1. INTRODUCTION AND BACKGROUND

1.1. Introduction: Growth through Science and Technology

Michael Porter (1990:6) states that a nation's principal economic goal is to produce a high and rising standard of living for its citizens. The ability to do so depends on the productivity with which a nation's resources are deployed. Porter defines productivity as "the value of output by a unit of labour or capital." He argues that productivity is the prime determinant for a country's standard of living, as it determines the per capita income of a nation. In other words, by increasing the productivity of the citizens in a country, the per capita GDP will increase, from which economic growth should follow.

Technological change is seen as a key driver for growth in a country. Charles Edquist (1997:1) argues that it is almost universally accepted that technological change and other kinds of innovations are the most important sources of productivity growth and increased material welfare and that this has been the case for centuries.

Technological change has provided firms with the power to circumvent scarce factors via new products and processes. The use of materials, energy and other resource-based inputs has either been substantially reduced or synthetic substitutes have been developed.

Modern materials, such as engineering plastics, ceramics, carbon fibres and silicon, used in producing semiconductors, are cheap and ubiquitous, considerably reducing the importance of scarce factors at large. Automation and process innovations resulted in a reduction of the labour content within many industries, thereby rendering access to high technology more important than low local wages (Porter, 1990:14).

It will be shown in the next section that this argument also holds true for the South African economy, since it has became increasingly dependent on technology and technological progress. The section also explores the pivotal role that technological progress has played in South Africa's economic growth performance over the past decades.

1.2. The Role of Technological Change in the South African Economy

Fedderke (2002) investigated the nature and extent of changes in the underlying production structure of the South African economy by identifying the main sources of economic growth and any changes that might have occurred in their relative contributions/importance over time. He performed a simple accounting exercise to break down output growth into growth in capital, growth in labour and growth in technology or total factor productivity.

Table 1-1: Contributions to Growth: 1970 – 2000 (%)

Period	Real GDP Growth	Sources of Growth	
		Constant Returns to Scale	*Decreasing Returns to Scale*

		Labour Growth	Capital Growth	Technology Growth	Technology Growth
1970-1979	3.03	0.80	3.64	-1.41	-0.30
1980-1989	2.24	0.42	1.72	0.10	0.62
1990-1999	1.58	-0.52	0.58	1.52	1.73

The above table indicates that the single strongest contributor to output growth during the course of the 1990s is a strong rise in technology. While output growth in the economy as a whole was driven by growth in factor inputs during the 1970s and 1980s, the 1990s saw a growing reliance on technological improvements and efficiency gains in the economy.

This phenomenon can in part be ascribed to the decline in formal sector employment in South Africa during the 1990s. Consequently, growth in labour inputs could not possibly have added to the growth in real output of the economy. As far as the declining contribution of capital is concerned, the growth performance of the South African economy can in turn be ascribed to the declining investment rate that South Africa has experienced.

Fedderke finds that the contribution of technological progress to South African growth in aggregate has been rising steadily since the 1970s, but that it has contributed a rising share to a declining growth rate in output.

The increased and substantial contribution of technology growth since the 1990s reflects the policy and institutional changes during that specific period. During the post-apartheid era, South Africa engaged in policies for social upliftment in support of education, health, crime and infrastructure. More importantly, South Africa also gained access to world markets and economies. International trade and investment offered important vehicles for technological spillover effects, while greater private sector participation in the economy increased the scope for technological innovation.

It can be concluded from the above section that science and technology indeed plays a pivotal role in the development and growth of the South African economy. Technological progress has become the engine of economic growth and a powerful tool to be used by economic policy makers to address the growth and employment problems of the South African economy effectively.

1.3. The Role of R&D in Technological Change

In the literature the importance of a country's ability to perform R&D as well as the role it plays in a country's ability to improve its competitive position is widely acknowledged and documented.

Chris Freeman (1978) introduced the concept of a National System of Innovation (NSI) to describe and interpret the performance of Japan, the economically most successful country of the post World War II period. Freeman defined the NSI as "the network of institutions of private and public sectors, whose activities and interactions initiate, import, modify, and diffuse new technologies". The systemic approach of innovation is based on the perception that innovations are ultimately brought about by the various components and the relations between them.

The innovation systems approach aims to identify the key components playing a central part in performing the system's functions. Freeman (1992:170) acknowledges the importance of R&D in formal scientific and technical organisations within the NSI. He believes that although R&D is not the only source of technical change, it is one of the foremost points of entry for new scientific development and the central focus for the development of new products and processes in most branches of industry.

R&D is also introduced as a form of organisational learning. Cohen and Levinthal (1989) argue that R&D plays a dual role within an economy. They assert that R&D not only generates new information, but also enhances the ability to assimilate and exploit existing information. The ease and character of learning in an industry influences and affects both the R&D spending and condition the appropriability and technology opportunity conditions in an industry. The cost of learning is borne from the development of a stock of knowledge, which constitutes absorptive capacity.

A significant benefit of R&D is its contribution to the current knowledge base. Cohen and Levinthal believe that since the long-term investment in developing an R&D capacity is substantial, it is not a trivial issue and is a matter of urgency that should be looked into (Cohen and Levinthal, 1989).

The above section concludes that R&D plays a crucial role in the NSI. Although not the sole driver of technological change, it certainly remains a pivotal one. R&D not only plays a key part in the development of innovative knowledge, it also enhances the ability to absorb knowledge and to keep up with technological change in the external environment.

Another key factor established in the above section is that the development of R&D requires a considerable investment in terms of time, funds and effort.

The following section provides a brief description of the development of the South African R&D system.

1.4. History of the South African R&D System

The use and development of new technology and science in South Africa has been an integral part of Africa in terms of both identity and culture. Archaeological discoveries dating back as far as the first Stone Age provide evidence of the success with which S&T has been employed on this continent (CENIS, 2000). These facts and artefacts testify to the technological abilities of the indigenous people of Africa as well as the central place that science and technology had in their lives.

The first formal documentation of scientific and technological activities in South Africa dates from the 18th century when the Cape colony attracted scientists from a bold young science born of the European Renaissance (CENIS, 2000).

1.4.1. Science for the sake of knowledge

During 1751 to 1880, scientific exploration in South Africa was an activity mainly conducted by travelling scholars. An example is Abbot de la Caille from the French academy of science who, apart from other important contributions, determined the position of nearly 10 000 stars classified in order of brightness and identified 42 nebulae (Marais, 1999: 174).

Another factor that spurred scientific exploration was the abundance of fauna and flora in the Cape colony. Since 1652, collections and examples were sent to Europe for further study. However, the foreign scientists' interest also extended beyond fauna and flora to include areas such as geomorphology and mineralogy (CENIS, 2000).

Given the dispute over ownership of the Cape colony between the English and the Dutch, many field notes were never published, resulting in a large amount of work being duplicated locally. Each change in military fortune resulted in the losing party destroying the knowledge thought to be of strategic importance (CENIS, 2000).

The English's final occupation of the Cape in 1810 was followed by the establishment of a number of public institutes and organisations, such as the Vaccine institute in Cape Town (1811), The Royal Observatory (1820) and The South African Museum (1825) (Naude & Braun, 1977:70).

Since 1830, private initiatives had spawned colleges such as the South African College at the Cape as well as colleges at Grahamstown, Bloemfontein and Stellenbosch. Many of these colleges gained university status after 1873. In 1873, the University of the Cape of Good Hope was opened. The period between 1906 and 1916 also saw the establishment of a number of colleges, including those at Pretoria, Natal and Fort Hare.

1.4.2. Industrialisation and 'science for practice'

The discovery of gold and diamonds in 1867 to 75 resulted in a large numbers of people agglomerating to search for precious materials. The 1886 gold rush to the Witwatersrand not only created the need for a better-developed mass food production as well as a rail and road system but also for a mechanism to cope with pressing shortages of, amongst others, wood and timber (CENIS, 2000). The vertical and horizontal value chains that consequently developed around the mines formed the basis for the modern economy (Kahn, 2004:1).

The novel circumstances also altered the face and grounds for operating science in South Africa. The mining enterprises' dire need for professionals, such as engineers, geologists, geophysicists, doctors and chemists, aggravated by the colony's inability to supply these resources, resulted in the necessary professionals being imported from Europe. This also resulted directly in science as a career becoming a reality. The last decade of the 19th century saw many professional societies being established to increase the standing of the numerous disciplines (CENIS, 2000:9).

The demands of the new system for more people, mass production of food supplies and importation of unchecked plant stock placed a lot of stress on the environment, which, in turn, led to a series of disasters, such as human and plant diseases as well as animal parasite attacks. The government turned to science for answers to these problems by hiring world-renowned specialists, who were later replaced by young scientists. Science was indeed employed successfully to solve many of these problems.

Following the successful development of a serum for rinderpest by Theiler (a French specialist from the Pasteur Institute in France), government gave permission that an institute aimed at developing and producing vaccines and sera against human and animal diseases be founded. Theiler's successes in controlling epidemics therefore resulted in government building the country's first Institute of Research, namely Onderstepoort, which opened in 1908.

Private initiative added a second important dimension to research performed locally. The mining industry noticed a high incidence of illness amongst employees, which impacted negatively on production. This problem led to the establishment of the second research institute in South Africa, the South African Institute for Medical Research (SAIMR), which was originally funded mainly by the mining sector to research occupational diseases.

Born from the necessity of production, South Africa took its first steps towards producing 'home-grown', applied research. From this, government was also pressurised for assistance in basic research activities.

1.4.3. The period between WWI and WWII (1920's -1930's)

As universities in South Africa grew, they started to show some interest in performing research in the paradigm of 'science for the sake of knowledge'. Research within these organisations tended to have no association with either social needs or the movement of science worldwide. During this period, academic university research remained within the realms of botany, entomology, zoology, human palaeontology and archaeology. Universities produced preciously little work of significance outside these fields.

Until the 1940s, the leading figures of fundamental science were however from institutions other than universities. During this period, the paradigm of 'science for doing' dominated the field by providing research scientists with better working conditions and facilities.

Factors promoting applied research in the inter-war period were even more prevalent. Following the Ministry of Mines' movement to an increasingly more scientific approach to geological surveying, a wealth of minerals was discovered and new mining companies were formed, thus enhancing the need for more engineers, scientists, geologists, experts in mechanics, etc.

The emergency of energy problems resulted in the Institute of Fuel Research being formed in 1932. This led to the exploitation of local oil and coal, but also to the establishment of an iron and steel industry to stimulate such a measure.

Other industries were also converted to science, for example the Natal sugar refiners, who established research facilities for the valorisation of by-products as well as entomology.

The Ministry of Agriculture was also convinced of the many merits associated with an involvement in science, resulting in, amongst others, the Departments of Agriculture being established at the Universities of Pretoria and Stellenbosch.

WWI revealed the weaknesses of an economy dependent on primary products. The Industries Advisory Board, established in 1916, under auspices of the Ministry of Mines and representatives of commerce and industry, appointed a Scientific and Technical committee and undertook to formulate an industrial development policy. This decree resulted in the creation of a foundation for funding university research.

H.J. van der Bijl was appointed as the Prime Minister of the Union of South Africa's Scientific Advisor. Van der Bijl developed a strategy to resolve research priorities, thereby ensuring South Africa's future independence in techno-scientific areas. Although the strategy achieved little more than gathering dust initially, van der Bijl eventually (at least partly) succeeded in accomplishing his plan as head of public companies ESKOM (responsible for electricity production, founded in 1923), ISCOR (Iron and Steel Corporation) and IDC (Industrial Development Corporation, founded in 1940).

1.4.4. The Nationalist ideology: strategic science

As WWII broke out, the South African economy had to substitute many of its imported products, including oil. The country also had to supply armies in Africa as well as the Middle East with items, ranging from vaccines to food.

During this period, South Africa was required to evolve manufacturing abilities for spare parts, i.e. aircraft, boats, etc., and to start manufacturing armaments such as rifles, bombs, armoured vehicles and precision equipment, e.g. RADAR. The search for minerals such as chromium, titanium, vanadium and uranium received a new boost. Industry was rushed into action. Capabilities within South Africa were tracked down and where unavailable, imported from Europe. The outbreak of WWII therefore resulted in South Africa experiencing its first industrial revolution, from which it would not revert back to a purely primary economy (CENIS, 200:23).

The South African Prime Minister, General Jan Smuts, a scholar and philosopher, appointed B. Schonland as scientific adviser to the Prime Minister. His major task was to formulate plans for establishing an organisation to advise the South African government on the best methods for developing the country's natural resources to the full and to co-ordinate scientific research in the national interest. Schonland's proposals adopted the Australian and Canadian research councils as the most appropriate models. In June 1945, the Scientific Research Council Act was passed. A few months later, on 5 October 1945, a state research laboratory was established, which today constitutes the Council for Scientific and Industrial Research (CSIR) (Marais, 1999:69).

In less than five years, the CSIR set up five national laboratories specialising in physics, chemistry, materials, telecommunications and industrial psychology. These laboratories were both well equipped and endowed with excellent personnel. The CSIR grew from only 70 employees in 1945 to 4 000 in 1970.

National programmes were created, entailing the co-operation of various institutes to participate in research over an extended period in a complex area of constant interest for the country. These programmes included Antarctic research projects, atmospheric physics and space physics, atomic energy and other forms of energy. Since 1980, these programmes included university research for public organisations such as ESCOM, SASOL, the Chamber of Mines, etc.

For a while, the CSIR continued to play the role of initiator for projects with strategic significance for the future. The following are examples of its research programmes:

- microelectronics, integrated circuit design, chemical process technologies, physics and metallurgy of electronic devices
- applied mathematics, computer science and industrial statistics; and
- nuclear physics, application of radioisotopes for medical treatment and diagnosis, construction of the cyclotron in 1955 replaced in 1977 by an accelerator, built and set into operation by the CSIR.

In 1952, the CSIR was placed under the Department of Economics' control. This led to the loss of the CSIR's inter-ministerial status and its capacity for arbitration. The president of the CSIR was also no longer automatically the Scientific Advisor to the Prime Minister.

Other research institutes slowly started to emerge independent from the CSIR. The following table (Marais, 1999:74) tracks the evolution of the other science councils. Marais stresses that although the establishment at first appears smooth and progressive, it was often a complex and highly politicised route.

Table 1-2 Evolution of Science Councils in South Africa (Marais, 1999:74)

Council	Origin	Date	Location	Ministry
CSIR	N/A	1945	Pretoria	DTI
SA Bureau of Standards	CSIR	1945/62	Pretoria	DTI
Atomic Energy Corp	CSIR	1948/59	Pelindaba	Minerals & Energy
C Minerals Technology	D Mining	1981	Pretoria	Minerals & Energy
Human Sciences RC	Education	1969	Pretoria	ACST
Medical Research C	CSIR	1969	Bellville	Health
Agricultural Research C	Agricultural	1992	Pretoria	Agricultural
Council for Geosciences	Geological Surveys	1992	Pretoria	Minerals & Energy
Foundation for Research Development	CSIR	1990	Pretoria	ACST

National Research Foundation	FRD/HSRC	1999	Pretoria	ACST

Although South Africa lagged behind other commonwealth countries in terms of the establishment of science councils, the organisational space became densely populated since the 1960s (Marais, 1999:87). The 1960s and 1970s were characterised by tight government control of the science councils and the council presidents were all ministerial appointments. Government control over universities was less effective. The government thus found it easier to create ethnic universities and regain a degree of control over their governance (CENIS, 2000:32).

As the apartheid policy was institutionalised more rapidly, it led to the promulgation of the Extension of University Education Act in 1959. The act resulted in four new universities being established for students of specific population categories, namely the University Colleges of the North (Turf loop), Zululand, Western Cape and Durban-Westville. The Fort Hare Transfer Act restricted students attending this university to Xhosa-speaking Africans (CENIS, 2000:31).

During the early 1980s, five more universities with the same basic ideological framework were established. Race remained one of the main criteria determining access to higher education until the late 1980s. These universities, now referred to as Historically Black Universities (HBUs), focused primarily on vocational training on an undergraduate level. The proportion of students on postgraduate level was very small. Master degrees and doctorates awarded from these universities represented approximately 1% of the total number of all degrees and diplomas awarded. R&D expenditure by HBUs during 1991/1992 represented 7% of the national R&D expenditure of the university sector (Marais, 1999:80).

Technikons were established in 1978 along the same line as British polytechnics. These educational bodies emphasised skills training, which inhibited them from developing a research culture. Technikons were granted a research mandate in 1983 and degree-awarding status in 1993. This decree stimulated R&D activities in Technikons on the levels of policy development and postgraduate training. During the 1990s and 1980s, the FRD and HSRC started programmes for promoting R&D in these institutions (Marais, 1999:81).

1.4.5. The 1980s and early 1990s

Government adopted the system ‘Framework Autonomy and Base Line Funding’ for the management of the science councils in April 1988. A government subsidy was fixed to force councils to secure funding from clients in the public or private sectors. This system was enforced specifically to increase linkages between councils and industry (Kaplan, 1995:8). In this respect, implementation of the framework can be regarded as successful.

However, this decree held a number of negative consequences for research culture within the councils. The councils’ research portfolios became increasingly more market driven, which resulted in a shift in focus from the socio-economic and development goals. Collaboration between institutes declined and competition became the order of the day. This shift towards a more market driven model came under fire (CENIS, 2000: 35).

The political situation in South Africa underwent a significant change in the 1980s and early 1990s. The Mass Democratic Movement began playing a more significant role in S&T issues, while African National Congress (ANC) spokespersons and bodies called for a change in the system (CENIS, 2000: 35).

The elections on 27 April 1994 were a watershed event. The new government reviewed public policies and developed new policy imperatives, thereby setting the country on a course where all citizens could benefit from and contribute to economic growth and social development. The main priorities of the new South African government were focused on the socio-economic development of previously disadvantaged individuals.

1.5. Major Developments in the South African S&T System after 1994

1.5.1. The macro policy context

The new government launched a Reconstruction and Development Programme (RDP) as a policy framework for integrated and coherent social and economic progress. Published in 1994, the White Paper on Reconstruction and Development aimed to build a democratic, non-racial and non-sexist future for South Africa (GOV, 1994).

In late 1995, government adopted the principal blueprint for action aimed at growth and development, namely the Growth and Development Strategy (GDS). This strategy, an elaboration on the RDP, was built on the following six pillars (DACST, 1996: 73):

- investing in people as the productive and creative core of the economy
- creating employment on a large scale while building a powerful, internationally competitive South African and Southern African economy
- using enhanced investment in household and economic infrastructure both to facilitate growth as well as improve the quality of life of the poor
- a national crime prevention and security strategy to protect the livelihood of our people to secure the wealth of the country and promote investment
- transforming government into an efficient and responsive instrument of delivery and empowerment, able to serve all South Africans while directing government resources primarily to meet the needs of the poor majority; and
- using a system of welfare 'safety nets' to draw the poorest and most vulnerable groups progressively into the mainstream of the economy and society.

As the goals set in the RDP failed to deliver on its promises, the RDP office was closed on June 1996.

Despite its previous commitment to socialism, the new ANC government adopted the Washington consensus and implemented a structural adjustment programme (Kahn, 2004). On 14 June 1996, the government published the policy document on growth, employment and redistribution strategy. This strategy differed from the RDP in its clear commitment to a neo-liberal, macro-economic policy. The core elements of the integrated strategy are (Department of Finance, 1996):

- a renewed focus on budget reform to strengthen the redistributive thrust of expenditure
- a faster fiscal deficit reduction programme to contain debt service obligations, counter inflation and free resources for investment
- an exchange rate policy to stabilise the real effective rate at a competitive level
- consistent monetary policy to prevent a resurgence of inflation
- a further step in the gradual relaxation of exchange controls
- a reduction in tariffs to contain input prices and facilitate industrial restructuring, compensating partially for the exchange rate depreciation
- tax incentives to stimulate new investment in competitive and labour absorbing projects
- speeding up the restructuring of state assets to optimise investment resources
- an expansionary infrastructure programme to address service deficiencies and backlogs
- an appropriately structured flexibility within the collective bargaining system
- a strengthened levy system to fund training on a scale commensurate with needs
- an expansion of trade and investment flows in Southern Africa; and
- a commitment to the implementation of stable and coordinated policies.

Together, the governments of 1994 and 1999 produced more than 800 acts of parliament to drive a modernisation agenda. These acts included, amongst others, the Labour Relations Act (1996), the Public Finance Management Act (1999) and the Employment Equity Act (1998). These three items of legislation were aimed specifically at improving labour relations and institutional governance. The Higher Education Act (1999) provides the framework for the re-organisation of higher education through a series of institutional mergers. In theory, the Immigration Act (2002) provides a mechanism to address scarce skills through foreign recruitment, but in practice erects administrative barriers that are likely to impede inward flows (Kahn, 2004:10).

The following section discusses the science and technology policy in South Africa against the background of the macro-policies discussed in this section.

1.5.2. Science and technology policy

Under the previous government, management of S&T was divided. The responsibility for science rested with the Department of Education, while the Department of Trade and Industry was responsible for technology. Previously, the key source of advice to government on science policy was the Scientific Advisory Council, located in the Department of National Education. The council was however criticised for a lack of transparency, its composition of its membership and a limited oversight of the system.

Following the 1994 democratic elections, the Department of Arts, Culture, Science and Technology (DACST) took over the management responsibility. The creation of the Ministry and Department of Art, Culture, Science and Technology in 1994 was a step towards creating a vehicle for government to focus its role in developing a science and technology system that would respond to the government's priorities.

The South African government published a consolidated policy entitled The White Paper on Science and Technology: Preparing for the 21st century in 1996 (DACST, 1996). The policy was designed specifically to reinforce the pillars of the GDS. The White Paper acknowledged the importance and the role that technological innovation will play in the further development of the South African economy (DACST, 1996: 9) by stating:

"*The development and application of science and technology within a national system of innovation (NSI) in South Africa will be central to the success of the Growth and Development Strategy (GDS) of the Government as it seeks to address the needs of all South Africans. In keeping with a variety of political, constitutional, social, and economic changes introduced by the government, the NSI as an enabling framework for science and technology is intended to support the six pillars of the Growth and Development Strategy.*

The stimulation of a national system of innovation will be central to the empowerment of all South Africans as they seek to achieve social, political, economic, and environmental goals. The development of innovative ideas, products, institutional arrangements, and processes will enable the country to address more effectively the needs and aspirations of its citizens. This is particularly important within the context of the demands of global economic competitiveness, sustainable development and equity considerations related to the legacies of our past. A well-managed and properly functioning national system of innovation will make it possible for all South Africans to enjoy the economic, socio-political and intellectual benefits of science and technology." (DACST, 1996:8)

In this policy space, the White Paper on Science and Technology (DACST, 1996) approved by Cabinet in 1996, established a policy framework for science and technology in South Africa based on the concept of an NSI.

The issues the White Paper addressed as systemic failures requiring concerted national action were spelt out as follows (OECD, 2000:1):

- a fragmented and inadequately co-ordinated science and technology system
- the erosion of innovative capacity
- poor knowledge and technology flows from the science base into industry
- poor networking both within the region and in the global context
- inefficiencies and poor levels of investment in research and development
- imbalances created by past policies and actions; and
- a poor competitive position within the global environment.

Policy development took cognisance of the nature and strength of the institutions/organisations within the NSI, their relationships with one another, their importance to the economy and South African society in particular and the implications and impact of various other government policies. The focus sought a science and technology alignment with new thrusts in areas such as education, communication, labour, health, trade and the environment (OECD, 2000:1). The new policy had the following objectives:

- broaden the scope of policy from S&T to innovation
- recognise R&D as crucial to growth and to the improvement of quality of life
- supports the co-ordination and non-duplication of structures
- pursues the levelling of historical inequalities and human capacity building
- provides core funding in terms of a three-year cycle through the Medium-term Expenditure Framework (MTEF) for capacity building and maintenance in R&D and related activities, while R&D services for clients are managed on a commercial basis with full cost recovery; and
- requires regular reviews of government Science, Engineering, and Technology Institutions (SETS) (DACST, 2002:6).

The following section describes the research topic and problem dealt with in this research project.

1.6. Research Problem

The previous sections clearly illustrated that South Africa's R&D system enjoyed a steady development over a number of centuries. Over time, crucial policy decisions regarding the investment of resources in an R&D system are made. These decisions have long-term consequences on the system and have a direct impact on the system's current and future ability to function and produce R&D output.

There exist some concern regarding the sustainability of the production of R&D output and R&D capacity in South Africa. Recent trends indicated the following evidence of disinvestments and decay of South Africa's R&D capacity:

- R&D expenditure in SA decreased from 1.2% of GDP in 1987 to 0.76% in 2001. This is rather low when compared to the OECD average of 2.15% (DACST, July 2002)
- evidence shows that South Africa's position as a knowledge creator is declining. In 1990, South Africa created 0.8% of the world's scientific output, while creating only 0,5% in 2002 (DACST, July 2002); and
- more alarming evidence that South Africa has an ageing R&D workforce. A lack of rejuvenation in the human resource base resulted in researchers in the age group 30 - 49 decreasing from 77% in 1990 to 45% in 1998 ((NACI, 2002), (Boshoff, 2003)).

Questions arise concerning the detrimental effects these trends could have on South Africa's ability to generate R&D output. As problems are addressed insufficiently and the system is allowed to decay, the costs of rebuilding the system might increase even further. A research question is posed:

What is the delayed effect of R&D investment or the lack thereof on the South African NSI's ability to produce R&D output?

The main research objective is to develop a computer simulation program of R&D performance and the creation of R&D output in the NSI. This model will in turn produce a tool to be used for policy testing, what-if scenario testing or policy optimisation.

The purpose of the model is to simulate R&D output generated in the South African system of innovation and to model and explain the effect the presence/lack of long-term investment in R&D and R&D resources could have on the system's ability to produce R&D output.

Examples of scenario tests on the higher education sector model are:

- how can a constant investment in the South African higher education system affect its ability to produce R&D output and absorb knowledge?
- how can an increasing/decreasing level of investment in the South African higher education system affect its ability to produce R&D output and absorb knowledge?
- how can the introduction of dedicated researchers in the system (science chairs) influence system performance?
- how can a delayed reaction to the decay of R&D capacity influence the system and the cost to rebuild lost capacity?
- how can the introduction of better time management skills in academic and research personnel influence system performance?

Examples of scenario tests on the public sector system model are:

- how can a constant investment in the South African public sector affect its ability to produce R&D output and absorb knowledge?
- how can an increasing/decreasing level of investment in the South African public sector affect its ability to produce R&D output and absorb knowledge?
- how can a movement away from the framework autonomy policy influence the system?

Examples of scenario tests on the private sector system model are:

- how can a constant investment in the South African private sector affect its ability to produce R&D output and absorb knowledge?
- how can an increasing/decreasing level of investment in the South African private sector affect its ability to produce R&D output and absorb knowledge?
- how can the introduction of fiscal incentives influence R&D expenditure and the ability to produce R&D output and absorb knowledge?

The following section explores the rationale behind the research project and states the motivation for having a model capable of displaying the dynamic properties of the South African R&D system.

1.7. Rationale for the Study

The rationale behind this study is that adopting a computer simulation model of a dynamic system as an analytical tool will expose complex system behaviour. This will result in a better understanding of the system as a whole. Through its effectiveness in capturing and exposing the state of the system, the model improves on more conventional methods for evaluating policy effectiveness (Moles & O'Regan, 2003).

In developing this model and by using the corresponding simulation programme, decision-makers in government and industry are provided with a tool to analyse policy alternatives. The model will provide a better understanding of the interrelationships between different elements of the NSI, in particular those interacting as funders and performers of R&D. This model will also aid decision makers in enhancing the efficiency of addressing problem areas within the South African R&D system.

1.8. Expected Contributions

Very little has been done in the field of creating dynamic models of NSI's. Carlsson et al (2002:236) states that the empirical analysis of studies carried out on NSI are mainly on static data. Many studies tend to be descriptive and consequently fail to capture the system's dynamic behaviour. This complicates the comparison of nations' relative positions over a period of time. According to Carlsson, there is nothing preventing a more dynamic analysis. At present, none of the descriptions of the South African NSI adequately explains either causal relationships or the dynamic behaviour of the South African R&D system and resulting R&D outputs.

This research project uses the system dynamic methodology's ability to model complex dynamic systems. The research will contribute to the system dynamics body of knowledge by illustrating the use of the system dynamics methodology and computer simulation for planning and managing R&D investments within the South African R&D system.

The contribution made by this thesis to the body of knowledge is that the development of a system dynamic model will result in the establishment of a dynamic hypothesis of the development of new knowledge through R&D in an R&D performing sector. The dynamic hypothesis will in turn lead to a method for modelling the effect of R&D investment on the development of an R&D capacity, i.e. the system's ability to absorbed knowledge and produce R&D output. The above is essentially a dynamic description of the process around creating and absorbing knowledge through R&D activities.

The dynamic hypothesis was tested and validated by applying the conceptual model to the South African R&D system. This application can also be classified as a contribution to the state of knowledge regarding R&D activities within the South African R&D system. The conceptual model was applied to the following three R&D sectors in South Africa: namely:

- the Higher Education System (HES), i.e. universities, universities of technology and technikons

- the public sector, i.e. science councils, state departments and museums; and
- the private sector, i.e. South African companies.

This thesis illustrates the model being applied to test different scenarios. A number of conclusions are consequently drawn regarding the South African R&D system and its ability to produce R&D output.

The system dynamics model developed in this research project is intended to be used as a policy tool for government or policy makers to aid them in the development of S&T policy.

1.9. Thesis Outline

The following is a graphical representation of the thesis structure.

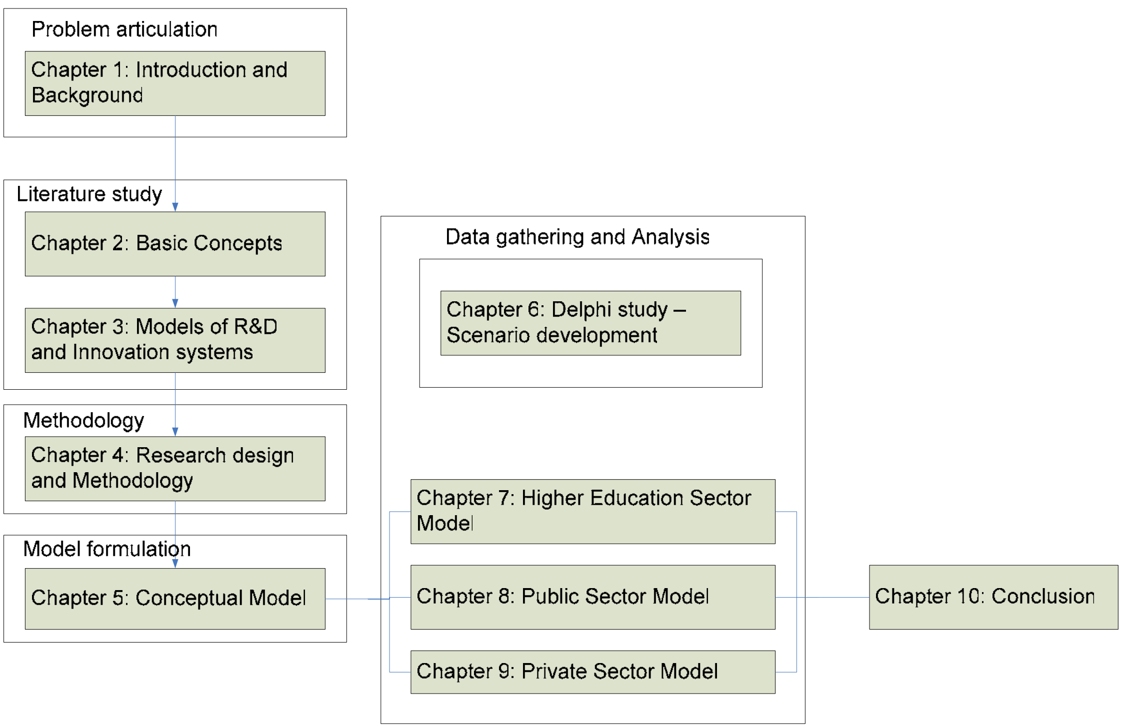

Figure 1-1 Graphical representation of the thesis structure

1.9.1. Basic concepts of R&D and innovation systems

Chapter 2 covers a comprehensive literature overview of the most authoritative scholarship available at present. The chapter comprises both a discussion as well as a critical analysis on the evolution of the innovation concepts from the first linear models to the current NSI framework.

Chapter 3 documents and critically analyses models developed for evaluating R&D and innovation systems. This includes quantitative and qualitative models of R&D, innovation and other related concepts. A section is also allocated to discuss previous attempts to develop system models of R&D and innovation. The chapter finally provides examples of system dynamics models created for single R&D project models as well as models that have been developed for R&D and innovation on a more aggregate level.

1.9.2. Research design and methodology

Chapter 4 comprises a presentation of the project's research design. The chapter also includes a discussion on the system dynamics methodology and explains its suitability for the problem at hand.

1.9.3. The conceptual model

Chapter 5 focuses on the development of a conceptual system dynamics model for the South African system of innovation. The knowledge obtained during the literature review enables an identification of the major elements necessary to represent the system's relevant aspects. These elements establish the structure of the model, while causal relationships and feedback loops between elements are conceptualised.

1.9.4. Data Gathering and Analysis

Chapter 6 documents the research project's primary data gathering phase. This includes a detailed discussion on the questionnaires and responses received from a group of experts participating in the Delphi study. Conclusions drawn from the Delphi study is used to develop a selection of scenario tests, which are run on the system models developed in Chapters 7 to 9.

Chapters 7 to **9** document the process of applying the dynamic hypothesis to the higher education sector, public sector and private sector in South Africa. The chapters also discuss the secondary data gathering process and document the data sources. The model-testing phase and simulation runs are also discussed. Each model is discussed separately in the following chapters:

Chapter 7: Higher education sector model

Chapter 8: Public sector model

Chapter 9: Private sector model

1.9.5. Summary and conclusions

Chapter 10 highlights the contributions made to the body of knowledge in this research project by discussing the areas in which the model has contributed to a better understanding of R&D in the South African system of innovation. Based on the outcome of the scenario tests on the models, certain recommendations are made regarding R&D policy in South Africa. Finally, a section of chapter 10 is allocated towards self-assessment and lessons learnt from this project.

2 BASIC CONCEPTS OF R&D AND INNOVATION SYSTEMS

2.1 Purpose and Outline of the Chapter

This chapter documents a comprehensive literature study that represents the most authoritative material available at present in the field of innovation studies, especially within the NSI framework. This chapter provides a more detailed overview of the key concepts and frameworks used in the model developed in this research project. Various authors' theories and frameworks are discussed and critically analysed.

2.2 The Concept of Innovation

The innovation process cannot always be restricted to technical innovations. Schumpeter conceived the innovation process in a broad way and derived his definition of innovation by means of the production function (1939: 87):

"… this function describes the way in which quantity of product varies if quantities of factors vary".

Schumpeter defines innovation as the set-up of a new production function. In doing so, he includes a new commodity as well as new organisations. Schumpeter's (1934) definition of innovation includes the following five types of innovation:

- new or improved products
- production techniques
- organisational structures
- discovery of new markets; and
- use of new input factors.

Each of these forms of innovation possesses the potential of increasing productivity and therefore the competitiveness of a nation (Porter, 1990).

Throughout the innovation literature, authors provide a number of different definitions of innovation (Edquist, 1997). The following instances serve as examples:

- although referring specifically to technological innovations in the NSI, Nelson and Rosenberg (1993: 4-5) defines the concept of innovation quite broadly by including not only the first introduction of a new product to the market but also its diffusion
- Carlsson and Stankiewitz (1992) focus mainly on the 'technological systems' approach, i.e. the role of a technological system of innovation to initiate, diffuse and modify technology. This concept of innovation also include process as well as product technology; and
- Lundvall includes 'new forms of organisations' and 'institutional innovations' in his definition of innovation (Lundval, 1992:8, 9).

Edquist (1997:9-10) states that when a system of innovation approach is followed, authors focus mainly on technological innovation and are consequently interested in organisational and institutional change.

This section documents an overview of the concept of innovation within a systems framework. It should be noted that innovation has not always been viewed as a complex systemic process and that the understanding of the concept evolved over a period of time. The following section provides a brief overview of the evolution of the innovation concept.

2.2.1 The linear model of innovation

The 1960s saw the development the linear model of innovation, a concept that led to much discussion. This model of innovation states that the innovation process starts with the onset of basic research. The model depicts a system in which the development of new technologies follows a clear-cut time sequence that originates in research, involves a phase of product development and leads to production and commercialisation (OECD, 1994b). According to this model, the innovation path exists by being pushed by advances in science or pulled by needs of markets.

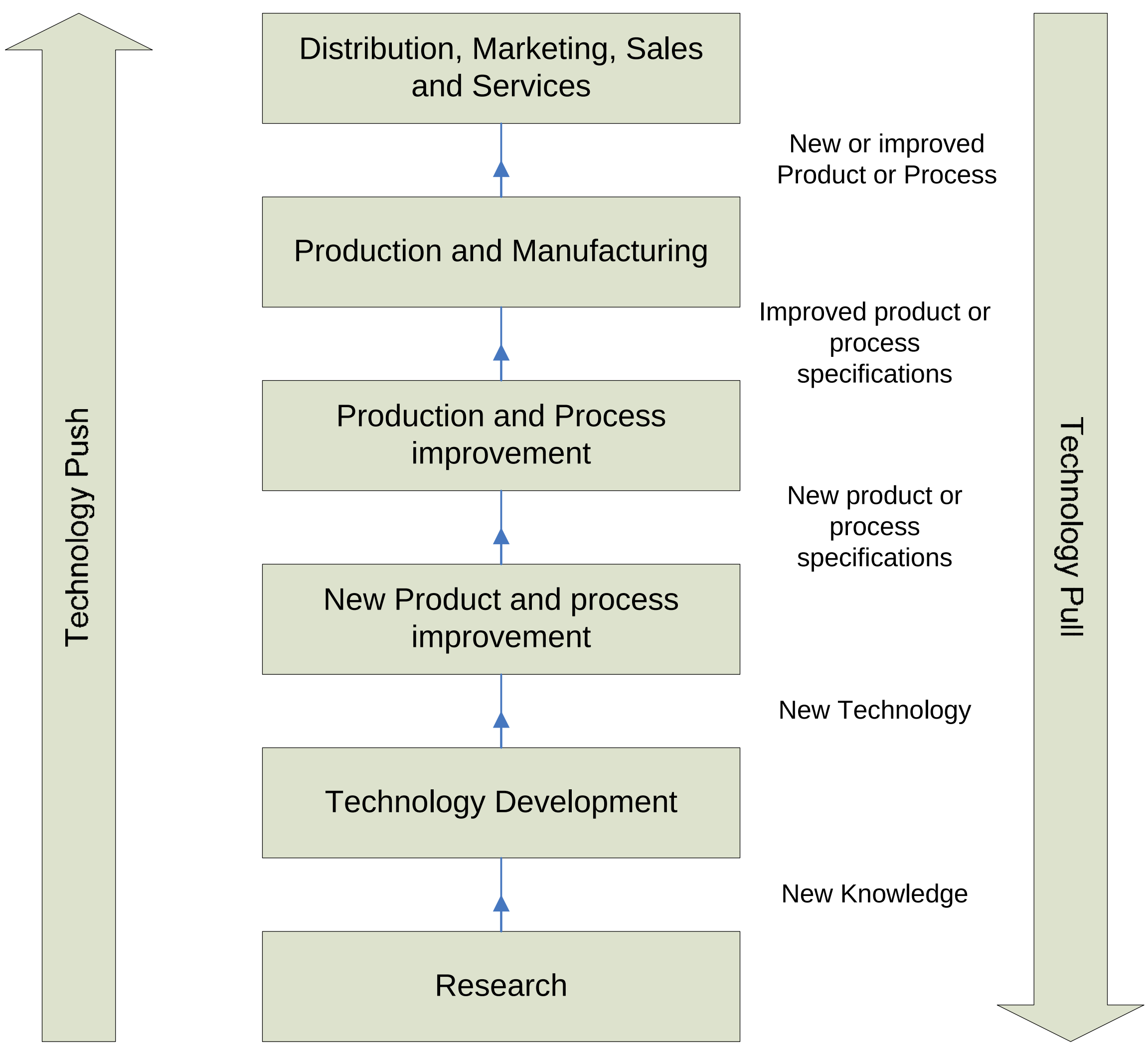

Figure 2-1: The Linear Model of Innovation

During the majority of the 1970s, the merits of both the science-push as well as the market-pull models were discussed. Market-pull models were criticised for its simplistic use of the market as a causal mechanism, whereas the science-push model was rejected for its failure to acknowledge the role that the market plays. Both these models were criticised for failing to acknowledge the complex interactions between involved groups (Rogers, June 1998:24).

2.2.2 The chain-linked model of innovation

The chain-linked model of innovation was essentially an improvement on the linear model in that it acknowledged interactiveness and feedback between stages. This model recognises that although innovation can draw on existing knowledge, it could also lead to the creation of new knowledge.

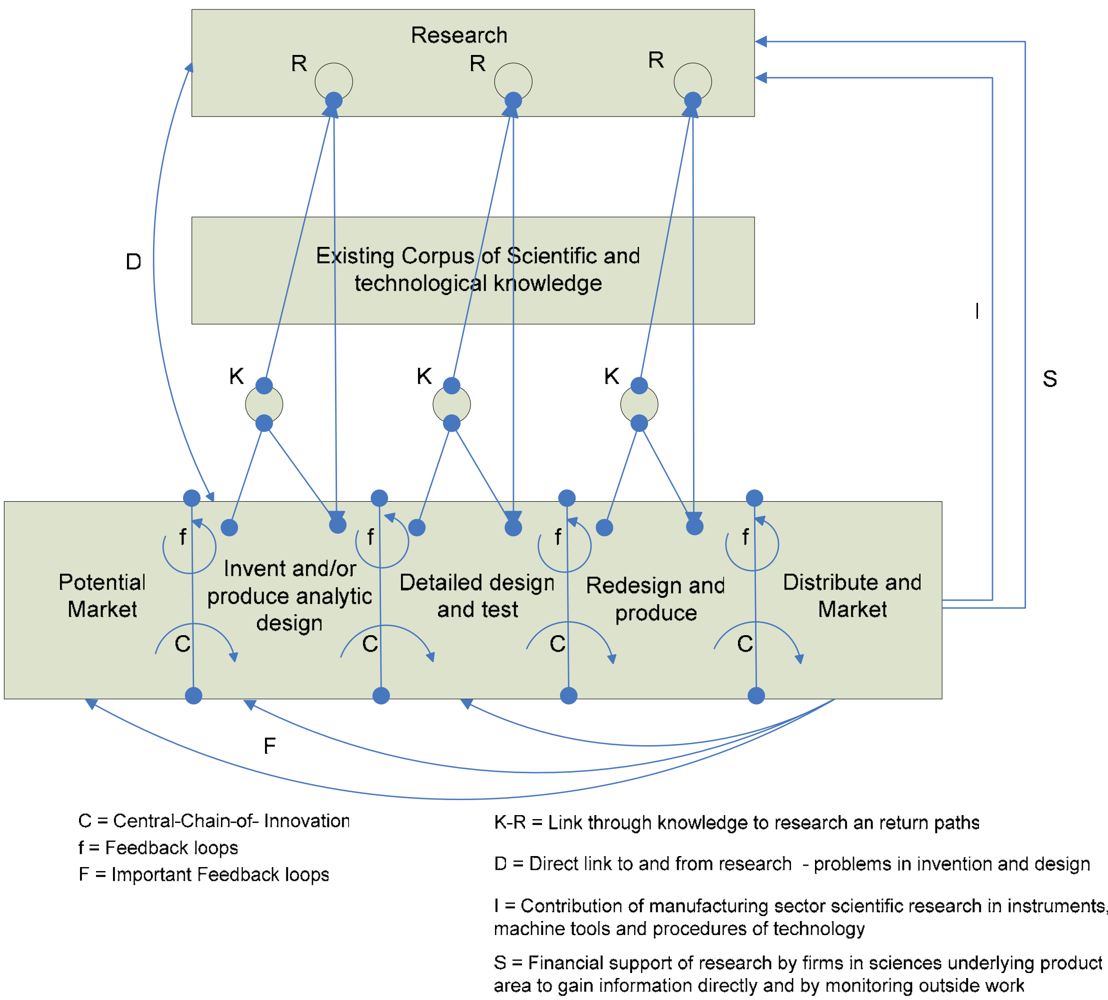

Figure 2-2: The Chain-linked Model (Kline and Rosenberg, 1986)

The chain-link model depicted in Figure 2-2 conceptualises innovation in terms of interaction between market opportunities and the firm's knowledge base and capabilities. Each broad function involves a number of sub-processes with highly uncertain outcomes. Accordingly, there is no simple progression, which often necessitates going back to earlier stages to overcome difficulties in development. This signifies feedback between all parts of the process. A key element in determining the success of an innovation project is the extent to which firms manage to maintain effective links between the phases of the innovation process. The model emphasises, for instance, the central importance of continuous interaction between marketing and the invention/design stages.

The chain-link model views research not as a source of inventive ideas but as a form of problem solving to be called upon at any point. When problems arise in the innovation process, as they are bound to do, a firm draws on its knowledge base at that particular time, which comprises earlier research findings as well as technical and practical experience. The research system takes up the difficulties that cannot be settled with the existing knowledge base, and so extends it if successful (OECD, 1996:25).

Accordingly, the chain-link approach does not view research simply as the work of discovery that precedes innovation. Research is a complex and internally differentiated activity, which is an adjunct as opposed to a precondition to innovation. The above is in line with the results gained from studies of innovative behaviour, which indicated that innovations rarely result from research activities alone (OECD, 2002d).

2.2.3 Summary

This thesis centres on the concept of R&D from an NSI perspective. This section discusses two earlier models of innovation, both of which acknowledge the role of R&D in the innovation process.

The first model, i.e. the linear model of innovation, describes the process of innovation as a linear process originating with the creation of new knowledge, i.e. research. This is an extremely simplistic view and fails to acknowledge the complex feedback loops and dynamics involved in innovation and the R&D processes.

The second model, i.e. the chain-linked model of innovation, acknowledges the feedback loops, the more complex nature of innovation and the role of R&D as an adjunct rather than a precondition to innovation.

The above clearly indicates that R&D has been acknowledged as integral in the innovation process even in the very first models of innovation. The concept has since evolved from viewing R&D as the entry point of innovation to acknowledging it as a problem-solving device throughout the entire innovation process. The latter approach also implies that R&D is not the only entry point to innovation.

The most recent framework aimed at explaining the inherent complexity of innovation is the systems view. Before explaining the system of innovation concept in more detail, attention is given to the system concept in general.

2.3 The System Concept

Interest in systems originates from the need to understand dynamic behaviour. The focus lies in the interactions within the system that ultimately produce growth, fluctuation and change (Forrester, 1974:4-1). The following section comprises a discussion on the definition, classification and structure of a system.

Forrester (1974, 1-1) defines a system as "a grouping of parts that operate together for a common purpose".

Blanchard and Fabrycky's reasoning aimed at defining a system was documented in the book entitled Systems Engineering an Analysis, (Blanchard and Fabrycky, 1998:2). They state that a system is an assemblage or combination of elements or parts forming a complex or unitary whole. A set of items, facts, methods or procedures can only qualify as a system if the group as a whole has functional relationships between elements, unity and a useful purpose.

Blanchard and Fabrycky (1998:2) ultimately define the systems concept as follows: "A system is a set of interrelated components working together toward some common objective or purpose."

According to Blanchard and Fabrycky (1998:2), systems are made up of components, relationships and attributes. These constituents are discussed below:

- *components* are the operating parts of the system and consist of input, process and output. Each system component may assume a variety of values to describe a system state as determined by a control action and one or more restrictions
- *attributes* are the properties or discernable manifestations of the components of a system. These attributes characterise the system; and
- *relationships* are the links between components and attributes.

Following their definitions of a system, Forrester as well as Blanchard and Fabrycky also expressed some thoughts on defining system boundaries, i.e. making a decision on which components to include in the system.

2.3.1 The System Boundary

Blanchard and Fabrycky (1998:2-3) assign the following properties to the set of components of a system:

- the properties and behaviour of each component of the set affects the properties and behaviour of the set as a whole
- the properties and behaviour of each component of the set depends on the properties and behaviour of at least one other component in the set; and
- each possible subset of components has the two properties listed previously, i.e. the components cannot be divided into independent subsets.

Both the definition of a system as well as the properties listed above implies that a system must have behaviour that is not exhibited by any of its subsets. Blanchard and Fabrycky (1998:2) believe that although the components of a system qualify as systems themselves, each system forms part of an even bigger system in the hierarchy.

It is therefore imperative to define the precise system under consideration by specifying its limits, boundaries or scope. Everything outside the boundaries is considered to be the environment.

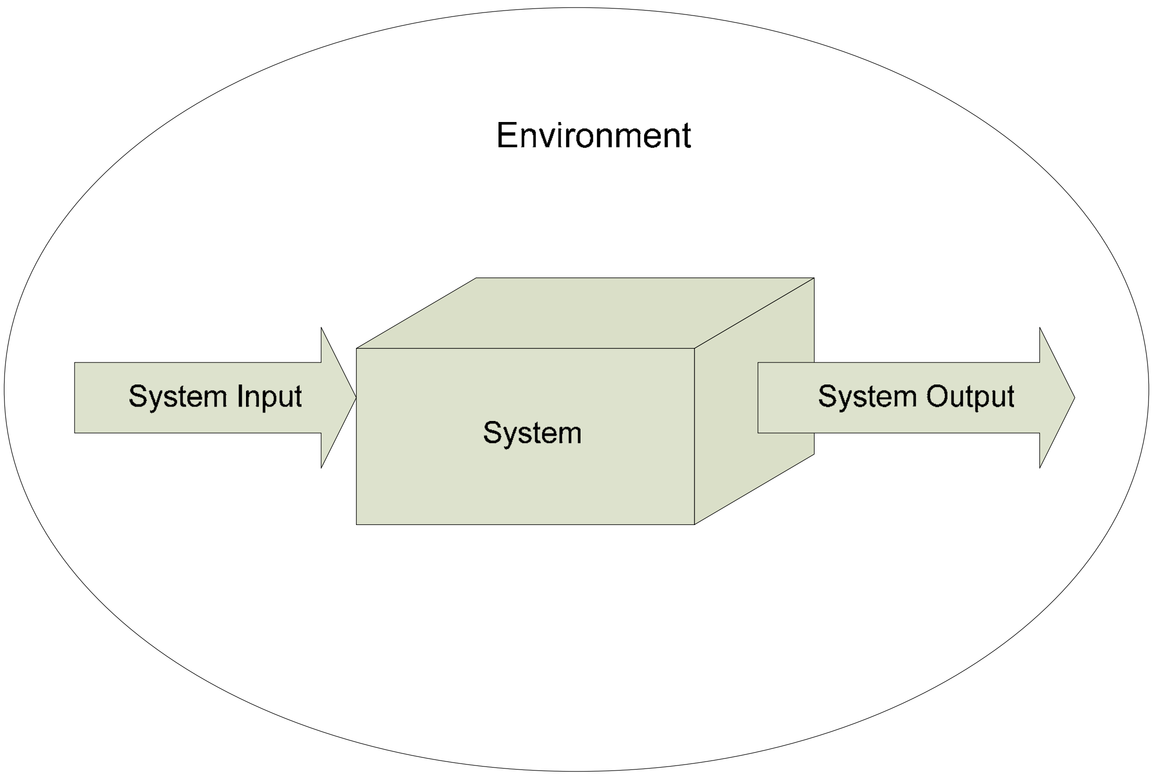

Figure 2-3: The System Interacting with its Environment

Blanchard and Fabrycky (1998:3) state that no system can function in complete isolation from its environment. Materials, energy and information often pass through boundaries as inputs to the system. The reverse is however also true: materials, energy and information pass through the system to the environment, which can also be referred to as output.
Figure 2-3 visually depicts the interaction between a system and its environment. Blanchard and Fabrycky's (1998:3) definition of a total system is: "The total system, at whatever level in the hierarchy, consists of all components, attributes and relationships needed to accomplish an objective."

Forrester (1974:4-2) illustrates similar views on defining the system boundary by stating that the specific behaviour of a system must be produced by a combination of interacting components. These components lie within a boundary that defines and encloses the system. Forrester (1974:4-2) defines the boundary of a system as the "smallest number of components within which the dynamic behaviour understudy is generated".

Forrester also acknowledges that structure organises in many layers of hierarchy and recognises the existence of sub-structures within every structure.

2.3.2 Classification of Systems

In an attempt to increase understanding, Blanchard and Fabrycky (1998:4-7) classify systems according to the following descriptions:

- *natural and man-made systems*: natural systems are those that result from natural processes, while man-made systems require some form of human intervention through components, attributes and relationships
- *physical and conceptual systems*: physical systems manifest in physical form, comprising real components, while conceptual systems represent attributes of components, e.g. ideas, plans and concepts
- *static and dynamic systems*: static systems have one structure without activity, e.g. a bridge, while dynamic systems combine structural components with activity, e.g. a school consists of buildings, students, teachers, books, etc.; and
- *closed and open systems*: a closed system does not interact with its environment. The environment simply provides the context for the system. An open system allows information, energy and matter to cross its boundaries. Open systems therefore interact with their environment, e.g. plants and business organisations.

Forrester (1974:1-5) distinguishes between two types of systems:

- *open systems* are characterised by outputs responding to input, where the outputs are isolated from and have no influence on the inputs. Past action has no effect on future action. Open systems neither observe nor act on their own performance; and
- *feedback systems (closed systems)* are influenced by their past behaviour. Such systems have closed loop structures that return results from the system's past actions to control future action:
  - positive feedback systems generate growth processes wherein action builds a result that generates still greater action, e.g. bacteria multiply to produce more bacteria, which, in turn, increases the rate at which new bacteria is generated; and
  - negative feedback systems seek a goal and responds as a consequence of failing to achieve the goal, e.g. a watch and its owner form a negative feedback loop when the watch is compared to the correct time and consequently adjusted to eliminate errors.

2.3.3 Structure of Systems

Blanchard and Fabrycky believes that understanding and defining the objective of a system is integral when analysing a system (Blanchard and Fabrycky, 1998:2): "The objective or purpose of a system must be explicitly defined and understood so that the system components may be selected to provide the desired output for each given set of inputs. Once defined, the objective or purpose makes it possible to establish a measure of effectiveness to indicate how well the system performs. Establishing the purpose of a human-made system and defining its measure of effectiveness is often a challenging task."

The purposeful action of a system is the function of a system. Where the function of a specific system is to alter material, energy or information, such a system will use inputs, processes and outputs. Such systems are composed of structural components, operating components and flow components (Blanchard and Fabrycky, 1998:2). These types of components are better defined as:

- *structural components*: the static parts of the system
- *operating components*: the parts performing the processing; and
- *flow components:* materials, energy and information being altered.

Forrester (1974:4-1) organises a system in the following hierarchy of major and subordinate components. The closed system that generates behaviour is created within a boundary and is independent of outside inputs:

- feedback loops as the basic element from which systems are assembled
- rates (or policies) as the other fundamental variable within a feedback loop
  - the goal as one component of a rate
  - the condition against which the goal is compared
  - the discrepancy between goal and apparent condition; and
  - action resulting from the discrepancy.

This above section explored the systems concept and explained the various system constituents, i.e. components, relationships and attributes.

2.3.4 Summary

The discussion of the systems concept is extremely insightful for the purpose of this thesis. It can be concluded that the challenge of defining a system lies in the formulation of the purpose of the system. Once the purpose is formulated, it becomes much easier to measure the system's effectiveness, or in other words, how well the systems transform input into output.

A thorough understanding of the purpose of a system also simplifies the process of selecting the main components. The modeller should select elements in the system that contribute to that system's behaviour.

Also very insightful to the purpose of the thesis is that all systems form part of a larger system. A decision regarding the system boundary as well as the aggregation level of the model is therefore necessary.

The following section focuses on introducing the system of innovation approach and discusses the differing views that various authors have on the components, relationships and attributes of the system.

2.4 Systems of Innovation

Chris Freeman was the first author to introduce the systems of innovation approach. He introduced the concept of a NSI to describe and interpret the performance of Japan, the country that was economically the most successful in the post World War II period. Freeman (1987) defined the NSI as "the network of institutions of private and public sectors, whose activities and interactions initiate, import, modify, and diffuse new technologies".

The systemic approach of innovation is based on the perception that innovations are ultimately brought about by the various components and the relations between them.

The innovation systems approach aims to identify the key components playing a central part in performing the system's functions. Before analysing the NSI concept in more detail, the reasons, merits and problems of analysing systems of innovation on a national level is discussed in the following section.

2.4.1 The analysis of innovation on the national level

The majority of innovation systems research is defined on a geographic scale. Although the national level proved predominant in the past, research has since been performed on regional and local level.

A number of researchers have argued against referring to systems of innovation on a national level. Lundvall (1992:3) disputes the use of studying innovation systems on a national level, whereas Nelson and Rosenberg (1993: 5) argued in favour of a sectoral approach. Pavitt's (1984) research focussed on innovative firm behaviour and functions as well as qualities and sources of technologies, consequently pursuing the development of a sectoral taxonomy of technological development as opposed to a geographical approach. Howells (1999: 67) suggested that regional systems of innovation could provide an additional layer to the NSI approach. He believes that geographical distance, accessibility, agglomeration and the presence of externalities provide a powerful influence on knowledge flows, learning and innovation.

Bo Carlsson and his team developed the 'technological system' approach within the framework of a research project on Sweden's technological systems and future development potential. This approach describes technology systems in different technology fields. Carlsson et all (1992: 49) argues that whereas the nation has natural boundaries, many technological systems co-exist. According to Carlsson, the size of a technological system depends on the technology and market requirements, various agents' capabilities as well as the degree of interdependence among agents. Technological systems can therefore be local, regional, national or international.

Strong arguments in favour of referring to systems of innovation on a national level also exist. Nelson's case studies (Nelson, 1993) conclude that differences on a national level exist in language, culture, standard of living, lifestyle, consumption patterns and the size of public sector. Public policies are designed on national level, which highlights the influence that politics and policy ultimately have on innovation processes.

Arguments both for and against analysing innovation on a national level can therefore be presented with a certain amount of conviction. Since the main objective of the model building study is the development of a policy tool for government officials to formulate national R&D policies, the national level approach is chosen. As Lundvall (1992, 3) points out that although globalisation and regionalisation might be interpreted to weaken the coherence and relevance of a national system, studying innovation on a national level will highlight the role and workings of a NSI.

The above arguments indicate that the national systems approach still plays an integral part in supporting and directing processes of innovation as well as learning. The national systems approach therefore remains relevant for the purpose of this study.

The decision to analyse the NSI on a national level also directs the system boundary definition for the model building study.

2.4.2 Components of systems of innovation

Authors tend to use the terms ‘organisation’ and ‘institution’ rather inconsistently in the literature analysed (Balzat, 2002; Edquist, 1997). The term ‘institution’ is used to refer to both organisations as well as institutions. As this study distinguishes between these terms, a proper definition of ‘organisation’ and ‘institution’ is necessary. The definitions provided by North (1994) are adapted for the purpose of this study.

Organisations comprise groups of individuals bound together by some common purpose to achieve certain objectives. Organisations include political bodies, e.g. political parties, the senate, a city council and regulatory bodies, economic bodies, e.g. firms, trade unions, family farms and co-operatives, social bodies, e.g. churches, clubs, athletic societies, etc. and educational bodies, e.g. schools, universities and vocational training centres.

Institutions are the humanly devised constraints that structure human interaction. These include formal constraint, e.g. rules, laws and constitutions, as well as informal constraints, e.g. norms of behaviour, conventions and self-imposed codes of conduct.

North (1994) states that: “It is the interaction between institutions and organisations that shapes the institutional evolution of an economy. If institutions are the rules of the game, organisations and their entrepreneurs are the players”.

He argues that the emerging organisations are a direct reflection of the opportunities provided by institutions, e.g. if a country’s institutional framework rewards innovation, innovative organisations are bound to flourish.

As the interest of this thesis is focused mainly on the framework of analysing innovation from a systems perspective, drawing parallels between the generic definition of a system as defined by Blanchard and Fabrycky (1998) and the structure of a system of innovation is almost automatic. A number of interesting conclusions can be drawn from a study by Carlsson et al (2002), where the same general definition of a system was applied to technological innovation systems.

Table 2-1: Structure of Systems of Innovation

Generic System Definition (Blanchard and Fabrycky, 1998)	System of Innovation (Carlsson, 2002)
Component	Organisations
Relationship	Linkages between organisations
Attributes	Institutional environment

Although Carlsson formulated this definition for technological systems, it is also generally applicable to systems of innovation in the structural sense. This is therefore a useful starting point in terms of defining the system for the purpose of the model building study.

As North pointed out, the institutional environment shapes the way that organisations are formed but is, in turn, shaped by the way that organisations interact within a system. The following section documents and critically analyses the views of several researchers on the topic of NSI.

2.5 Research on the NSI Framework

Since its original formulation, the concept of systems of innovation has attracted the attention of many researchers working in institutional economics and innovation as well as policy-makers in both developed and developing countries (Niosi, 2002). The remarkable diffusion of the concept has led to its application in several countries and areas. Chris Freeman, Bengt-Ake Lundvall and Richard Nelson were the main pioneers of the system of innovation framework. The following sections aim to discuss their work and views shortly.

2.5.1 Comparative analysis of innovation systems

Richard Nelson assembled a number of case studies to describe the main features of the innovative systems of high, medium, and low-income countries (Nelson, 1993). Nelson defines the NSI as: "...The set of institutions whose interactions determine the innovative performance of national firms". This study emphasises the influence and role of system specific institutional factors stimulating or impeding innovation or technological change. The study revealed tremendous differences between nations regarding their ability to initiate, import and diffuse new technologies. A collection of these studies has been published in Nelson's book titled "National Innovation Systems: A comparative Analysis". The main findings from this study are as follows (Nelson, 1993):

- *innovation processes cannot strictly be separated between nations*: although this approach is useful for analytical purposes, R&D activities are increasingly carried out on international level. While S&T workers are increasingly mobile across national borders, communication technology enables firms to communicate over huge distances. Goods are also imported and exported between nations

- *it is not always reasonable to make comparisons between countries*: differences between nations in their innovative behaviour and economic patterns were evident. The differences were less obvious between nations with a similar level of development. Nelson states that observed differences could be due to differences in the political circumstances, priorities, size and affluence of countries
- *private firms are not the only contributing factor:* the public and educational sector also plays an important role in influencing nations' innovative ability
- *low R&D statistics not always indicate low innovative performance:* the study revealed that low R&D performance does not always imply low ability to innovate. This outcome confirmed that innovation is not merely a linear process or simply outcome of R&D spending; and
- *strengths cannot be transferred easily:* innovative capabilities and economies develop over time. This makes it extremely difficult to transfer strengths from one innovation system to another. The degree of difficulty increases when the differences in the size, economic structure and institutional arrangements of countries are significant.

2.5.2 The NSI and interactive learning

Bengt-Ake Lundvall led a research team at the Aalborg University Centre to investigate the analytical content of the notion of NSI by looking at the roles that users, the public sector and financial institutions play (Lundvall, 1992). Lundvall defined an NSI in terms of 'elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge... either located within or rooted inside the borders of a nation state'. He acknowledges the influence that historical experience, language and culture will have on the national characteristics of the following elements:

- internal organisation of firms
- inter-firm relationships
- the role of the public sector
- institutional set-up of the financial sector; and
- R&D intensity and organisation.

Lundvall published his contribution, titled: "National Systems of Innovation: Towards a Theory of Interactive Learning" (Lundvall, 1992). His study is based on the following two sets of assumptions:

- knowledge is the most important resource in the modern economy. The most important process is therefore learning; and
- learning is predominantly interactive and therefore a socially embedded process. An understanding of the process ultimately involves consideration of the institutional and embedded context.

Lundvall acknowledges and emphasises that innovation cannot be localised exclusively in national borders.

Lundvall's work, "National Systems of Innovation: Towards a Theory of Interactive Learning", also documents the views of several other authors on the role of interactive learning. Johnson (1992) argues that where the economy is viewed from an institutional point of view as a process of communication and cumulative causation, learning can be conceptualised as the source of technical innovation. He adds that nearly all learning processes are interactive, and influenced by their content, rate and direction of the institutional set-up of the economy.

Johnson also discusses how institutions influence learning, growth of knowledge and innovations, which he defines as sets of habits, routines, rules, norms and laws that regulate the relations between people and shape human interaction. Given their ability to reduce uncertainty and thus the amount of knowledge needed by each individual, institutions are fundamental building blocks in society.

Johnson's learning argument can be summarised as depicted in Figure 2-4.

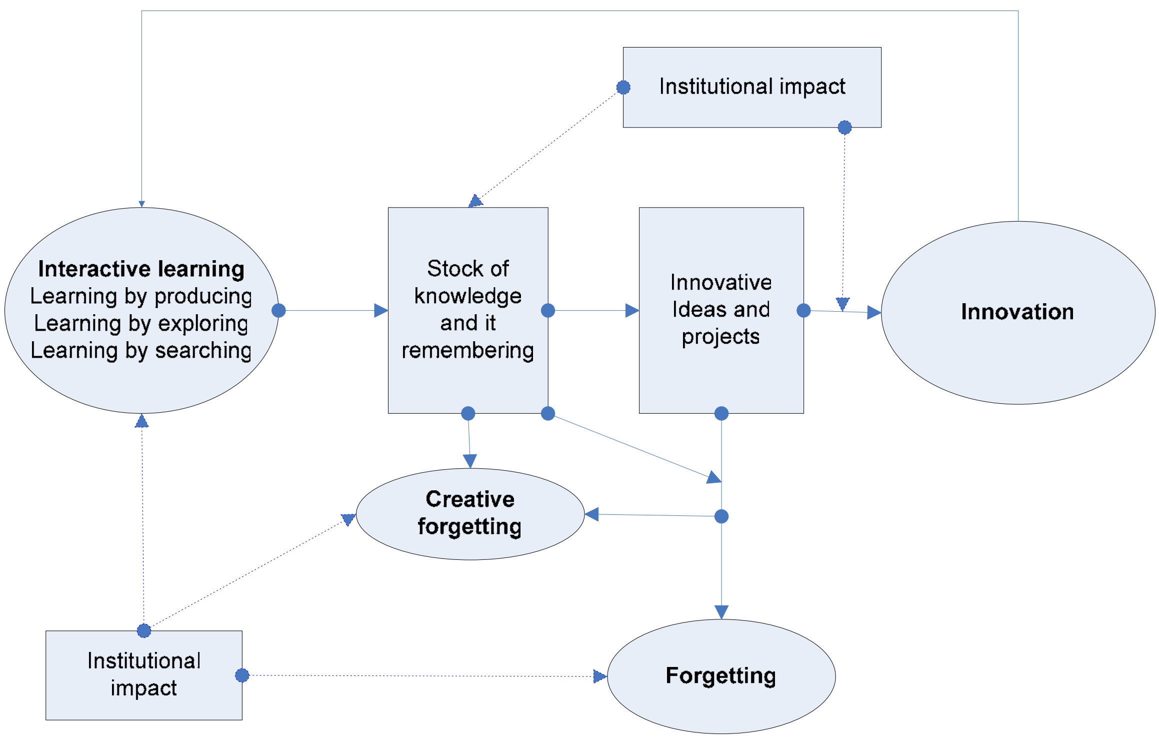

Figure 2-4: The Relations between Learning, Growth of Knowledge and Innovation

- Interactive learning in all its forms, i.e. learning-by-production, learning-by-searching or learning-by-exploring, contributes to the stock of economically useful knowledge.
- The stock of knowledge must be guarded against deterioration through continuous re-learning or remembering by doing.
- The stock of knowledge is primarily diminished through different kinds of forgetting. Creative forgetting could cause a feedback loop to increase the

knowledge stock.

- Parts of the new knowledge might translate to innovations through a selection mechanism.
- New knowledge must be applicable in many processes and products. Institutions must have the ability to exploit it.
- Johnson concludes by saying that the flows of knowledge, remembering and forgetting as well as the selection mechanism are shaped by institutional factors.

Andersen (1992: 68) stresses the importance of national linkages. He emphasises the importance of co-operation between firms as a necessary supplement to competition through analysing user-producer interaction. Andersen believes that many innovations/new possibilities are often discovered as by-products of existing production and sales activities. Often, more ambitious searching for and learning about new products also start with existing products and processes. He states that two 'lists' of demand specifications can be visualised, one containing errors, repair problems and larger breakdowns, while the other contains a list of ideas and wishes for new features, facilities and performance measures.

Christensen (1992: 147) discusses the importance of finance in the innovation process. "One of the most important institutional conditions for the process of innovation is the possibility of financing the process".

The role of finance in the HES is not discussed in this paper as the emphasis is mainly on the role of finance in firms. He draws attention to the importance of institutional factors in the financial system that supports innovation. Christensen stresses the influence of a degree of uncertainty surrounding the investment as well as risk adversity on innovation. His discussion also centres on the importance of interactive learning in finance as the lender-borrower close contracts repetitively and in the process, accumulates knowledge.

Freeman (1992:170) contributes to the volume by discussing formal scientific and technical organisations in the NSI. He 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 and the main focus for the development of new products and processes in most branches of industry. Freeman also focuses on the importance of organisational innovations in the NSI.

Freeman (1992:170) believes that as technology has become more complex, the role of the public sector increases in importance. Gregersen's (1992:128) discussion on the role of the public sector in creating, maintaining and developing the modern NSI argues that the public sector is one of the most important users of innovations. Public authorities define the room for 'innovative manoeuvre' by designing institutions, i.e. standards, patent, acts, etc., and other regulatory activities to control innovation as well as diffusing new products and processes.

This volume pays close attention to the roles played by finance, firms and the public sector. Lundvall (1992: 14) admits however that the volume does not contribute much to the vital role that the educational sector plays in the NSI. The vital point that the volume makes is the learning and the role played by R&D as a form of learning, a view that holds extreme merit for the purpose of this thesis.

2.5.3 Technologies, institutions and organisation

Charles Edquist offered an integral contribution with his book, entitled Systems of Innovation: Technologies, Institution and Organisations (Edquist, 1997). The volume aimed to determine the common foundations of the system of innovation approaches (Archibugi et all, 1999). Edquist (1997:15) identified nine common characteristics from the national systems of innovation literature. He focused particularly on the commonalities of the different approaches:

- *innovation and learning processes play a central role:* this contrasts with neo-classical analysis, where technological change is treated as an occurrence outside the economic system. Products and processes can be created, i.e. innovation, through the production of new knowledge or combining existing knowledge
- *holistic and interdisciplinary nature of the NSI approach:* the system of innovation approach, i.e. national, sectoral and technological, strives to include all the determinants considered important in the innovation process. The approach is interdisciplinary in including economic factors, institutions and organisations
- *the natural inclusion of a historical perspective:* history matters in innovation processes, innovation occurs over time. Innovation is also path dependent, i.e. small events are reinforced through positive feedback loops and become crucially important. Organisations also develop over time. The accumulation of knowledge and skills is central
- *differences between systems and a non-optimality:* systems of innovation have different structures of production. In some countries, raw material based production is dominant, while other countries find knowledge-intensive production more important
- *emphasis on interdependence and non-linearity:* innovations can be considered as the establishment of products and processes through the creation of new knowledge elements or combining existing knowledge elements in a new way. Knowledge elements do not originate at a central point but rather with different actors and agents (universities and firms). The literature analysed strongly emphasises the complex interaction of different elements with each other
- *the incorporation of product technologies and organisational innovations:* technological change is closely intertwined with organisational change, which is a key process of innovation. Edquist states that organisational change can in principle be analysed from the systems of innovation approach
- *the central role of institutions in the NSI approach:* in all the definitions presented in the literature, institutions that influence innovations are central elements
- *the system of innovation concept has a conceptually diffuse nature:* none of the major authors provide a clear guide on what to include in a (national) system of innovation. Problems exist around the vagueness of some concepts, such as 'institutions'; and
- *the focus of the literature on conceptual construct rather than a rooted theoretical*

framework: although the system of innovation approach is not a formal theory, it is rooted in various theories of innovation.

In Edquist's volume, Galli and Teubal (1997) contributed to the dynamic view on NSI. Their work included a description on the functions and building blocks of the NSI. They believe that following WWII, the NSI developed within a relatively sectoral or subsystem configuration, which can schematically be based on three R&D performing sectors, i.e. business, public and universities, with relative weak linkages, and a fourth basic infrastructural subsystem, i.e. bureau of standards, patent office, etc.

Galli and Teubal (1997: 346) stress the importance of distinguishing between function and organisation, as they tend to play increasingly more central roles. Galli and Teubal also introduce the concepts of hard and soft functions (Galli and Teubal 1997: 347).

Hard functions require hard organisations, those equipped with laboratories and performing R&D. These functions include:

- R&D involving universities and public and non-profit organisations; and
- supply of scientific and technical services to third parties, i.e. business sector and public administration, by industrial firms, technological centres, technical service companies, universities, governmental laboratories and ad hoc organisations.

Soft functions and related organisations, those without laboratories and not performing R&D, include the following:

- diffusion of information, knowledge and technology towards economic and public operators interfacing between knowledge suppliers and users. Such bridging organisations include various forms of innovation centres and liaison units at universities and public laboratories, etc.
- policy-making by government offices, technology assessment offices, academies universities as well as ad hoc for a national committees and councils, etc.
- design and implementation of institutions concerning patents, laws, standards, certifications, regulations, etc. These functions are usually performed by public or intermediate organisations;
- diffusion/divulgation of science culture through science museums, science centres, etc.; and
- professional co-ordination through academies, professional associations, etc.

Several linkages connect various players or components. Three types of linkages can be identified (Galli and Teubal, 1997: 347):

- market transactions
- unilateral flows of funds, skills, and knowledge, both embodied and disembodied within an NSI as well as externally between organisations and others located in other countries or NSIs; and
- interactions, such as user supplier networks.

Linkages between the players and components can be facilitated, enabled or embedded in a wide arrangement of institutional arrangements, e.g. laws, norms, policy-induced incentives, specific allocation, agreements, etc. Interactions between S&T can be in different contexts, namely geographical, sectoral or technological. Government plays a major enabling role through policy-making and the generation of linkage mechanisms and incentives.

Galli and Teubal identified major trends within the basic building blocks of the national system of innovation.

Building block 1: universities

- Universities provide higher education and perform basic research, thereby playing a key role in an NSI absorptive and generative capacity.
- Multi-disciplinary research has increased considerably to address the need for interdisciplinary approaches in complex problem solving.
- Diffusion of generic or mission-oriented research programmes.
- Increased interaction with the business sector to assess the achievements of basic research and to direct the performance of scientific activities.
- Establishment of interface units that offer the business sector a low transaction cost access mechanism to skills and knowledge.
- Establishment of university-industry joint research/technology development centres.

Building block 2: public sector

Three major kinds of R&D organisations exist in the public sector:

- mission oriented bodies and agencies supplying required knowledge, both technical and scientific, to ministries and other regional authorities
- basic or general bodies, e.g. CSIR and NRF; and
- publicly owned companies operating in areas such as oil, petrol and minerals etc., for example SASOL. These companies usually play a key role in an NSI, given the relatively high share of R&D performed in their laboratories. These companies also define technical standards for a vast number of supplying firms.

The public sector supplies the business sector with more and more scientific and instrumental capabilities. This is a result of budget cuts forcing the laboratories to look for innovative roles in the NSI. Publicly owned companies were also forced to restructure due to privatisation or budget constraints.

Building block 3: the business sector

Innovation processes in firms are increasingly moving away from a linear R&D process model to a model emphasising the full integration of roles among technical and market functions as well as the external provision of information, technology and advisory services. Stronger linkages between manufacturers and their customers are created through knowledge transfers on the better use of products.

Suppliers consequently play a more important role in updating and maintaining the technical standards and production quality of their customers. R&D contractors specialising in a field are an increasingly common occurrence, as is the spread of engineering, consulting and information service companies.

Building block 4: infrastructural subsystem
The infrastructural building block might play an increasingly important role in business sector restructuring and in promoting more interconnectedness among various NSI components. The building block comprises the following subcomponents:

- traditional infrastructural components with both the soft and hard functions, including patent offices, bureau of standards, geological surveys, extension services, statistical offices, science museums and science centres
- technological infrastructure; and
- policy development.

2.6 National Competitiveness

Porter (1990) contributed to the field by developing a framework to analyse relationships between the characteristics of national or regional systems of innovation and innovativeness in terms of industry competitiveness.

Porter indicates that proximity plays a fundamental role in competitiveness and that knowledge of national characteristics and capabilities is crucial to building competencies. Porter identified four broad attributes of a nation involved in shaping the environment where local firms compete.
forthwith referred to as the ‘diamond’, depicts the four determinants of a nation that can either promote or impede the creation of competitive advantage (Porter, 1990).

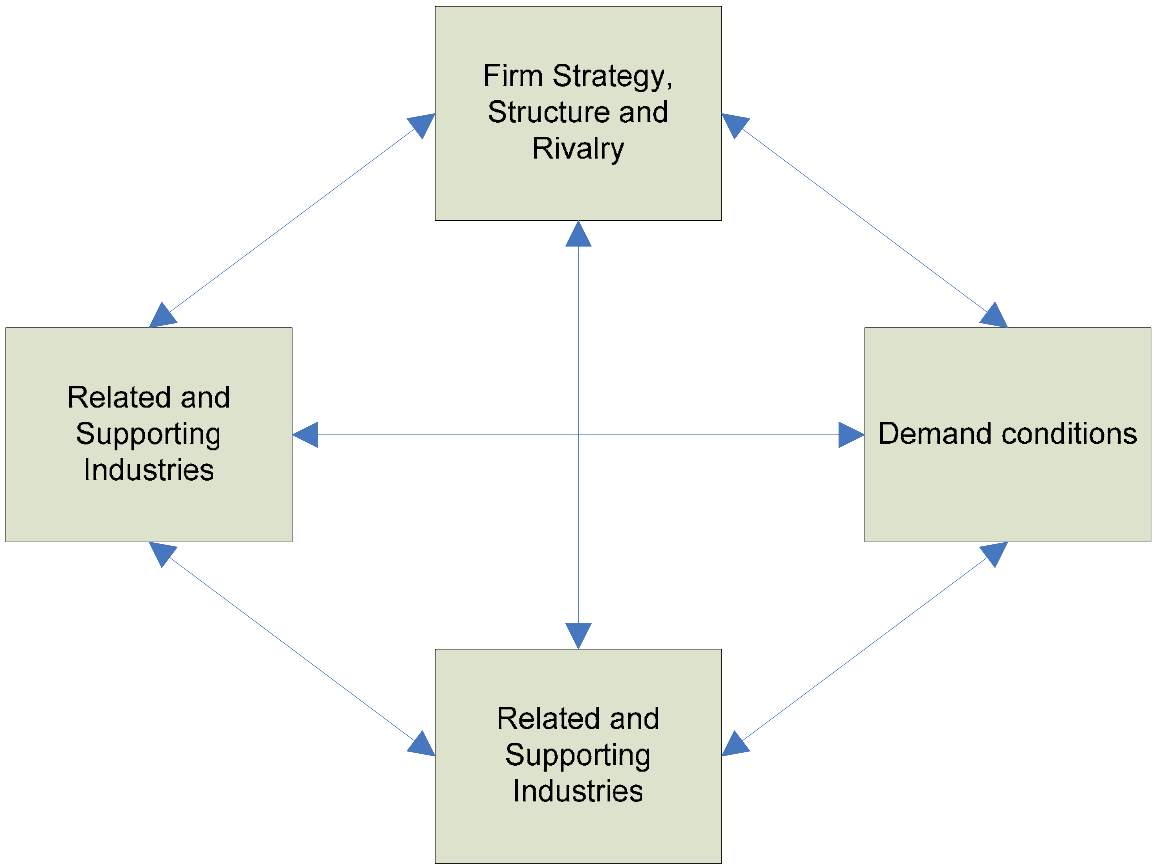

Figure 2-5: Porter's diamond

The four sides of the diamond comprise:

- factor conditions, i.e. human resources, physical resources, knowledge resources, capital resources and infrastructure
- demand conditions, especially 'competent demand' as represented by, for example, technically sophisticated customers. The *quality* of demand is more important than the *quantity* of demand
- links to related and supporting industries; and
- the firm's strategy, structure and rivalry refer to the conditions within a country that determines how companies compete as well as how they are created, organised and managed.

Although each economic activity is viewed primarily as an industry, the activity also forms part of a cluster of activities and agents as opposed to occurring in isolation. Porter also stresses that government could influence the creation of a competitive advantage either positively or negatively. Viewing government as an influencer or the national 'diamond' both clarifies and highlights this statement:

- government can influence *factor conditions* through subsidies, policies, educational policies, etc.

- the role government could play in shaping local demand conditions are often more subtle. Government may establish local product standards or regulations that could influence buyer needs. Government itself is often a major buyer of many of the nation's products, i.e. defence goods, telecommunication equipment, aircraft)
- government policy influences firm strategy, structure and rivalry through devices such as capital markets regulations, tax policy and antitrust laws; and
- government could shape and control relating industries by regulating the advertising media, supporting services, etc.

Because of the industry focus, Porter strongly emphasises the role of competition among actors within industries, thus market competition, while suppressing non-market interaction with entities outside the industry. In this sense, the system definition is narrower than in the national innovation system approach. The main focus is on a static or comparative static analysis (Carlsson, 2002).

2.7 Summary

To develop a systems model of R&D in the South African NSI, certain conclusions can be drawn regarding the nature and character of a system of innovation. The analysis of the literature on NSI also resulted in a higher level view being developed.

Human resources in the economy are organised in and belong to organisations within an NSI. In line with the belief that no system functions in isolation (Blanchard and Fabrycky (1998:2)), organisations can be described as systems that form part of a bigger system, e.g. the sector they belong to. Before discussing the role of organisations in more detail, the level of the individuals in the organisation is scrutinised. Organisations consist of individuals with certain capabilities. Individuals in these organisations possess, amongst others:

- *attributes:* tacit knowledge, skills or a capability to learn and forget, a role in the organisation (Lundvall, 1992), (Romer, 1990). Individuals also possess an ability to use the physical and capital resources as well as the infrastructure to perform their duties. These individuals are therefore important building blocks of organisations; and
- individuals also have relationships with other individuals (Linkages).

Nelson (1993), North (2001), Edquist (1997), Balzat (2002), Freeman (1992) and Johnson (1992) acknowledge the important role that organisations and institutions play in the development of organisations and their attributes within the NSI. These authors argued that the systemic nature of the NSI could be explained through the organisations in the system.

There are different types of organisations in an economy. Organisations can also be organised into sectors in the NSI. Lundvall (1992), Edquist (1997) as well as Galli and Teubal (1997) acknowledge the importance of the business sector but also emphasises the importance of organisations in the educational and public sectors. The following figure is the author's view on the basic structure of an NSI as described by Galli and Teubal (1997).

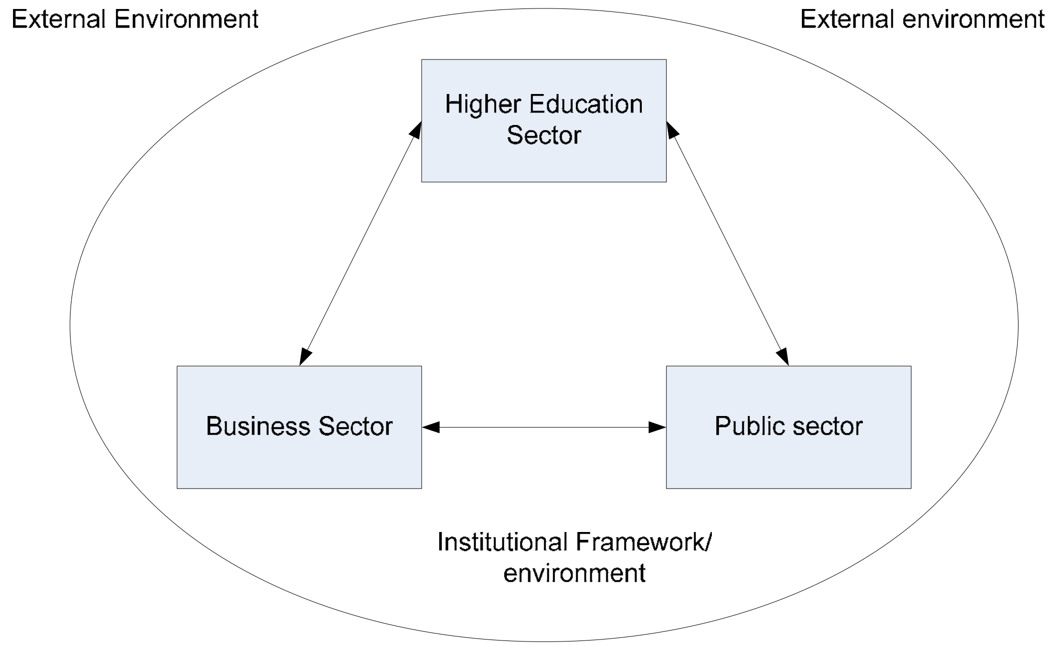

Figure 2-6: Simplified Structure of the NSI

Examples of organisations in the three sectors include the following:

- educational sector: This sector comprises higher education organisations, such as universities. The South African HES is characteristically only a recipient of funds for R&D, with which it is required to provide talented human resources, meet local needs in knowledge generation related to scientific progress, create and sustain centres of excellence in the social and physical sciences and engineering as well as participate in consortia and other joint research programmes (DACST, 1996: 22)
- public sector: This sector consists of science councils, publicly owned companies, museums and government departments. The main function of this sector is to define standards, perform research, diffuse knowledge, formulate policy, human resource development, the provision of infrastructure and the allocation of resources (DACST, 1996: 17)
- private sector: This sector includes all the other firms in the economy. The main function of this sector is to create wealth and to innovate; and
- infrastructural sector: This sector includes the components of the system, which enhances interconnectedness between other components in the NSI. Some of the components in this sector include policy making bodies, technology infrastructure, science centres, etc.

Figure 2-6 also depicted the interactions and relationships between players. These interactions and linkages are crucial to the system's nature and performance. Galli and Teubal (1997), Andersen (1992), Edquist (1997) and Lundvall (1992) agree that the linkages within an NSI are a vital contributing factor to the development and innovative behaviour of the system.

The environment within which the NSI interacts is also imperative. The NSI is not an isolated system and is influenced by other subsystems of an economy, for instance the legal system, tax system, financial system or the labour market (Balzat, 2002). Nelson (1993) and Lundvall (1992) also stress the influence of globalisation, the development of telecommunication technologies and the emergence of global companies on innovation processes.

We can conclude that government might well play an integral part in creating an environment conducive to innovation. Porter stresses the role that government plays in ensuring that the environment in which the system exists is inductive to innovation and R&D. The institutional framework contributes to the environment. According to North, the environment will determine the attributes of the organisations in the NSI. Galli and Teubal (1997) as well as Gregersen (1992) agree on the role of the public sector, and in particular government, in ensuring the quality of the linkages in the NSI.

3 MODELS OF R&D AND INNOVATION SYSTEMS

3.1 Purpose and Outline of the Chapter

The previous chapter introduced the concept of an NSI. The analysis and descriptions of other scholars' work in the previous chapter were mainly descriptive and textual analyses. Up to this point, no attention has therefore been given to the empirical measurement and treatment of innovation or systems of innovation.

This chapter will thus both review a number of the existing empirical analysis studies as well as discuss various authors' theories and frameworks.

The chapter also includes a discussion on the quantitative measurement of S&T as well as the shortcomings experienced with using these indicators. Various important econometric models developed for modelling the knowledge accumulation and knowledge based growth are also scrutinised. A section is allocated to analysing a number of measurement instruments aimed at gauging an NSI's efficiency and effectiveness.

The second half of the chapter focuses on existing system dynamics models of the R&D function and R&D systems. The chapter is concluded with the identification of a knowledge gap in terms of modelling systems from an NSI point of view as well as the development of a model for R&D activities in the South African system of innovation.

3.2 Quantitative Measurement of Science and Technology

The term 'indicator' is used with its traditional methodological connotation, namely operationalised attribute, ideally a quantitative form, of an abstract concept. Interest in the development of indicators stems from the need to monitor and enhance S&T capabilities.

S&T indicators can be defined as a series of data designed to answer questions surrounding the existing state of and/or changes in the science and technology enterprise, its internal structure, its relationships with the outside world and the degree to which it meets the goals set internally or externally (Fabian, 1979). The aim of S&T indicators is similar to that of social indicators, i.e. to obtain a picture of the state of S&T and to anticipate the consequences of scientific advances and technological change (Sirilli, 1998).

As noted previously, the study centres mainly on the R&D function within the NSI. This section will thus focus primarily on those indicators linked directly to R&D. The tendency in R&D assessment has been to emphasise quantitative input indicators, while the difficulty of assessing R&D output has tended to accentuate indicators such as expenditure on R&D, number of R&D personnel and number of R&D projects in a particular area. R&D output indicators as embodied in publications, patents and trade secrets, are commonly used in the industrialised countries. Output indicators tend to facilitate research intensity indicators, including publications per capita and per institution, discipline and country. R&D indicators can be categorised as follows (UN, 1997):

- *input:* focussing on resources, mainly human and financial, but also on information resources. Examples include R&D inputs collected in the OECD economies according to the procedures and categories described in the Frascati manual
- *output:* including new or reformulated knowledge as in embodied products, processes,

patents and publications:
  - patent data, i.e. records of the United States Patent Office (USPTO) and the European patent office and
  - bibliometric data on patterns of scientific publication and citation.
- *quantitative:* addressing input resources, i.e. the number of researchers, funding support as well as output, including publications, patents as well as financial indicators such as Return-on-Investment (ROI) and break-even index; and
- *qualitative:* focussing on input and output quality, originality, utility, conformity with original plans, sound use of resources, the quality of linkages to production and services sector as well as R&D communities within the country, the region and abroad.

This section documents various formalised measurement manuals for data on innovation and R&D. For a number of years, the Frascati manual was the only such manual, with four other manuals added recently. The Frascati manual family is based on experience gained from collecting R&D statistics in OECD member countries. The manual is a result of the collective work of national experts in the working party of National Experts on Science and Technology Indicators (NESTI). Over the past 40 years, the group, supported by an effective secretariat, has elaborated on the concept of S&T indicators and consequently developed a series of methodological manuals known as the Frascati Family, which includes manuals on the topics tabled below (OECD, 2002b):

Table 3-1: The Frascati Manual family

The Frascati Family	
R&D	The Measurement of Scientific and Technological Activities Series Frascati Manual: Proposed Standard Practice for Surveys of Research and Experimental Development R&D Statistics and Output Measurement in the Higher Education Sector. 'Frascati Manual Supplement' (OECD, 1989b)
Technology balance of payment[1]	"Manual for the Measurement and Interpretation of Technology Balance of Payments Data – TBP Manual" (OECD, 1990)
Innovation	OECD Proposed Guidelines for Collecting and Interpreting Technological Innovation Data – Oslo Manual (OECD, 1997a)
Patents[2]	"Using Patent Data as Science and Technology Indicators – Patent Manual 1994" (OECD, OCDE/GD(94)114, 1994b)
S&T personnel	"The Measurement of Human Resources Devoted to Science and Technology – Canberra Manual" (OECD, 1995)

The following sections analyse the formalised measurements of R&D input and output in more detail.

3.2.1 The measurement of R&D input

The Frascati manual is devoted to measuring R&D inputs. R&D, in turn, covers both formal R&D in R&D units and informal or occasional R&D in other units. The Frascati manual (OECD, 2002b) both presents the key guidelines and methodology for collecting R&D data and provides classifications to be used when collecting statistics. The manual also contains

[1] Deals mainly with problems of classifying and interpreting existing information.

[2] Deals mainly with problems of classifying and interpreting existing information.

definitions of the basic concepts associated with R&D and discusses how R&D relates to other relevant scientific and technological activities impacting on innovation and consequently also on socio-economic development.

South Africa has been conducting Frascati-style R&D surveys since shortly after the first manual was published in 1963. The first R&D survey based on OECD guidelines was conducted in 1966. Over the next 25 years up to 1993/4, South Africa conducted 18 regular official surveys. See Appendix A for a detailed account of the surveys conducted in South Africa.

3.2.2 Innovation surveys

The OECD was responsible for developing a framework for the measurement of innovation output. The Oslo manual on innovation surveys uses the systems of innovation approach from a theoretical and conceptual point of view. This approach defines innovation as a device aimed at solving problems arising at different stages. The manual covers innovation in the business enterprise sector and includes the following topics:

- innovation at the firm's level
- it concentrates on Technological Product and Process (TPP) innovation, with optional guidelines for other forms, such as organisational change; and
- it covers diffusion up to 'new to the firm'.

Following the first round of surveys performed in the OECD countries, various developing countries, such as Venezuela, Argentina and Brazil, joined in the phenomenon by conducting surveys based on the Oslo manual. These survey results indicated a number of definite differences between the Latin American firms and its First World counterparts. The differences were specifically obvious in terms of the nature and intensity of the firms' efforts geared towards technological innovation (Salazar, 2004), (Bogota, 2001):

- a much smaller percentage of firm effort is geared towards R&D, while innovation has increased in importance
- less effort is invested into basic than applied research
- innovation is based primarily on the acquisition of technology embodied in capital equipment
- the importance of organisational change in innovation processes; and
- fragmented flows of information within national systems of innovation.

Discussions were initiated to ultimately adapt the Oslo manual towards the specific needs of developing countries. These discussions resulted in the Bogota manual (2001), a manual based on the methodological conceptual and methodological base provided by the Frascati and Oslo manuals, but with alterations according to the unique character and specific characteristics of innovation systems and firms in the Latin American countries.

The Bogota manual has been revised once and has been used in Argentina, Uruguay and Colombia.

In South Africa, only one Oslo-type innovation survey has to date been carried out by the University of Pretoria in co-operation with the Eindhoven University of Technology in the Netherlands (Oerlemans L. A. G. et al, 2003).

One criticism of the innovation surveys approach is that its main concern is measuring inputs and outputs to innovation rather than focussing on the measurement of the processes, dynamics, relationships and interactions that affect innovation. Although the Oslo manual on innovation surveys uses the systems of innovation approach from a theoretical and conceptual point of view (Salazar, 2004), the questionnaires based on the manual collect little information on the dynamics of national and regional innovation systems.

Another option in measuring R&D and innovation output is to employ existing data sources. A substantial amount of methodological work was required before recommending an international standard practice for using existing sources to derive S&T indicators. Manuals dealing with both the technology balance of payments as well as the use of patents as S&T indicators have been published (OECD 1990, 1994b).

The following sections discuss the use of bibliometric data and patent data in the measurement of R&D output.

3.2.3 Bibliometric data

Since the 17th century, scientists have communicated their findings in international publications. This form of communication or the exchange of research results has become a crucial aspect of scientific endeavour.

The principle units of measuring in bibliometrics are scientific publications (Verbeek et al, 2002). A scientific publication usually contains a title, the names of the authors and their institutional affiliation. Although far from perfect, the publication is adopted as a building block of science and a source of data.

This approach defines the basic assumptions of bibliometrics. Bibliometric assessment of research performance is based on the principle that where a scientist have something important to say, he/she will publish the findings in the open international journal literature (Van Raan, 2004: 25). There are however some limitations to this approach. Scientific publications provide only a limited view of a complex reality as:

- journals are not the main carriers of scientific knowledge in all fields; and
- journal articles are not equivalent and differ widely in importance.

In most cases, the daily practice of inspired scientists indicates that they tend to communicate their results in scientific publications.

Work of some importance invokes reaction from colleagues. When scientific publications are published, we often see authors referring to their own earlier work or the work of other scientists. Scientific publications also reveal a number of citations to other publications that the author believes relevant to his/her article in some way (Verbeek et al, 2002). This process of citation is complex. As with publication counts, citations are also not an ideal monitor for performance. Citation analysis is based on scientists' reference practices, which means that the motives for referencing and citation might vary considerably. Van Raan (2004) concludes however that although the motives for referencing might differ considerably, the degree of uncertainty is not high enough to result in the practice of using citations in analysis loosing all meaning.

The use of Bibliometric data in the describing the 'forgetting phenomenon'

Scientists use other people's work in a distinctly characteristic manner. Various studies have been conducted using bibliometric data to estimate and study obsolescence of knowledge (Pollman, 2000). In these studies, two basic approaches have been distinguished, namely, the diachronous and the synchronous model:

- the diachronous approach is concerned with the use of a given set of publications in successive years; and
- synchronous studies proceed from the present to the past (Glanzel 2004).

When discussing the lifetime use of scientific information within the framework of documented science communication, it refers to the relevant information performing its intended function, namely, to be read and to impact on scientific research. The lifetime use of scientific information is therefore in part measurable by citations. A lifetime can consequently be interpreted as the period after scientific publications are no longer cited (Glanzel, 2004). In Bibliometric research the general conviction exists that the decline of references to a specific article per annum is exponential.

The following section discusses the use of patents as a measure of R&D output.

3.2.4 Patent data

Since its inception, the study of technological change has been hampered by the scarcity of appropriate data and, in particular, by the lack of extensive coverage for good innovation indicators (Jaffe and Trajtenberg, 2002: 25). Patents seem to be one important exception, since they are the only manifestation of inventive activity covering virtually every field of innovation in the majority of developed countries and over long periods of time. Jaffe and Trajtenberg (2002) state that patents have long since been reputed as a rich and potentially fruitful source of data for the study of innovation and technical change. The current stock of patents exceeds 6 million, with an additional flow of more than 150 000 patents yearly (as of 1999 to 2000).

A patent acts as a temporary monopoly to inventors for the use of a newly invented device. For the patent to be granted at the USPTO, the patent must be (Jaffe, Trajtenberg and Henderson, 2002:53):

- non-trivial, i.e. must appear non-obvious by a practitioner of the relevant technology; and
- useful, i.e. must have potential commercial value.

Smith (1998) explains that the motives driving parties to enter into a contractual arrangement necessarily influence how patent data can be applied as an indicator of inventive activity. As a contract, the patent-system caters to the assignee(s)' basic desire to appropriate profits accruing to the invention while catering to the system's basic desire of having the invention details spread to others, thus allowing the system to build on new knowledge. In line with this view, the state's motives involve:

- creating an incentive for actors in the economy to undertake inventive activities; and
- disseminating detailed information regarding inventive activities for future generations to build upon them.

The pitfalls associated with equating the patenting process with the level of innovative activity are widely recognised (Schmookler, 1966; Pavitt, 1982, 1988; Griliches, 1984, 1990; Trajtenberg, 1990). Griliches (1990: 1669) points out that:

- not all inventions are patentable
- not all inventions are patented; and
- inventions that are patented differ greatly in 'quality' in the magnitude of inventive output associated with them.

The non-rival nature of knowledge as a productive asset creates the possibility of 'knowledge spillovers', whereby one party's investment in knowledge creation produces external benefits by facilitating innovation by other parties (Jaffe and Trajtenberg, 2002: 379). Since Griliches' seminal paper on measuring the contributions of R&D to economic growth (1979), economists have attempted to measure and quantify the extent of knowledge spillovers.

Patent citations as a measure of knowledge spillovers
One line of research uses patent citations to identify a paper trail that might be associated with knowledge flows between organisations. Unlike bibliographic citations, patents perform a vital legal function, as it delimits the patent grant by identifying prior art not covered by a grant. Since the citations made from one patent to another has a legal goal and could have certain financial implications, gratuitous citations do not seem to be a concern in the case of patent citations. These citations does however open up the possibility of tracing multiple linkages between inventions, inventors, scientists and firms (Jaffe, Trajtenberg and Henderson, 2002: 155).

Jaffe, Trajtenberg and Henderson (2002: 161) classify the links between two patents into three groups:

- firstly, *spillovers accompanied with citations*: this is the case in which the use of patent citations to indicate a knowledge spillover is successfully implemented
- secondly, *citations where there was no spillover*: a more serious issue with the use of patent citation data to indicate knowledge spillovers is the case where the citation was added by the examiner but where the patentee was unaware of the patent being cited. In such a case, it is clear that no spillover occurred; and
- thirdly, *spillovers without generating citations*: an enormous amount of spillovers exist with no citations, since only a small amount of research output is ever patented. Many results of basic research are never patented. Jaffe states that it is plausible that basic research creates the biggest spillover.

Fro this discussion it is clear that the measurement of knowledge spillovers cannot be measured accurately using patent citations. The development and selection of indicators as a measurement of a country's R&D system depends on the goals set by the governing body.

3.2.5 Summary

Frascati surveys are used to measure R&D input. These surveys have been conducted in South Africa since the 1960s, thus indicating that time series data of R&D expenditure in the South African R&D system exists.

Only one Oslo-type innovation survey has to date been performed in South Africa. We can therefore conclude that no innovation time series data is available from this source.

The above discussions concluded that patents and scientific publications open up the possibility to perform detailed analysis in the relational structures of technological and scientific activity.

For the purpose of this study, we can conclude that patent data and scientific publications are an imperfect representation of the level of R&D output produced in a system. It is therefore important to acknowledge the shortcomings that may be encountered when following this approach. As these indicators are however the best available at present, the author chooses to go ahead in using these indicators.

3.3 Models of Knowledge Accumulation and Knowledge-based Growth

Economists and economic historians have studied the role of technology and technological change from as early as the 1950s (Griliches, 2000). Major economists from Smith, Ricardo, Marshall, Schumpeter and Kutznets were well aware of the importance of the role of technology and technological change and discussed the role it plays in economic growth and tensions in the economy.

At first, students of the subject preferred real and tangible measures of technological change, i.e. diffusion of big inventions of the time, such as tractors or combinations of the spread of hybrid seed and the transistor. This approach however tended to ignore aggregate productivity. It soon proved necessary to incorporate this aspect, as computations of economies seemed to have an extra portion of measured output growth that could not be explained by growth in measured inputs to changes in productivity. Economists realised that a new force at work was responsible for the unaccounted behaviour. Attention consequently shifted to inventive activity as well as formal and informal R&D efforts (Griliches, 2000).

Numerous authors have attempted regression analysis of productivity being related to some form of R&D. Since the first attempts in the late 1950s and early 1960s, the field has grown enormously. Griliches (1992 and 1995) provides a literature review. Many surveys have been done on the literature, listing countless studies around linking R&D and productivity ((Nadiri, 1993), (Mairesse and Mohen, 1995)).

The early studies failed however to provide a means of linking technological change to any overall aggregate result. Griliches (2000:46) states that “it was then relatively easy to think that the right thing to do was to regress the computed productivity numbers on some measure of R&D or inventive activity in the search for an explanation for it, treating R&D and scientific activity as another form of investment that creates a kind of long lived knowledge capital.”

The following sections describe a number growth models that views knowledge as a capital good.

3.3.1 The ideas-driven growth model

Romer’s theory is based on three premises (Romer, 1990: s72):

- technological change lies at the heart of economic growth and provides the incentive for continued capital accumulation. Together, capital accumulation and technological change account for much of the increase in output per hour worked

- technological change also increases due to intentional actions taken by people who respond to market incentives. The model is therefore one of endogenous rather than exogenous technological change; and
- the most fundamental premise is that instructions for working with raw materials are inherently different from other economic goods. Once the cost of creating a new set of instructions has been incurred, this new set can be used over and over at no additional cost.

The third premise implies that technology is a non-rival input, while the second premise implies that technological change takes place because of the actions of self-interested individuals. This thus holds that improvement in technology must confer benefits that are at least partially excludable. The first premise implies that growth is driven fundamentally by the accumulation of a partially excludable, non-rival input.

Non-rivalry has two important implications for the theory of growth:

- non-rival goods can be accumulated without bound on a per capita basis, whereas a piece of human capital, such as the ability to add, cannot. Each person only has a finite number of years to be spent on acquiring skills. When the person dies, the ability to create is lost. The non-rival goods, such as the knowledge created by that person, still remains in the system; and
- treating knowledge as a non-rival good makes it possible to sensibly discuss knowledge spillovers, in other words, incomplete excludability.

The Romer (1990) growth model comprises four inputs, namely capital, labour, human capital and an index of the technology level. While capital is measured in units of consumption goods, human capital is the distinct measure of the cumulative effect of activities, such as formal education and on-the-job training, ultimately measured by counts of people.

This theory articulates the economic foundations for a sustainable rate of technological progress. Romer's model (1990) employs the national ideas production function, i.e.:

$$\dot{A} = \delta H_A A_j \qquad \textbf{3-1}$$

This function holds that the aggregate stock of designs ($\dot{A}$) is a function of the total human capital employed in research (H_A). The stock of knowledge available to these researchers (A). δ is the productivity parameter. Romer's model is endogenous in two ways.

The R&D productivity and economic return from R&D ultimately determine the share of the economy devoted to the R&D labour market. In other words, where R&D activities generate money, money is allocated to the sector. A larger portion of the economy devoted to the R&D sector will result in more people being employed in the ideas generating sector. From this, it can be concluded that devoting more people to research leads to a higher rate of production of new ideas.

Productivity of new ideas is sensitive to the stock of ideas available. This ultimately results in a snow-ball effect: where there is current know-how or where ideas have been developed before, it is much easier to develop even more ideas. From this, it can be concluded that the larger the stock of knowledge and ideas in a country, the higher the productivity of idea workers in the economy.

This section briefly discussed Romer's endogenous growth model. In general, the literature scrutinised agrees that these factors included in Romers' model are crucial in explaining economy-wide innovation (Carlsson, 2002). Although Romer's model includes the crucial factors fundamental to R&D-based growth, it does not account for the diminishing returns to scale phenomena. The following section describes Jones' model of semi-endogenous growth.

3.3.2 Semi-endogenous growth theory

Jones (1995) believes that Romer's R&D-based model of economic growth is responsible for a prediction of a scale effect. If the R&D resources in the system are doubled, the per capita growth should also double automatically. Empirically, this prediction receives little support.

Jones suggests a refinement of the term 'endogenous' growth and argues that growth is endogenous in the sense that technological progress, which generates long run growth, results from R&D undertaken by profit maximising agents. He continues that long run growth is not endogenous as stated in the Romer model because traditional policy changes have long run growth effects. Jones thus proposes a 'semi-endogenous' growth model.

Apart from the specification of the R&D equation, the growth model proposed by Jones (1995) is very similar to Romer's growth model (Romer, 1990).

The R&D-based models in the endogenous growth literature (Romer (1990), Grossman and Helpman (1991a, 1991b, 1991c), Aghion and Howitt (1992)), share the counterfactual prediction of 'scale-effects'. This implies that an increase in the level of resources devoted to R&D should automatically increase the economy growth rate.

The prediction that the economy growth rate is proportional to the size of its labour force is however easily falsified. The scientists involved in R&D activities in the USA has increased from 160 000 in 1950 to nearly a million in 1988, yet the growth rate in America has not demonstrated anything close to a five-fold increase. Similar patterns can be seen for countries such as Japan, Germany and France where growth rates were constant and in some cases even declining. These observations led to Jones's claim that the assumption embedded in the R&D equation that the economy growth rate is proportional to the level of resources devoted to R&D is obviously false.

Jones proposes his model of semi-endogenous growth and follows the reasoning of Romer/ Grossman-Helman/ Aghion-Hewitt by stating that the Knowledge Stock (A) is the accumulation of ideas, and people develop ideas. The change in knowledge will consequently be equal to the number of people attempting to discover new ideas (L_A) multiplied by the rate at which R&D generates new ideas ($\bar{\delta}$):

$$\dot{A} = \bar{\delta} L_A \qquad \textbf{3-2}$$

Furthermore the rate at which new ideas are discovered can also be seen as a function of the amount of knowledge in the economy. Positive spillovers in the production of knowledge, δ

would therefore also increase the level of A. When parametrising the arrival rate δ, we get:

$$\bar{\delta} = \delta A^{\phi} \qquad \textbf{3-3}$$

In this equation, $\phi < 0$ corresponds to the case referred to in the literature as "fishing out", in which the rate of knowledge production decreases with the level of knowledge; $\phi > 0$ corresponds to the positive external returns case. Here $\phi = 0$ represents constant returns to scale.

Finally the possibility is considered that the duplication and overlapping of research reduce the total number of innovations produced by L_A units of labour. Arriving at the proposition that $L_A^{\lambda}, 0 < \lambda \leq 1$ belongs in the R&D equation. By incorporating all the above mentioned in the R&D equation Jones arrives at the following:

$$\dot{A} = \delta L_A A^{\phi} l_A^{\lambda - 1} \qquad \textbf{3-4}$$

where $l_A = L_A$ in equilibrium. l_A captures the externalities occurring because of duplication in the R&D process.

It can therefore be concluded that Jones' model is consistent with time series models applied in OECD countries. These growth models describe the development of entities dependent on the discovery of new ideas for their growth. It therefore proves sensible to apply these models to countries with advanced economies instead of countries where development can occur due to technology being transferred from other countries.

3.3.3 An econometric model of growth for South Africa

Du Toit et al (2004) analyse the determinants of technological progress, i.e. the total factor productivity, by incorporating the principles of endogenous growth theory. Against the background of structural changes in the production structure of the South African economy towards the increased contribution of technology in generating long-run economic growth, specific emphasis is placed on the role of technological progress in modelling the production function. In the past, South African production models primarily assumed constant technological progress over time, i.e. efficiency parameters were estimated as constants. However, production models must allow technology to improve over time to explain growth in output in the presence of diminishing returns to scale production structures.

Du Toit et al's model incorporates the new growth theory by specifying and modelling technology in terms of:

- the number of scientists and engineers in the economy
- the number of patents registered
- certain international factors, such as the degree of openness of the economy and an 'international position' index, constructed as a weighted average of factors such as the exchange rate, foreign investment and the levels of domestic and international competitiveness; and
- the expenditure on R&D is also incorporated in representing the allocation of resources

in the economy towards technology advancement.

Technological progress was subsequently estimated in terms of the standard variables suggested in the growth theory. The two-equation technology-growth model, consisting of a Cobb-Douglas production function and an endogenously specified technology function, is represented by:

$$Q_t = A_t K_t^{\alpha} L_t^{B} \qquad \textbf{3-5}$$

where Q_t is the Real GDP in period t, K_t is Real Capital stock in period t, L_t is total employment in period t and A_t represents technological progress. A_t takes the form of the following equation:

$$A_t = f(NSEDEB, PATENTS, INTPOD \; | R\&D, OPEN) \qquad \textbf{3-6}$$

where $NSEDEG$ is the Number of Natural Sciences and Engineering degrees, $PATENTS$ Number of patents registered, $INTPOS$ = International position index, $R\&D$ = A measure of expenditure on R&D, $OPEN$ = Openness of the economy to international trade

Du Toit and Koekemoer formed a number of conclusions and policy implications from their analysis of the estimation results and the response characteristics of their growth model. An important feature that surfaced from the estimations is that the South African economy exhibits decreasing returns to scale properties in production with regards to capital and labour inputs. The challenges faced by policy makers in South Africa are therefore demanding and multifaceted. These challenges include:

- resolving the structural problems that hamper saving/investment and the labour market absorption capacity of the economy, thereby addressing the decreasing returns to scale property of production with regards to capital and labour
- stimulating technological progress through incentive schemes, e.g. by sponsoring R&D and by creating legal mechanisms to protect the intellectual property rights of those who have invested in generating innovations at great cost
- improving and increasing human capital through training and skills development, thereby narrowing the existing skills gap in the economy. Another challenge is creating an environment where skilled individuals would be willing to participate in the domestic economy. It is therefore vital that the 'brain drain' tend, which at present depletes the stock of human capital of the South African economy, be eliminated
- improving access to existing knowledge, thereby improving the productivity of researchers and inventors
- reducing the barriers for the development and transfer of ideas and knowledge; and
- creating a social infrastructure and policy framework conducive to entrepreneurship and production. History has proven that economies in which the government provides an environment that encourages production and invention are extremely dynamic and successful.

3.3.4 Summary

This section discussed both the principal theories that influenced the current theory and views on the process of innovation as well as the part that these theories play in the economic growth of a country. This section documented a critical analysis of the models discussed thus far.

The analysis indicated that Romer acknowledges and identifies various crucial elements contributing to a nation's economic growth, namely R&D workers, a knowledge stock and the productivity with which these R&D workers are employed. Although most scholars agree that these parameters are crucial to economic growth, Romer can however be criticised for being too constricted. We can therefore conclude that Romer introduced a somewhat limited set of parameters.

Jones suggests a refinement of the term 'endogenous' growth and argues that growth is endogenous in the sense that technological progress, which generates long run growth, results from R&D undertaken by profit maximising agents. He disagrees with Romer by saying that long run growth is not endogenous due to traditional policy changes' long run growth effects. Jones thus proposes a 'semi-endogenous' growth model.

Jones' model is consistent with time series models applied in OECD countries. These growth models describe the development of entities dependent on the discovery of new ideas for their growth.

Du Toit et al (2004) analysed the determinants of technological progress, i.e. total factor productivity, by incorporating Jones's developments in growth theory on the South African economy. The outcomes of the model indicate that the South African economy can achieve higher levels of growth through the stimulation of both technological progress and R&D as well as the development of human resources in S&T.

Finally, this section concludes that R&D and the development of a capacity to create new knowledge as well as the ability to absorb new knowledge are crucial for a country's economic development. South Africa is no exception.

Many authors have challenged the character of knowledge as a capital good. The following section discusses the concept of knowledge, measurement methods and concepts around this topic

3.4 Knowledge in the Economy

Numerous authors agree on the importance of knowledge and the central role that it plays in the economy. Knowledge is indeed at the heart of organisational forms, as it determines the production, use and transfer of knowledge to such an organisation. Knowledge creates the possibility that a task will be fulfilled, either in the present or the future, by means of a situation-dependant selection, interpretation and valuation of information. Knowledge in terms of in an organisational form is often referred to as the knowledge stored in routines, comprising knowledge of individuals, combined through co-ordination with data and information embedded in machines, computers and other constructs.

Guilhon (2001) refers to the work of Jorna and others when he explains the differences between tacit, coded and theoretical knowledge:

- *tacit or sensory or behavioural knowledge* is knowledge of situations, events and individuals in the form of behaviour, procedures and habits. Tacit knowledge can be obtained by imitation of behaviour, which implies close and detailed observation

- *coded knowledge*, i.e. knowledge in the form of codes, such as languages, icons and formulas, can be taught and trained and is therefore by its nature more easily transferred than tacit knowledge. A prerequisite is however that the code system must be known; and
- *theoretical knowledge*, the reality is not connected to individuals or time, but consists of necessary causal relationships. This form of knowledge is in terms of explanations, for example a 'because' answer in response to a 'why' question. Complex and long 'why-because' chains may appear in this type of knowledge.

Tacit knowledge plays a fundamental role in the development of new knowledge. Nelson and Winter (1982) argues that the ability to deploy R&D activities depends on the involvement of tacit knowledge. Sharing tacit knowledge requires intensive interaction and, in many cases, the physical presence of actors involved in the sharing process (Jacobs, 1999), seeing that articulation of this kind of knowledge in, for example, coded knowledge is difficult or even impossible.

Smith's (1995) definition of knowledge resources offers insight into the nature of knowledge acquisition and the subsequent build-up of the internal knowledge base as a costly and painstaking process in which internal as well as external sources of information are used:

- *knowledge resources are differentiated and multi-layered:* a specific set of resources consists of different forms and levels of knowledge, for instance coded scientific knowledge or tacit knowledge embodied in the experience and skills of employees or other actors
- *knowledge resources are specific:* the knowledge of the firm is restricted and related to the competitive position of the company. This implies restrictions on the competence of the organisation, i.e. path dependency, and delimits the firm's action space. Furthermore, to bypass these restrictions and stretch the firm's competence, knowledge has to be acquired from the firm's environment
- *the development of knowledge resources is costly and cumulative (i.e. path dependency):* the upgrading of resources implies a costly search in which companies, by means of learning and adaptation, gain experience with specific knowledge, thus a cumulative process
- *knowledge resources are internally systemic:* learning is more than the enhancement of technological knowledge. To ensure that the knowledge is translated into innovations, market, finance and human resource knowledge is needed; and
- *knowledge resources are interactive and externally systemic:* interaction with other economic actors is necessary for the acquisition and exchange of knowledge.

Absorptive capacity refers to the firm's repertoire of innovation-directed problem solving routines consisting of knowledge of task execution. Knowledge for innovation is often 'borrowed' from the environment instead of being created by companies themselves (Schmookler, 1966, Von Hippel 1988). To this aim, knowledge for innovation must be absorbed through interaction and co-operation through feedback loops with the network of the firm's business relationships.

In the light of the focus in this thesis, i.e. modelling of the South African R&D system and the central role knowledge plays in the development of new technology; the following sections discuss models that have been developed for the creation and assimilation of knowledge.

3.4.1 Modelling absorptive capacity

Cohen and Levinthal (1989) published a seminal paper arguing the dual role that R&D plays in an economy. They argued that R&D not only generates new information, but also enhances the ability to assimilate and exploit existing information. The ease and character of learning in an industry influences both the R&D spending and condition the appropriability[3] and technology opportunity conditions in an industry.

In suggesting that knowledge is a capital good, Arrow (1962) and Nelson (1959) made the assumption that it could be realised without any cost by all firms located within the emission. Although they do not deny the existence of cost of learning, they argued that these costs are relatively small when compared to the costs of creating knowledge. Cohen and Levinthal argued however that the relatively small cost of learning could be ascribed to previous investments to increase absorptive capacity.

Cohen and Levinthal suggested that the long-term cost of learning was substantial and that this cost is borne from the development of a stock of knowledge, which constitutes a firm's absorptive capacity. A significant benefit of R&D is thus its contribution to a firm's knowledge base.

Cohen and Levinthals' model acknowledges the sources of knowledge used by a firm as:

- the firm's own R&D knowledge
- knowledge originating from competitor spillovers; and
- knowledge originating from outside the industry

Cohen and Levinthal assume that an increase in a firm's stock of knowledge will result in an increase in the firm's income. They characterise the determination of an increase in the stock of knowledge (x) as follows:

$$z_i = M_i + \lambda_i(\theta \sum_{j \neq i} M_j + T) \qquad \textbf{3-7}$$

M_i represents a firm's investment in R&D, while λ_i is the fraction of knowledge in the public domain that the firm is able to assimilate and exploit, and thus represents the firm's absorptive capacity. θ is the degree of intra-industry spillovers, while T depicts the level of extra-industry knowledge. Other firm's investment in research and development represented by M_j also contribute to z_i.

This model holds that a firm's capacity to absorb externally generated knowledge depends on its R&D effort. The equation implies that the firm is unable to assimilate what has not been spilled out. Firms are inherently unable to passively assimilate external available knowledge and therefore have to invest in its own R&D to its absorptive ability. It can therefore be concluded that not only the absorptive capacity but also the appropriateness is endogenous.

[3] Appropriability in an economical sense can be defined as the environmental factors that govern an innovator's ability to capture profits generated by an innovation

Cohen et al. consider the absorptive capacity to be a function of M_i as well as β. The variable β reflects the characteristics of both the outside knowledge, which renders R&D more or less critical to the maintenance, as well as development of absorptive capacity.

Cohen and Levinthal continue to develop a description of the marginal return to the firm's own R&D. For n firms where each firm chooses its R&D levels to maximise profit and they know the R&D levels of the other firms as given (e.g. symmetric Nash equilibrium). This results in each firm's profit to be a function of not only its own knowledge z_i but also the technological knowledge of all the firms in the industry. Rivalry is incorporated by assuming that an increase in a firm i's rival's knowledge will decrease the firm i's profits and marginal benefit from increasing its knowledge. Differentiating $\prod^i$ with respect to M_i yields:

$$R \equiv \prod_{zi}^{i}\left[1+\gamma_{M_i}(\theta\sum_{j\neq i}M_j + T)\right] + \theta\sum_{j\neq i}\gamma_j\prod_{zj}^{i} \qquad \textbf{3-8}$$

Where R yields the marginal returns to own R&D. If this expression is derived for each firm and set equal to 1, i.e. the per unit cost of R&D, a set of equations is generated that characterises each firm's optimal R&D policy given its competitor's R&D levels. When solved simultaneously the equations yield the equilibrium value of each firm's R&D.

3.4.2 Modelling knowledge accumulation

In the light of Jones' criticism of endogenous growth theory, Caballero and Jaffe (1993) developed a model for the estimation of the growth of knowledge. The current state of knowledge x (the current level of diffused and not yet obsolete knowledge in the system) is increased in the presence of research labour x. Caballero and Jaffe developed the following equation for the growth of general knowledge:

$$\dot{A} = \Gamma \cdot \lambda n_t \qquad \textbf{3-9}$$

Γ is taken to be the contribution of the weighted sum of contributions made by all existing vintages to current innovations. Therefore Γ does not include knowledge that is so new that it has not had time to diffuse to innovation workers, nor does it include obsolete knowledge. The knowledge variable is taken to be equal to:

$$\Gamma = \int_{-\infty}^{t} a(t,s)\lambda n_s ds \qquad \textbf{3-10}$$

Breaking down the equation even further, $a(t,s)$ is the marginal contribution of a vintage s sector to current innovations, given by the following equation:

$$a(t,s) = \delta \cdot e^{-\beta(A_t - A_s)} \cdot (1 - e^{-\lambda(t-s)}) \qquad \textbf{3-11}$$

β is the rate at which old ideas become obsolete, thus useless in the production of new knowledge, where λ is the rate of diffusion of older ideas into current general knowledge.

Caballero and Jaffe set the marginal contribution of old knowledge to the development of new knowledge as a function of the citation rate. Where $C_{t,s}$ is the number of observed citations by current patents (of year t) of older patents (of year s):

$$a*(t,s) = \frac{C_{t,s}}{S_t \cdot P_s} \quad \textbf{3-12}$$

Caballero and Jaffe performed estimations using U.S. data on patents and patent citations. By using their model, they characterised the process of creative destruction. The most important findings from the estimations of the citations function $a(t,s)$ were:

- ideas diffuse rapidly, within one or two years
- The rate of ideas' obsolescence has increased from 3% in the 1900's to up to 12% in 1990; and
- the rate $\dot{A}/n$, where $\dot{A}$ is measured in new innovations, has decreased substantially between 1960 and 1990 (almost 30%), thus indicating either reduced spillovers of older ideas of new knowledge (decrease in δ) and/or an increased rate of knowledge obsolescence (increase in β).

3.4.3 Fundamental stocks of knowledge

The majority of reported research and development is expended in areas where the direct contribution cannot be measured. Griliches (1987) states that because a large component of research and development is aimed at final consumer products rather than process innovations, it is only reflected in those productivity measures where producers succeed in appropriating its fruit.

$Y = F(X,K,u)$ is a production function connecting the measure of output to an index of conventional inputs such as labour and capital (X), the current state of technical knowledge (K) and u which include all other unmeasured determinants of output of productivity. Griliches assumes a Cobb-Douglas production function form of function $F()$.

$$Y = DC^{\alpha} L^{\beta} K^{\gamma} e^{\lambda t+u} \quad \textbf{3-13}$$

D is a constant, t is the time index, e is the natural logarithm, and α,β,γ and λ reflect the parameters to be estimated. The current level of technological knowledge K is defined to take the following form

$$K_t = a_0 [W(B)R_t]^{\eta} e^{\mu t+\upsilon} \quad \textbf{3-14}$$

In line with the primary aim of the thesis, the main point of interest in this equation would be $W(B)R_t$ the current level of technological change. Griliches defines a stock of current and past levels of R&D expenditures, yet warns that the measurement of R&D capital is a very broad concept, perhaps even too broad to be identified. Although the contribution of science to an industry is also probably not measurable, Griliches focuses on the contribution of industrial R&D and formulates an expression for R&D capital. A number of issues do however arise from this:

- R&D processes take time and the current R&D may only have an impact after several years. An assumption regarding the lag structure of the contribution of R&D capital will therefore have to suffice in some instances
- past R&D efforts depreciate and become obsolete. An assumption regarding the period that the knowledge will remain relevant is therefore necessary; and
- the level of knowledge in any one sector or industry is not only derived from the own

R&D investments but also affected by the knowledge borrowed or stolen from other sectors or industries, i.e. spillovers.

It is however vital to take into account that very different types of knowledge exist and that R&D output results are embodied in people, blue prints, patents, books, etc. Griliches believes the option of aggregating these different types of knowledge should also be considered carefully. He argues that aggregation in this case is in no way worse than aggregating national output in GNP, which also consists of al kinds of factors. The lack of a direct measure of R&D output introduces an inescapable layer of inexactitude and randomness in the formulation.

Griliches opts against using patents and publications, as they are only available in a limited range of sectors and industries. He argues that R&D output is largely unobservable and that it would therefore make more sense to treat it as an input than an output.

In Griliches' model the output of a single firm (Y_i), depends on the index of the conventional output of the i-th firm (X_i), its specific knowledge capital (K_i) and on the state of the aggregate knowledge in the industry K_a.

$$Y_i = BX_i^{1-\lambda}K_i^{\gamma}K_a^{\mu} \qquad \textbf{3-15}$$

From this formulation an aggregate of firms' output would result in the following expression:

$$\sum_i Y_i = B(\sum X)^{1-\gamma}K_a^{\mu+\gamma} \qquad \textbf{3-16}$$

This provides a framework for reconciling micro and macro results in this area.

Academic Research

Using the exact production function formulation employed by Griliches (1987), Adams (1990) uses the methodology by formulating the production function to include stocks of knowledge among the inputs. The analysis aims to measure the relationship between measures of academic science and multifactor productivity growth.

In Adam's model, the stock of knowledge can be measured by the:

- employed scientists and engineers; and
- a stock of papers.

Adams measured the stock of knowledge in different fields of science, using the following formulation:

$$N_{t,f} = N_{t-1,f}(1-\delta) + P_{t,f} \qquad \textbf{3-17}$$

N is the stock of knowledge in field of science f in period t or $t-1$. The stock of knowledge from previous periods are depreciating, this is modelled using the parameter δ. P is the number of papers published in year t, field f. Adams then formulates a knowledge stock of a whole industry as follows:

$$K_{t-m} = \sum_{i=m}^{T}\sum_{f=1}^{F} L_{t-m,j} N_{t-k-i,j} \qquad \textbf{3-18}$$

where T the total is number of years in the analysis, F is the number of scientific fields and k is an additional lag that measures the duration of the search for useful science. The variable L stands for the number of scientists and engineers employed in the sector.

By the expression of the knowledge stock of an industry in the production function as formulated by Griliches, Adams obtains several estimates for the contribution of academic knowledge to productivity growth rate in the USA.

3.4.4 Learning curves and the effect of learning on cost

Learning or experience curves have been documented in a wide array of industries. The learning curve arises when workers and firms learn from experience. As experience grows, workers find ways to work faster and reduce errors. Typically, the unit costs of production decreases by a fixed percentage every time that cumulative production experience doubles.

According to Sterman (2000), cost reductions of 10% to 30% per doubling of experience have been documented in the work of Teplitz (1991), Gruber (1992), Argote and Epple (1990). To incorporate a learning curve into the R&D system, an assumption has to be made that any cost reduction is reflected in the price.

Sterman provides the following expression for the effect an increase in experience (E with E_0 as initial experience) might have on cost (C with C_0 as initial cost):

$$C = C_0 (E / E_0)^c \qquad \textbf{3-19}$$

For a doubling in experience the cost has fallen a fraction f. The expression will consequently be:

$$C = C_0 (1 - f) = C_0 (2E_0 / E_0)^c \qquad \textbf{3-20}$$

Therefore the value of the parameter c can therefore be computed using the following expression:

$$c = \ln(1 - f) / \ln 2 = \log_2 (1 - f) \qquad \textbf{3-21}$$

Thus, for a fraction varying between 10% and 30%, x can vary between (–0.15 to -0.51). The following figure provides a graphical representation of the effect that an increase in R&D knowledge might have on the cost needed to produce R&D output.

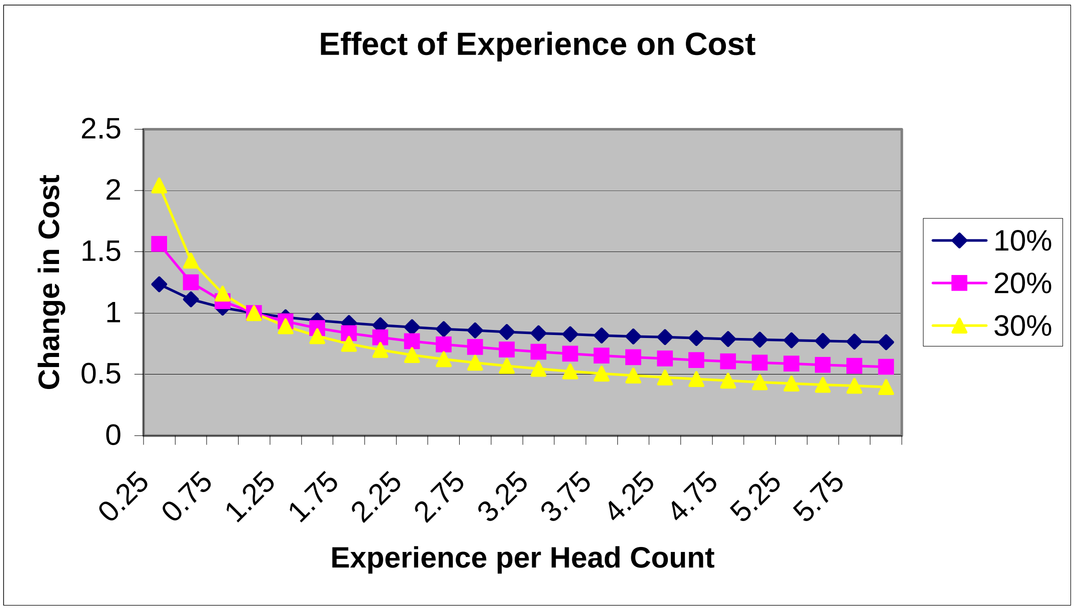

Figure 3-1: The effect of Experience on Cost

Learning by doing, R&D and the resulting process improvement 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.

3.4.5 Summary

An important and insightful model developed by Cohen and Levinthal (1989) is based on the argument that the R&D process is not merely the creation of new knowledge but that the performance of R&D also results in the development of an absorptive capacity that enables the system to absorb knowledge from the external environment. The absorptive capacity then develops a capacity in the system that ultimately equips an R&D system to create its own knowledge.

This model holds important implications for the dynamic behaviour inherent to the system model developed in this thesis. The model is applied to the firm level and incorporates not only the knowledge spillovers from the firm's own industry but also from outside industries. The model however does not incorporate the effect of decaying knowledge stocks in the system, i.e. forgetting.

Caballero and Jaffe (1993) developed another important model for estimating the growth of knowledge. Knowledge increases in the presence of research labour. Caballero and Jaffe's model again emphasises the important role that human resources play in a system's ability to accumulate knowledge. As the model acknowledges the exponential decay of knowledge in a system as well as the time it takes for the diffusion of older ideas into current general knowledge, it is therefore able to incorporate the flows of knowledge from its creation to the time that it becomes obsolete.

An important aspect of Caballero and Jaffe's model for the purpose of this study is the modelling of the contribution of old knowledge to the development of new knowledge as a function of the citation rate. This approach is also followed in the thesis.

This section also discussed a model developed by Griliches, who defines a stock of current and past levels of R&D expenditures. Although he acknowledges that the contribution of science to an industry is probably not measurable, he focuses on the contribution of industrial R&D and formulates an expression for R&D capital.

Griliches opts against using patents as a measure of R&D output as patenting is only done for a number of industries. The lack of a direct measure of R&D output (knowledge) is a source of inexactitude and randomness in the formulation of the model. The decay of knowledge (modelled as an exponential decay function) is however included in the model. Although the model acknowledges the presence of knowledge spillovers between firms, it ignores intra-industry spillovers of knowledge.

Finally, the section discussed the modelling of learning and the effect of learning curves on the efficiency of workers. Sterman illustrated the use of system dynamics to model learning of human resources in a system. This modelling technique is useful for the purpose of this thesis for modelling the development of tacit knowledge or experience in human resources employed in the South African R&D system.

3.5 Models and Quantitative Analysis of Systems of Innovation

This section comprises a brief description and a critical analysis of various quantitative analysis and assessment models of systems of innovation.

3.5.1 Comparing performance of NSIs

Niosi et al (1993) proposed studying institutions by means of ratios between basic inputs, i.e. expenditures and personnel, and outputs, i.e. patents, publications, internal reports, innovations and new products, followed by an analysis of their interaction via such variables as size, ownership and control as well as and regional distribution. The following table summarises a number other possible measurements of performance:

Table 3-2: Measurements for the NSI

Performance measure	Explanation
Monetary flows (Niosi et al, 1993)	Financing of innovative activities, both public and private
Technology flows (Niosi et al, 1993)	Citation analysis in patents, publications, licensing (when available), technological alliances and joint R&D
Tacit knowledge (Niosi et al, 1993)	Personnel flows between firms, universities and government laboratories
Efficiency (Niosi et al, 1993)	Analysis of patents and publications
Openness (Niosi and Bellon, 1994))	Foreign direct investment in R&D, trade statistics in high-technology, international payments for technological services

Some people are better than others at performing a specific task. This rule also applies to organisations. Some organisations are thus naturally better at performing some tasks than others. Following this reasoning, Niosi proposes a comparison of organisations with similar missions to measure performance. Niosi (2002) defined two terms when dealing with an NIS's performance:

- the 'x-inefficiency' is the gap between observed performance and existing best performance, i.e. maximum output observed in equivalent organisations; and
- the x-effectiveness is the degree at which institutions attain their organisational missions.

An example of a typical mission for a university would be producing human capital, i.e. graduates.

Noisi stresses the importance of developing meaningful and reliable indicators for innovation. The following table provides possible indicators for measuring NSI performance:

Table 3-3: Examples of Indicators for NSI performance

	Level	Indicators (Benchmarks)
Effectiveness indicators	University	University graduates as a percentage of new enrolment
	University	University publication per university
	Industry	Industry patent per industrial researcher
	Government policy	Number of firms conducting R&D
	Government policy	Number of research universities
Efficiency indicators	University	Cost of university graduates
	University	Cost of university publications (publications/HERD)
	Industry	Cost of industry patents (total industrial patents/BERD)
	Government laboratories	Cost of government laboratories' patents
Quality of output	All institutions	Citations to patents
	All Institutions	Citations to publications
	Industry	Number of innovations
	Industry	Export of technologically intensive goods and services
Flows/synergy		**Personnel flows among organisations**
		Knowledge flows
		Technology transfer
		Technological alliances
		Machinery diffusion
		Financial flows
		Venture capital for new high-technology firms
		Government subsidies for R&D
		Regulatory flows
		Intellectual property registration
		Legislation on standards
		Anti-trust and cooperative rules and laws
		Human flows
		University graduates supply and demand by discipline and institution
Ratios and indexes	At NSIs level	GERD/GDP
		Revealed technological advantages
		Input/output macroeconomic ratios
		Trade balances on high-technology goods and services

Niosi’s contribution touches on one of the biggest problems obstructing the analysis of innovation as well as the modelling of innovation systems, namely the availability of indicators. Even where indicators are available, the process of analysing the systems remains difficult.

3.5.2 Interrelationships among the elements of the NIS

The model developed by Nasierowksi et al (1999) is a comprehensive causal model of the interrelationships among the elements of the NIS, the first model of its kind in literature. The model contemplates how NIS inputs affect NIS related outputs, from patents of various kinds to citations and publications. These, in turn, are expected to affect technological progress through its effect on productivity.

Nasierowksi et al started out by identifying elements that characterise a country's NIS as well as the interrelationships embedded in the system. The following steps led to the development of this model:

- identifying the elements that characterise a country's NIS
- the variables to measure these elements; and
- interrelationships embedded in each individual system.

The elements of the NIS are defined by organising the various NIS elements into different groups, namely inputs, moderators and outputs.

Inputs: these are directly responsible for the present and future development of a country's NIS:

- the current state of the human contribution to the NIS, in quantitative and qualitative terms, through an analysis of the country's R&D employment structure; and
- the country's state and involvement in the development of human resources, through investment in future human capabilities.

The variables measuring the input elements are defined as follows:

Table 3-4: **Input variables measuring the elements of the NIS**

Symbol	Name	Description
GERD	Gross Domestic Expenditure on Research	A measure of R&D expenditure incurred within a given country during a given period
FDI	Foreign Direct Investment	A measure of the increasing importance of foreign sources of technology in the composition of a country's NIS
BRD	Degree of involvement in R&D in the private business sector	Ratio of business-to-government expenditures on R&D
EM	Employment in technology-oriented programs	Total R&D personnel in country
EME	Engineers/scientists in R&D programs	Percentage of EM
EDU	Total education expenditures	Percentage of GDP
EDUT	Tertiary education expenditures	Percentage of GDP

Moderators: the model provides for moderators, which are considered to have an impact on the relationships between inputs and outputs. These elements influencing the effect can be summarised as:

- prosperity of a nation is dependent on the nation's ability to innovate, thus accumulated S&T capability
- *cultural characteristics* to include the impact that the characteristics of a society has on linkages within the system. This model uses Hofstede's (1991) four dimensions of culture, i.e. MAS, PDI, UAV and IND
- patterns of technological development; and
- *size in terms of people and economic wealth* as a measure of a country's ability to absorb and generate novelties.

Table 3-5: Moderators measurement variables

Symbol	Name	Description
PPP	Purchasing Power Parity	Proxy of a country's ability to pay for technological progress
LIT	Size of a country's literate population 15 years or over	Proxy for a country's past commitment education
MAS	Masculinity index	The extent to which the dominant values in society are characterised by assertiveness, the acquisition of money and things as well as indifference to others
PDI	Power Distance Index	The extend to which society accepts that power in institutions and organisations is distributed unequally and thus accepts high levels of social and economic inequity
UAV	Uncertainty Avoidance Index	A measure of the proclivity to avoid uncertain situations, i.e. the extent to which a society feels threatened by uncertain and ambiguous situations and tries to avoid them by providing greater career stability, more formal rules and believing in absolute truths and the attainment of expertise.
IND	Individualism Index	A measure of the proclivity to avoid individualistic attitudes and hence expect others in groups of which individuals are part of family/organisations to look after them.
GDP	Gross Domestic Product	A measure of a country's size by wealth, in billions of US$
POPU	Size of country by population	In millions of people
LFOR	Size of country's labour force	Percentage of POPU in the labour force

Outputs: the degree of proficiency of the use of inputs and moderators in the generation of technology. Three sets of output are used, namely:

- solutions
- knowledge base; and
- productivity.

Table 3-6: Output measurement variables

Symbol	Name	Description
PAUS	Patents in the US by residents of a given country	A measure of excellence and importance of the discovery
PATE	External patents by residents	A measure of a country's involvement in international business co-operation and export activities
PATR	Patents by a country's residents	A measure of the local's effort in the investment in solutions for the internal demands of one's country
PATT	Patents by residents and non-residents in the country	A measure of the combined effects of the local and international business community in the country's 'investment in solutions' effort
PUB	Publication counts	A measure of the country's ability to create the 'knowledge base'
CIT	Citation counts	A measure of the perceived quality by others of a country's knowledge base
PRO	Productivity	GDP per employee per hour

To develop the I/M/O model of an NIS, data from 41 countries were used. The number of possible constructs was decreased considerably through the study of possible interrelationships among the elements of individual NISs.

From the list of 41 countries, the analysis of the data resulted in two consistent patterns. As a result, a binary value was added to the NIS data set to identify the cluster that each of the countries belong to. Cluster 0 countries proved to be more inclined towards technological development and acquisition and than cluster 1 countries. These countries were wealthier, had higher literacy rates, invested more in their human resources and were more likely to attract foreign investments. There was also a higher incidence of business involvement in R&D. It seems that the market size measured by population rather than GDP/wealth determine a country's preferred R&D policies towards its domestic market by favouring local outputs either short term, i.e. patents, or long term, i.e. publications. Cluster 0 countries dominate the generation of outputs, especially in terms of overall quality (PAUS), quantity (PATT), acceptability by others (CIT) as well as ultimate economic reward of increased productivity (PROD).

The I/M/O structures examined each country in terms of its double role as receptor and generator of R&D technology.

As a receptor, the factor loadings suggest the following four characteristics to be the most important:

- *R&D culture*: the following variables are linked to a country in cluster 0:
  - individualistic (INV)
  - highly productive (PROD)
  - high purchasing power (PPP)
  - concerned with the development of the human base (EDU, EDUT); and
  - has longer term outputs (PUB, CIT)
- *short term output activity*, as a measure of the extent to which past R&D investment translates into short-term solutions:
  - local patent activity (PATT); and
  - inside the frontiers (PATR) or outside a country (PATE).
- *quality of output activity* relates to the competitive advantage that wealthy countries (GDP) enjoy in the production of high quality outputs (PAUS); and
- *market potential* provides an indication of a country's ability to consume new technologies in terms of earning potential (LFOR) and educational level of population.

As a generator, factor loadings suggest the following five characteristics to be the most important:

- *innovative capacity*, this deals with the country's ability to generate new technology:
  - high productivity (PROD)
  - purchasing power (PPP)
  - highly educated population (LIT); and
  - a private sector able to invest in R&D activity.
- *investment in future*, representing the investment in human capital (EDU, EDUT) for the future as well as the degree of confidence that the international community portrays in the country (FDI)
- *initiative* considers factor valuing individual decisions making (INV) as well as the

international perception of the country's long-term R&D potential (CIT)

- *patent quality* as the country's ability to generate new technology of high quality (PAUS); and
- *short term output activity* as the country's ability to generate quantities of new ideas and technology (PATT).

This model developed a framework for the analysis of a country's NIS by considering the NIS as a sector of the economy. As a result, elements are characterised according to their roles in the NIS.

3.5.3 Innovative capacity

Furman et al (2002) developed a non-descriptive analysis in an attempt to enable a more formalised cross-country analysis of NSIs. The analysis focuses on measuring a country's *innovative capacity*. Innovative capacity in this context is defined as: "National innovative capacity is the ability of a country - as both a political and economic entity - to produce and commercialise a flow of new-to-the world technologies over the long term."

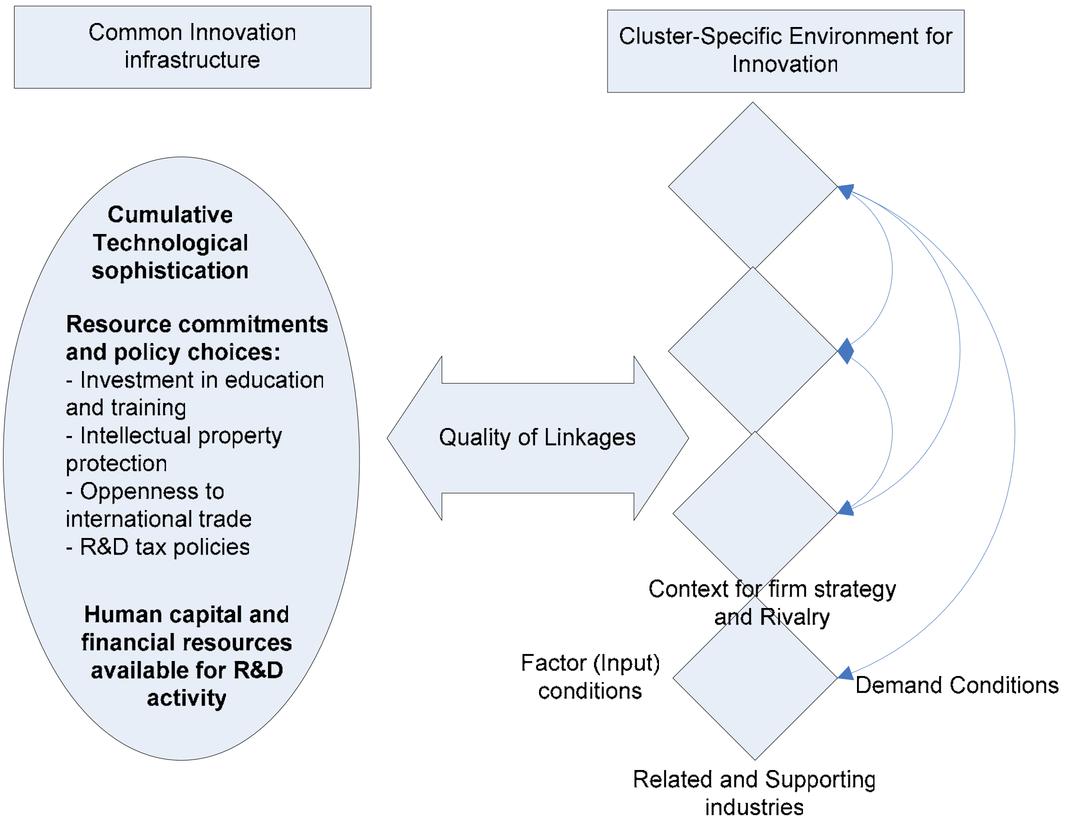

Figure 3-2: The National Innovative Capacity Framework

National innovative capacity is not the realised level of innovative output per se but rather reflects more fundamental determinants of the innovation process. This measurement attempts to reflect variation in both economic geography, e.g. the level of spillovers between local firms, as well as cross-country differences in innovation policy, e.g. the level of public support for basic research or legal protection for Intellectual Property (IP).

Where the ideas-driven growth model (Romer, 1990) and the theories of industrial competitive advantage (Porter, 1990) incorporate the role of public policies in shaping the rate of innovation, the national innovation systems literature on the other hand (Nelson, 1993) emphasises the role government plays with policy and specific institutions. As depicted in Figure 3-2, the model is constructed on three building blocks that incorporate the mentioned theories:

- *common innovation infrastructure:* the ideas-driven endogenous growth theory (Romer, 1990) focuses on the economy-wide 'knowledge stock' as well as the size of the R&D labour pool
- *cluster specific innovation environment:* the microeconomic environment influences the firms that ultimately produce innovations. The cluster-based theory of national industrial competitiveness (Porter, 1990) highlights the microeconomic underpinnings of innovation in national industrial clusters. This includes the input supply and local demand conditions as well as the nature and intensity of local rivalry; and
- *quality of linkages:* the strength of the common infrastructure influences the innovative output of the cluster environments and vice versa.

The model employs patent data to evaluate the rate of technological innovation. The authors acknowledge the limitations of using patent data.

3.5.4 Flows and dynamics within the NSI

The model discussed in this section was developed at a workshop on S&T indicators held by the Red Iberoamericana de lndicadores en Ciencia y Tecnologia (RICYT) at the Universidad Nacional de Quilmes in Buenos Aires, Argentina. This workshop discussed the topic of measuring stocks and flows of knowledge in a national system of innovation.

CPROST (1997) developed a model to analyse the flows and dynamics within the NSI, based on the following assumptions regarding the characteristics of an NSI:

- firms form part of a network of public and private sector institutions whose activities and interactions initiate, import, modify and diffuse new technologies
- an NSI consists of linkages, both formal and informal, between institutions
- an NSI includes flows of intellectual resources between institutions; and
- an analysis of NSIs emphasises learning as a key economic resource. The analysis also yields that geography and location still matter.

Figure 3-3 (CPROST, 1997) depicts a simplified national system of innovation (NSI). The purpose is however not to define all the elements and their inter-relationships, but instead to paint a picture of the major linkages.

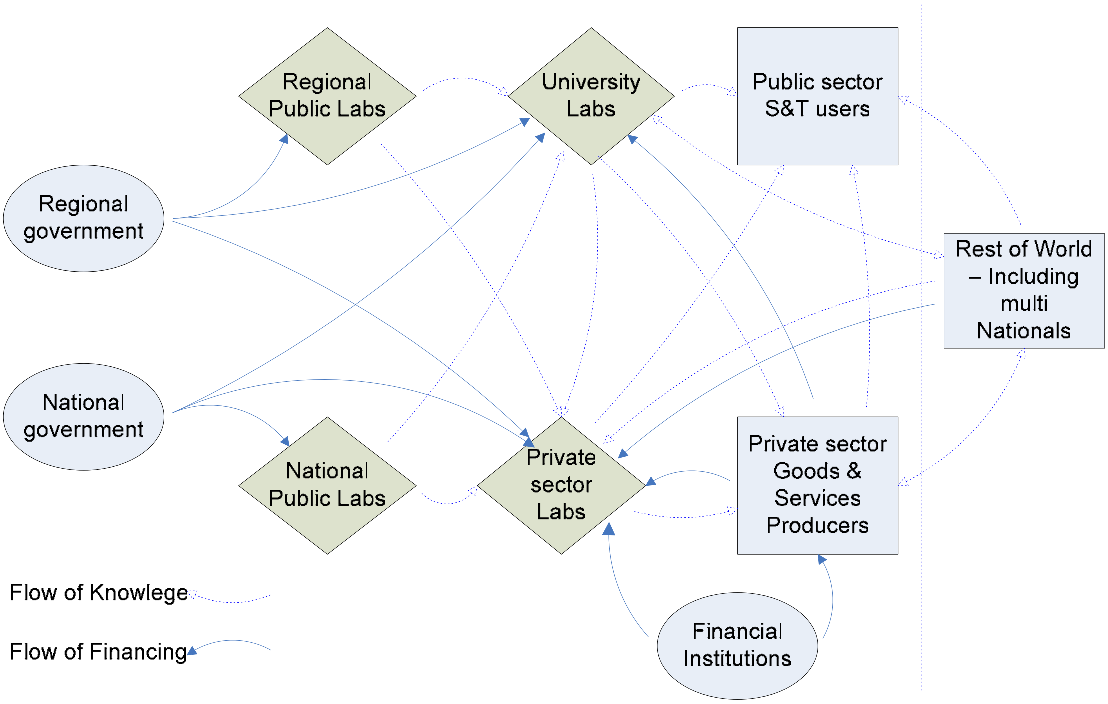

Figure 3-3: Flows within a simplified NSI (adapted from CPROST (1997))

This model is based on Edquist's view of the important role that organisations and institutes play in the analysis of the NSI. From insights gained from the work shop it was decided that it was indeed necessary to acquire the ability to measure the stocks and flows of knowledge among institutions, both public and private, and, if necessary, to develop indicators appropriate to this task. Innovation does not necessarily occur only in the private sector, but to date, there has been no procedure offered for assessing and quantifying innovation in the public sector.

During the development of the model, the following indicators were identified as crucial for information on the British Columbia system of innovation:

- investment in knowledge through R&D expenditures in each of the governmental, business and higher education sectors (*Benchmark:* R&D expenditures as a percentage of GDP)
- production and trade of high-technology products (*Benchmark:* revealed competitive advantage by sector)
- output and trade in high-technology services (*Benchmark:* balance of trade in services)
- investment in knowledge through training scientists and engineers, including social scientists and health care professionals (*Benchmark:* ratio of students who are citizens to labour force or population)
- productive use of knowledge, i.e. human capital, through the employment of trained engineers and scientists, including social scientists and health care professionals (*Benchmarks:* trends in real economic growth, mortality and morbidity); and
- census of innovating firms by sector (*Benchmark:* increase rate of the number of innovating firms).

The above led to an attempt to identify the more important linkages in the British Columbia system of innovation for policy analysis, using the admittedly imperfect measure of R&D

funding.

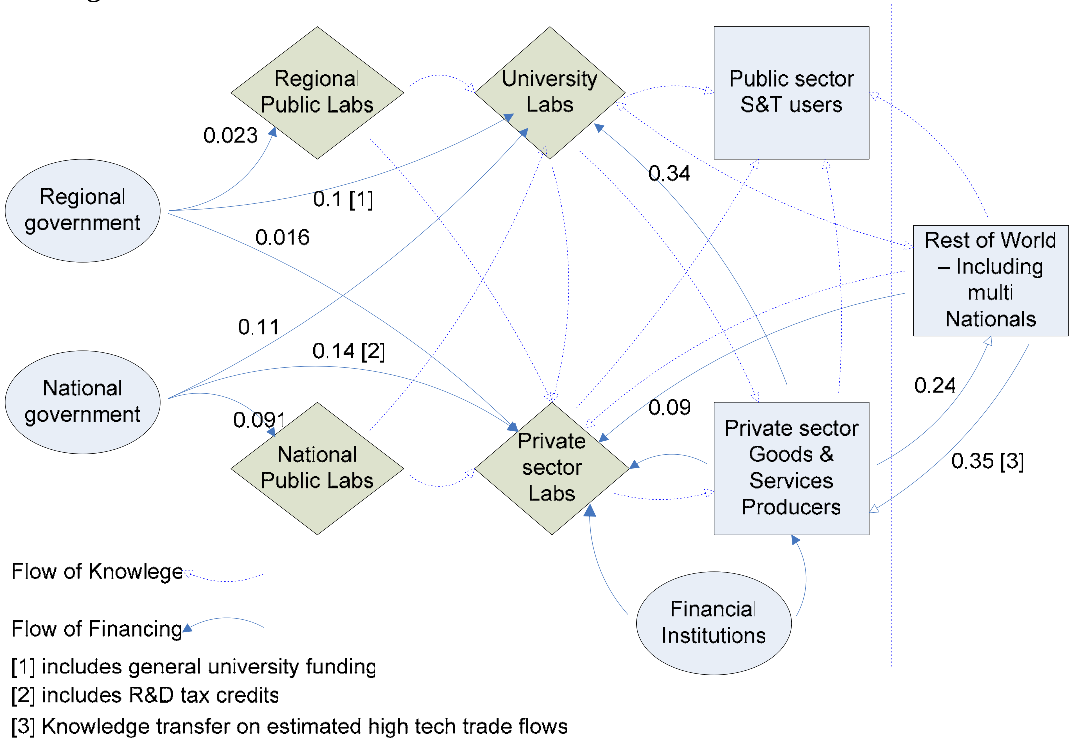

Figure 3-4: British Columbia system of innovation (adapted from CPROST (1997))

Using data available from Statistics Canada for 1993, the R&D funding linkages taken from Figure 3-3 are shown in Figure 3-4. The figures are shown as a percentage of gross GDP to facilitate comparisons with other NSIs. In addition to R&D funding flows, estimates of the value of the flows of the knowledge embedded in private sector transactions in intellectual property and high-technology products are also included.

A similar static analysis has been conducted on the South African system of innovation regarding the flow of funds. The following figure depicts the most important flows of R&D funds between the sectors in the South African system of innovation.

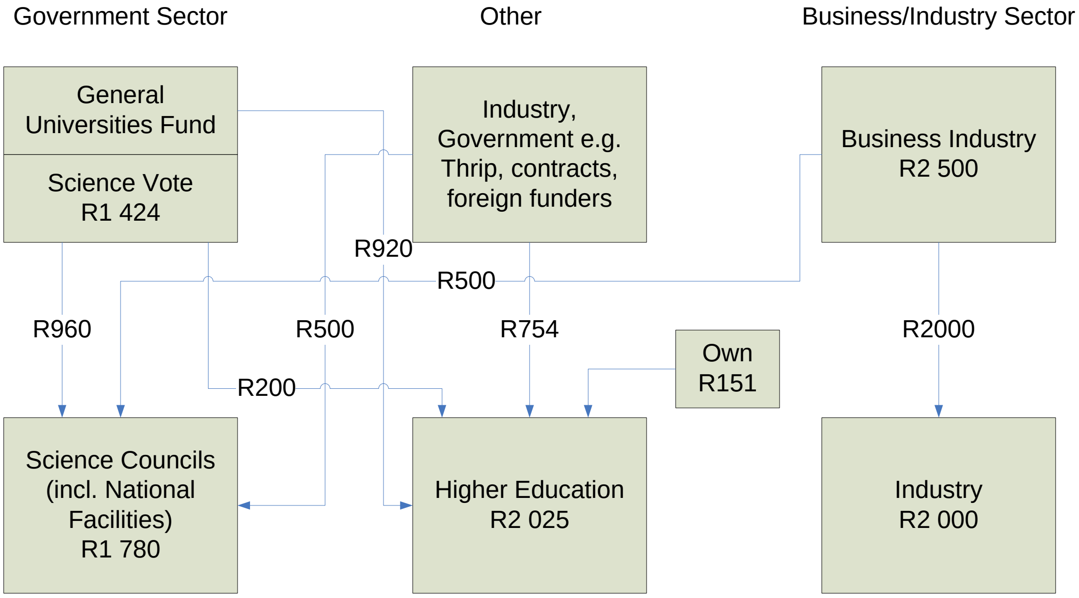

Figure 3-5: Flows of R&D Funding in the South African System of Innovation

Figure 3-5 depicts the estimated R&D expenditure (DACST, 2002) for 2000 in South Africa. The three R&D performing sectors together with the main sources of R&D funding are included.

The following conclusions can be drawn regarding the South African R&D system (DACST, 2002):

- R&D expenditure is mainly sourced from the government and industry sectors
- the HES as well as the business and industry sector perform the majority of the country's R&D
- higher education R&D is funded mainly by government, i.e. from General University Funds (GUF), research agency funding, THRIP as well as contracts from government departments and related institutes, such as parastatals. In contrast, the HES contributes minimally to its own research funding, i.e. only approximately 7%, from non-contract income sources, e.g. student fees, interest, donations, etc.; and
- roughly 56% of the funding for science councils is channelled through the parliamentary science vote. The remainder is made up of contributions from industry (29%). government contracts and foreign funders (15%).

The country's total estimated gross expenditure on R&D for 2000 was R5.725 billion. This total excludes military R&D, which, some sources estimate to total approximately R300 million for 2002. The figure also excludes research performed by research NGOs and consultancies.

3.5.5 Summary

Interesting conclusions can be drawn from empirical measurement of the modelling studies discussed in this section. Although the purposes differ considerable, all these models portray one common feature: each of these models was developed in an attempt to measure and model innovation from the NSI framework perspective.

Niosi et al (1993) did not develop an empirical model but made some propositions in terms of how the empirical analysis of institutions should ultimately be conducted. His propositions included both studying institutions by means of ratios between basic inputs, i.e. expenditures and personnel, and outputs, i.e. patents, publications, internal reports, innovations and new products, as well as analysing their interaction via such variables as size, ownership and control and regional distribution. The use of ratios of measuring performance is a practical and easy-to-implement approach. This framework does however not contribute to our understanding of the dynamics inherent to an innovation system and is thus considered useful only to compare different systems with each other.

The model developed by Nasierowksi et al (1999) was the first of its kind and established comprehensive causal interrelationships among the elements of the NIS. The model contemplates how NIS related inputs affect the NIS related outputs. It can be concluded that R&D culture, short-term output activity, quality of output activity and market potential are the most important factors determining a country's ability to absorb innovations. The model also concluded that where a country's ability to generate innovations is concerned, the following factors are crucial: innovative capacity, investment in future, initiative, patent quality and short-term output activity. The model attempts to include the development of scientific knowledge, i.e. publications, as well as technology outputs, i.e. patents in terms of innovation outputs. The model structure however relates inputs to outputs through moderator variables and does not provide for complex feedback dynamics in the innovation process.

Furman et al (2002) developed a measurement instrument to enable a more formalised cross-country analysis of NSIs. The analysis focuses on measuring a country's *innovative capacity*, where national innovative capacity is defined as a country's ability to produce and commercialise a flow of new-to-the world technologies over the long term.

The outcome of this model combines the work of Romer, Porter and Nelson for the modelling of technology output measured in terms of patents. This model therefore focuses on measuring firms' innovative capacity and does not provide an analysis for other types of organisations. The model's analysis is therefore only applied to the private sector, which means that it greatly ignores the role of the public sector and the HES. Although the model acknowledges the feedback nature of the ideas produced through the existence of a knowledge stock, no other feedback mechanisms in innovation systems are included.

The section introduced a static analysis of the flow of funds in the British Columbia's NSI, after which a similar model of the flow of R&D funds in the South African system of innovation was introduced. Although these frameworks fail to provide added insight in terms of the high-level flow of funds between sectors and institutions, it is a static analysis and does therefore not include the dynamics involved in the process of R&D or innovation.

It can therefore be concluded that a major drawback of most of the models discussed up to this point was its failure to include dynamic feedback loops in the system's behaviour. As the thesis deals with the development of a dynamic model of R&D in the system of innovation, the following sections discuss the development of system dynamics models of R&D.

3.6 System Dynamics Models of R&D and Innovation Systems

Roberts (1978:279) states that once system dynamics work was initiated at MIT, students began to notice potential applications in the areas of technology organisations as well as R&D activities. He argues that this reaction was a natural consequence, given the nature of the methodology's engineering background as well as the initial practitioners. Most practitioners hailed from a technical background and were thus inclined to apply the methodology to areas of interested as well as those field that they were familiar with, which turned out to be R&D. This application produced a heavy concentration of MIT theses on research and development management problems, with spin-off problems in industry and government. Roberts categorises the work done into three main areas:

- dynamics associated with R&D projects
- phenomena associated with the whole R&D organisation, especially resource allocation among projects or areas; and
- interrelationships between the R&D effort and the total corporation or government agency.

In his volume, Roberts (1978:280) stated that up to that specific time, very little has been done in the line of single R&D projects. Repenning (1999) states that since Robert's volume in 1978, the majority of system dynamics models focused on describing and modelling specific development projects, while fewer models were centred on multi-project management of the relationship between R&D function and the rest of the enterprise.

Repenning (1999) reasons that the lack of interest in the R&D function might in part be attributed to the dramatic success enjoyed by single project models. According to Repenning, Pugh-Roberts consulting company used Roberts' approach in dealing with single project dynamics (Roberts, 1964) to help Ingall, a huge shipyard, to settle a multi-million dollar claim against the United States Navy (Repenning, 1999). The same company also developed a huge model for Litton industries encompassing the entire design, development and engineering phases of the DD and LHA shipbuilding programmes. Pugh-Roberts have since become the industry leaders in system dynamics modelling.

Since the vast amount of literature on system dynamics models of R&D deal with single project models, the following section briefly describes some of these models.

3.6.1 SD models of single project R&D and R&D on the firm level

In his volume, Roberts (1978) describes an R&D simulation model developed by Weil, Bergan, Roberts (1978) as a management tool to decide on strategy. The model's use is described in terms of the different ways in which R&D strategies can be implemented.

Repenning (1999) lists some influential models of R&D. Abdel, Hamid and Madnick, (1991) developed a model of a single projects R&D system for applications to software development, while Homer's (1993) model dealt with the construction of pulp and paper mills. Ford and Sterman (1998) developed a single project R&D model of the design and development of semi-conductors.

Milling's (2001) product innovation process model depicts the development of new technology by incorporating an evolutionary module of product improvement. This model is applied on a single firm and single product level.

Hilmole, Helo and Kekale (2004) analysed a theoretical model of a start-up technology company as an input-delayed economic transformation process. The purpose of this model is to reach a better understanding of the working of the system where three different parameters are changing, namely R&D productivity, R&D share and budgetary expenses. Qingrua Xu et al (2004) model the motivational aspects of human resources in an R&D company. The company's performance is modelled as a function of competency and incentive.

Moizer and Towler (2004) developed a generic model characterising and capturing the causal feedback structure and performance behaviour inherent to a generic R&D system within a firm. Alternative what-if scenarios are tested on the mode to estimate the effect of R&D resource decisions coupled with changes in market demand.

Hansen, Weiss et al (1999) developed a model aimed at depicting funding allocations within a firm with considerable R&D activities. The issues relating to spending is the ever-present struggle between redistributing profits to investors versus reinvesting in the R&D function. A second decision regarding spending is to decide on the type of R&D expenditure in terms of basic, applied and experimental development. The model uses the system dynamics methodology to illustrate the effect of the allocation of funding to different phases in the R&D process. The model therefore aims to optimise resource allocation in real organisations.

Repenning (1999) states that measured in dollars, single project models have influenced management processes much more than any other type of application within the system dynamics methodology. Acknowledging the gap in the literature as well as the need for models to address multiple project situations, he developed a model for the environment of multiple R&D projects and the allocation of resources between them.

3.6.2 System dynamics models of R&D and innovation on a macro level

Up to this point, the R&D models discussed dealt mainly with those developed on either a single R&D project level or on a firm level. These models only provided for R&D processes involved in the development of one or in some case more products within a firm. We can therefore conclude that many system dynamic models of R&D have been developed on the firm level. The question arises: what about R&D on a more aggregated level?

Since this thesis deals with the development of a system dynamics model of R&D on the national level, the following section focuses on models in the literature dealing with R&D and innovation models on a national, regional or industry level. Surprisingly, few system dynamics models dealing with government policy for R&D on a system of innovation level could be found in the literature. The following sections briefly describe and discuss some of the models and a number of findings that resulted from them.

3.6.2.1 Regional innovation system of Jilin province in China

Zhang et al (2004) explore the definition and function of the regional innovation system as well as analyse its framework, operation mechanism and systemic characteristics.

Zang et al state that the system dynamics approach coincides with the regional system of innovation framework. Regional innovation systems are developed on the base of feedback chains existent in the system that ultimately results in a more complex structure within the system, i.e. feedback complexity. The aforesaid therefore indicates to the existence of complex, interdependent relationships between elements in the regional innovation system, of which many have non-linear characteristics.

The model divides the regional innovation system into five subsystems, namely:

- *innovation environment subsystem:* regional innovation resources distribution, regional economy and regional innovation culture
- *government activities subsystem:* activities and functions of government as a unit of institutional innovation
- *enterprise activities subsystem:* activities and economic effects of innovative enterprises
- *research organisation activities subsystem:* activities and effects of research organisations as units of knowledge generation when participating in innovation alliances; and
- *intermediaries subsystem:* functions of intermediaries when providing innovation services and improving regional innovation.

From the analysis, a model with 27 equations and 67 level variables was developed (for the full model, see Zang et al 2004). The model's output and response is gauged by measuring the following four variables:

- *GDP:* the regional macro-economic operation effect as a whole

- *number of intelligent workers:* this is an important resource of innovation that reflects the region's ability to train, maintain and attract talented human resources
- *management benefit of government:* measurement of government working efficiency and of the corresponding ability of the regional innovation system to function; and
- *efficiency of R&D:* a variable reflecting the abilities of research organisations for the co-operation in innovation and industrialisation as well as the intention and conformity of regional technological innovation resources.

The model was used to analyse the development, operation and performance of the regional innovation system in the JiLin province. The model was also used to make policy recommendations to the government regarding the development of the regional innovation system.

The above section therefore concludes that the system dynamics methodology has been implemented successfully in the development of a regional system of innovation. The model was used as an analysis tool to examine the development, operation and performance in the JiLin province in China. The model is extremely relevant to this study as the development of the model illustrates the applicability and usefulness of a system dynamics model of innovation activities on a meta-level. It should also be noted that more accounts of such models exist.

The following section describes a system dynamics model that has been developed to simulate and analyse the long-term investment policies in military R&D in Taiwan.

3.6.2.2 Long term investment in military R&D in Taiwan

As Taiwan progressed from a developing country to a Newly Industrialised Country (NIC), its weapons acquisition policy evolved from the initial foreign weapon acquisition policy to independent R&D. The weapon R&D budget share in Taiwan's major weapon development budget thus gradually rose from 0% to 0.5% of GDP. Taiwan has progressively accumulated sufficient knowledge and experience of the key technologies to develop its own weapon systems. Technological maturity allowed Taiwan to purchase more advanced weapon systems. However, since pressures from the international armaments market forced the weapons acquisition policy back towards the earlier foreign weapons purchasing policy, R&D budget share dropped to below 0.3% of GDP.

Jan and Jan (2000) developed a system dynamics model depicting the effect of long-term investment in military R&D in Taiwan. They believe that R&D should exist for a country to be able to develop or acquire high technology. The investment in R&D capacity comes at a very high cost and accumulates slowly. If not supported, the capacity will vanish quickly. The different R&D purposes, functional demands, and system complexities differentiate the applied sciences in weapon systems R&D technology from those in ordinary civilian industries. Foreign R&D skills cannot be transplanted directly and a nation must be completely self-reliant.

The following stock and flow diagram was taken from Jan and Jan (2000). The model simulation indicates that where key technologists vanish, decades are required to make up for the loss. Reaching a balance between foreign acquisition and self-development therefore proves a long-range strategic problem for Taiwan.

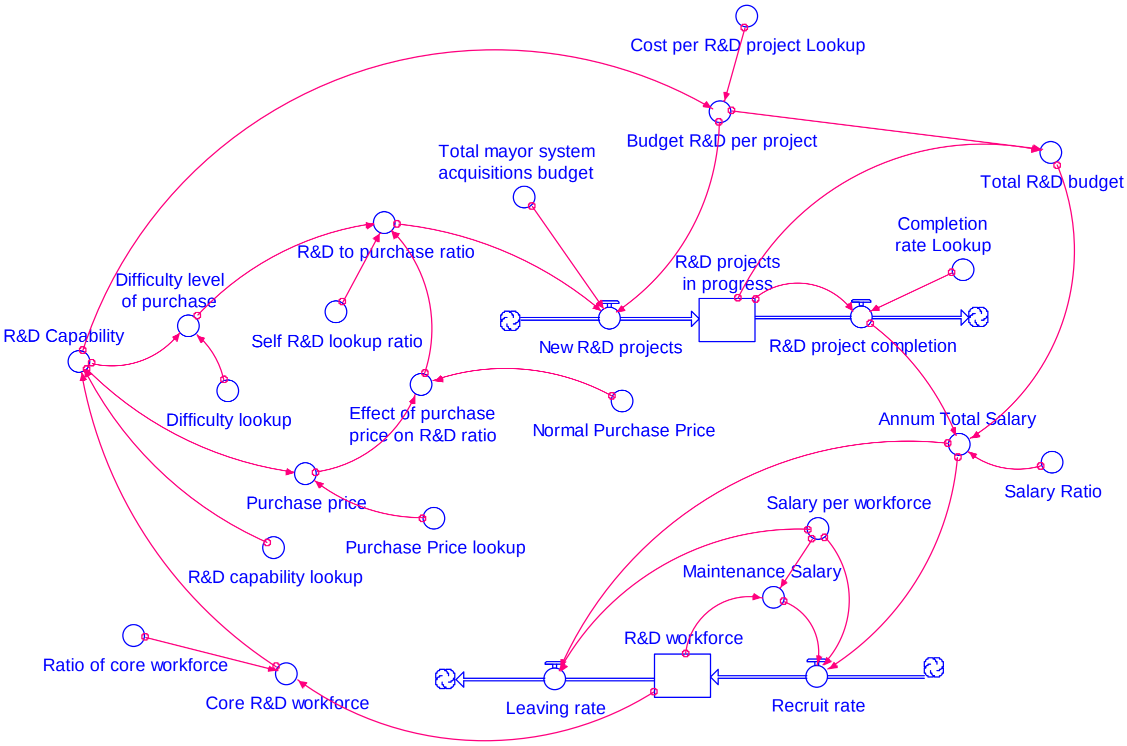

Figure 3-6: Stock and Flow Diagram from Jan and Jan's (2000) Model

The Taiwanese experience reveals that R&D capacity is a key factor in weapons acquisition policy making for NICs. Such a capacity is slow to establish and costly to maintain. Inappropriate policies also have the ability to erode such capacity rapidly. This study applies system dynamics methodology to analyse the problem. It assists in examining the characteristics of weapon system development and constructs a dynamic model to improve understanding of the structure of weapon system development. The study also provides a basis for a clearer and broader understanding of future policy making considerations for NICs.

A similar model has also been developed for the South African armament industry (see Buys, 1990).

This section discussed and illustrated the use of a system dynamics model to develop a model of the development of R&D capacity in the armaments industry. Many of the concepts included in the model also apply to general R&D capacity development, an issue that will be discussed in more detail in the model development chapter in this thesis.

The following section describes a system dynamics model developed to simulate and analyse funding decisions in R&D investment in South Korea.

3.6.2.3 Leverage strategy to R&D investment in South Korea

Over the years, the Korean R&D investment institution has made substantial commitments to the expansion of total funding packages awarded to selected national R&D projects. Increases in the dollar amounts of these targeted projects resulted in the stage-by-stage evolution of Korean technologies. What demarcates the Korean national R&D investment institution from its international competitors is the unusually high discrepancy between the total investment stock and consequential research results that have the benefit of international recognition (Park, Oh and Kim, 2004).

To various studies conducted before the system dynamics model was created failed to address these structural issues inherent in the Korean R&D system, especially on the dynamic structure of making funding decisions. Although some extant studies noticed the ongoing decisional problems within the Korean national R&D system, a knowledge gap was identified that no empirical simulation models had been fully developed or tested that could detect underlying structural anomalies rampant in the R&D system.

Park et al (2004) identified three cyclical loops of strategy, structure, and efficacy. These interact continuously with each other to produce both intended and unintended outcomes of national R&D projects. The causal loop diagram is depicted in Figure 3-7.

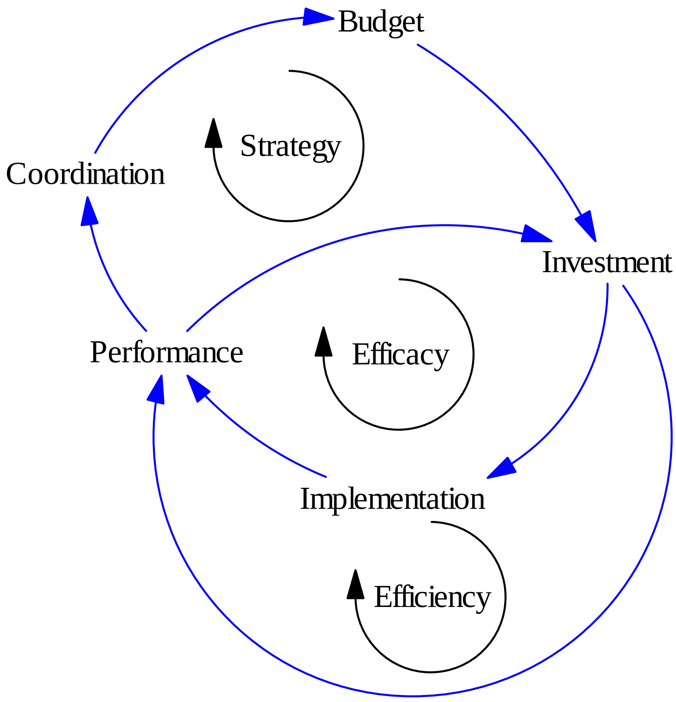

Figure 3-7: Three Cyclical Loops of Strategy, Structure and Efficacy (Park et al, 2004)

Research performance is examined both quantitatively and qualitatively. The quantitative option simply implies count all completed projects within a given deadline, while qualitative measurement relates to researchers' attitudes.

The number of completed projects measures research performance by researchers' actual attitudes. The actual attitudes concept incorporates both will and real activity levels held by researchers and are expressed in terms of the level of confidence on research performance held by researchers multiplied by their actual research activities. It is assumed that the level of confidence is correlated with researchers' positive attitudes toward their projects. The efficacy loop has the following stocks and flow structure:

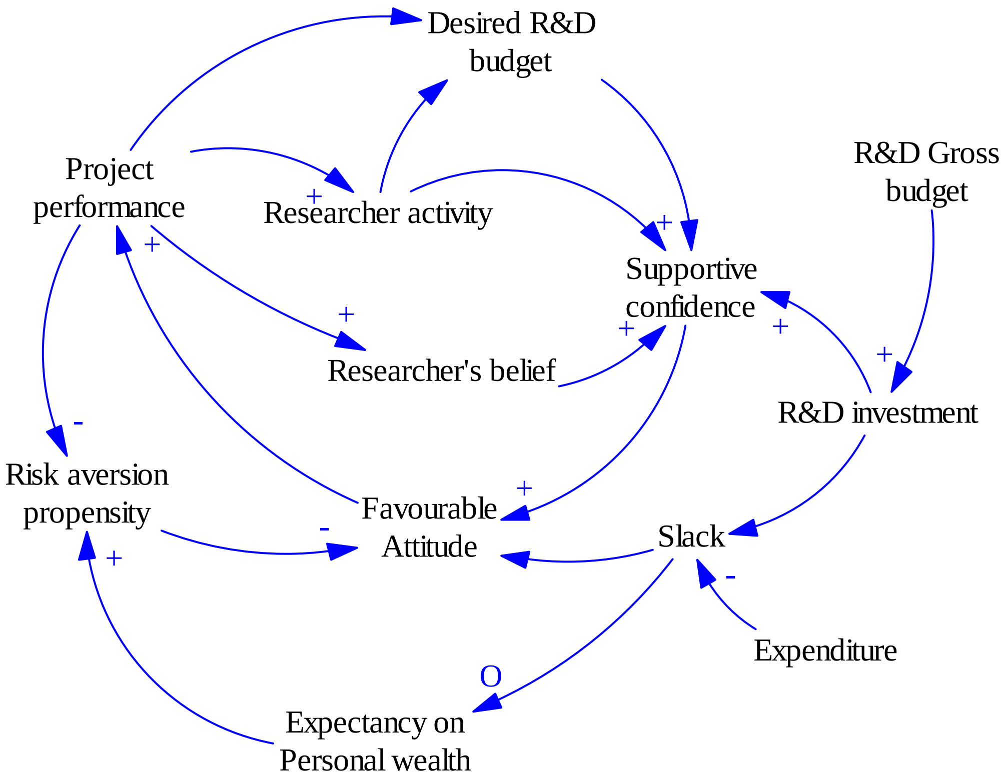

Figure 3-8: The Efficacy Loop (Park et al., 2004)

NIS projects can be classified into competency building programmes and strategic technology development programs.

Capacity building programs include foundational science, human resource development and short-term projects. It is thus assumed that knowledge accumulation will grow exponentially past a specific tipping point, although this will not be visible in early stages.

Strategic technology development programmes usually include long-term projects for developing strategically targeted new technologies, although they quickly adapt to changing environments. It is assumed that the finished results of each project might be extremely visible, although new technologies can easily become obsolete when the market is saturated. In the long run, strategically developed technologies disappear from the market. Strategically developed technologies maintain linkages between different dimensions of technologies. In a linear relationship between stages of technological development, basic technology serves as a basis for application and add-on technologies. Absorptive capacity determines the learning capacity and how successful it is applied in the domestic environment.

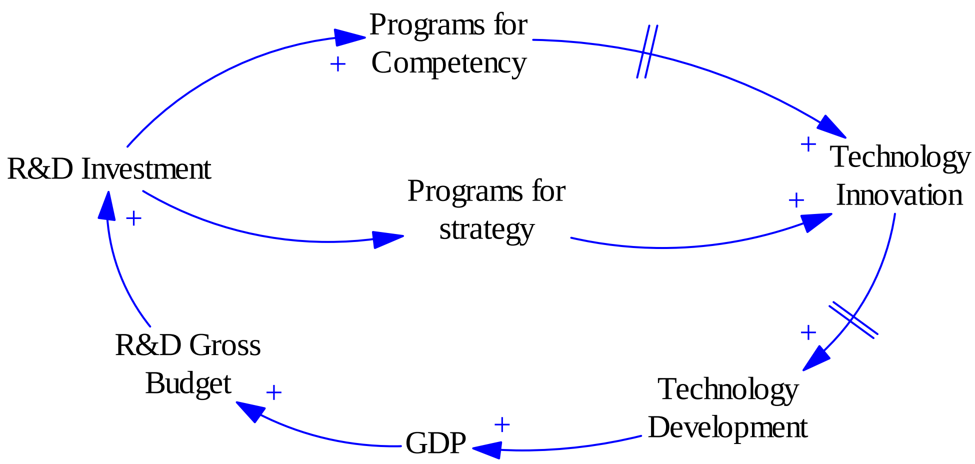

Figure 3-9: The Efficiency Loop (Park et al., 2004)

The model simulation runs yielded output which showed that emphasis on application and 'add-on' or developmental technologies resulted in long inter-stage temporal gaps, although their short-term economic benefits were obvious.

In a similar vein, myopic investments in specifically targeted technologies in strategically designed R&D projects led to decreasing levels of absorptive capabilities, whereas far-sighted investments brought about adversary results. Finally, it was found that an initial investment package did not have significant impact on the level of researcher efficacy, which predicts a more complex dynamics of researcher motivation structures than usually assumed.

The above section therefore holds that a system dynamics model explaining the influence of R&D investment in the South Korean innovation system has been developed. This model simulates the effects of different types of R&D investment decisions on the R&D capacity of South Korea. It should also be noted that many qualitative aspects, such as 'researchers' beliefs', etc. are included in the model. The use of unquantifiable concepts in system dynamics models has unleashed much criticism in the approach.

3.6.3 Summary

This section thus describes how system dynamics models have been implemented to foster a better understanding of dynamics in R&D systems. Models developed for R&D on the project level as well as on the firm level were scrutinised.

The second section focussed on existing models developed for the analysis of system dynamics models of R&D on the macro level. These models clearly indicated that R&D investment plays a crucial role in the development of R&D capacity in an innovation system. This was especially clear in the model developed for the Taiwanese armament industry as well as the model for R&D investment in the South Korean R&D system.

The section therefore concludes that the system dynamics methodology has been employed previously for the implementation of an R&D model of a system of innovation. Zhang et al (2004) specifically comments on the use of the system dynamics approach within a system of innovation framework. The prevalence of feedback chains in innovation systems cause structural and behavioural complexities results in non-linear interrelationships between elements in innovation systems.

3.7 Models of the South African System of Innovation

The following sections focus on a number of models and accounts that have been developed especially for the South African system of innovation.

3.7.1 The technology colony framework

South Africa has been described as a technology colony [De Wet, 2001], i.e. countries where the NSI is so poorly developed that it is dependent on foreign technology. The product life cycle model for the technology colony is depicted in Figure 3-10.

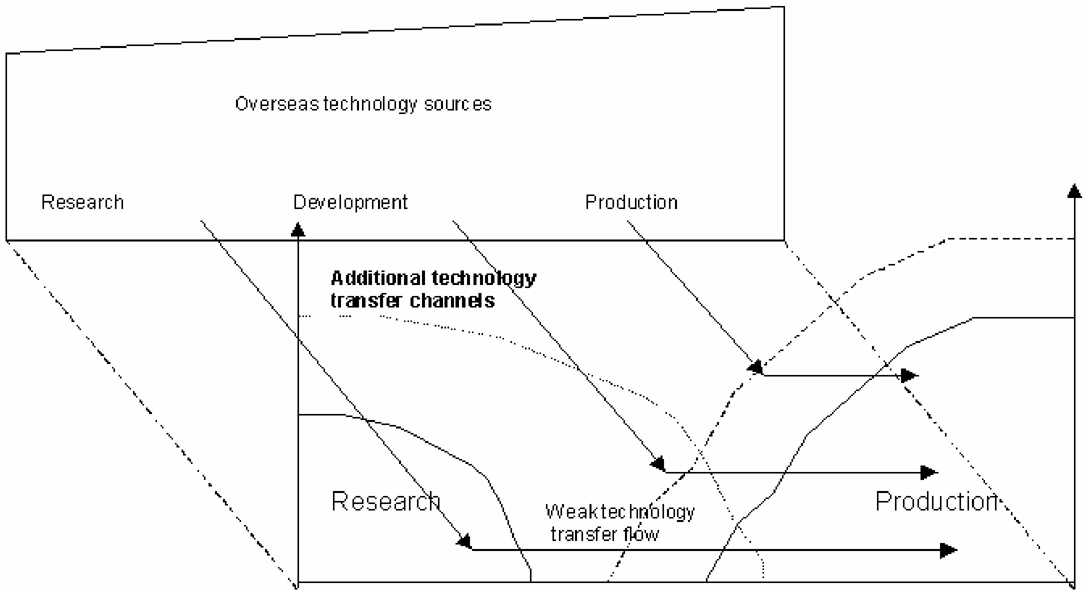

Figure 3-10: The Product Life Cycle with the Effects from Backwards Integration

A technology colony has the following features:

- the predominant industrial business activity is the manufacture and 'trade-in-final-products' end of the products lifecycle
- a small group of activities exist in the research end of the lifecycle. These are the R&D activities of tertiary education institutions; and
- there is a large flow from the developed world into the colony. This occurs in the form of licensed product designs, processes, subassemblies and final products, often implemented through a subsidiary or multi-national firm.

Although there is only a small insignificant flow from the R&D sector to the industrial sector, there is a certain degree of communication between local and foreign R&D institutions.

3.7.2 The system theory model of innovation

Buys (2001:2-3) proved that by reversing the linear model of innovation, technology colonies could attain technological independence. By applying the concept that the NSI consists of a set of interacting subsystems, Buys (2001:8-11) developed a five-stage process of backwards integration. He used his system theory model of innovation to characterise the South African system of innovation (Buys, 2004).

Buys (2001) proposed that the NSI can be defined to comprise the following subsystems:

- research
- technology development
- new product/process development
- product/process improvement
- the production and manufacturing; and
- the distribution, marketing, sales and services.

With De Wet's model of the technology colony in mind (De Wet, 2001), Buys went one step further by developing a model where a NSI is viewed as a set of functional subsystems interacting with each other and with foreign systems of innovation by transferring products, services, information and knowledge as depicted schematically in Figure 3-11 (Buys, 2002).

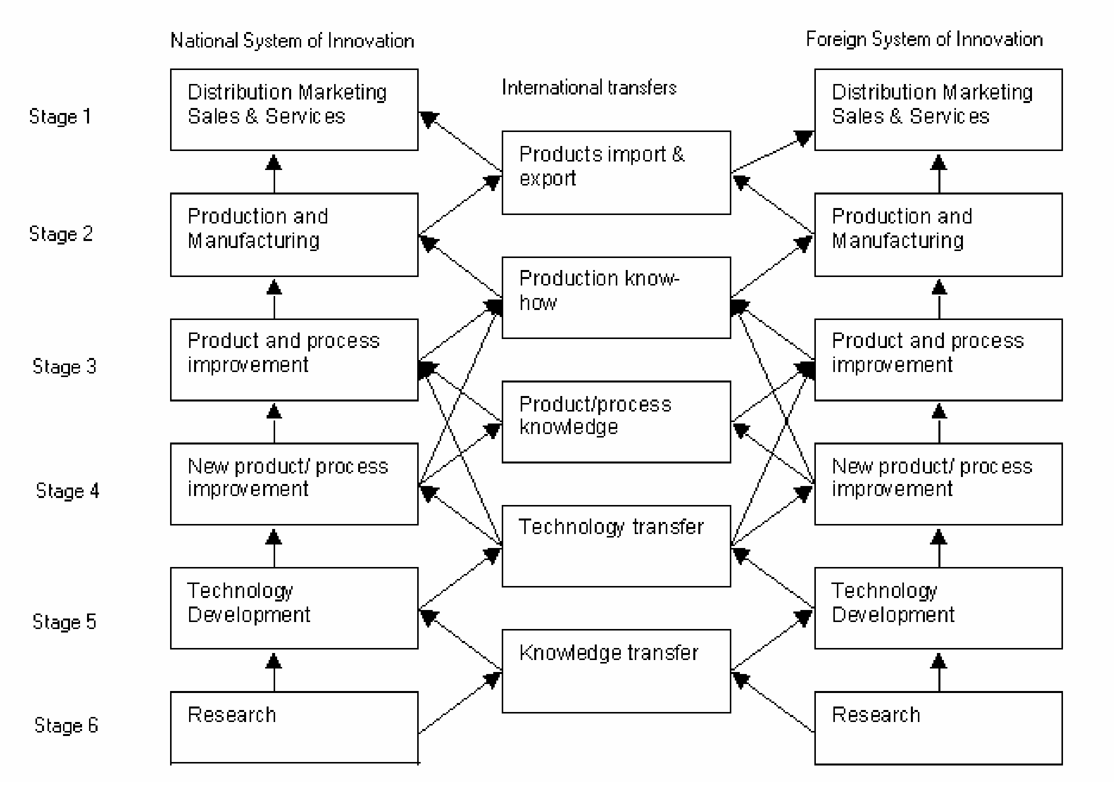

Figure 3-11: System Theory Model of the NSI

Buys applied the system theory model of innovation to the backwards integration process and identified five stages of industrial development:

- stage 1: local distribution, marketing, sales and after sales services as well as foreign products and services
- stage 2: local production and manufacturing of products and services using foreign process technology
- stage 3: local improvement of products and processes using foreign technology

- stage 4: local development of new products and processes using foreign technology; and
- stage 5: local technology development.

Buys classified South Africa to be in stage 3 of the backwards integration process. The advantages of being a technology follower might include that firms take even less time and spend less money to deploy innovation like in the case of Japan. Follower countries should however aim to progress through the stages of backwards integration to build competitive capabilities for the future.

3.8 Shortcomings of Current approaches – Knowledge Gap

The research survey concludes that there exists a vast literature of econometric models of R&D production as well as the economic contribution of R&D on a country's economy. The literature surveyed produced a small sample of a much larger literature on models formulated to explain productivity increases as a result of R&D and spillover effects. Many of these models were developed using the econometric approach where a number of inputs to a production function are identified, after which it is estimated to fit a curve. None of these models were developed from an NSI framework perspective. In general, these models thus lacked the inclusion of the feedback dynamics of innovation from a system perspective.

In 2002, Carlsson et al (2002:236) stated that the empirical analysis of studies carried out on NSIs involved mainly static data. Since then, not much progress has been made. This complicates the comparison of nations' relative positions over a longer time period. Another shortcoming of the empirical analysis of NSI studies is that many tend to be descriptive and consequently fail to capture the system's dynamic behaviour.

The lack of dynamic models is also noticed in the models dealing with the South African system of innovation. These models are successful in what was set out to accomplish, thus describing the character of the system and deriving strategies from the descriptions. These models are however not equipped to capture the dynamic characteristics of the system and to simulate the long-term effects of changes to the system. These models also fail to provide a dynamic account of the effect of R&D investment on R&D activities within the South African NSI.

A number of models of systems dynamic models of R&D on an aggregate level were discussed. The models indicated that system dynamics can be implemented to build a useful model of R&D and innovation on a macro level. Although system dynamics has been used to formulate strategy within the South African S&T system, no model of R&D output as a function of long-term effects of investment in R&D is presently available for South Africa.

A knowledge gap is therefore identified from the models discussed in this section, thus none of these models describe the systemic nature, interdependence of elements and the prevalence of feedback loops in the R&D function within a NSI framework adequately.