Presenting and analyzing Research and Development dynamic structures in national innovation systems

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Abstract

The main objective of this paper is to develop a model of R&D performance in base of system dynamic approach and the creation of R&D output in the national innovation system (NIS). The purpose of the model is to simulate R&D output generated in the system of innovation specially in national level. The paper concludes with statistic analysis of model components and remarks relationships between variables affecting R&D measures in NIS.

Keywords

NIS (national innovation system); R&D (research and development); system; dynamic analysis

1.Introduction

Research and development (R&D) can be defined as any project to resolve scientific or technological uncertainty aimed at achieving an advance in science or technology. Advances include new or improved products, processes and services or in other words it can simply be defined as technical pursuit of a new technology or decision to support a strategic goal. R&D is concerned with three strategic purposes (Roussel et al, 1991):

· To defend, support, and expand existing business

· To drive new business

· To broaden and deepen a company's technological capabilities

Inherently then, R&D involves both selection decisions at a given instance and the management of the competence development over time.

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 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.

It is important to see R&D structures via systematic viewpoint. Blanchard and Fabrycky believes that understanding and defining the objective of a system is integral when analyzing a system (Blanchard and Fabrycky, 1998): "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." The purposeful action of a system is the function of a system. Forrester (1974) organizes a system in the following hierarchy of major and subordinate components. The closed system that generates behavior 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 paper's main goal is presenting of dynamic models for R&D structures within innovations systems specially in national level. We present this model in base of system dynamic approach and then we analyze R&D measures in statistics methods. In this relation, the remainder of the paper is organized as follows: literate review of innovation systems and their components with emphasis on dynamic models for R&D, research methodology by creating theoretical model of R&D dynamic model , model analysis via statistics methods, and sum up and suggestion for further works.

2.Literate Review

2.1. National Innovation Systems

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 National System of Innovation(NSI), Nelson and Rosenberg (1993) defines the concept of innovation quite broadly by including not only the first introduction of a new product to the market.

• 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).

Edquist (1997) 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. 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.

2.2 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) disputes the use of studying innovation systems on a national level, whereas Nelson and Rosenberg (1993) 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. Carlsson et all (1992) 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) points out that although globalization and regionalization 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.

2.3 System Dynamics Models of R&D and Innovation Systems

Roberts (1978) states that once system dynamics work was initiated at MIT, students began to notice potential applications in the areas of technology organizations 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 categorizes 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.

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).

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.
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.
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. 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.
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 1.

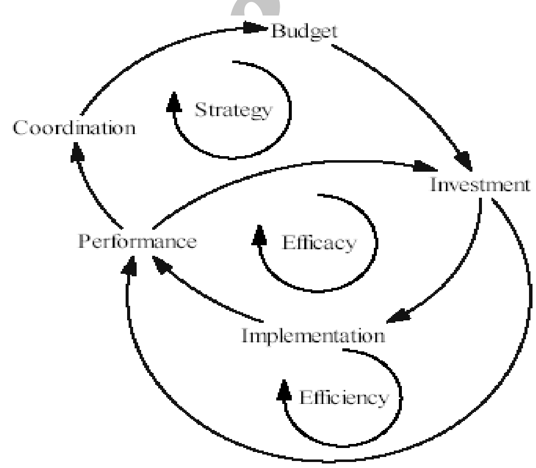

Figure 1: Three Cyclical Loops of Strategy, Structure and Efficacy (Park et al, 2004)

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 causal structure in figure 2.

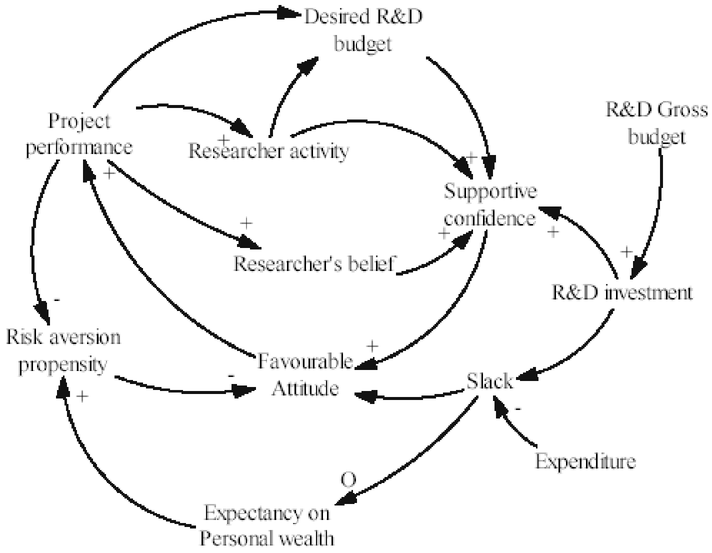

Figure 2: The Efficacy Loop (Park et al., 2004)

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. 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.

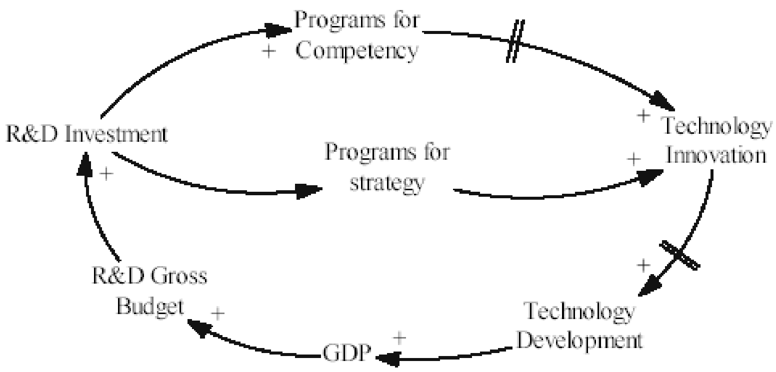

Figure 3: The Efficiency Loop (Park et al., 2004)

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.

2.4. The system theory model of innovation

Buys (2001) 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 developed a five-stage process of backwards integration. Buys 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 4 (Buys, 2002).

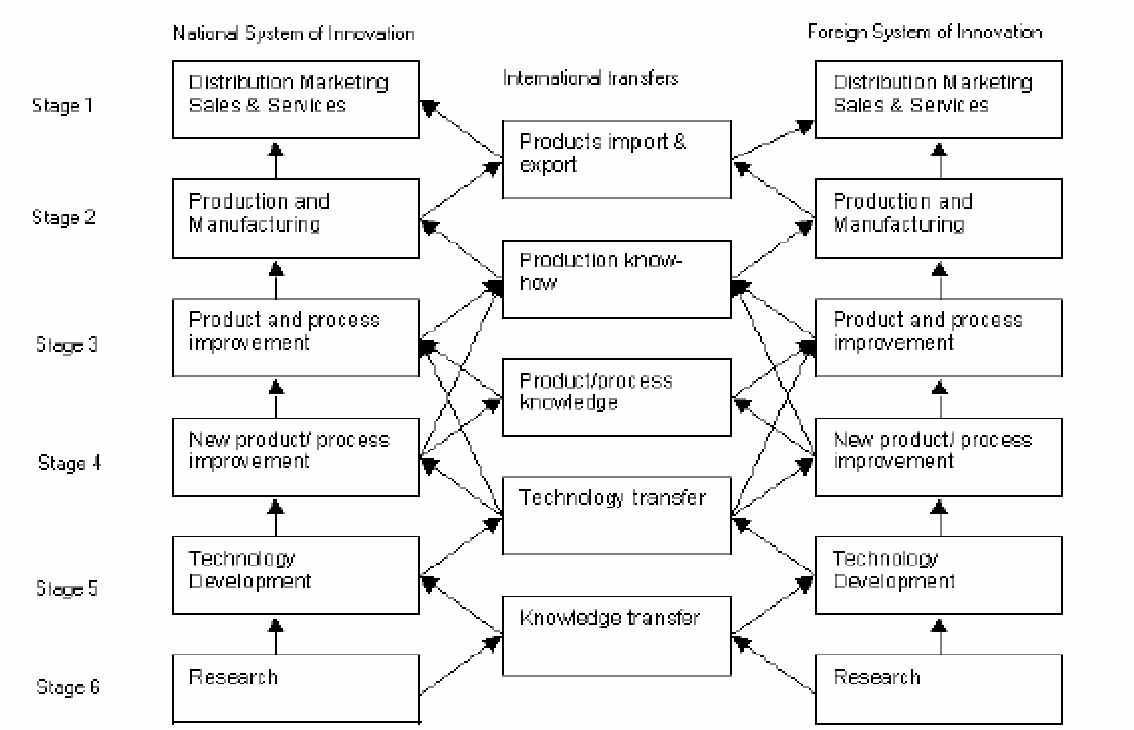

Figure 4: System Theory Model of the NSI

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.

3. Research Methodology

3.1. Theoretical Underpinning of the Dynamic Hypothesis

Freeman (1992) believes that although R&D is not the only source of technical change, it remains one of the main points of entry for new scientific development as well as the main focus for the development of new products and processes in most branches of industry. It is crucial for any nation to develop an R&D capacity. The literature study concluded that an R&D investment aimed at developing an R&D capacity to create new knowledge as well as the ability to absorb new knowledge is important for a country's economical development ((Jones, 1995), Du Toit (2004)). History plays an imperative role in the level of a system's development (Edquist, 1997). Within a complex system, events and developments are path dependent and take place over time. Small events are reinforced through positive feedback loops and become crucially important. The model developed in this section acknowledges the important role that the accumulation of knowledge and skills play in the development of an R&D system. Romer (1990), Porter (1990), Lundvall (1992) and Johnson (1992), Niosi (2002), Nasierowski and Arcelus (1999) agree on the presence of human resources as an important input to the performance of R&D. Human resources engaged in R&D activities over a period of time, resulting in both the human resources building up and encapsulating tacit knowledge, know-how and skills. All the above are developed through experience. Non-codifiable knowledge or tacit knowledge encompasses the following:

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

3.2. The internal generation of new knowledge

The definition of R&D as documented in the Frascati manual states that R&D comprises the creation of knowledge, including knowledge of man, culture and society through the use of the stock of knowledge to devise new solutions (OECD, 2002c). This definition highlights the central role that knowledge plays in generating new knowledge. Romer (1990), Lundvall (1992) and Rosenberg (2000) also support this view in their work. The literature also acknowledges the role of capital resources (Christensen, 1992) and capital assets as an important input to the R&D process ((OECD , 2002), (Porter, 1990). In the formulation of the model, capital assets stock is modeled as an aggregate stock of previous investment in equipment, land and buildings used by human resources to perform R&D.

The figure 5 captures this dynamic hypothesis

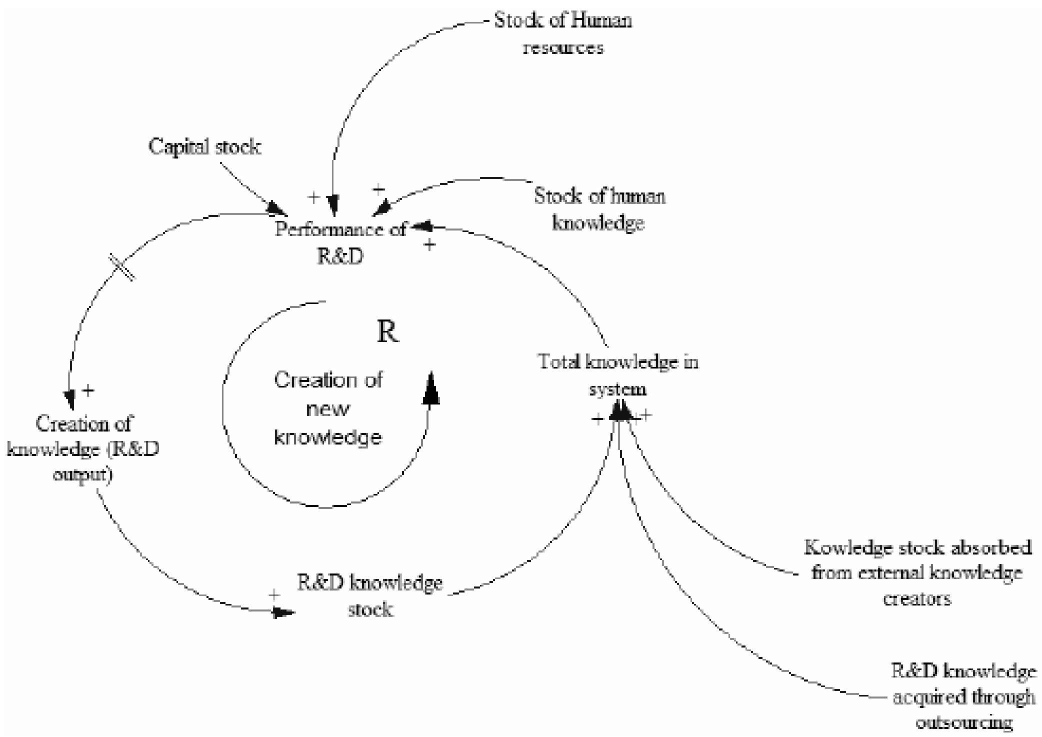

Figure 5: The creation of knowledge by utilising existing knowledge

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

3.3. The absorption and acquisition of external knowledge

Werker and Fritsch (1999) provide a detailed explanation of the factors that influence the generation of knowledge. They believe that an organization's performance with regards to the generation of knowledge depends on its ability to combine internal knowledge and external knowledge in a new way. This thus proves that the performance of R&D is also dependent on the acquisition and absorption of knowledge from external sources. It is also a direct implication that the organization must at least possess the ability to identify, absorb and apply new knowledge for its own means, a process commonly referred to as the 'absorptive capacity' (Cohen and Levinthal, 1990). Fritsch and Werker (1999) state that besides the ability to absorb information, the amount of knowledge actually transferred into the organization is also dependent on the quantity, quality and the kind of knowledge available in the external environment. The figure 6 represents a dynamic hypothesis as derived from the theory

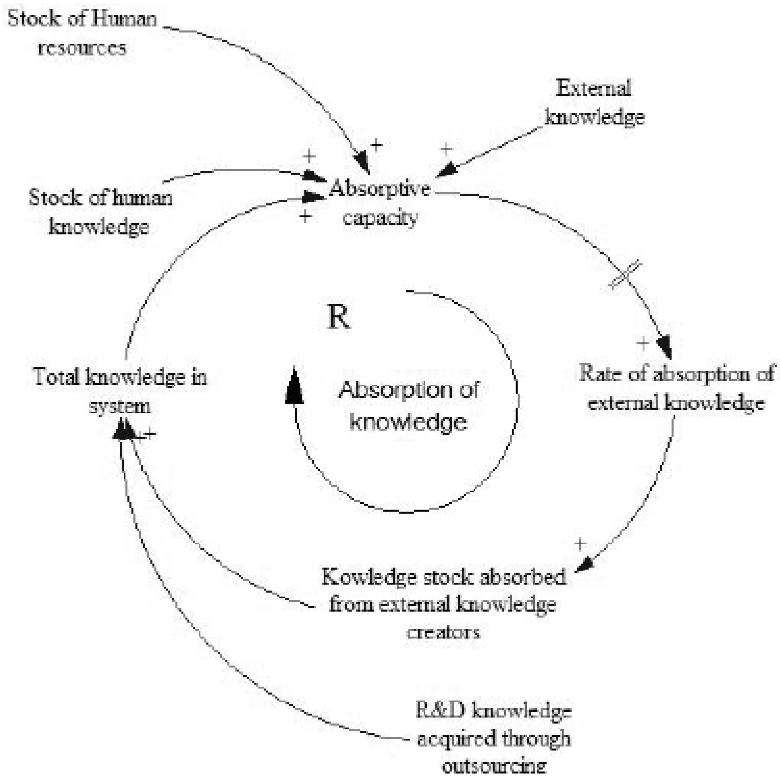

Figure 6: Absorption of Knowledge through Knowledge

The dynamic hypothesis displayed in Figure 5-5, represents a reinforcing loop for building system knowledge through the absorption of external knowledge.

The loop displays dynamics involved in the absorption of knowledge from the external environment. This can only be achieved if the system has a level of absorptive capacity. The dynamic hypothesis assumes that the system's absorptive capacity depends on the presence of human resources, tacit knowledge and experience as well as previously generated and accumulated knowledge in the system. The absorptive capacity is also influenced by the external knowledge stock's characteristics. The system draws on its absorptive capacity to accumulate knowledge from the external environment. As the successful performance of R&D depends on the successful integration of external and internal knowledge stocks, the following section deals with integrating the two reinforcing feedback loops that have been derived.

3.4. The integration of knowledge stocks

This section develops a dynamic hypothesis for the development of new knowledge. Figure 7 displays a dynamic hypothesis that incorporates the reinforcing loops derived from previous sections.

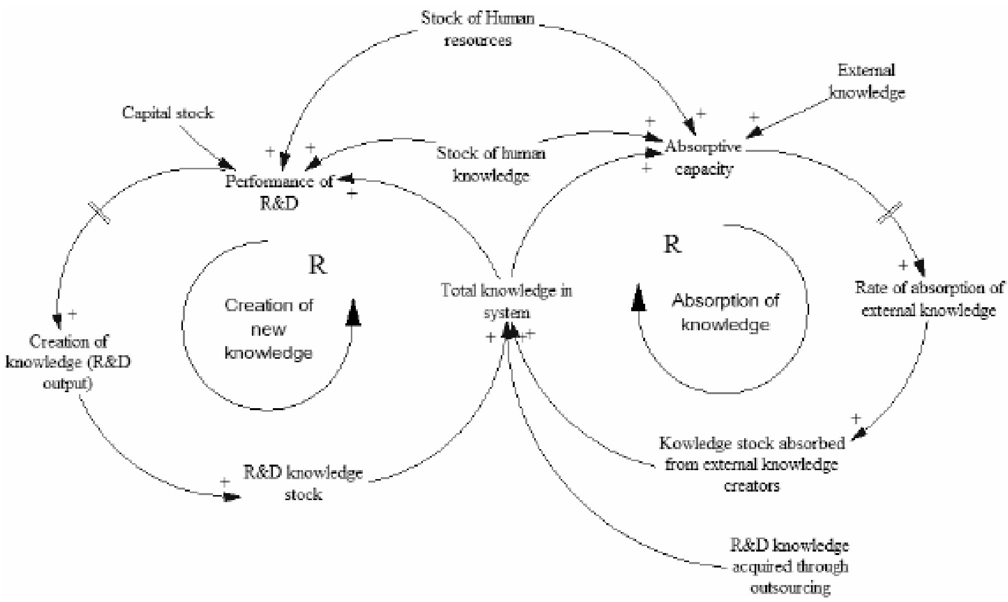

Figure 7: Casual loop diagram of an R&D system

Figure 7 depicts a Casual loop diagram (CLD) for integrated feedback loops of the creation of new knowledge and the absorption of knowledge. The creation of knowledge and the absorption of knowledge depend on the system's previous investment in human resources, the corresponding human knowledge stock as well as the current knowledge stock, i.e. the R&D knowledge stock and integrated external knowledge stock. The CLD clearly depicts the relationships *between variables and the system's feedback structure. CLDs however do not provide a way of communicating the model's physical structure. It also fails to capture the accumulation of goods as a result of flows in the system. The CLD developed up to this point is consequently expanded into a stock and flow diagram.*

4. Research funding and model analyzing

The following output is obtained from the model. The accuracy with which the trend is recreated is considered to be sufficient for the purpose of this study. A visual inspection indicates that the general trend is recreated quite well. The actual data gathered is however subject to an amount of fluctuation. The coefficient of determination (2 R), the fraction of the variance in the data explained by the model, is computed at 0.46, which indicates that the average of the model runs equals contains roughly 46% of the variation in the actual data.

The production function for the creation of patents in the public sector differs from production functions estimated in the public sectors. This can be ascribed to the lack of a measure for the absorbed knowledge in the public sector due to experimental development. The expression developed does therefore not include the feedback loop from the absorption of knowledge, as developed in the conceptual model. The expression is a simpler one, only taking into consideration the following:

- *R Patents: R&D output rate in the system (patents)*
- *S FTE: Number of researchers in the system*
- *A ExpDev: fraction of funding directed towards experimental development; and*
- *A State: the ratio of research expenditure funded by the state, assumed to be directed towards non-contract research.*

A multiplicative model is developed for the development rate of papers per fulltime person working in the system:

$$\frac{R_{Patent}}{R^*_{Patent}} = b * \left(\frac{S_{FTE}}{S^*_{FTE}} * \frac{A_{ExpDev}}{A^*_{ExpDev}} * \frac{A_{Statet}}{A^*_{State}}\right)^a$$

This expression is linearised by taking the log-linear form:

$$\ln\left(\frac{R_{Patent}}{R^*_{Patent}}\right) = \ln(b) + a * \ln\left(\frac{S_{FTE}}{S^*_{FTE}} * \frac{A_{ExpDev}}{A^*_{ExpDev}} * \frac{A_{Statet}}{A^*_{State}}\right)$$

The following expression is thus used to perform the regression for estimating the parameters. The regression is executed and the following estimates for the parameters are obtained: (see Table1)

Table 1: Regression Output of the Patent Creation Rate in the Public Sector

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                         The REG Procedure
                           Model: MODEL1
                    Dependent Variable: Rdout

          Number of Observations Read              20
          Number of Observations Used              20

                       Analysis of Variance

                                  Sum of           Mean
Source                  DF       Squares         Square    F Value    Pr > F

Model                    1       1.05369        1.05369      27.02    <.0001
Error                   18       0.70194        0.03900
Corrected Total         19       1.75563

          Root MSE              0.19748    R-Square     0.6002
          Dependent Mean        0.12720    Adj R-Sq     0.5780
          Coeff Var           155.24845

                       Parameter Estimates

                         Parameter       Standard
Variable          DF      Estimate          Error    t Value    Pr > |t|

Intercept          1       0.02274        0.04852       0.47      0.6450
ftepattypestate    1       1.02316        0.19683       5.20      <.0001

                         The REG Procedure
                           Model: MODEL1
                    Dependent Variable: Rdout

                    Test of First and Second
                      Moment Specification

                    DF    Chi-Square    Pr > ChiSq

                     2          2.11        0.3488

                     The AUTOREG Procedure

                 Dependent Variable    Rdout

               Ordinary Least Squares Estimates

      SSE                     0.70194207    DFE                        18
      MSE                        0.03900    Root MSE              0.19748
      SBC                     -4.2437275    AIC                -6.2351921
      Regress R-Square            0.6002    Total R-Square         0.6002
      Durbin-Watson               1.5178    Pr < DW                0.0875
      Pr > DW                     0.9125
NOTE: Pr<DW is the p-value for testing positive autocorrelation, and Pr>DW is the p-value
for testing negative autocorrelation.

                 Q and LM Tests for ARCH Disturbances
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The Total Regress R-Square 0.6002 statistic indicates that the model accounts for 60% of the variation of the percentage time spent by staff on R&D activities. The variable included in the model (ftepattypestate) is highly significant. The Durbin Watson test statistic is 1.5178 with (Pr < DW = 0.0875 > 0.05 and (Pr < DW = 0.9125) < 0.95, which indicates that the model does not have autocorrelation. Colinearity tests conducted on the data revealed that all the condition indexes from the regression model are much smaller than 30. We can therefore conclude that no colinearity is present.

The test proved that the model residual is stationary and the variables are cointegrated, thus implying that the regression is not spurious. We can therefore conclude that the model is not spurious and that we can use the result to develop the model of R&D in the public sector further.The parameters have therefore been estimated for the following expression:

$$\ln\left(\frac{R_{Patent}}{R^{*}_{Patent}}\right) = \ln(b) + a * \ln\left(\frac{S_{FTE}}{S^{*}_{FTE}} * \frac{A_{ExpDev}}{A^{*}_{ExpDev}} * \frac{A_{Statet}}{A^{*}_{State}}\right)$$

5. Overall shortcomings of study

It was corrected for as far as possible by using the main data for the Human Resources count data in this sector. It was found that the methodological changes did not exist for the survey for the Public and Private sector. It is also important to keep in mind that the indicators used for the quantification R&D output are imperfect proxies of the level of R&D output produced in a sector. Although using patent and scientific paper output as measures of R&D output is a widely acknowledged and used measure, the relevance of using it in Iran (with a developing economy and R&D system) had to be tested. As no better source of data or of measuring R&D input or output could be obtained; the existing measures had to be used. Care must be taken with the interpretation of the results, as the time series data on which the regression was done spans only 20 years (20 data points), which could contribute to the over or underestimation of some of the parameters in the system. It is acknowledged that uncertainty exists regarding the estimated parameter values. A common problem in modelling social systems is the level of uncertainty as well as the difficulty of finding ways to quantify soft variables included in these systems. This model is no exception. The model fails to include the effect that soft issues might have on the percentage time that staff in the system will spend on R&D activities. Examples of these disregarded variables include institutional culture, changes in people's attitude towards R&D and policies implemented to urge R&D output, such as including R&D output by staff as a measure in their annual performance review. This list can be expanded. It is however impossible to obtain measures for these values over a 20 year period. This is just one of the difficulties experienced when modelling a social system. Conclusions that can be drawn from this section are that although this study does suffer from shortcomings, as much as possible was done to identify these issues and where possible all in the author's power was done to compensate for it or where no correction was possible, the limitations were clearly stated.

6. Future Work

The model developed in this thesis employs Frascati R&D survey data as well as patent and scientific publication output data. These are all standard R&D input and output indicators. This also opens up the possibility of applying the model to other countries. Where better continuity existed in the methodology followed, more developed countries could facilitate a more complete set of time series data from R&D surveys. In this instance, the possibility arises that the model could be applied on a more detailed level of aggregation, such as a scientific field level.

Future work can also include expanding the model from being merely expenditure driven to including demand functions for R&D expenditure, incorporating a feedback loop from the R&D activities in the system. Future work can incorporate the effect that the training of skilled human resources. Future work can also include the model's R&D output being linked to an econometric model of the GDP growth of a country. The improved model could incorporate a feedback to R&D expenditure as a percentage of GDP.

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