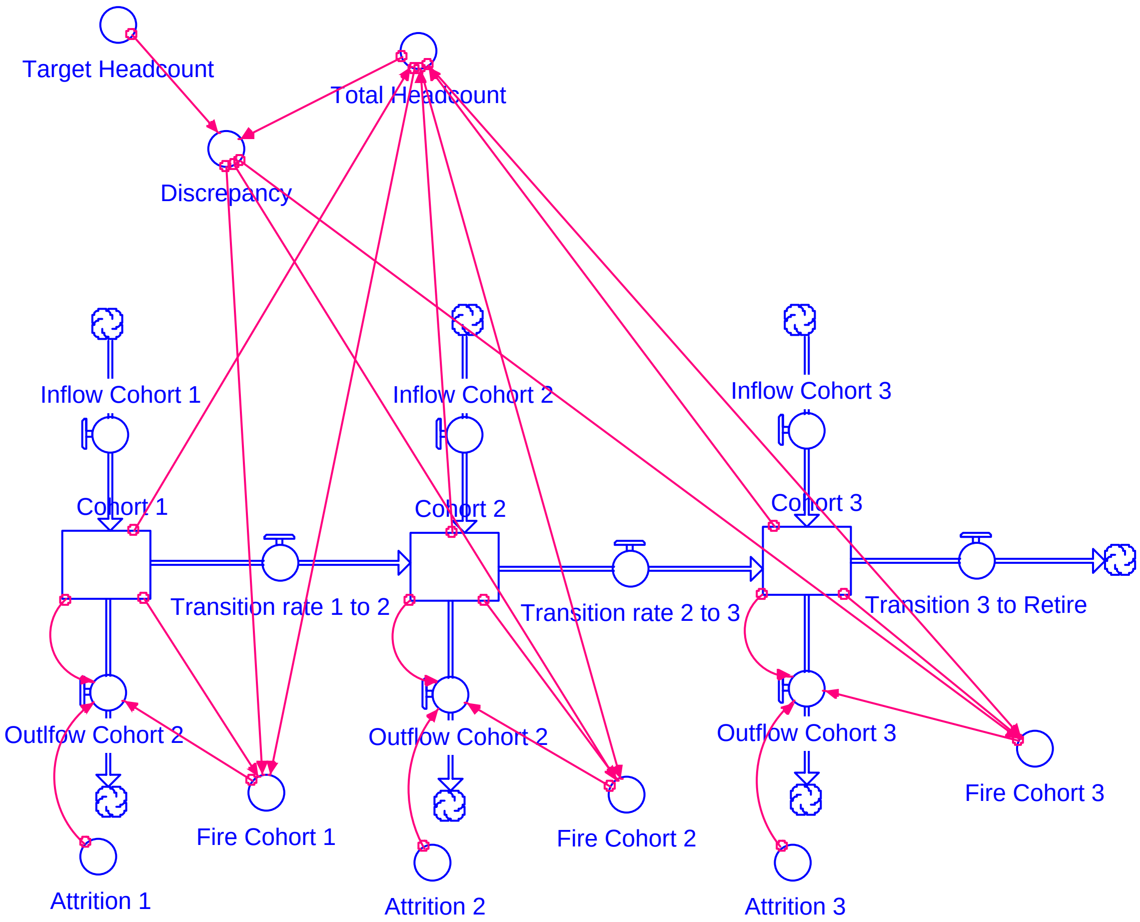


Figure 5-10 Ageing Chain Dynamic with Outflow Dynamic Included

It is safe to assume that the human resources will flow in the same distribution as represented in the cohorts.

If *Discrepancy* < 0 then

Fire Cohort (i) = ABS (Discrepancy* $S_{HR}(i)$/Total Headcount) **5-5**

The natural attrition of human resources in the system is also included in the dynamic model. $Attrition(i)$ is included as a percentage of the total stock of people in each of the cohorts $(Cohort(i))$.

$R_{outflow}(i)$ = ABS ($Discrepancy * S_{HR}(i)$ /Total Headcount)+ $Attrition(i) * S_{HR}(i)$

5-6

It is essential that $Attrition(i)$ has to be estimated for the model.

5.5.2 The fulltime equivalent researchers in the system

The number of fulltime equivalent researchers employed in the system is computed from the actual headcount of people employed in the system in terms of the percentage time headcount personnel actually spent on R&D.

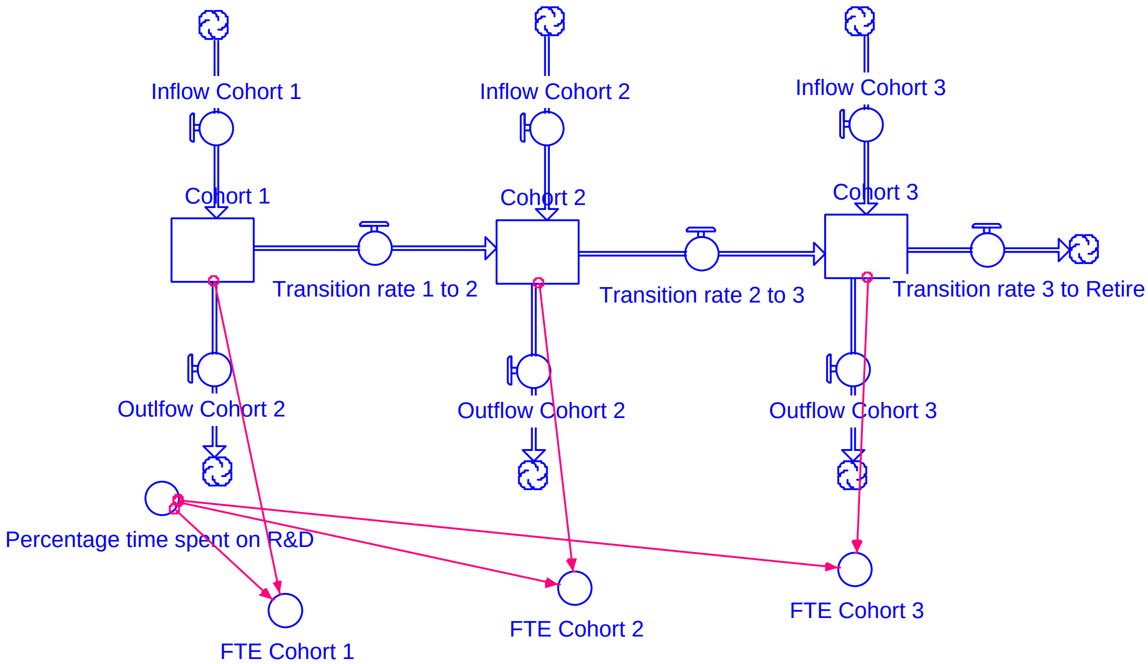


Figure 5-11 Dynamic for the Computation of the FTE Researchers in the System

In mathematical terms, the above can be expressed as follows:

$$FTE(i) = S_{HR}(i) \times \%TimeSpentonR\,\&\,D \qquad \textbf{5-7}$$

The value of $\%TimeSpentonR\,\&\,D$ has to be estimated for the sector on which the model is applied.

The following section takes a closer look at the development of the model in terms of the capacity developed in humans as they perform research.

5.5.3 Experience stocks

R&D is also introduced as a form of organisational learning. Cohen and Levinthal (1990) argue that R&D not only generates new information, but also enhances the ability to assimilate and exploit existing information. The long-term investment in developing R&D capacity is substantial and far from a trivial issue. The cost of learning is borne from the development of a stock of knowledge, which constitutes absorptive capacity.

Sterman (2000) employs learning curves in system dynamic models. Learning curves or experience curves have been documented in a wide range of industries. These curves arise as workers and firms learn from experience. As experience grows, workers find ways to work faster and reduce errors. Typically, the unit costs of production is bound to fall by a fixed percentage every time that cumulative production experience doubles. Learning by doing, know-how and are embedded in the organisation's capital stock, worker knowledge and routines. Although this knowledge stock is slow to develop, it also takes time to decay, provided that the human resources remain in the system.

It is therefore a safe assumption that a person should become more efficient and effective as his/her R&D experience level increases. This can be ascribed to the experienced person embodying a higher concentration tacit knowledge and more co-operation and relationships with other researchers than the average graduate who has just completed his/her studies. Following this reasoning, an assumption is made that as the average level of experience in the system increases, the tacit knowledge, know-how, general capability and co-operation of the researchers in the system is also bound to rise.

The following stock and flow structure is developed in an attempt to capture these flows and accumulation of human resources and experience:

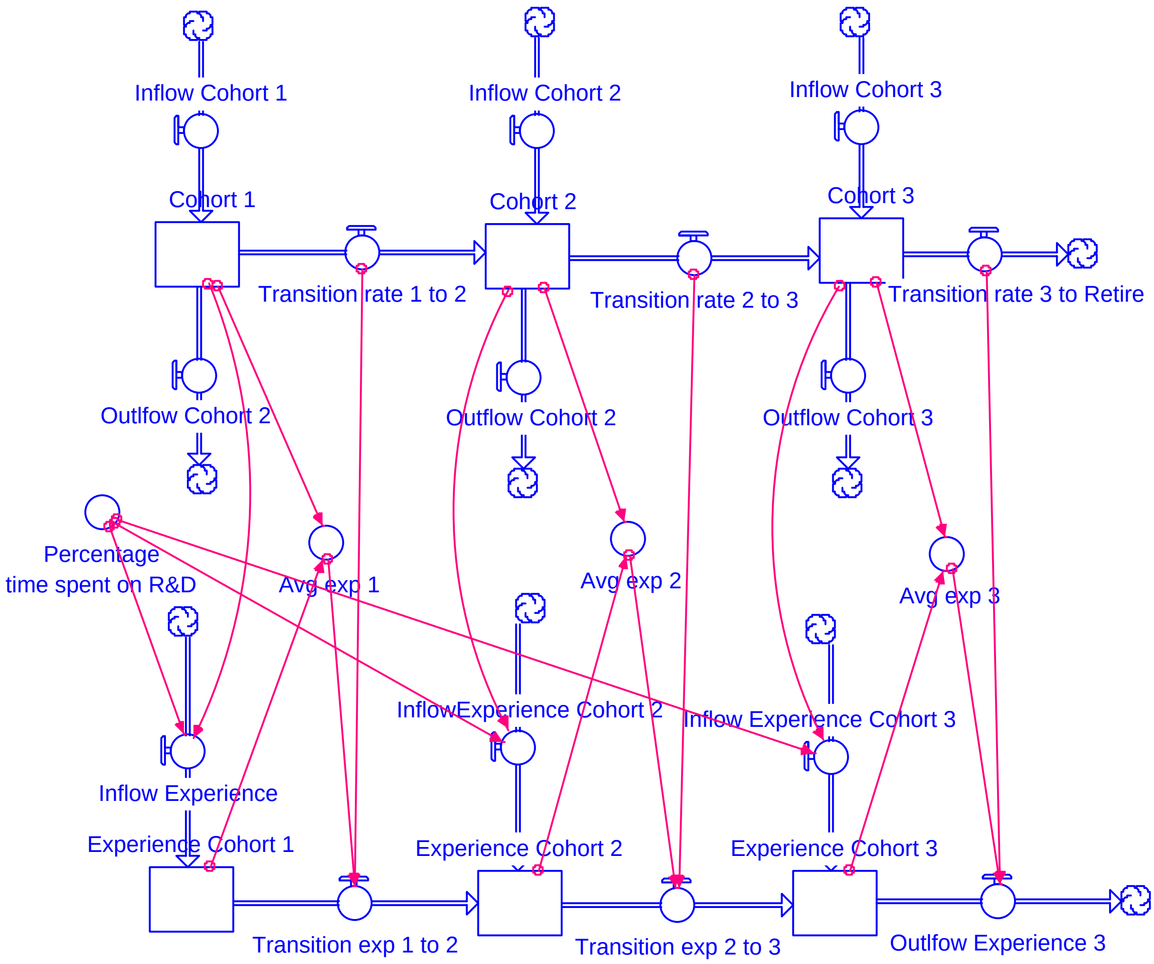


Figure 5-12: The Stock and Flow Diagram of Human Resources and Experience.

The stock of human knowledge is quantified in terms of years of experience. This is based on the argument derived from theory in a previous section that researchers with more experience possess more tacit knowledge and skills.

The stocks of skills in the system ($S_{skills}(i)$) thus accumulate at a parallel rate to academic and research personnel gaining more R&D experience. These stocks therefore accumulate with the fulltime equivalent researchers working in the system ($FTE(i)$). As academic and research staff matures and moves from one cohort to the next ($R_{iransition}(i,i+1)$), the relevant experience is also transferred ($A_{AvgExperience}(i)$).

Another mechanism not depicted in Figure 5-12 through which more skills can be gained is the rate at which the system employs new personnel ($R_{\inf low}(i)$) with an average level of experience that these new appointees already possess as researcher ($A_{New-\exp erience}(i)$). As researchers leave the system ($R_{outflow}(i)$), experience and tacit knowledge will also be lost to the R&D performing sector. Another factor that adds to the stock of skills depreciating is people 'forgetting' or knowledge falling in disuse.

To ensure that the system continues to produce research output, a human resource stock is imperative, especially one that is continually replenished with new graduates. The current experience stock, measured in total years experience in R&D by al human resources in the system, is therefore identified as an important input to the performance of R&D in the system.

This section described the human resources subsystem of the model. The following section focuses on the role of knowledge stocks and human resources in the performance of the system.

5.5.4 Effect of investment on R&D and assimilation of knowledge

Recalling the two major feedback loops, i.e. the creation of knowledge and the absorption of knowledge,) identified in the development of the CLDs, two rate equations are computed from the stocks in the system:

- rate of knowledge creation; and
- rate of knowledge absorption.

For the purpose of this model, a performance index for each of these rates is formulated.

Since the human resources and knowledge stocks contribute to the overall effectiveness of the generation of new knowledge and the absorption of knowledge in varying ways, two different parameters are defined for the system performance. The system performance parameter for the development of new knowledge is defined as $A_{Performanc\ e}(R\&D)$, while the system performance parameter for the assimilation of new knowledge is defined as $A_{Performanc\ e}(ABS)$.

Change in system performance because of human resources

An important factor that contribute to the R&D system performance ($A_{Performanc\ e}$) is the availability of human resources. The change in the system performance as a result of changes in the human resources stock (HR) can thus be expressed as follows:

$$\text{Change in } A_{Performanc\ e}(R\&D) \text{ because of } HR = \left(\frac{HR}{HR^*}\right)^{a_5} \qquad \textbf{5-8}$$

and

Change in $A_{Performance}(ABS)$ because of $HR = (\frac{HR}{HR^*})^{\beta_5}$ **5-9**

Note: HR^* refers to the reference value of the Human Resources (HR) stock

Change in system performance because of knowledge

Knowledge however has been identified as one of the influencing factors of system performance. The following stocks are included in the formulation of the production function of the absorption and the creation of knowledge:

- R&D knowledge stock (S_{RD}): stock of R&D output generated in the system
- absorbed knowledge stock ($S_{Absorbed}$): knowledge external to the R&D performing sector that has been absorbed by performing R&D activities; and
- human resources knowledge stock (S_{skills}): tacit knowledge and research skills inherent to the human resources working in the system.

The additive formulation for the influence that knowledge stock might have on the system performance ($A_{Performance}$) is thus formulated as follows:

Change in $A_{Performance}(R\&D)$ ***because of knowledge***$= (\frac{S_{HR}}{S^*_{HR}})^{a_1} * (\frac{S_{Absorbed}}{S^*_{Absorbed}})^{a_3} * (\frac{S_{RD}}{S^*_{RD}})^{a_4}$ **5-10**

and

Change in $A_{Performance}(ABS)$ ***because of knowledge*** $= (\frac{S_{HR}}{S^*_{HR}})^{\beta_1} * (\frac{S_{Absorbed}}{S^*_{Absorbed}})^{\beta_3} * (\frac{S_{RD}}{S^*_{RD}})^{\beta_4}$

5-11

Change in system performance

From both the changes in system performance because of the knowledge in the system as well as the human resources present, a multiplicative formulation was chosen. The multiplicative nature of the formulation of the model indicates that human resources and knowledge must exist together in the model for the system to be able to perform. The fractional change in the system performance can thus be formulated as the following expressions:

Change in $A_{Perf}(R\&D) = (\frac{S_{HR}}{S^*_{HR}})^{a_1} * (\frac{S_{Absorbed}}{S^*_{Absorbed}})^{a_3} * (\frac{S_{RD}}{S^*_{RD}})^{a_4} * (\frac{S_{Skills}}{S^*_{Skills}})^{a_5}$ **5-12**

Change in $A_{Perf}(ABS) = (\frac{S_{HR}}{S^*_{HR}})^{\beta_1} * (\frac{S_{Absorbed}}{S^*_{Absorbed}})^{\beta_3} * (\frac{S_{RD}}{S^*_{RD}})^{\beta_4} * (\frac{S_{Skills}}{S^*_{Skills}})^{\beta_5}$ **5-13**

Now that an expression of the fractional change in system performance resulting from changes in the elements of an R&D system has been formulated, the feedback loops feeding from and into the system performance parameters can be characterised. Both the CLD as well as the outline of the stock and flow diagram indicate that the model consists of two reinforcing feedback loops.

- absorption of external knowledge; and
- creation of knowledge.

The following sections describe these feedback loops in terms of their stock and flow structures in more detail.

5.5.5 Loop 1: absorption of external knowledge

The following figure depicts the stock and flow diagram developed for the knowledge absorption and acquisition subsystem.

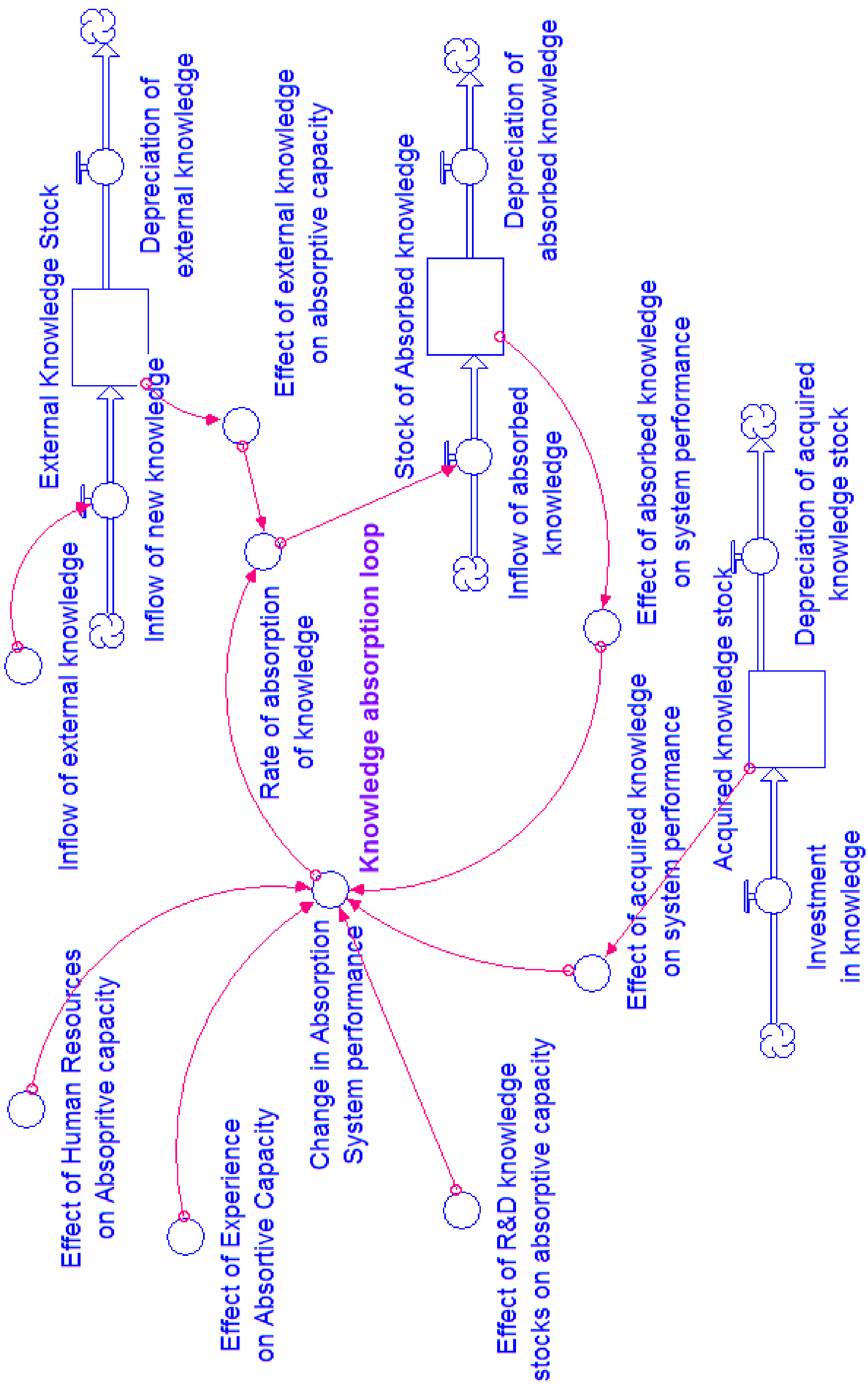


Figure 5-13: The Absorption of External Knowledge

In this stock and flow diagram, the rate at which knowledge is created in the external environment ($R_{External}$) is defined to be exogenous to the system. As knowledge is created in the external environment, it forms part of the total stock of knowledge in the external environment ($S_{External}$).

$$S_{External} = \text{Integral} (R_{External} - \text{Depreciation rate of external knowledge}) \tag{5-14}$$

As R&D is performed in the system, knowledge is absorbed from the external environment. The rate at which the system absorbs the knowledge is defined as the absorptive capacity. The model defines the absorptive capacity as the rate at which the system is able to absorb knowledge from the external environment. The quantity, quality, applicability and context of the knowledge ($S_{External}$) in the external environment also impact on the system's ability to absorb the knowledge ($R_{Absorbtion}$). This absorption rate is modelled through the following mathematical equation:

$$\text{Knowledge absorption rate } (R_{Absorbtion}) = R^{*}_{Absorbtion} * (\text{Fractional Change in } A_{Performance} (ABS))*(\text{Change in Absorptive capacity because of } S_{External}) \tag{5-15}$$

With

$$\text{Change in absorptive capacity because of } S_{External} = \left(\frac{S_{External)}}{S^{*}_{External}} \right)^{\beta_7} \tag{5-16}$$

The rate at which knowledge is absorbed feeds into the stock of knowledge that has been absorbed from the external environment ($S_{Absorbed}$). The accumulation of the absorbed knowledge stock is depicted as follows:

$$S_{Absorbed} = \text{Integral} (R_{Absorbtion} - \text{Depreciation rate of absorbed knowledge}) \tag{5-17}$$

The absorbed knowledge stock ($S_{Absorbed}$) feeds back into the system equation for the change in system performance.

The second feedback loop whose output affects the system performance is the performance of R&D. The following section describes this loop in more detail.

5.5.6 Loop 2: the performance of R&D

The second reinforcing loop deals with the internal creation of knowledge in the system. The following stock and flow diagram displays the 'internal generation of knowledge' loop.

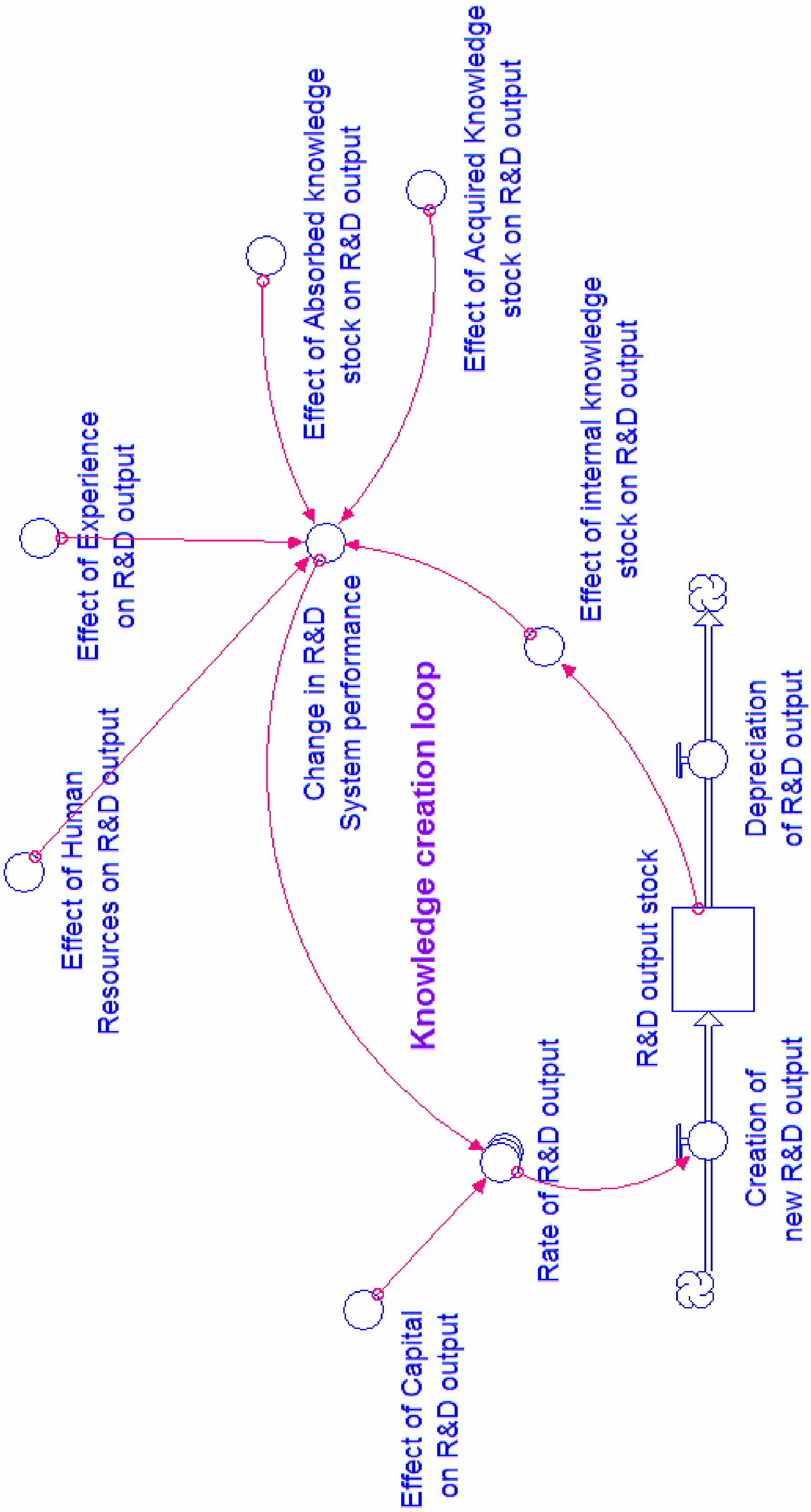


Figure 5-14: Stock and Flow Diagram for the Performance of R&D

In the development of the CLD, it was derived from theory that the rate of the creation of new knowledge $R_{R\&D}$ dependent on the stock of Human resources and different types of Knowledge contained in the system. The effect the knowledge has on the creation of knowledge is already integrated in the System performance parameter ($A_{Performance}(R\&D)$).

R&D knowledge stock = Integral (rate of creation of R&D output - depreciation of R&D knowledge)

$$S_{R\&D} = \textbf{Integral} \ (R_{R\&D} \ \textbf{- depreciation of R\&D knowledge}) \qquad \textbf{5-18}$$

Performance of R&D (rate) = (Reference rate of R&D in 2001)* (Change in $A_{Performance}(R\&D)$)

$$R_{R\&D} = R^{*}_{R\&D} * A_{Performance}(R\&D) \qquad \textbf{5-19}$$

Closing the reinforcing feedback loop, the R&D knowledge stock feeds back into the system performance computation equation.

5.5.7 Conclusion

This section identifies the basic elements of the R&D performing unit. The causal loop structure of an R&D performing sector was derived from theory, after which stock and flow diagrams were developed. The following is an integrated stock and flow diagram, depicting both feedback loops in the system:

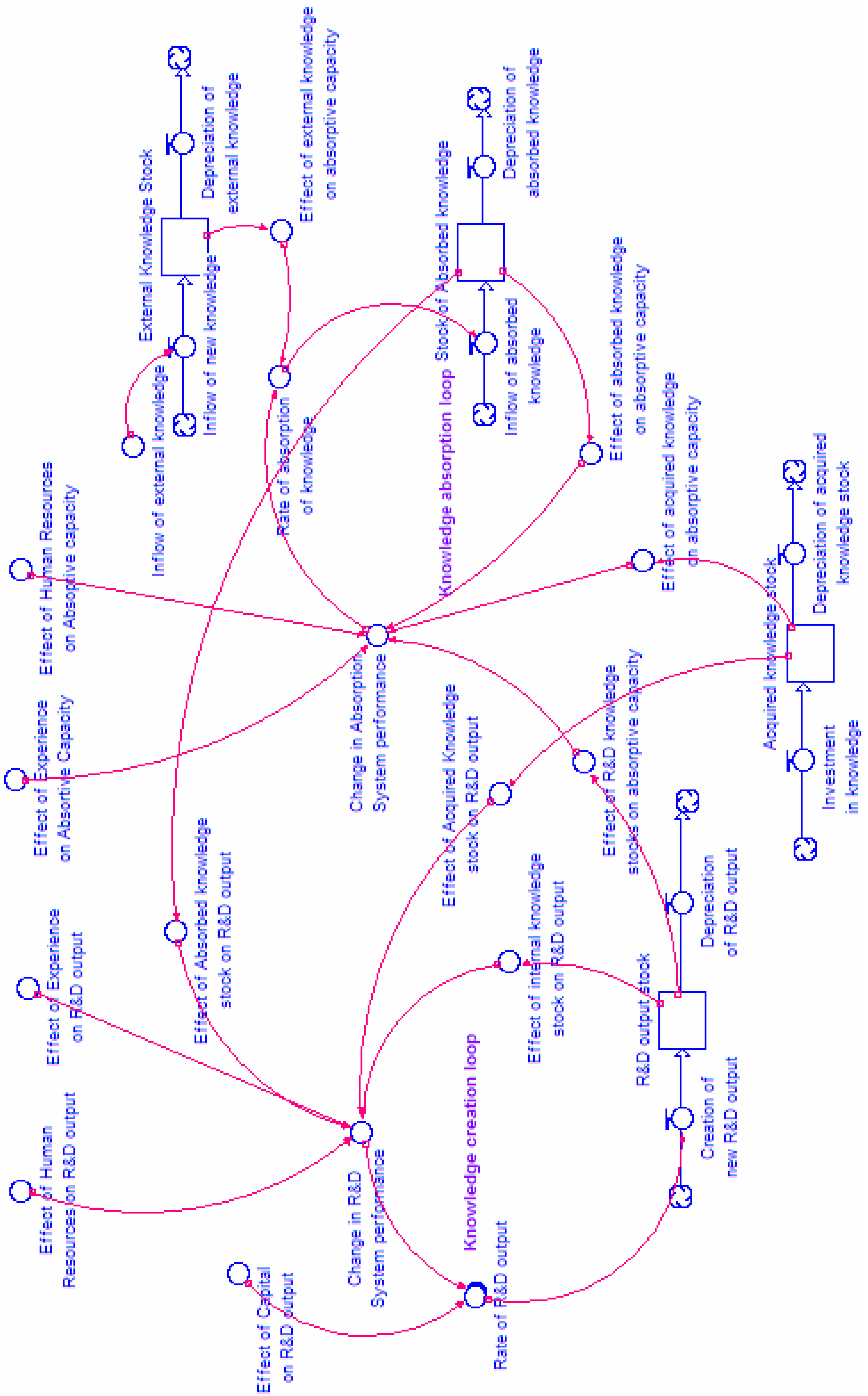


Figure 5-15 Stock and Flow Diagram with Absorption and Creation of Knowledge

The basic building block of the system has now been derived. As emphasised in the first section of this chapter, the system dynamics model developed is a generic model of R&D on a sector level. The following step in the development of a model of R&D in South Africa is therefore to apply and modify the conceptual model on South Africa's three R&D performing sectors.

University of Pretoria etd – Grobbelaar, S S (2007)

5.6 Chapter Summary

This chapter documents the development and derivation of a system dynamics model of R&D activities in an R&D performing sector. The stock and flow diagram developed in this chapter follows directly from the CLD derived in the previous sections. The theoretical model developed will be applied to the three R&D performing sectors as discussed in previous sections of this chapter.

The following chapters document the data gathering, testing and calibration of the model of R&D in the South African system of innovation.