Investigation of the Critical Factors in the Early Stage of the Innovation Process in Biotechnology: A System Dynamics Approach

Elham Tayaran

A Thesis
in
the Department
of
Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science
(Industrial Engineering) at
Concordia University
Montreal, Quebec, Canada

September 2011

Concordia University
School of Graduate Studies

This is to certify that the thesis prepared,

By: **Elham Tayaran**

Entitled: **Investigation of the Critical Factors in the Early Stage of the Innovation Process in Biotechnology: A System Dynamics Approach**

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Industrial Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

Dr. Y. Zhang	Chair
Dr. N. Bhuiyan	Examiner
Dr. J. Struben	Examiner External
Dr. A. Schiffauerova	Supervisor

Approved by: Dr. A.K.W. Ahmed
MASc Program Director
Department or Mechanical and Industrial Engineering

Robin Drew
Dean, Faculty of Engineering and Computer Science

Date:

Abstract

Investigation of the Critical Factors in the Early Stage of the Innovation Process in Biotechnology: A System Dynamics Approach

Elham Tayaran

Introducing new products and innovations plays an important role in changing the competitive paradigm of biotechnology. Considering the valuable, rare and unique capabilities that innovations provide, the firms must understand the crucial factors affecting their success in innovation and how to manipulate these factors to enhance their performance. The two important stages of innovation are the front end of innovation and new product development. The first stage has an important effect on the outcome of the innovation process in biotechnology. Although the main factors that impact these firms' innovative activity in the early stage have been determined in literature, the details about the relationship between them still remain unclear. In order to facilitate a better understanding of the dynamic behaviour of these interactions and feedback mechanism, a System Dynamics simulation model, demonstrating the early stage of innovation in biotechnology, is developed. Using this methodology, we create a dynamic learning environment to explore the effectiveness of using either internal or external sources of knowledge as innovation strategies. Different scenarios have been tested to identify the impacts of the firm's innovation policy on its innovative performance. It was found that focusing on the exploitation of external sources of knowledge is a suitable strategy for an increase in the target knowledge, however it should be deployed considering internal factors such as the R&D expenditure and the firm's initial policy regarding either of the sources of knowledge. The main contributions of this thesis involve the identification of

the influential factors of the early stage of the biotechnology innovation process, the examination of their interactions and the final recommendations in terms of the firms' best innovation strategies under various conditions.

Acknowledgements

This dissertation would not have been possible without the direction, guidance, and assistance of many people, who I would like to deeply thank for their support.

I would like to sincerely thank my adviser, Professor Andrea Schiffauerova. I am very fortunate to have had an adviser who has helped me throughout this entire process with dedication and enthusiasm. Her insightful ideas and helpful comments have both helped me stay on track as well as giving me the freedom to explore on my own to get the most out of my research experience.

Professor Jeroen Struben, assistant professor at McGill University, has been very patient and accommodating, and a pleasure to work with. His insight and advice gave me a new perspective on the system dynamics approach, which helped me greatly while I formulated my model.

I am also grateful to Babak Shahmansoori and especially Nasim Barzanian for being wonderful friends and providing encouragement and practical advice. They were with me throughout this process and made this experience more enlightening, rewarding, and enjoyable.

I extend a very warm, grateful thank you to my parents, who gave me love, energy, and have always provided me with the emotional support I needed to get to where I am today.

Most importantly, none of this would have been possible without the love and companionship of my husband, Majid Hoseini. I cannot express in words all the encouragement, motivation and guidance he has given me throughout the past two years.

Finally, I appreciate this opportunity given to me by Concordia University.

Table of Contents

List of Figures

List of Tables

Chapter 1

1.1. Introduction

The importance of biotechnology activities in today's economy is emphasized by many authors (Afuah, 2002; De Carolis, 2003; Nicholls-Nixon and Woo, 2003; Zott, 2003; Galbreath, 2005, Baker, 2003). In Canada, biotechnology is considered as one of the most dynamic and strategic high-technology sectors, providing a significant contribution to science advancement and innovation, thousands of jobs, as well as large exports. Canada ranks second in terms of the number of biotechnology firms in the world, after the United States (Van Moorsel *et al*., 2007). The important role that biotechnology activities play in the Canadian economy is often discussed in literature (e.g. Traore, 2004). Canada's educated population, proximity to the United States, and availability of research and development facilities provide suitable conditions for successful biotechnology businesses to grow in Canada (Van Moorsel *et al*., 2007).

Obviously, Canadian firms' competitiveness in biotechnology highly depends on their ability to introduce new products and innovations. Innovations provide firms with valuable, rare and unique sources of capabilities to establish and sustain a competitive advantage (Barney, 1991). Innovative firms have the flexibility to change the existing technological patterns and shape new trajectories; such firms can easily reinvent themselves or develop new businesses (Burgelman, 1983). Innovations enable the firms to better satisfy the existing customers' needs and desires, to attract completely new customers and to enter new markets. The innovation process should thus receive the utmost attention in the corporate planning of every company.

The innovation process can be divided into two main stages: front end of innovation and new product development (Herstatt and Verworn, 2001). Front end of innovation precedes the formal and structured process of new product development. Its role is to produce ideas for new product concepts and to select the ideas that fit with the firm's business strategy. The importance of early stage activities in the success of the innovation process has been emphasized by many studies (Kim and Wilemon, 2002; Khurana and Rosenthal, 1998; Brem and Voigt, 2009). According to Cooper and Kleinschmidt (1994), "the greatest differences between winners and losers were found in the quality of pre-development activities." Even though the front end of innovation clearly creates the groundwork for the whole innovation process and is generally regarded as one of the greatest opportunities for improvement (Koen *et al*., 2001), the existing innovation models found in literature most often consist only of the new product development phase, while the front end of innovation stage is omitted or trivialized.

Decision making during the early stages of innovation has a great effect on the outcomes of technology-oriented companies. In biotechnology, which is highly research-intensive, the importance of research and development (R&D) activities and other practices that precede the formal process of the development of a new product is even more pronounced. However, research focusing on the biotechnology innovation process is quite rare. The innovation process in biotechnology is usually presented as a set of sequential activities (Hall and Baghchi-Sen, 2002). This linear model demonstrates neither the interactions of various determinants of innovation nor their influence on the firm's performance (Hall and Baghchi-Sen, 2002; Khilji *et al*., 2006). The real innovation process in biotechnology is more complex and iterative, and thus it needs to be

investigated through more appropriate methods to reveal all of its complexities and interdependencies.

The presented thesis intends to shed some light on this important but still undiscovered and blurred part of the innovation system. The thesis' main objective is to improve the understanding of the dynamics of the technological innovation through the design of the dynamic model representing the early stage of the biotechnology innovation process and through the subsequent simulation of this model. This will allow us to evaluate the factors that have an impact on the innovation process and to investigate those organizational policies that can enhance the outcome of this process.

This thesis is structured as follows: Chapter 2 reviews the related literature in innovation, with a special focus on the front end of innovation and reports the research questions; Chapter 3 presents a brief review of the main concepts of system dynamics methodology that are used in this research; Chapter 4 discusses the variables of the model, where their relationship is introduced and defined; Chapter 5 reports the results of the simulation and discusses the main findings; Lastly, Chapter 6 draws the main conclusions and suggests future research directions.

Chapter 2

2. Literature review and research objectives

2.1. Innovation

2.1.1. Definition

Being innovative, which means bringing new products into the market, is the key factor for organizations to maintain their competitiveness and survival in the market. New technologies, changing customer needs and the shorter life cycle of existing products force firms to introduce innovations in order to ensure their long-term sustainability. Otherwise, their place would be taken by other companies in the marketplace (Utterback, 1994).

Innovation is defined as the creation, development, and implementation of ideas that result in new or improved products. These ideas have practical or commercial benefits (Zaltman *et al*., 1973; Van de Ven, 1986; Damanpour, 1991), but not all of the ideas will end up as new products, and this is what constitutes the difference between invention and innovation. Based on Porter's study (1990), innovation consists of commercialization, whereas invention does not.

Another definition, proposed by Rainey (2005), states that "Innovation involves changes and improvements to technologies, products, processes, and services that result in positive contributions for customers and other constituents of business organizations".

2.1.2. History

The early innovation processes consisted of generating the ideas, testing the ideas,

developing the ideas into products, and eventually launching the products to a market. It was initially believed that it was only a few people (such as owners or stakeholders) who managed the process and who decided on whether to eliminate or keep a new project (Axelrod, 2008). As it can be implied, the important decisions and much of the innovation process depended highly on the knowledge of stakeholders.

Companies started accepting the funnel concept in their R&D process later, possibly in the 1930 or 1940s. The funnel concept made it possible for a firm to evaluate and develop many ideas while managing their costs and risks. The funnel is named based on the notion that at the beginning, a firm generates many ideas but only a few preferable ideas are eventually funnelled down through the R&D process. Since the progress through the R&D process accumulates greater and greater expenses, using the funnel concept helped with evaluating and ignoring less preferable ideas as early as possible in the new product development process, and thereby not only reducing the risk of developing undesirable new products, but also managing the cost. The above process was divided into two main parts around the 1930s or 1940s:

1) R&D process

2) New product development and commercialization processes.

The study of innovation has attracted much interest since the 1980s, when companies realized that their future was strongly affected by their ability to innovate. Books with titles like “Innovate or Die” (Matson, 1996) and quotes like “Company has two functions: innovation and marketing, everything else are just expenses” (Drucker, 1985) were just a few of the messages in the popular media of that period which blasted that innovation was vital.

2.1.3. Concept

Innovation is a process of converting opportunities into something for practical use (Tidd *et al*., 1997). In addition to creating a competitive advantage for companies, organizations also found innovation to be the major factor of economic growth and wealth of a nation (Galanakis, 2006). Other researchers (Lundvall, 1992; Porter, 1990; Freeman and Soete, 1997; Stoneman, 1995) considered innovation as the socio-economic driver for growth. As it was argued by Sundbo (1998) and also supported by Galanakis (2006), governments could even solve the economic and social problems of their countries, such as productivity and unemployment rates, by promoting innovation. However, they are not always successful (Galanakis, 2006).

Furthermore, two types of innovation are identified in literature based on the levels of innovativeness: incremental innovation and radical innovation. Incremental innovations are defined as minor improvements to existing products by using existing technology and are targeted for the existing market (Reid and de Brentani, 2004; Munson and Pelz, 1979). Radical innovations are characterized by fundamental changes in the technology used compared to the earlier product (Balachandra, 1997). Utterback (1994) called innovation "a life-or-death ingredient" for a firm. He suggests that incremental innovations are created in order to meet today's market demands, but in order to assure long-term survival, the firms need to generate radical innovations as well.

Innovation is a creative new solution in response to the frequently expressed and latent needs of customers and stakeholders. The importance of innovation has been widely recognized because of its major role for sustaining the prosperity of most organizations and companies. Considering the importance of having new products in the

market and the cash flow as a result, innovation is the solution to maintain a firm position to compete in a demanding world (Rainey, 2005). Innovativeness, in addition to establishing a basis for the firms` survival, provides them with the possibility to choose different options to satisfy their customers (Banbury and Mitchell, 1995; Koc *et al*., 2007). The effective deployment of innovation has been also identified as highly critical in order to enhance organizational performance.

2.1.4. Innovation theories

Given the importance of innovation, four different factors are considered as the drivers of product innovation (Cooper, 1999): technological advances, intensified customer needs, shorter product life cycles, and increased world competition. Furthermore, in order to understand the nature of innovation, several theories about the generation of innovation have been identified (Rothwell, 1994). These are classified into five groups as follows:

1. The Technology Push Theory

   This theory is based on a simple process in which a new product is pushed into the market by scientific and technological advances. This was a prevailing theory in 1950s.

2. The Market Pull Theory

   This theory involved also a simple process in which the need for a new product is created by the market at the time. The theory was dominant in 1960s.

3. The Coupling Innovation Process Theory

This theory, which is a combination push-pull theory, represents innovation as a sequential process but not necessarily a continuous one. It consisted of sets of interdependent stages and feedbacks to the previous stage. The connections between different parts of an organization, in addition to the relations with outside of the organization, create a complex net that link together the firm, the technological and scientific community and the marketplace (Rothwell and Zegueld, 1985). This theory was powerful during the 1970s and early 1980s.

4. The Functional Integration Innovation Process Theory

This theory drew inspiration from the Japanese in the automobile and electronics industries. In this theory, industries take advantage of the different stages of the New Product Design and Development (NPDD) process in a parallel mode, instead of in a sequential mode. The parallel approach provides a functional integration around a project that makes it possible to combine the expertise of the different specialists. This arrangement results in reducing the completion time and the rework that may be required at later stages of the process (Imai *et al*., 1985).

5. The Systems Integration and Networking Innovation Process Theory

This theory was founded based on the previous one, but it emphasizes the need for continuous change. Creating a network of suppliers, customers and other firms is suggested to resolve the problem of the higher complexity of new products. Furthermore, using new tools and technologies such as simulation and rapid

prototyping in the innovation process facilitates the process during the design and development stages. In fact, efficiency and speed in this process are the key benefits, derived mainly from continuous interactions across the innovation network.

6. The System of Innovation Theory

A new generation theory was developed in the 1980s and the 1990s. This theory aims at identifying the social and economic effects of the process that generate innovation across a nation. The sixth generation theory tries to relate the policy of innovation players and the ability of firms to innovate, which could affect the wealth of a nation (Sundbo, 1998; Edquist, 1997). As mentioned by Chang and Chen (2004) "the system of innovation approach is useful because it makes it possible to describe, understand, explain and influence the process of innovation". The factors that have an impact on innovation can be identified by studying the system of innovation (SI). One of the SI approaches is the national system of innovation. Chang and Chen (2004) quote Freeman's (1987) definition for NSI as "the network of institutions in the public and private sectors whose activities and interactions imitate, import, modify and diffuse new technologies".

2.1.5. Main components

Herstatt and Verwon (2001) proposed that the innovation process (see Figure 2.1) consisted of two main stages: Front End of Innovation (FEI) and New Product Development (NPD).

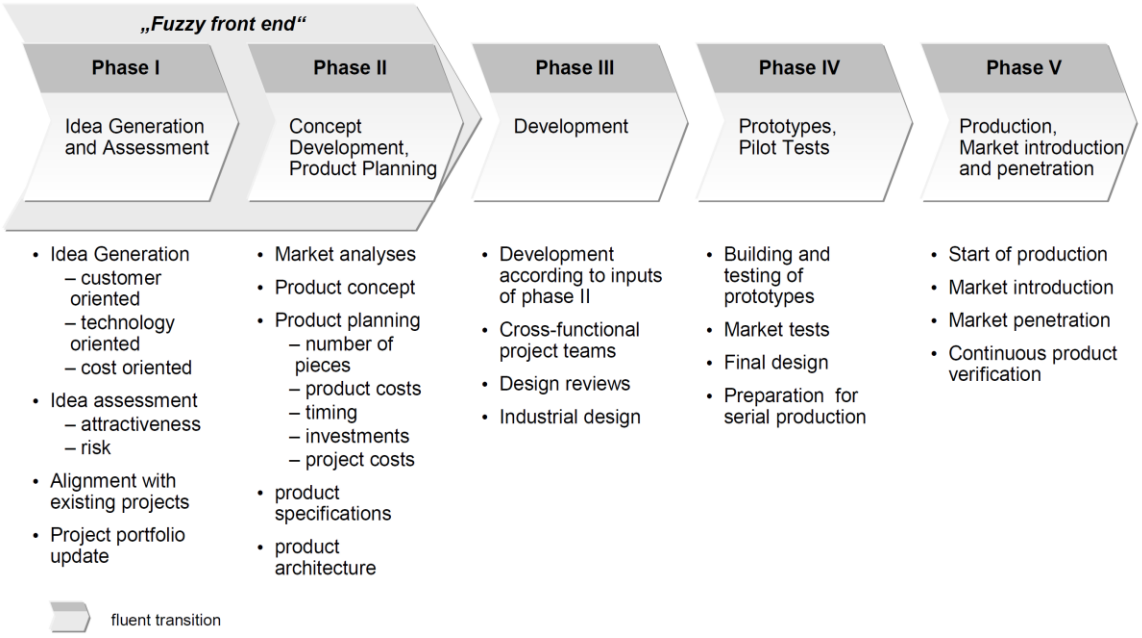


Figure 2.1 Two main components of the innovation processes (Herstatt and Verwon, 2001)

FEI, which was initially popularized by Smith and Reinertsen (1991), is the first stage of the innovation process. This stage is also addressed by the term Fuzzy Front End (FFE). According to Herstatt and Verwon (2001), idea generation and concept development are the main activities of the FEI. Additionally, this term is defined by Reid and de Brentani (2004) as the initial stage of idea development and the time and activities spent on the idea to make it ready for the development stage. FEI is then followed by the NPD stage. New product development is a stage in which a new product is developed and launched to the market. Substantial commitments in time and monetary terms are made during this stage. This stage compared to the earlier stage is more structured, goal oriented and linear. The NPD process has been studied in the scientific community from different angles and it has been subjected to modeling on multiple instances (Milling, 2002). The modeling-based research concentrated mostly on understanding the flows in

the innovation process from an operational level with a focus on project implementation and project management (Ford and Sterman, 1998). Thus far, the majority of researchers have addressed only the process of NPD and the dynamic relationships among them (Milling, 2002), and compared to NPD, FEI has been investigated to a lesser extend in the literature.

2.2. Fuzzy Front End

2.2.1. Introduction

As it was mentioned, the front end of innovation (FEI) is the first stage of the innovation process. This stage has been labelled by different terms in the literature, e.g. as the "early stages of the product development" (Nobelius and Trygg, 2002; Khurana and Rosenthal, 1998), "early phases of innovation, early innovation phases" (Lichtenthaler *et al.,* 2004), "pre-development" (Cooper and Kleinschmidt, 1994; Hüsig and Kohn, 2003), "pre-project activities" (Verganti, 1997), "Fuzzy Front End (FFE)" or "pre-phase 0" (Khurana and Rosenthal, 1997, 1998; Koen *et al.*, 2001). In this research, the terms "fuzzy front end (FFE)" and "early phase of innovation" are used interchangeably in order to refer to the first stage of the innovation process.

Frequently in the literature, the term "Fuzzy Front End" is used for addressing the first stage of innovation (Khurana and Rosenthal, 1997, 1998; Verwon *et al*., 2008; Zhang and Doll, 2001; Kim and Wilemon, 2002; Reid and de Brentani, 2004). The ambiguous term "Fuzzy" was first used by Smith and Reinertsen (1991). The term has been used differently by scholars in the field. For example, the word "fuzzy" emphasizes the uncertain and unpredictable nature of the front end of innovation process (Koen *et al.*,

2001). Likewise, fuzziness is considered by Kim and Wilemon (2002) as the ambiguity about technology, market, required resources and strategy-fit with the company. Zhang and Doll (2001) separated front end activities from front end fuzziness and argue that embedded fuzziness in this stage is due to environmental uncertainty. Finally, Hüsig *et al.* (2005) believed that this fuzziness comes from the perception that the front end activities are unstructured and not sequential.

The early phase of innovation has many definitions in the literature. The definition usually states the type of activities which take place in the early phase of innovation. Basically, "those activities that take place prior to the formal, well-structured New Product and Process Development" (Koen *et al*., 2001) are involved in the early phase. In other words, the early phase of innovation is the stage in which "organization formulates a product concept and determines whether or not it should invest resources to develop the idea" (Kim and Wilemon, 2002).

2.2.2. The early phase of innovation activities

The activity-based definitions of the early phase of innovation can help with understanding the activities which take place in this stage, however further clarification is required. Khurana and Rosenthal (1998) defined FFE as the stage which includes "product strategy formulation and communication, opportunity identification and assessment, idea generation, product definition, project planning and executive review."

According to Cooper (1988), the main activities are "generation of ideas, initial screening, preliminary evaluation, and concept evaluation". Similarly, Hüsig *et al*. (2005) proposed three general phases for the early phase of innovation: opportunity

identification, idea generation and finally concept development.

There is no common agreement as to the deliverables and results at the end of the early phase of innovation. Nevertheless, a well-defined product concept, product definition, development requirements and business plan with respect to the firm strategy are the common results of this stage (Kim and Wilemon, 2002). In addition, it was noted that the early phase of innovation or FFE should create a formal project plan to be executed in the development stage (Nobelious and Trygg, 2002; Koen *et al*., 2001; Khurana and Rosenthal, 1997). Moreover, deliverables at the end of FFE vary widely from industry to industry.

2.2.3. Importance of the early phase of innovation

Different studies claim that the performance of early stage activities significantly affects the success of the new product development process (Kim and Wilemon, 2002; Khurana and Rosenthal, 1998; Brem and Voigt, 2009). According to Cooper and Kleinschmidt (1994) "the greatest differences between winners and losers were found in the quality of pre-development activities." It is also argued that the final outcome resulting from the improvement in the early phase activities is much more valuable than the one which is brought about by the improvement in the design engineering process (Zhang and Doll, 2001).

The early phase of innovation is also called "the root of success" for discontinuous product innovation (Reid and de Brentani, 2004). The study of Cooper and Kleinschmidt (1988) revealed that generally the pre-development activities received fewer amounts of resources (only at 6% of dollars and 16% of man-days of the total) in comparison to the

practical stages of development and commercialization. Interestingly, by observing the success process, Cooper and Kleinschmidt (1988) noted that companies which succeeded in product development had spent twice as much money and time on the early phase compared with the money expended on unsuccessful projects.

The empirical findings from the study conducted by Verwon (2009) provide additional support for the importance of fuzzy front end activities for the project execution and project success. Nevertheless, even though many researchers emphasized the importance of the early phase of innovation, only a few references gave details on why it is in fact so essential. The following reasons were pointed out by Glassman (2009) to elucidate the vital role of FFE in the innovation process:

1. The costs involved in the innovation processes are the first obvious reason that clearly illustrates the value of the early phase of innovation.

2. The early phase of innovation is directly responsible for introducing high quality ideas into the innovation value chain or new product development (NPD) processes.

3. The early phase of innovation activities could reduce the uncertainty, which in turn can result in better achievements in terms of concepts, project plans, and selections of tasks for the project during the new product development process.

4. Finally, having a deep understanding of the early phase of innovation would aid companies in generating and selecting those ideas which could fit with the

company's capabilities and strategies.

Figure 2.2 shows the characteristics of fuzzy front end (Herstatt and Verwon, 2001). According to Herstatt and Verwon (2001), different methods and tools can be applied for managing innovation and analyzing the front end of innovation based on the amount of available information about the market and technology.

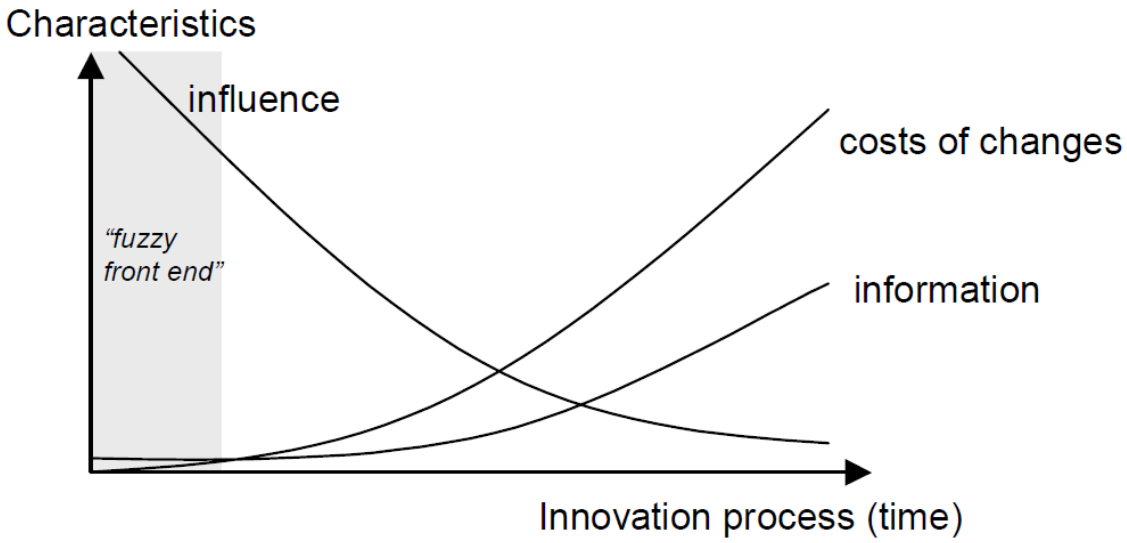


Figure 2.2 The characteristics of FFE during the innovation process (Herstatt and Verwon, 2001)

2.2.4. Structured or unstructured fuzzy front end

Using a structured or an unstructured fuzzy front end has been matter of debate between researchers. While some authors (Tang, 1998; Benner and Tushman, 2002; Reid and de Brentani, 2004; Nobelius and Trygg, 2002; Poskela and Martinsuo, 2009; Markham *et al.*, 2010) believed in unstructured early phase of innovation, some scholars argued that formal and structured process in the early phase leads to more successful products (Khurana and Rosenthal, 1998; Montoya-Weiss and O'Driscoll, 2000).

Furthermore, Hüsig *et al.* (2005) empirically showed that better FFE results could be obtained from a structured FFE. Process formalization is defined by Poskela and Martinsuo (2009) as "specifying procedures to be followed and monitoring that work activities are proceeding in accordance with the defined procedures." Poskela and Martinsuo (2009), who are opposed to a formal process for early phase of innovation, pointed out that the identified benefits of having a formal process are typically provided without taking into careful consideration the different types of innovation or front end projects.

Most of the formal FFE processes have been criticized because they tend to adopt one single FFE process for the early phase of innovation with no regard to the contextual factor. For example, Nobelius and Trygg (2002) illustrated that there is no one best model for the early phase of innovation. They argued that, although the main activities of the early phase of innovation always include a mission statement, concept generation/screening/definition, business analysis and finally project planning, their sequence, duration of each activity, level of assigned resources and perceived importance would differ based on the type of project and type of industry. On the other hand, it was concluded (Hüsig *et al*., 2005) that structured early phase processes could result in better technical and market info, creating more satisfying results for the NPD managers, and also better patent portfolios.

2.2.5. The lack of research on the early phase of innovation

To date, despite the identified importance of the early phase of innovation, this stage is the greatest weakness in the innovation process studies. Many researchers noted that in

comparison to the research on the new product development process, little research has been done on the early phase of innovation itself (Kim and Wilemon, 2002; Khurana and Rosenthal, 1998, 1997; Nobelius and Trygg, 2002; Zhang and Doll, 2001; Reid and de Brentani, 2004; Brem and Voigt, 2009; Koen *et al*., 2001; Poskela *et al*., 2005). For example, Koen *et al*. (2001) mentioned that in the early phase of innovation, there is even no common language or definition of the important elements of this stage. Similarly, Murphy and Kumar (1997) proposed two reasons for the lack of research in this area:

- The early phase of innovation is a dynamic and unstructured stage; hence these characteristics make the early phase difficult to study. For example, the creativity degree of the organization highly affects the idea generation process and as a result makes conceptualizing this process challenging.

- Unlike the NPD stage, the early phase of innovation is characterized by a high level of informality, therefore it can be seen that firms mostly rely on accepted rules for developing product concept. This issue makes it difficult to provide the best practice of the early phase of innovation.

2.3. Process models of the early phase of innovation

As stated above, there have only been very few studies on the early phase of innovation, compared to the new product development phase that has attracted much greater research attention. As argued by Cooper and Kleinschmidt (1990), the early phase of innovation was initially limited to one factor e.g. the ‘quality of predevelopment

activities'. However, since the 90', more detailed studies have been carried out to shed some light on the early phase of innovation (Kim and Wilemon, 2002; Herstatt and Verworn, 2001; Nobelius and Trygg, 2002; Khurana and Rosenthal, 1998, 1997; Murphy and Kumar 1997; Moenaert *et al*., 1995; Zhang and Doll, 2001; Reid and de Brentani, 2004; Poskela *et al*., 2005).

Theoretical consideration and qualitative studies are the two groups comprising the majority of the early phase of innovation literature (Verworn, 2009). The following sections will describe in detail the most important models in both groups.

2.3.1. Qualitative Models

2.3.1.1. Cooper's stage-gate process

Stage gate process (Cooper, 1990) can be considered one of the most commonly applied models for managing NPD and also FFE processes. The model is based on a simple concept of checking the quality of each stage by putting a control unit after it, which is illustrated in Figure 2.3.

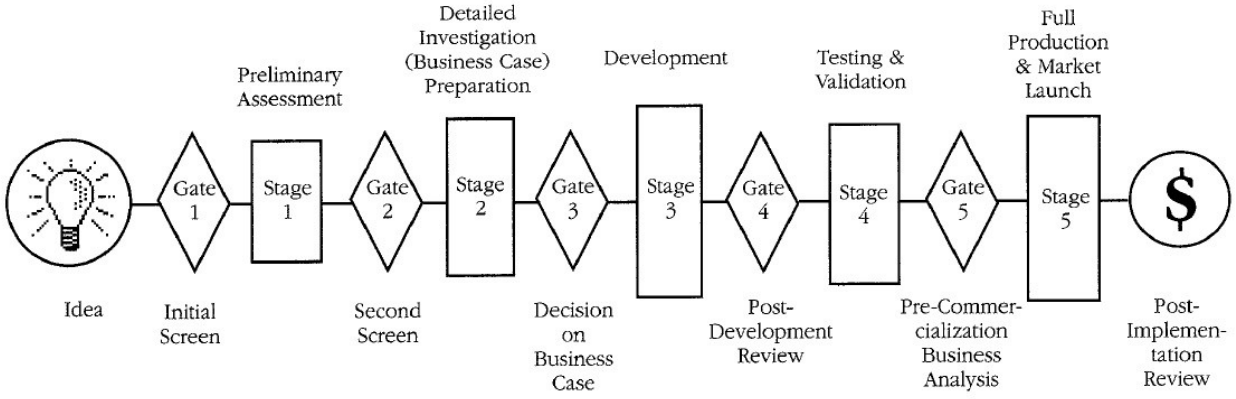


Figure 2.3 The full stage gate model (Cooper, 1990)

A stage consists of a set of activities which is followed by a gate to control the stage's deliverables. The innovation process is divided into predetermined set of stages, where the number of stages is varied between four and seven according to the type of company. The part that is more related to the early phase of innovation is shown in Figure 2.4.

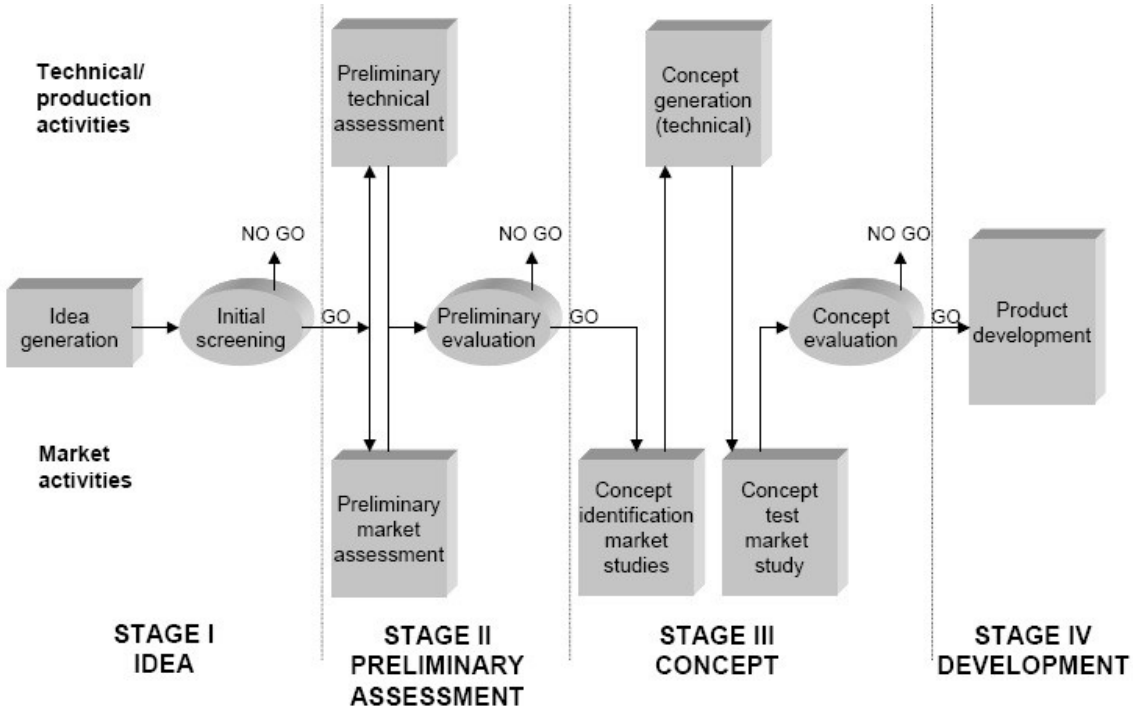


Figure 2.4.The stage gate process (Cooper, 1988)

The process starts with the idea generation and then the ideas move through the process after the best ones are selected. At the first gate, the ideas are screened against a set of predefined criteria, then in the next stage, a limited amount of information regarding market and technical aspects will be acquired. Accordingly, in each stage more detailed information is gathered and the ideas are investigated in depth. The aim is to

provide a well prepared business plan that includes the product concept, product justification and an action plan for the NPD process.

Cooper (2008) in his recent paper introduced a next-generation version of the stage gate process to improve the model performance. Moreover, he explains some possible misconceptions and challenges that are encountered when the stage gate process is being used. One often debated issue of the stage gate process is the linearity of the visual model (Nobelius and Trygg, 2001; Reid and de Brentani, 2004; Poskela and Martinsuo, 2009). In this study Cooper however argued that, although the model visualization is laid out in a sequential fashion, each stage includes a large amount of looping and iterations.

The stage-gate model is considered one of the most linear and formal models to manage the early phase of innovation, and as such it has been criticized by the authors who disagree with the formality in managing the FFE process. (e.g. Nobelius and Trygg, 2001; Reid and de Brentani, 2004; Markham *et al*., 2010; Poskela and Martinsuo, 2009; Tang, 1998). For instance, Tang (1998) in his study argued that the stage-gate model cannot sufficiently describe some essential characteristics of the innovation process such as learning and developing competency. Another criticism comes from Schroeder *et al.* (1989) who claim that Cooper's model is not able to appropriately cope with organizational factors.

Moreover, even with the wide application of this method in NPD, the stage-gate model does not include the early FFE activities, like opportunity identification or information exploration (Glassman, 2009). Additionally, more focus is applied on funnelling the number of poor ideas rather than on looking for new opportunities (Poskela *et al*., 2005).

2.3.1.2. Khurana and Rosenthal FFE model

Khurana and Rosenthal (1997; 1998) proposed a holistic process view of front end activities, including foundation elements and project-specific elements. Foundation elements, or non-project-specific elements, include product strategy formulation and implementation, product portfolio development and product line strategy in order to support the decision making of new product development.

Project-specific elements are activities that help organizations develop a product concept, market requirements and finally an action plan. They synthesized these elements into the process view as it is illustrated in Figure 2.5. Khurana and Rosenthal (1997) emphasize the importance of a structured strategy for dealing with development of a new product. They also carefully examined the front end practices in 18 business units from twelve U.S and Japanese companies. The authors discovered that those organizations that support the holistic approach the early phase of innovation have a higher chance of attaining success. The holistic view will be achieved by covering all four key front end factors: product strategy, product definition, project definition and organizational roles.

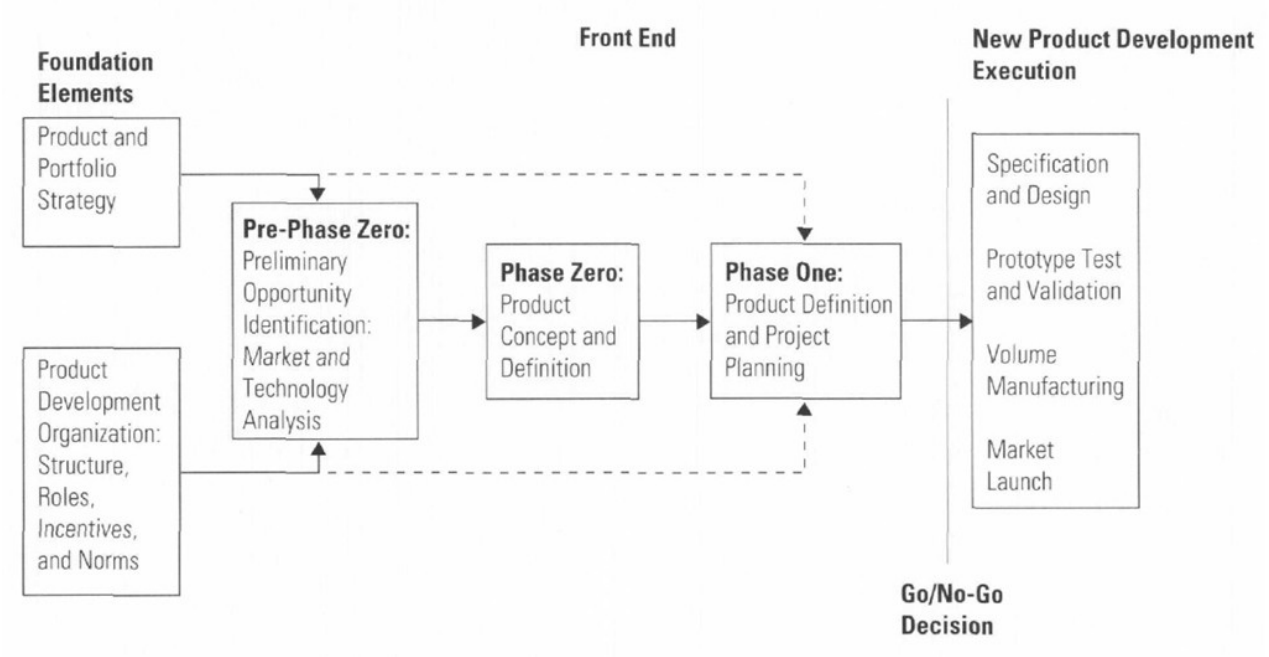


Figure 2.5. A model of FFE process (Khurana and Rosenthal, 1997)

As seen in Figure 2.5, Pre-Phase Zero activities, which generally involve opportunity identification, idea generation and market analysis, are very important for the following phase – Phase Zero. In Phase Zero, the customer needs and wants, technologies capabilities, product requirements and required resources will be defined.

The holistic view for managing the early phase of innovation can be achieved by two different approaches: formal process or cultural-driven approach. Analyzing multiple case studies reveals that the formal process approach is mostly applied by European and American firms, whereas the Japanese firms tend to control the front end through strong organizational culture and business point of view based on cross-functional interactions. Both of these two approaches are considered viable models for implementing a holistic front end.

Although Khurana and Rosenthal (1998) attempted to achieve a better understanding of the early phase of innovation, they have primarily focused on incremental innovation.

They argued that, although a more formal approach worked well in incremental innovations, the processes aiming at radical innovations and products tend to be more loosely defined, less structured and less explicit. Other authors (e.g. Nobelius and Trygg, 2002; Raid and de Brentani, 2004) confirm that formal processes, including the Khurana and Rosenthal's holistic process, cannot fulfill the need of the early phase for a radical innovation.

2.3.1.3. Koen's new concept development model

Another popular process model, which is one of the non-linear and iterative process models, is the new concept development model (NCD) developed by Koen *et al*. (2001). They attempted to bring the common language to define the front end of innovation processes by the NCD model. They believe that the circular shape of the model indicates the flow, the circulation and the iteration of ideas within the FFE process. This is in fact considered a major benefit of this model. The model, as shown in Figure 2.6, is made up of three key components: inner area, engine and influencing factors.

1. The inner area consists of five elements: opportunity identification, opportunity analysis, idea genesis, idea selection and concept development. The arrows between the elements show the flow of an idea within the model. The elements can interact with each other in a more random and non-sequential manner irrespective of their position in the model. Koen *et al*. (2001) in their model demonstrate the inner part of the model as elements rather than processes in order to avoid any implied controls that could be used to manage front end

activities. The process can start with any of the idea genesis or opportunity identification, but it finally results in a concept development. The explicit distinction between the opportunity and the idea was not found in either Cooper's model (1988) or Brem and Voigt's model (2009), and thus makes the Koen's model superior.

2. The leadership and culture of organization controls the "engine" that feeds different elements. Due to the importance of these factors in the new product development, the engine is located in the center.
3. Finally, the influencing factors include business strategy, governmental policy and environmental regulations. Since the whole process of FFE is affected by these factors, they have been shown in Figure 2.6 as the black wheel surrounding the other elements indicates.

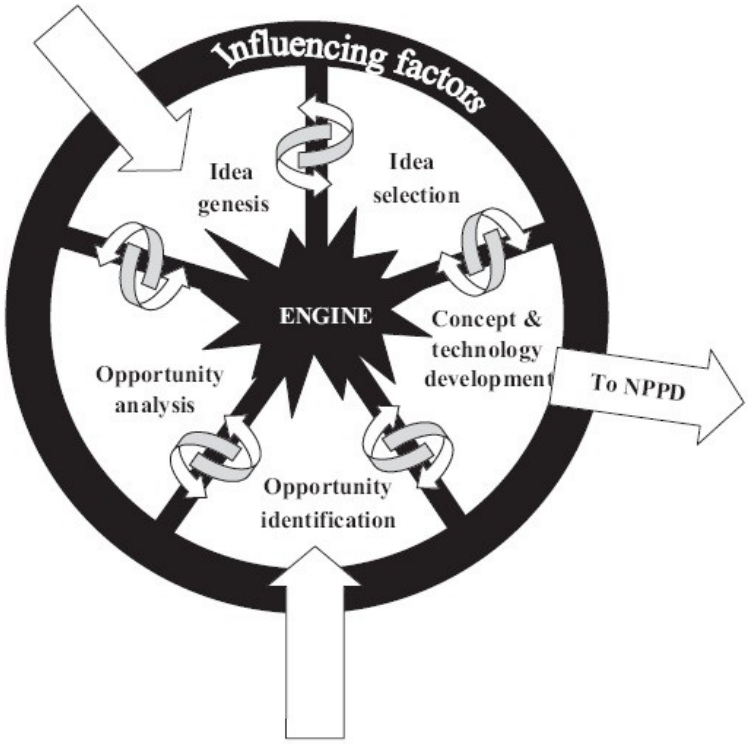


Figure 2.6. The new concept development model (NCD) by Koen *et al*. (2001)

2.3.2. Theoretical consideration

2.3.2.1. A Theoretical model of discontinuous innovation

While the majority of studies so far have only focused on the best practice model for the late fuzzy front end, few studies have taken into consideration the early fuzzy front end in their model (Reid and de Brentani, 2004). Late fuzzy front end activities are the activities and decisions that are involved in idea generation and concept development (Cooper, 1990; Urban and Hauser, 1993). Early fuzzy front end activities, which involve the identification and the structuring of opportunities and the collection of information, have been addressed to a lesser extent (Reid and de Brentani, 2004).

Considering the fact that the FFE process highly depends on the type of innovation (Khurana & Rosenthal, 1998), understanding the complex nature of the early fuzzy front end is very important for developing radical innovations. In this regard, a theoretical model of the fuzzy front end information flow and decision-making process has been developed for discontinuous (radical) innovations (Reid and de Brentani, 2004). As indicated by authors, the theoretical model is built on combining three key perspectives, which themselves are also drawn from NPD and TIM (Technology and Innovation Management) literature. These perspectives are environmental, individual and organizational, and represent the factors that could have effects on decision making in the fuzzy front end process. In this study, the fuzzy front end of NPD is described as a string of decisions taking place over three proposed interfaces: boundary, gatekeeping and project. Figure 2.7 shows the proposed model of FFE. Further, the authors demonstrate the nature of fuzzy front end for the discontinuous innovation in the form of a series of propositions as follows:

- In the incremental innovation, the problems or opportunities will be identified by an organization and then will they be directed by individuals.
- In the discontinuous innovation, which is different in the nature from incremental innovation, the problems or opportunities will be identified by individuals and the subsequent search for further information is also performed by individuals.
- In case of discontinuous innovation, information for a new idea is obtained from the environment by boundary spanning individuals through an interface called the boundary interface, stimulated by communication as well as by the perception and by the reconstruction ability of individuals.

- In the discontinuous innovation, information moves from boundary spanning individuals to gatekeeping individuals (often the same person) in the organization. This movement is made through an interface called the gatekeeping interface, motivated by information sharing.
- In case of a discontinuous innovation, information flows from the organization to the project level through the project interface. Here, the information depends on the evaluation of the ideas in the formal first screen and on the degree of the match between the ideas and a strategic arena of the firm. However, even a new strategic area can be developed during this process.

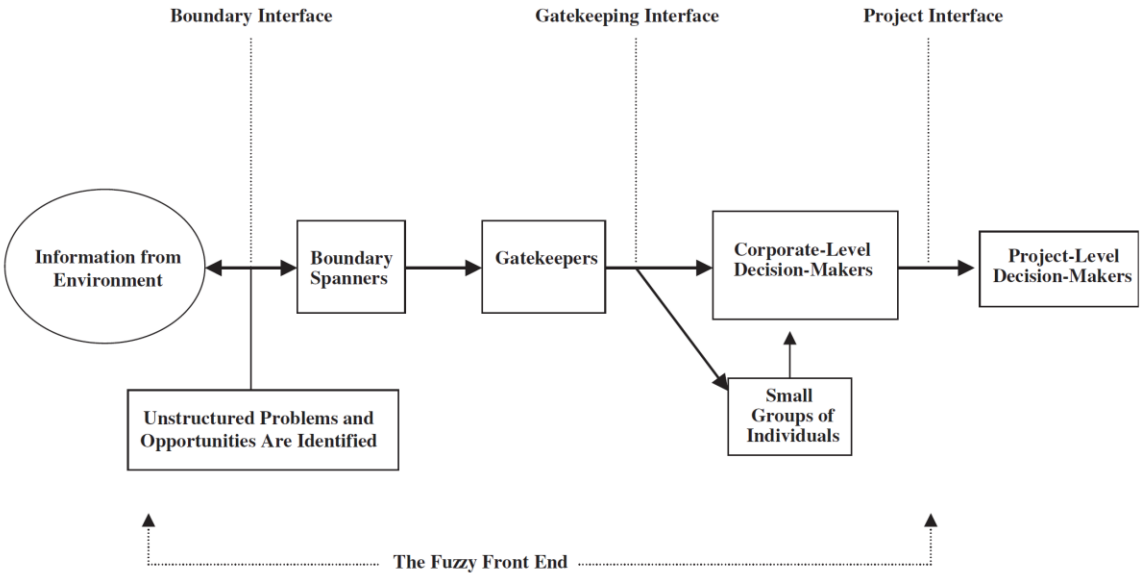


Figure 2.7.The fuzzy front end model proposed by Reid and de Brentani (2004)

2.3.2.2. FFE and the role theory

Consistent with Reid and de Brentani (2004), Markham *et al.* (2010) carried out a study in order to understand the set of roles moving a project through the early phase of innovation. In their research, the term "Valley of Death" is used to show the activities that occurred between the two well-defined activities - research and formal NPD. According to the authors, the selection of this term is due to the lack of resources and expertise in this stage of development. As argued by Reid and de Brentani (2004), previous researches on early phase of innovation focused primarily on the preparatory tasks performed before a concept is accepted to a formal NPD. Markham *et al.* (2010) recognized the gap between the activities and the roles of the organization participating in this stage of product development and attempted to identify the informal roles, activities and processes in the Valley of Death. In their study, they shed some light on the nature of work of pre-development stage and propose that there are three major activities in the early stage, which are (a) awareness, (b) demonstration, (c) acceptance and transfer. These activities are carried out by three key informal, overlapping roles: *champion, sponsor* and *gatekeeper*. The model is illustrated in Figure 2.8.

The authors proposed that as the project progresses, the different roles emerge to perform relevant activities. At the beginning a *champion*, whose responsibility is to identify the ideas and select them, has the greatest importance in this stage but his influence decreases as the project moves on. After champion, a *sponsor* has the greatest impact since his role is to persuade other people in the organization to perform the project. A *gatekeeper* has the highest ranking of importance at the end since he sets the specific criteria to decide whether to accept the development of ideas into the formal

development. Furthermore, Markham *et al.* (2010) argued that these activities do not necessarily need to be performed linearly; however each step must be dealt with before the project enters the formal development stage.

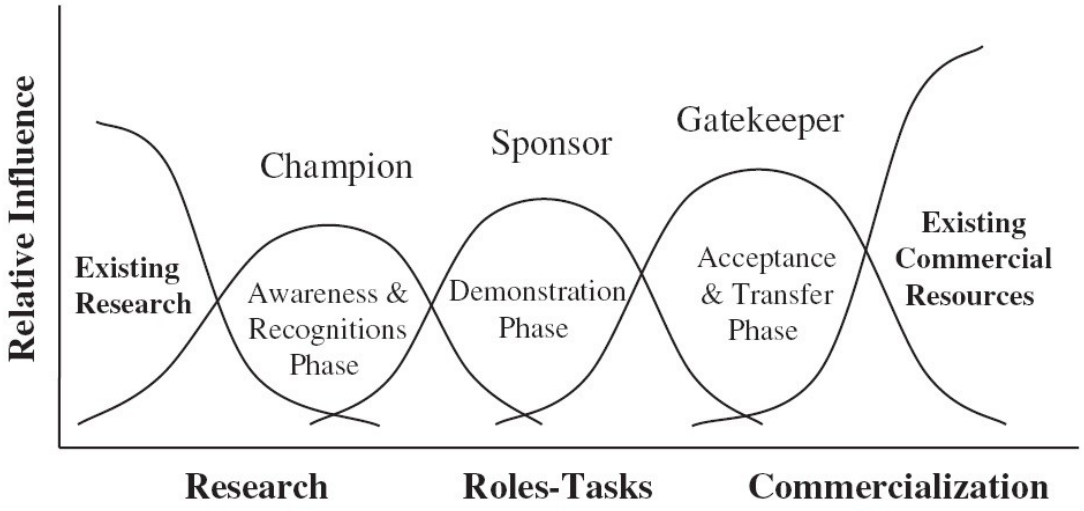


Figure 2.8. Model of roles and activities over the FFE process (Markham et al., 2010)

2.3.2.3. A causal model

Parallel to the studies approaching the FFE from a theoretical consideration, Zhang and Doll (2001) proposed a model in order to find the relationship among FFE, foundation elements, team vision and success of NPD. Their proposed model is demonstrated in Figure 2.9. They mentioned that the meaning of the FFE, derived from the term "front-end fuzziness", was still vague, and imprecise. Fuzziness was often used in a very broad sense, and hence could refer to both the exogenous causes (like environmental uncertainty) and the internal consequences (like the team vision).

Otherwise, it was mentioned that no researchers had studied the FFE separately from the consequences of fuzziness. The authors identified that the important factors in their model are the foundation elements, environmental uncertainty and team vision. This model could help researchers with managing the fuzzy front of NDP by separating the FFE and unclear team vision.

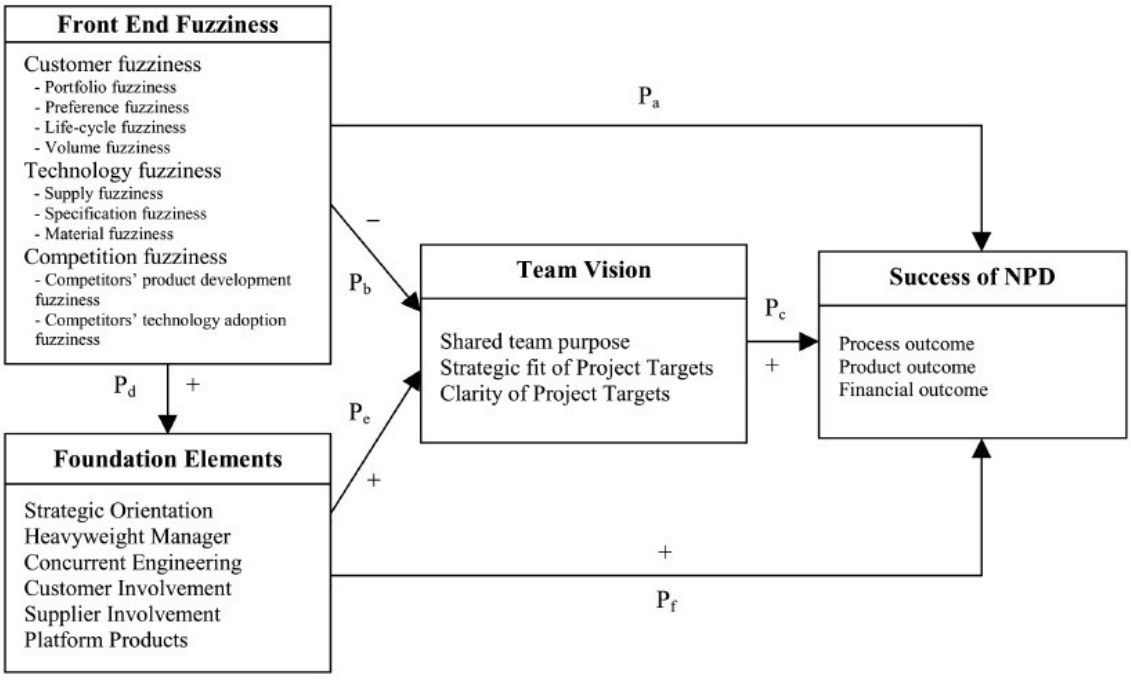


Figure 2.9 The fuzzy front end and success of new product development model. (Zhang and Doll, 2001)

The model is a conceptual framework which could suggest the relationship among front-end fuzziness, foundation elements, team vision, and success of NDP as follows:

1) The front-end fuzziness has negative effects on the success of NDP

The uncertainty related to customers and technology usually results in less rational work

in an organization. Customer fuzziness such as the "uncertainty of demand and appropriate product characteristics" complicate the NDP. On the other hand, technology fuzziness such as the "uncertainty of design, process functions and manufacturing capability" brings additional uncertainty about the time to market, product integrity and the NDP cost. This fuzziness could result in a less controllable product development.

2) The front-end fuzziness has negative effects on team vision

The customer, the technology and competitor's uncertainties, or the environmental fuzziness in general all greatly complicate the activities of a design team. Due to these uncertainties, developing the products' concept and the projects' work plan is difficult for the team.

3) Team vision has a positive relation with the success of NDP

The more information about the needs of current and potential future customers is shared among the team members, the better understanding of the product concept can be achieved, which, in turn, facilitates the formulation of a customer-focused mission. Such shared information makes the project objectives more focused on real customer requirements, which consequently results in a greater success of the new product.

4) The front-end fuzziness has positive effects on foundation elements

In order to cope with the ambiguity and uncertainty of customers, technology and competitors, organizations need to develop special mechanisms to avoid, reduce or take advantage of the uncertainties. These mechanisms are foundation elements, also called

coping mechanisms (Gerwin and Tarondeau, 1982), and include strategic orientation, concurrent engineering, heavyweight manager, customer and supplier involvement and platform products. Therefore, the environmental uncertainty requires the firm to improve its foundation elements and have more flexibility to respond to the fuzziness.

5) The foundation elements have a positive effect on team vision

The foundation elements could help the firm to avoid the ambiguity. Consequently, it could help the team improve its knowledge about customers, technologies and competitors, and such shared knowledge in turn improves the team vision.

6) The foundation elements have positive effects on the success of NDP

The foundation elements improve the productivity and flexibility of a firm, which results in a more valuable product, low cost manufacturing and less time to market delay. Customer orientation makes the product more valuable to customer while technology orientation reduces the cost of manufacturing. Competitor orientation helps in decreasing the time to market period and heavyweight manager reduces engineering change time and improves the productivity.

2.3.2.4. Strategic and operative levels of FFE

Along with a few articles which address both the strategic and operative level of FFE (Zhang and Doll, 2001; Khurana and Rosenthal, 1997), Poskela *et al.* (2005) created a holistic view of the front end phase by considering both aspects at the same time. The main feature of their model is a clear distinction between the strategic level and the

operative level of the front end activities. In this study, a considerable effort was made to examine the integration mechanism of these two levels and to analyze the challenges how they are perceived by managers.

Poskela *et al*. (2005) proposed that there is no best way for the effective integration of strategic and operative level front end activities, and the best practices should thus be modified based on the type of a certain industry. This also agrees with the studies of Loch (2000) and Tidd (2001) who had previously presented similar conclusions.

2.3.3. Summary of early phase process models

Table 1 compares the nature, research methods and the key findings of the previously described process models.

Table 1. Studies on the early stage of innovation process

Authors	Method	Description	Industry	Key Findings
Brem and Voigt (2009)	Literature and single case study	Defined a framework to show the important and crucial factors of fuzzy front end by considering both market pull and technology push theory	German software companies	Theory-based conceptual framework for fuzzy front end to be used by German software industry
Koen *et al*. (2001)	A group effort of eight companies surveyed 23 companies to evaluate the proficiency of each element of the proposed model (NCD)	There was no common language or definition for the FFE. Therefore, a theoretical construct was developed to address this shortcoming.	Mixed-highly innovative companies	- Theoretical construct - There is a strong correlation between the proficiency of the front end of innovation in a company and its level of innovativeness
Khurana and Rosenthal (1997, 1998)	Exploratory study of fuzzy front end activities in 11 companies by	Introducing a system view of fuzzy front end to help companies in the way they manage the front end process. The research is	Mixed-Japanese and European	- Introducing front end stages - Having a system perspective to integrate front end

	interviewing 75 managers	followed by conducting case studies to identify challenges and solutions.		process - There is no one solution for front end process of all companies
Poskela *et al*. (2005)	Multiple case studies by applying inductive case study approach. The data was collected through semi-structured interview	Considering both the strategic level and operative level of FFE and analyzing how these two aspects can be effectively integrated.	Mixed – innovation intensive Finnish companies	The most important integration mechanisms are : - Informal communication and interaction - Top down strategy formulation and implementation - Yearly strategic planning
Zhong and Doll (2001)	Using uncertainty theory	They try to make a better understanding of front end fuzziness which is broadly identified as environmental uncertainties. However, by presenting a theoretical framework they try to make a distinction between the exogenous cause and internal consequences of fuzziness.		The conceptual model reveals that: - The front end fuzziness has negative effects on the success of NDP and on team vision. - Team vision has positive relation with the success of NPD - The front end fuzziness has positive effects on foundation elements. - The foundation elements have positive effect on team vision and on the success of NDP.
Reid and Brentani (2004)	Using literature of NPD and innovation management	The goal of this study was to clarify the nature of front end process of radical innovation and to develop a model in this regard. In their model, three perspectives about innovation were jointly applied.		- Three different interfaces of front end process were identified - A model of the front end in terms of the proposed interfaces was presented - Then, the nature of fuzzy front end was introduced by developing proposition for both

				incremental and radical innovation.
Merkham *et al.* (2001)	- On line survey of 272 product development and management association members (PDMA) - Empirical methodology	Identifying the activities and roles constructing the gap between two well known stages of innovation, i.e. research and formal NPD which is addressed here by Valley of Death		- Different roles of front end activities were introduced. - *Champion* to identify and advocate new ideas. *Sponsor* to persuade other people in the organization to perform the project. A *gatekeeper* to establish specific criteria to decide whether the ideas go into the formal development.

2.4. Innovation process in biotechnology industry

As demonstrated, reviewing extant literature reveals various process models of the early stage of innovation that provide a firm with a better understanding of the activities and roles involved in the early stage of innovation. They also offer a framework based on which firms can assess their processes according to the best practices. However, the application of these models has been limited to investigating the innovation processes within the traditional industries that mainly introduce incremental innovation, while the biotechnology industry has been overlooked. Therefore, further evaluation is required to extend the understanding of the early phase of innovation beyond the traditional field of inquiry.

In the current economic climate, the importance of technological innovations is more apparent for the high-tech industries, such as biotechnology, whose sustainability in the market highly depends on introducing new technologies (Hall and Baghchi-Sen, 2002; Afuah, 2002; García-Muiña *et al*., 2009). The biotechnology industry is generally composed of biotechnology firms, research institutes and related industrial firms. These related industries include agriculture, computer, medical devices, pharmaceutical, chemical and environmental industries (Hall and Baghchi-Sen, 2007).

Biotechnology is considered to be one of the vital growth areas for the emerging knowledge economy. Biotechnology has a high ability to shape the way we live by improving human health and quality of life (Gans and Stern, 2004). The increasing number of diverse biotechnology firms in Canada makes the innovation a critical factor for firm survival. This has resulted in an increased interest in the innovation process in the past few years.

There are particular characteristics of innovation in biotechnology, which makes it quite distinct from other technologies. Todtling and Trippl (2007) used the concept of "knowledge base" to obtain a better understanding of these differences, as presented in Table 2.

Table 2: Synthetic and analytical knowledge base (Todtling and Trippl, 2007)

Key features	
Synthetic knowledge base Traditional industries (e.g. industrial machinery, engineering)	**Analytical knowledge base** Knowledge based industries (e.g. biotechnology, ICT)
• Dominance of tacit knowledge and practical skills	• Dominance of codified (codifiable) knowledge, complementary role of tacit knowledge
• Application or novel combination of existing knowledge	• Application of widely shared and understood scientific principles and methods
• Low level of R&D	• Systematic basic and applied research , formally organized knowledge processes (e.g. in R&D departments)
• Strong orientation on solving specific problems articulated by customers	• Strong reliance on scientific research inputs from universities, government labs and other research institutions
• Learning by doing and interacting, user-producer relationship	• Learning by exploring, university-industry partnerships
• Incremental innovation	• Radical innovation

Biotechnology is very science-intensive and largely uses abstract and codified knowledge (Todtling and Trippl, 2007). Considering the generation of sustainable competitive advantage, tacit knowledge is also necessary for successful innovation in biotechnology industry (Oliver, 2003; Khilji *et al*., 2006). In addition, the knowledge

base of biotechnology is very complex and sources of knowledge are broadly dispersed (Todtling and Trippl, 2007). Making alliances with other biotechnology firms, university research institutions and all other external knowledge sources, played an important role in providing biotechnology companies with faster access to knowledge and a quick reaction to any changes. The innovation process in biotechnology is characterized by high R&D cost, global competition, rapid changes, long development time as well as considerable degree of uncertainties. On average, as shown in Figure 2.10 the entire biotechnology innovation process can take 15 years (Khilji *et al*., 2006).

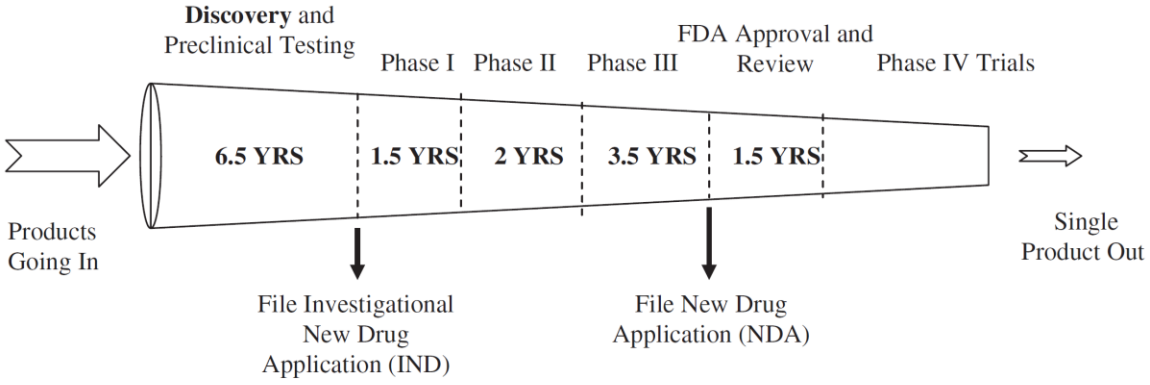


Figure 2.10 A drug process in biotechnology (Khilji et al., 2006)

Innovation process in biotechnology generally has been presented by a sequence of activities that transform an idea into a commercial product (Hall and Baghchi-Sen, 2002). However, various sources of literature demonstrate many differences in defining and naming of the stages in different models. According to Heinonen (2009), product development process in biopharmaceutical industry has two main stages: discovery and development. The innovation process starts with the discovery of new molecules, which

ultimately leads to the filing of patents. In the development stage, preclinical and clinical developments are carried out.

Khilji *et al*. (2006) claimed that innovation process comprises of two main stages, prediscovery and postdiscovery. Prediscovery stage, or stage of invention, consists of basic research and R&D activities, whereas in the postdiscovery stage, a tangible commercial product is finally achieved. Their representation of the biotechnology innovation process is shown in Figure 2.11.

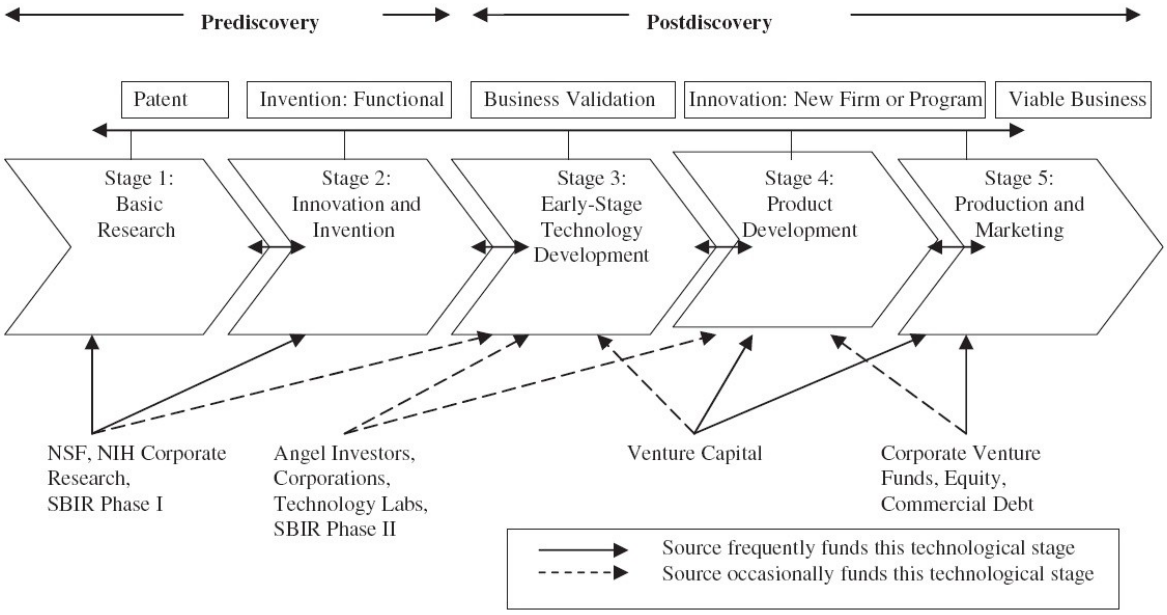


Figure 2.11 Biotechnology innovation process (Khilji et al., 2006)

Hall and Baghchi-Sen (2007) also defined the innovation process in biotechnology in two main stages: earlier stage and later stage. Earlier stage is characterized by heavy R&D, and leads to patent application and approval, while later stage includes commercialization of product and process and finally leads to the creation of a new or redesigned product or process.

However, Van Moorsel *et al*. (2007) considered four stages for new biotechnology product development after the idea generation stage. It could be implied from their paper that the authors assumed that an idea is first generated by public sectors and then it reaches the firm. As it is illustrated in Figure 2.12, these four stages are: firm-level R&D, clinical testing or field trial, regulatory phase and finally market development stage. They also grouped these four stages into two phases: early focus (stages one and two) and late focus (stages three and four).

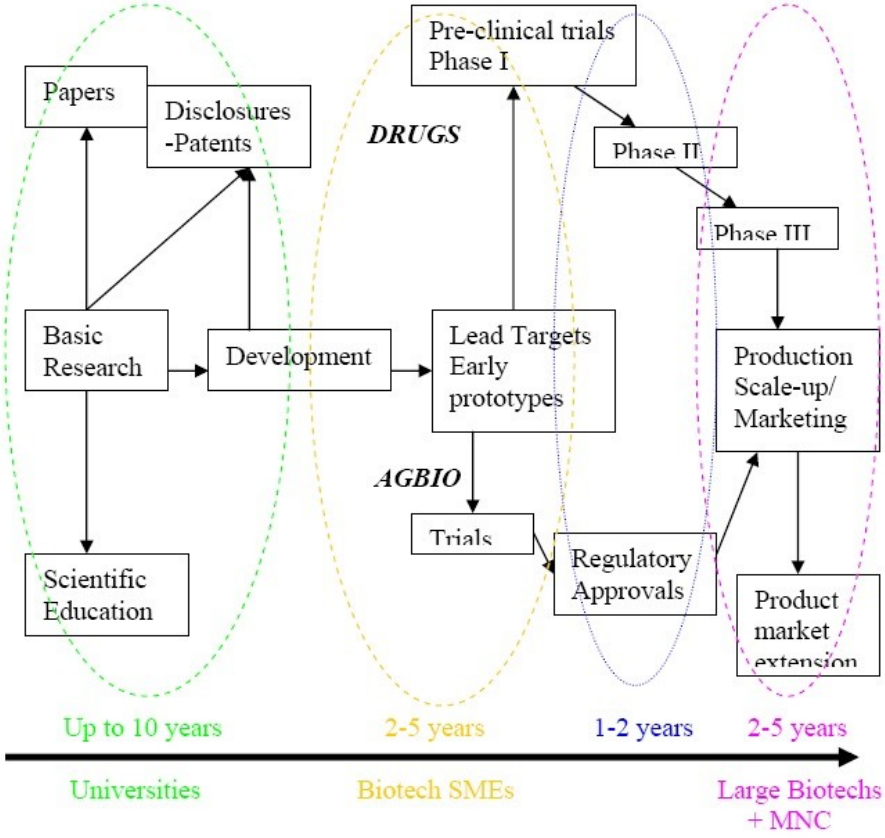


Figure 2.12 Biotechnology development process (Van Moorsel et al., 2007)

As seen, the use of the term "front end of innovation" in the scientific literature related to biotechnology innovation is rare or nonexistent. This stage of innovation was

typically addressed by the terms of the *discovery stage* or *early stage*. Despite ever growing body of literature on the innovation process in biotechnology, there are only very few studies about the nature of the early stage in the innovation process.

Hall and Baghchi-Sen (2002) and Khilji *et al*. (2006) argued that the linear representation of the innovation process in biotechnology is inappropriate, since it cannot demonstrate feedback mechanism and interaction of various elements in the process. Especially the actual early stage of the innovation process is more iterative and complex: in house research together with external collaboration provides a knowledge source for generating new ideas. These two sources complement each other rather than being substitute (Arora and Gambardella, 1994; Valle and Gambardela, 1993). The amount of information absorbed by the firm from external collaboration is also related to its own level of knowledge and capabilities. Although the biotechnology industry is well known for making frequent collaboration agreements, establishing the collaboration in the discovery stage is difficult (Khilji *et al*., 2006). Nevertheless, companies with high level of internal knowledge have better potential opportunity to get involved in collaboration relationships with other partners (Arora and Gambardella, 1994; Hall and Baghchi-Sen, 2007).

The various described interactions among different elements of the innovation process reflect the inherent complexity of this process. In order to understand the behaviour of this complex system, an in-depth investigation of these factors and the relationships among them is required. In this regard the following part reports the critical elements of the early stage of innovation process in biotechnology.

As it was stated earlier, only few studies have been conducted to examine the relationships and feedbacks among the factors comprising the early stage of the innovation process, particularly in the context of high-technology industries. Existing studies are mostly based on a mixed set of industries or on a traditional industry, but biotechnology is rarely considered (Khilji *et al*., 2006). Given the importance of biotechnology for Canada and the mentioned lack of research in this field, further research work is needed to investigate the innovation process in biotechnology, and this is also the general objective of this thesis.

2.5. Significant elements of the early stage of innovation in biotechnology

2.5.1. Sources of knowledge

Innovation in biotechnology is a result of research and development activities and other kind of learning activities that are usually undertaken with the aim of acquiring a new product (Marsh and Oxley, 2005). Product introductions in biotechnology are mainly initiated by scientific breakthroughs in the laboratory, while the market need is the principal driving force for further development and commercialization of the product (Hall and Baghchi-Sen, 2002). Therefore, acquiring knowledge has a great role in the search process for an innovation (Nelson, 1982).

The resource-based view of the firm (RBV) suggests that a firm's resources and capabilities are critical for surviving in the market place (Penrose, 1959; Barney, 1991). Many scholars (Kogut and Zander, 1992; Petraff, 1993; Henderson and Cockburn, 1994; Hill and Deeds, 1996; Deeds *et al*., 1997) emphasized that intangible resources, such as knowledge, play a key role in maintaining a firm's competitive advantage. Several

studies in the strategy literature claimed that a variation in a firm's performance is highly dependent on the resources or capabilities of the firm, especially when these capabilities are impossible or difficult to imitate or trade (Cockburn *et al*., 2000; Teece *et al*., 1997). Since biotechnology is highly research-intensive, the competitive advantage strongly depends on the continuous accumulation of relevant knowledge. In this regard, the fast creation of knowledge and the way how to manage it have been the focus of research for firms and region success (Dangelico *et al*., 2010). One of the fundamental questions in the strategy field pertains to how this resource can be created, maintained and enhanced. The sources of technological knowledge can refer to the tools that firms can utilize to accumulate knowledge in order to exploit it with an aim to introduce innovative products or processes (Garcia-Muina *et al*,. 2009).

Many scholars (Malerba, 1992; Zahra and Nielsen, 2002; Garcia-Muina *et al.,* 2009; Hu and Hsu, 2008; Dangelico *et al*., 2010) argued that new knowledge can be generated by two alternative means: the firm's own R&D (internal sources) at one extreme, and the acquisition of knowledge in competitive markets and the interorganizational linkage (external sources) at the other. Internal sources can be defined as all the methods for accumulating knowledge through the firm's own learning processes, such as conducting internal research and development activities (R&D) and the experience acquired by performing organizational process and studying via research projects (Nieto Antolin, 2001) .

External sources can refer to any type of accumulation and incorporation of technological knowledge in which a third party is involved. The direct purchase of technology, technology incorporated in machinery required, licensing contract,

university-industry linkages and relationships among firms are examples of external knowledge (Todtling and Trippl, 2007; Garcia-Muina *et al*., 2009). In fact, the external learning process involves learning by imitation and learning by interaction (Dangelico *et al*., 2010). Learning by interaction refers to the continuous exchange of information among firms, firms and research organizations, and firms and customers. On the other hand, learning by imitation is based on a one-side exchange of knowledge among innovative actors, which can be obtained by consultation of scientific and technical publications, as well as participation at events such as conferences and trade fairs (Dangelico *et al*., 2010).

Early research about the internal source of knowledge (Beer, 1959), later supported by another scholar (Garcia-Muina *et al*., 2009) reveals that this knowledge has a greater strategic value compared to external knowledge. Internal source of knowledge provides firms with breakthrough innovations that can create competitive advantages for them, since it prevents other firms from imitating a firm's distinctive capabilities. This could be justified by the characteristic of this type of knowledge due to its tacitness and specificity (Matusik, 2002; McEvily and Chakravarthy, 2002; Schroeder *et al*., 2002, Garcia-Muina *et al*., 2009). The term 'tacit knowledge' refers to the knowledge which could not be easily expressed, shared, and transferred by means of language.

Despite the obvious benefits of employing internal sources of knowledge, there are some drawbacks involved. The innovative process associated with these types of knowledge is more iterative, time consuming, and expensive, and firms are faced with greater uncertainties and risks. External sources of knowledge, on the contrary, are cheaper and less risky, but at the same time, the external knowledge cannot generate a

competitive advantage on its own, since it is easily available to rivals (Garcia-Muina *et al*., 2009). However, in biotechnology, which is characterized by rapid and complex technological change, it is hard to find all the necessary competencies needed to innovate under a single roof. Hence, the companies cannot rely only on internal source of knowledge (Shan and Song, 1997).

In this regard, making strategic alliances and other collaborative agreements among universities and other biotechnology and pharmaceutical firms are well-accepted strategy for achieving innovation (Hall and Baghchi-Sen, 2002; Coombs and Deeds, 2000). A strategic alliance is a partnership that incorporates resources and core competences for achieving similar goals (Hitt *et al*., 2007). Making collaborations allows individual firms to advance their scientific discoveries when there is a lack of specific resources or expertise. However, a significant strategic commitment to R&D is critical for a knowledge intensive technology, such as biotechnology, in order to achieve the competencies required to succeed, despite the level of technology developed in-house or accessed through external resources.

2.5.2. Absorptive capacity

The increasing number of firm-university linkages raises the question of whether firms can improve their ability to use and exploit such knowledge. Even though the external knowledge is easily available to competitors, the firms cannot gain benefit from it equally. The concept of *absorptive capacity* brings attention to the fact that when knowledge exists outside of the firm, even if it is in public domain, it cannot be effortlessly and freely absorbed by all the firms. Instead, investing in particular activities,

such as research and distinctive capability is required to allow firms to identify, assimilate, transform and exploit outside knowledge more effectively (Cohen and Levinthal, 1990).

The level of a firm's prior knowledge allows the firm to recognize valuable new information, absorb it and incorporate it into creating new knowledge. A firm has a high absorptive capacity to process new information and ideas when they have a well-developed foundation of knowledge in that field. On the contrary, when the knowledge level of the firm is low for a particular field, it will not be able to recognize new valuable knowledge and exploit the new information that might be important for their product (Deeds, 2001). In competence-based technologies, such as biotechnology, the ability of the firm to recognize valuable knowledge that may be useful for them in the future is vital for the firm's success (Deeds, 2001).

Several activities have been identified in literature that may contribute to the creation of a firm's absorptive capacity. Cohen and Levinthal (1990) considered R&D investments as an important factor to their conceptualization of absorptive capacity. They have regarded R&D as both a source of innovation and a mean for developing the firm's ability to recognize new, external knowledge. The firm's basic research (Rosenberg, 1990; Lane & Lubatkin, 1998), the routines of a firm (Zahra and George, 2002), employee skills (Vinding, 2006; Muscio, 2007), collaboration with an external scientist (Cockburn and Henderson, 1998; Zucker *et al.,* 1998), technological overlaps (Mowery *et al.,* 1996; Prager and Omenn, 1980), and trust and cultural compatibility among firms (Lane *et al.,* 2001) are other activities that can enhance knowledge acquisition capabilities of firms and develop absorptive capacity.

In fact, absorptive capacity improves the ability of a firm to evaluate the probability of success for turning a given basic knowledge into a valuable product. It is more likely for a firm with a higher absorptive capacity to pursue projects with a higher probability of success. Furthermore, due to their superior knowledge, the firms with a greater absorptive capacity can understand any changes in new knowledge faster and can eventually change their research efforts more rapidly to adjust to the new information stream.

2.5.3. Funding

Funding is considered to be a backbone of biotechnology, since firms spend huge amount of money on research and development activities (Hall and Baghchi-Sen, 2002). The funding can be provided to the biotechnology firm from different investment sources. Financing in start-up companies is mainly supplied by government research funds and venture capital firms, but firms also search for capital from angel investors, government programs and initial public offerings (Shan *et al.,* 1994; Van Moorsel *et al.,* 2007). However, even though startup companies may have funding to invest on R&D activities and early parts of development, they often lack the necessary testing facilities and equipment for further development and commercialization of a product. It is really difficult for biotechnology firms to attract venture capital market to carry them through the entire innovation process. The reason is that capital markets are mostly focused on short term results, which usually cannot be gained by the investment in biotechnology innovations. The long term development process, as well as regulatory processes, may significantly slow down the progress of a product in the development pipeline. Consequently, a firm has to combine different sources of funding such as public funds,

venture capitals and debt financing to survive its operations (Greis *et al.,* 1995; Hall and Baghchi-Sen, 2002). Nevertheless, the amount of investment in R&D differs based on a firm's commitment to research and development activities. This is represented in the literature by R&D intensity, defined as the percentage of a firm's revenues spent on research and development (Hall and Baghchi-Sen, 2007). High R&D intensity firms are mainly characterized by low revenue and focus more on the earlier stages of innovation, which usually involve heavy R&D investments and access to university research. Low R&D intensity firms mostly focus on the later stage of the innovation process, which includes commercialization of the product or process (Hall and Baghchi-Sen, 2007).

Commitment to research and development activities, using external knowledge, making alliances with major research institutes, a supply of skilled scientists, access to venture capital and government support are all critical factors for the achievement of a successful innovation process. Although each aspect is individually significant, their combined utilization creates a complex system that can be hardly controlled without having planned strategies. In this regard, managers and policy makers need to know how these factors affect each other, and which strategies improve firm performances the most under different conditions.

2.6. The purpose and questions of the research

The importance of innovation for biotechnology firms and its role in providing the firm with capabilities that are essential for its success underscore the need to understand the structure and nature of the biotechnology innovation process. In this thesis, the main research questions are related to this process: How are innovations created in research-

driven high technology firms such as biotechnology, and what are the key determinants of the successful innovation process? What roles do these factors play in the innovation process? How can they affect the innovation output in the biotechnology? Where should these firms focus their efforts and resources in order to enhance their innovation outcome, while taking into account their characteristics and limitations? These are interesting issues that have significant implications for the policy makers and managers of biotechnology firms.

Despite the extensive body of knowledge within the determinants and the effects of successful innovations, there is still a lack of research and information elucidating the dynamic nature of policy decisions and feedback mechanisms of innovation process. In this regard, this research intends to supplement the literature by investigating the factors that enhance innovation performance in biotechnology during the research stage. In doing so, our two main objectives are:

***Objective 1*: Contribute to a better understanding of the early stages of the innovation process in biotechnology**

- Develop a comprehensive model that represents the relationships and interactions among several identified factors
- Use the model to investigate the behavior of a firm under various conditions and to determine its best innovation strategies. This can provide managers with important information about factors that have an effect on the outcome of the early stage of the innovation process

- Supply policy makers with a tool which will help them identify the most significant issues in policy making for facilitating the whole organization's growth through the innovation process

***Objective 2*: Investigate the effects of various policies regarding different sources of knowledge on the innovation process outcome**

- Determine the appropriate policies in proportion to the firm's characteristics in order to pursue their innovation goals that can serve as recommendations for policy makers
- Provide insight about the effects of various sources of knowledge on the firm's expected innovative plan
- Examine the impact of the firm's initial condition on the R&D strategies

Chapter 3

3. System dynamics methodology

3.1. The relevance of system dynamics method to the research topic

In the context of biotechnology, a new established firm is faced with an environment where many large and small companies are competing with each other to develop a new product (Deeds, 2001). In most cases, these firms only have a few tangible assets and required talent and skills to compete with other firms. The only way they can compete and maintain their position is with their research capabilities.

In this regard, firms should identify different technological policies in order to improve their scientific and technological capabilities. Given the limited resources and numerous investments of a high technology company, the manager needs to make a critical decision about how to reasonably allocate these resources, including human resources and funding (Deeds, 2001). Investing in internal R&D activities and utilizing external sources are two important sources of acquiring new knowledge that a firm should invest in. However, each of the strategies has its own characteristics. Therefore, it is required for the manager of a biotechnology company to determine the levels of investment in each of these areas to maximize the performance of the company.

The decision of how to exploit different sources of information for creating innovation resources is not a static decision. To maintain a competitive advantage, a biotech firm must constantly review their previous decisions on the allocation of resources to timely react to any changes. A firm also needs to identify different strategies in order to respond to a variety of internal and external conditions. While analytical models in biotechnology innovation (Van Moorsel *et al*., 2007; Traore, 2004; Kang and

Lee, 2008) provide valuable insights into potential factors and drivers contributing to the creation of new knowledge and innovation, they do not provide a temporal understanding of the dynamic nature of policy decisions and feedback mechanisms.

In the literature, system dynamics modeling is suggested as a possible methodology to capture this dynamic decision process because of the methodology's ability to deal with both quantitative and qualitative variables and the existence of a supportive computer-based modeling package (Galanakis, 2006; Dangelico *et al*., 2010; Garcia *et al*., 2003). Several authors have used a system dynamics methodology to analyze specific problems related to decision making in the technological innovation process (Garcia *et al*., 2003; Galanakis, 2006; Lin *et al.,* 2006; Dangelico *et al*., 2010; Wu *et al*., 2010).

For example, Dangelico et al., (2010) utilize system dynamics modeling to investigate the influence of knowledge and proximity dimensions (geographical, cognitive and organizational) on the firms' decision on whether to join a technological district. Their analysis shows that the amount of knowledge spillovers and the level of proximity dimensions affect the number of outgoing and ingoing firms on a dynamic basis with respect to time. Knowledge spillovers are defined by Griliches (1979) as "working on similar things and hence benefiting much from each other's research" (quoted in Feldman, 1999, p.7). Similarly with system dynamics, the behavior of the agglomeration process in a technological district is justified through explaining some of the fundamental reinforcing and balancing loops (Dangelico et al., 2010).

In this research, a system dynamics simulation model of the early stage of innovation in biotechnology is developed to gain a better understanding of the dynamic behavior of

this complex system. Different scenarios are created and tested with system dynamics modeling to explore managerial implications of decisions regarding the extent of developing knowledge internally or acquiring external knowledge over time.

The existing system dynamics models of the innovation process focuses on the general aspects of innovation and only provides an overall understanding of the different factors that form an innovation system (Galanakis, 2006). The work of Garcia *et al.,* (2003) is the only one that employs system dynamics modeling for investigating different innovation policies, but their study was not designed specifically for biotechnology.

Using system dynamics allows us to achieve our twofold purpose. First, we contribute to the understanding of factors affecting the earlier stages of the innovation process in biotechnology, as well as developing a comprehensive model that represents the interactions among identified factors for innovation creation, resource allocations, and feedback mechanisms over time. Secondly, system dynamics allows developing a simulation model by which we can investigate the effects of different sources of knowledge on the innovation process outcome in the early stages of the innovation which may help policy makers develop more effective policies in order to satisfy their innovative goals.

3.2. The system dynamics methodology

System dynamics modeling was founded by Forrester (1968) and developed recently by Coyle (1996), Maani and Cavana (2000) and Sterman (2000). It maps the decision-making process, operating polices and information flow in an organization by combining information feedback theory and behaviour decision theory (Morecroft, 1985; Sterman,

1987). System dynamics can also be used to analyze policy decisions and their corresponding feedback. Decisions of a firm or a supply chain network usually show the dynamic complexity (Forrester, 1968; Morecroft, 1985), which can be very difficult to capture in static models.

3.3. Different types of the system's elements: stocks and flows

The stocks' elements represent an accumulation of measureable items such as the age, the total amount of budget, or the whole number of cars within a country. Stocks are not necessarily limited to physical tangible concepts and they may also represent intangible items such as the accumulated knowledge of developing patents in the R&D department of a firm.

Flow elements represent the inflow and/or outflow to/from stocks. The role of auxiliary variables applies to the model through the flow elements. Policy-making scenarios can be applied to the system by controlling the flow elements, initial status of stock or auxiliary variables.

3.4. Time Delays

Time delay is another important aspect for developing system dynamics models since the delays allow for a temporal element to be added to the development process.

3.5. The relationship of the system's element: feedback cycles

All dynamics of the system take place because of the interactions of just two types of feedback loops, positive (or self-reinforcing) and negative (or self-correcting) loops (Sterman, 2000).

In positive loops, a variable constantly feeds upon itself to reinforce its own growth or collapse. For example, as shown in Figure 3.1 more chickens result in more eggs laid, which will hatch and be added to the chicken population, leading to even more eggs, and so on. A Causal Loop Diagram or CLD captures the feedback dependency as it is shown in the example of chickens and eggs. The loop identifier R in the center of the loop shows that it is a self-reinforcing loop.

The positive (+) and negative signs (-) on the arrows indicate the relationship between the variables in the model. The polarity specifies the influence of the independent variable on the dependent one. A positive sign means that by increasing or decreasing the independent variable, the dependent one will also increase or decrease, respectively. A negative sign indicates an opposite trend, so the dependent variable will decrease or increase as the independent variable is increased or decreased, respectively.

A balancing (also known as self-correcting and virtuous) loop is a loop that restricts its own growth (Sterman 2000). The balancing loop or negative loop is a loop that exhibits goal-seeking behaviour. The balancing loop changes its value while being affected by a variable in the system. The loop obtains an equilibrium state when the goal is reached. The S-shape (or logistic) growth curve and the asymptotic growth (decay function) are normally assigned to the balancing loops (Sterman 2000). An example of a negative loop is shown in Figure 3.2. As the chicken population grows, more road

crossings will lead to fewer chickens. More road crossings means that more chickens stand the risk of getting hit by a car, hence this leads to fewer chickens. The loop identifier B in the center of the loop shows that this is a balancing loop.

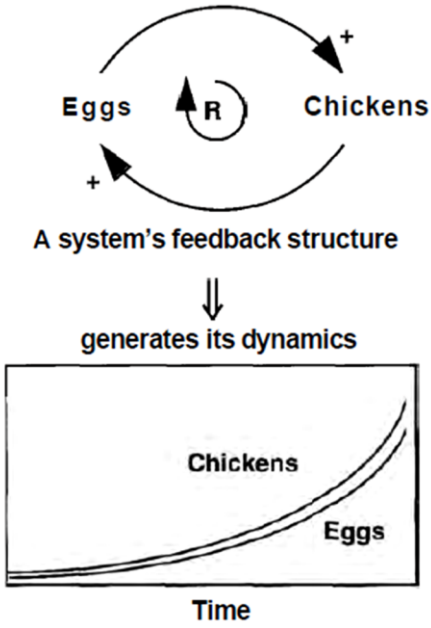


Figure 3.1 A positive feedback loop (Sterman 2000: 13)

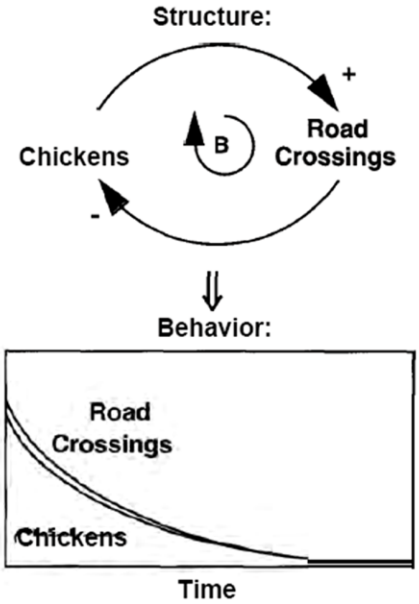


Figure 3.2 A negative feedback loop (Sterman 2000: 13)

Chapter 4

4. The model description

4.1. The description of the causalities: the causal model

4.1.1. The big picture of causal model

The aim of this modeling is to better understand the early stage of the innovation process in biotechnology companies. The structure of the model includes (a) the significant elements that form the whole system of innovation at its early stage and (b) the relationships among these elements which underlie the dynamics of the innovation process. Regarding the elements of the systems, reviewing the literature illustrates the following as the main influential items in the early stage of innovation: the R&D activities, external source of knowledge, absorptive capacity and funding components. In addition to these elements, another aspect of the structure of the model is the causal relationships among these elements. The causal diagrams, as explained in the previous chapter, help us to portray the relationships among the identified factors in order to illustrate the whole causality of the system. The causal diagram developed in this study for the early stage of innovation at the biotechnology firms contains five causal loops: knowledge creation, knowledge accusation, capital raising, venture capital investment, and R&D lock-in. The following section introduces these five causal loops and their interrelationships in detail.

4.1.2. The first loop: knowledge creation

As it was described earlier, knowledge for innovation can be provided by two main sources: internal sources and external sources. A firm's research and development efforts mainly supply internal sources, while external sources can be provided with the acquisition of knowledge in competitive markets (Dangelico *et al*., 2010; Garcia-Muina *et al*,. 2009; Todtling and Trippl, 2007). These relationships are shown in Figure 4.1 the positive signs above the arrows indicate that the more R&D effort the firm exerts the more profound internal learning, the more it will achieve and the more knowledge is created for generating innovation. Also it is shown that the level of knowledge will increase with an augmented utilization of external sources.

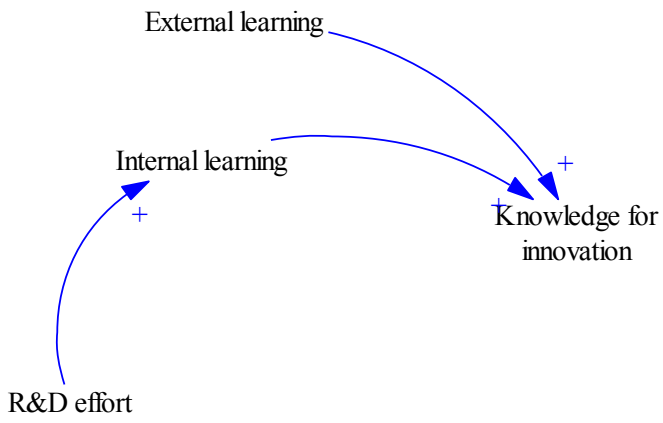


Figure 4.1 Sources of knowledge creation

Once the firm has accumulated knowledge from various sources, the tacitness of knowledge needs to be manipulated and altered for developing innovations. The process of converting tacit knowledge into messages such as databases, patents, papers, user manuals, etc. is called knowledge codification (Albino *et al*., 2001; Balconi, 2002;

Garcia-Muina *et al*., 2009). In biotechnology, the firms have a high propensity to patent their discoveries because preventing them from duplication and securing royalty income is critical for their output (Scherer, 2002). Patents are therefore well-accepted measures of innovation, regardless of whether the innovation reaches commercial ends. De Luca *et al*. (2010) claimed that in biotechnology, due to the length and complexity of scientific exploration, indicators which are common in traditional industries such as the market performance or the number of new products, cannot be fully utilized to describe innovation performance. As a result, the accumulation of knowledge results in the creation of innovation in terms of patents. The arrow connecting the "knowledge for innovation" and "the idea generated" in Figure 4.2 demonstrates this relationship. Eventually, the existing innovative ideas and information of a firm influence the internal learning of the firm by both changing the direction of future R&D activities and enhancing internal learning from experience gained by creating innovation and representing them with patents (Galanakis, 2006; Dangelico *et al*., 2010). These relations lead to creation of our first positive loop, Knowledge creation, represented in Figure 4.2. This loop describes that the more a firm carries out research and development, the more the internal learning of the firm will be enhanced to ultimately results in the creation of new knowledge and innovation. Then, the created innovation will direct the forthcoming R&D and continues on.

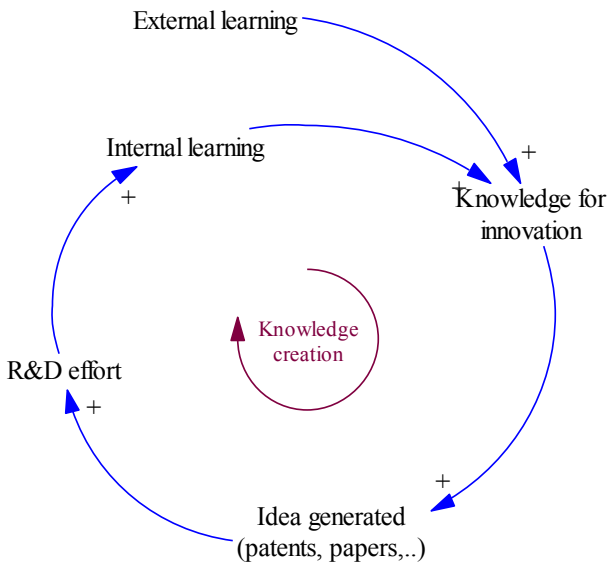


Figure 4.2 Knowledge creation loop

4.1.3. The second loop: knowledge acquisition

It is very important for the success of a biotechnology firm to consistently keep acquiring knowledge from beyond its boundaries (Coombs *et al*., 1996; Dodgson and Rothwell, 1994). Through external sources, the firm is able not only to obtain new knowledge that could be directly exploited in various research projects, but it can also gain enough new information to constantly re-evaluate its projects' portfolio (Deeds, 2001). However, it has been suggested by Cohen and Levinthal (1990) that the firm cannot easily absorb this knowledge without exerting its own effort, *i.e.* the firm needs to invest in building its *absorptive capacity*. Absorptive capacity enables the firm to recognize and assimilate valuable knowledge, then transform and apply the knowledge to new products.

There are several possible measures of absorptive capacity that are established in the literature. Most commonly, "the amount of R&D investment" is recognized as an appropriate indicator (Cohen and Levinthal, 1990; Zahra and George, 2002; de Jong and Freel, 2010), and has been also proposed for measuring the absorptive capacity among small firms (Muscio, 2007). Moreover, the number of qualified scientists is also considered an important proxy for measuring the absorptive capacity in small to medium-sized biotech firms (Muscio, 2007). This is also consistent with the research of Reid and de Brentani (2004) in which human attributes, such as perception (quick identification and interpretation ability), reconstruction (representation ability) and classification (evaluation), allow firms to separate potentially relevant and irrelevant information from the environment.

As Figure 4.3 shows, undertaking more R&D activities as well as more qualified scientists working in the firm will provide the company with an improved ability to acquire knowledge from external sources, and thus to increase its absorptive capacity. These relationships create our second positive loop. This loop is demonstrated by thicker arrows in Figure 4.3 as the Knowledge acquisition loop. This feedback loop expresses that conducting more research activities improves the firms' ability to absorb and exploit external knowledge so that the firm can expand its knowledge level. The developed knowledge, in addition to internal knowledge of the firm, provides the basis for subsequently applied R&D.

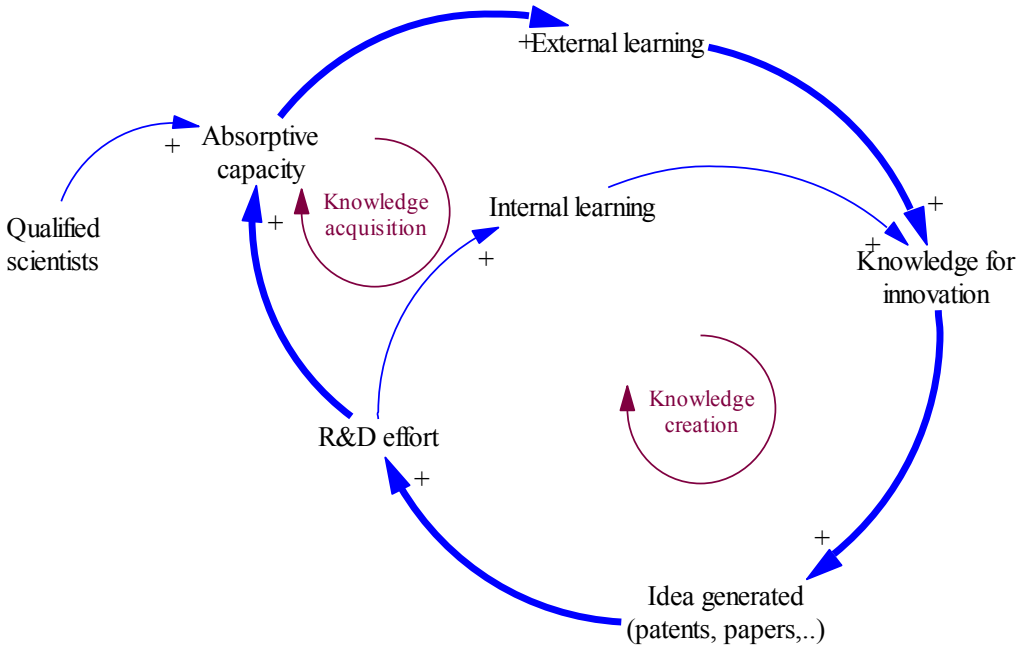


Figure 4.3 Knowledge acquisition loop

4.1.4. The third and forth loops: capital raising and venture capital investment

Many researchers emphasized the importance of funding in the success of new product development in biotechnology (Hall and Baghchi-Sen, 2002; Pisano, 2006; Heinonen, 2009). As it was argued by Heinonen (2009), there is a positive correlation between the amount of investment in R&D activities and the number of new products. According to Pisano (2006) only a few companies are profitable because while they are developing a new product, they are not producing any revenue through commercial products due to the long production cycle.

As mentioned earlier, a biotechnology firm needs to spend millions of dollars on research and development activities. Biotechnology companies are usually funded through public money, especially in the earlier stages of product development. However, the other sources of financing will be replaced as the firm grows. The primary source of

funding is often supplied by the founder or other individuals (Heinonen, 2009). Firms also seek capital from sources such as government programs and business angels. Searching for venture capital is extremely important for biotechnology companies since development projects in this field are characterized by high levels of uncertainties and require a significant amount of money. It is estimated that the cost of the development of a new drug is from USD 500-800 million, roughly 40% of which is shared for discovery and preclinical studies. (Tollman *et al*., 2001; Bains, 2004; Dickson and Gagnon, 2004). The total development time is on average between 12 to 15 years for a new drug to be discovered and go though pre-clinical and clinical trials to get finally approved (Amir-Aslani and Negassi, 2006; Khilji *et al*, 2006). The long development process can be justified by the rising number of clinical trials that need to be conducted before the approval is granted. It is only after this process that some revenue can be gained.

Figure 4.4 demonstrates the different sources of financing as well as their relationships with other elements of the innovation process. As shown in Figure 4.4, their relations form our third positive loop, which is Capital raising. This loop represents that the government, private sectors and venture capital are the main sources of financing. However, by investing more money in R&D activities, the firm can spend more on conducting research which leads to an increase of ideas generated by a firm.

Besides acquiring funding from public resources, a firm can generate revenue by selling or licensing its intellectual property (IP) (Van Moorsel *et al*., 2007). Some firms only focus their efforts on development activities with the intention of granting or selling their IP instead of bringing a product into commercial ends. Intellectual property transfer through sale of patents, licensing agreements or material user agreements provides

opportunities for networks to share their resources as well. As a firm generates more innovations in terms of patents, it can sell or license more of its intellectual properties and more money becomes available to spend on R&D activities, thus creating a reinforcing loop labelled by Capital raising. As a result, the firm can conduct more research to create novel technology and generate more money, although the rise in the number patents can directly affect the intention of private sector for investing in novel technology.

In addition, Niosi (2000) suggests that patents are highly important for biotechnological companies, since they act as a signal for venture capital investors indicating a unique and valuable technology. A firm with an accumulated higher number of patents thus has a better chance to attract the investors. The positive arrow between the ideas generated and venture capital in Figure 4.4 represents this relationship.

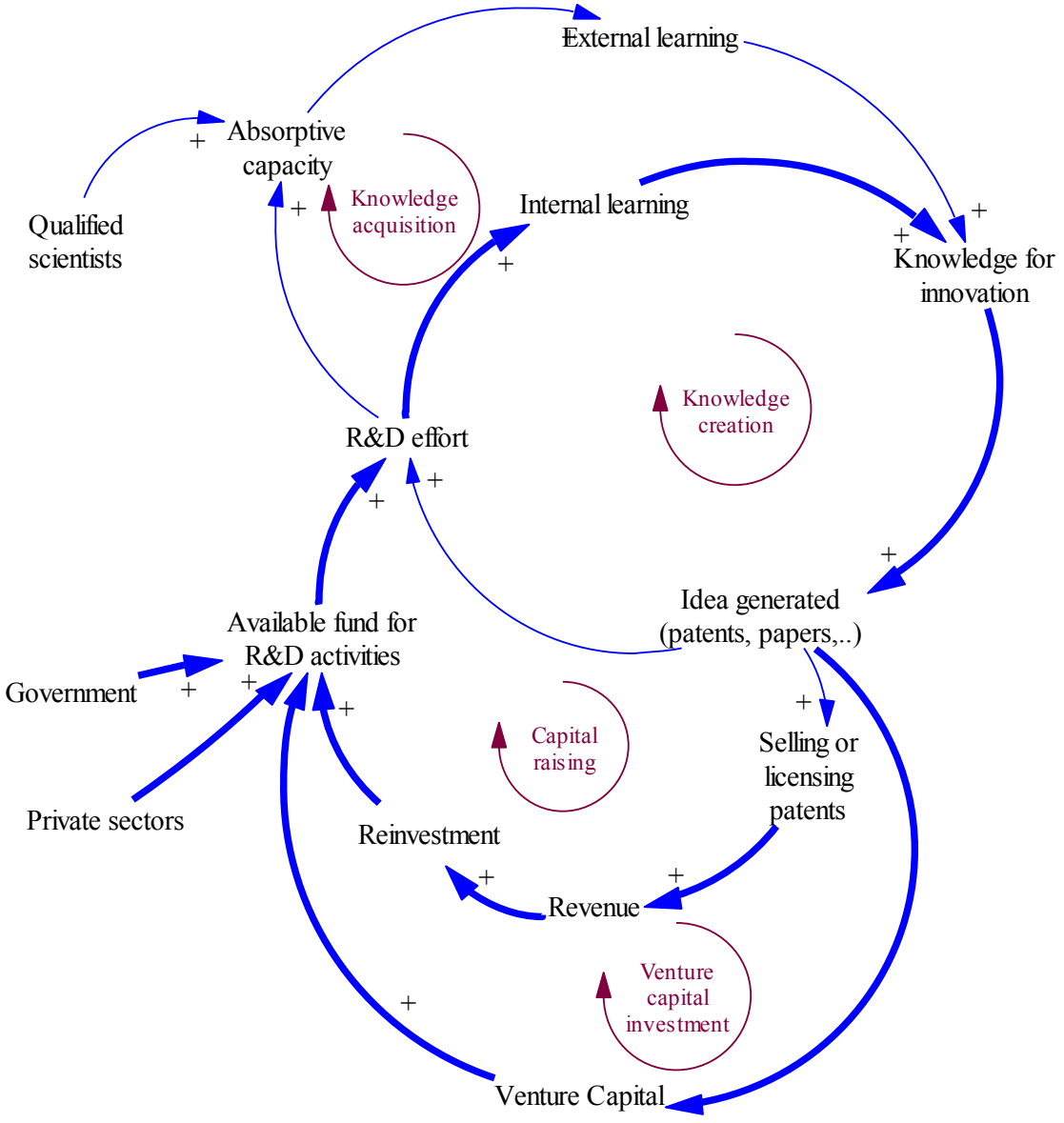


Figure 4.4 Capital raising loop

4.1.5. The effect of firm size

Firm size is measured in biotechnology in terms of both funding and available resources and has a great effect on the firm's capacity to innovate. The firm size can also be defined by the number of available employees. The entrepreneurial nature of small firms is restricted by a lack of resources; however, large firms also have limitations

because of their bureaucratic nature. This suggests that medium sized firms (50-150 employees) have the most effective innovative activities by having more resources than small firms and less bureaucracy than large firms (Van Moorsel *et al*., 2007).

Large, integrated high-technology firms mainly take part in all levels of the innovation process, which consists of basic research, product development, and finally commercialization. Smaller high-technology firms designate themselves as a product developer between universities that perform basic research and establish companies, in order to enhance their commercialization capacity. The biotechnology in Canada is dominated by small and medium sized firms (SME) that devote much of their operations to research and development (Hall and Baghchi-Sen, 2002).

The number of employees in the R&D activities also has an impact on the creative capacity at the R&D stage. Traore (2004) empirically demonstrated that a 10% increase in the number of biotech R&D employees raises creative capacity by 30%. Hence, as it is shown in Figure 4.5, the firm size impacts both the venture capital source of funding and the resources available for R&D activities. It affects them positively since by increasing or decreasing the size of firm, the amount of venture capital will increase or decrease respectively. Similarly, firms have fewer resources and employees for performing research and development as their size decreases.

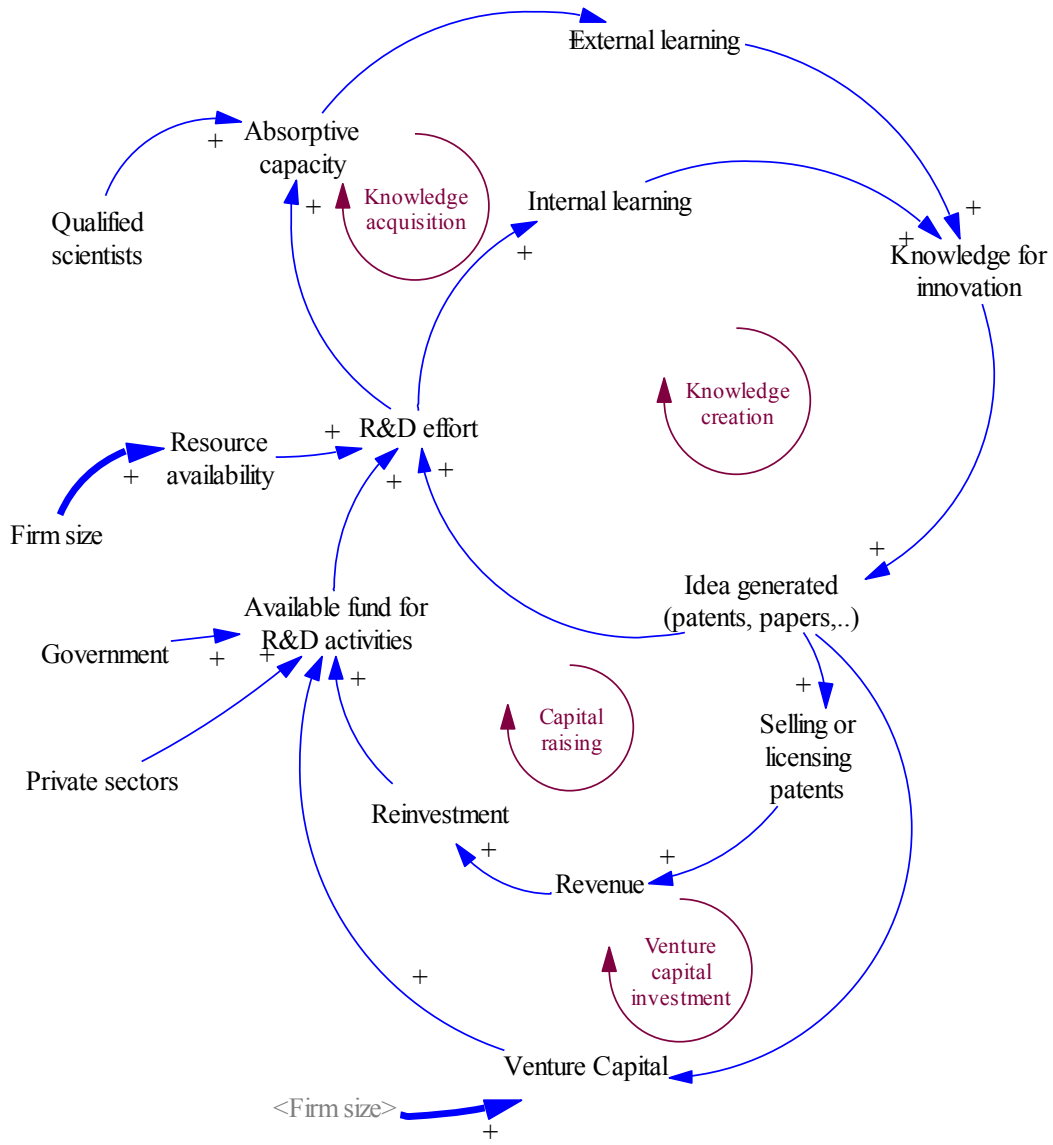


Figure 4.5 Firm size effect

4.1.6. The fifth loop: R&D lock-in

The previously described "knowledge creation loop" and "knowledge acquisition loop" represent how higher levels of R&D effort will lead to the creation of more innovations. However, this relationship is not always viable and will eventually cause a reverse effect on the innovation outcome (Kang and Lee, 2008). More investments on R&D activities increase the number of patents, but the correlation between them is in the

form of an inverted U shape, probably because of financial constraints for biotechnology (Arvanitis, 1997). According to Khilji *et al*., (2006), most available funds are dedicated to R&D activities during the discovery stage. Since private sectors are not interested in investing in the research projects during the discovery stage due to the lack of commercial products during this stage, high uncertainties and an expected long period before the revenue generation. This in turn has an effect on the total available funds and the R&D available funds. Hall and Baghchi- Sen (2002; 2007) also claim that spending more on R&D because of too many regulatory procedures and financial constraints slows down the recognition of commercial output. Therefore, the unintended effect of performing too many R&D activities and dedicating most of the available funds to them creates a balancing loop, labelled by a R&D lock-in.

Figure 4.6 represents this loop, in which more investment in R&D activities over time leads to the decline in the number of commercial products. This decrease in products means that less private investors are willing to invest in research and development activities. Ultimately, because of the decline in one important source of revenue, the available funds are reduced and it leads to a decrease in the research efforts of the company.

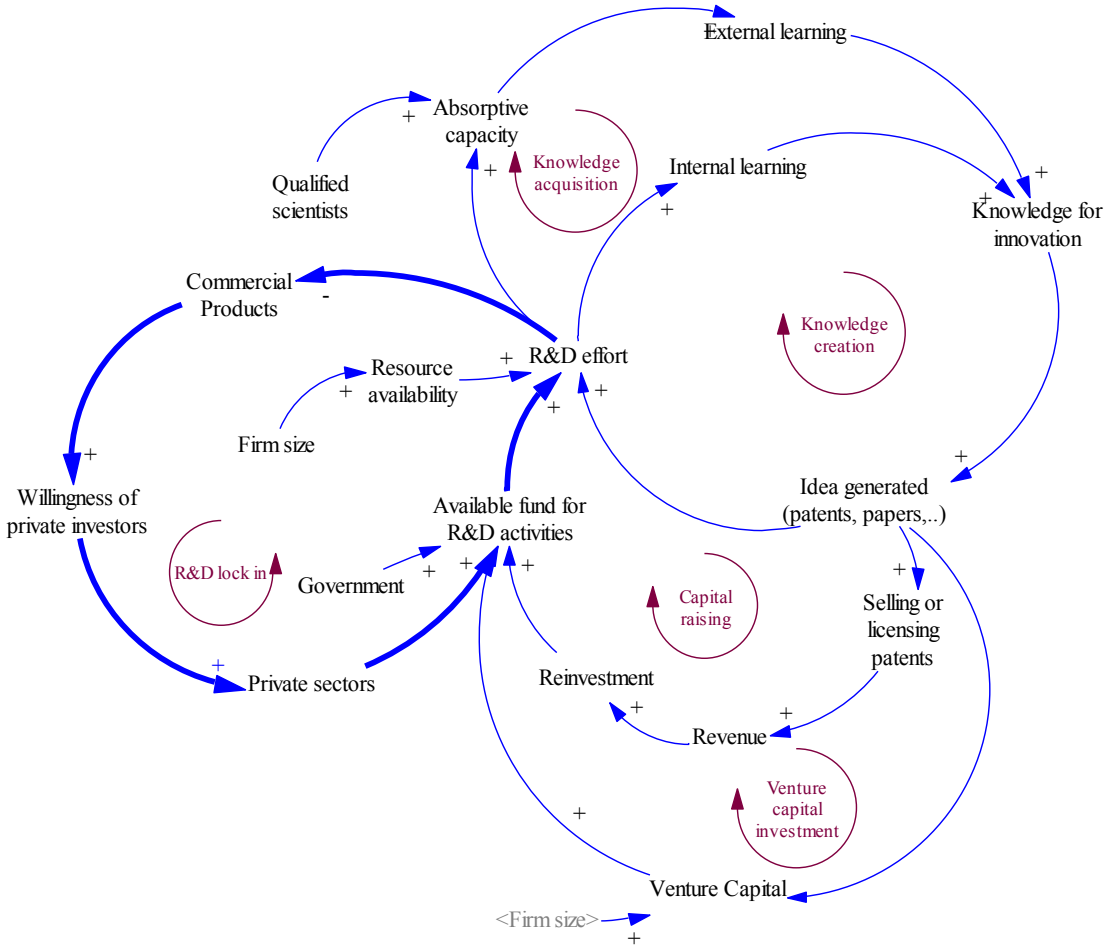


Figure 4.6 R&D lock in loop

4.2. Formalizing the model for a computer simulation

Since the modeling process is an iterative process, which consists of formulating and testing the hypothesis, the equations and functions of the interrelationships are defined and the causal diagrams are transformed into a fully formalized model through a system dynamics software package, Vensim. The following causal diagrams, in addition to demonstrating important factors identified in the previous section, represent various conditions that reflect a firm's decision to use a particular source of knowledge. The simulation model and equations are also built based on these causal diagrams.

From the causal models developed in the previous section, it can be concluded that a firm can either create all of its knowledge and resource requirements through internal R&D activities or utilize external resources, such as creating strategic alliances and acquiring knowledge from external parties. Nevertheless, obtaining external knowledge and exploiting it to generate new knowledge largely depends on the ability of a firm to recognize and develop external resources. This ability highlights a very important aspect of organizational learning, defined as absorptive capacity. Absorptive capacity can be generated through R&D activities, directly through staff training, or can be developed as a by-product of a firm's manufacturing operations (Muscio, 2007).

4.2.1. Performance gap

In this model, the critical decision of when and to what extent the knowledge should be developed internally or externally is made according to the size of the knowledge performance gap.

$$PG\,(t) = (target\ knowledge\ value - actual\ knowledge\ value) \quad (4\text{-}1)$$

The choice of this measure is consistent with the study conducted by Garcia *et al.* (2003). However, the performance measure used in this thesis is not based on financial performance indicators, such as the return on assets, sales growth or profit margin. These are inappropriate because biotechnology firms do not have any history of profits or earnings due to the long production cycle and the inherent complexity of scientific explorations (De Luca *et al*., 2010).

Instead, the biotechnology firms' value is constrained by intangible assets that the firms possess, and these are represented by their knowledge. Therefore, the performance measure is defined by the value of knowledge created in the firm. It is assumed that the firm sets a performance target for the amount of knowledge it is planning to create. The knowledge created by either source of information*, i.e.* internal or external, produces distinct values for the firm. Knowledge that is created by internal learning involves more uncertainties and is riskier compared to information that can be achieved through external learning (Garcia-Muina *et al*., 2009). Nevertheless, knowledge and resources acquired internally are more likely to provide the firm with breakthrough innovations that can lead to the creation of a competitive advantage for the firm (Matusik, 2002; Schroeder *et al*., 2002, Garcia-Muina *et al*., 2009).

A zero performance gap indicates that the actual performance of a firm is equal to the anticipated target performance. In this situation, it is assumed that a firm equally focuses on internal research and external resources. A positive gap indicates that the firm lags behind its target and a negative gap reflects that the actual performance exceeds its target.

4.2.2. The role of external resources

Knowledge acquisition and partnership has been viewed by many scholars as a well-known strategy to deal with challenges faced by biotechnology companies involving drug discovery (Greis et al., 1995; Edwards et al., 2003; Amir-Aslani and Negassi, 2006). This strategy helps biotechnology companies to achieve more efficiency in their research and development activities in order to improve their performance goals. Major pharmaceutical companies have a strong desire to tap into external strategies because they provide them with rapid access to both intellectual property and capability (Amir-Aslani and Negassi, 2006).

Recent research has suggested that barriers that impede a successful innovation process are the primary motivation for companies to pursue the acquisition of knowledge from outside of the company (Greis et al., 1995; Amir-Aslani and Negassi, 2006). Amir-Aslani and Negassi, (2006) argued that the growing R&D costs, increasing development time frames, the decrease in productivity, the increase in investor expectations, and the need for a new paradigm for drug development are all challenges that pharmaceutical companies encounter during drug discovery. In the past, pharmaceutical companies have had the time to develop competencies, but due to the increasing expectations of the investors and the intensifying competitiveness of the market, they no longer have this luxury. Hence, outsourcing R&D efforts and knowledge acquisition have been considered as a new strategy to speed up the drug development process.

In this model, it is assumed that when the gap is positive, i.e. the knowledge level of the firm falls behind its target, the company will try to close the performance gap with a fast and less risky alternative source of knowledge, which is external knowledge. The

positive performance gap can be created by an increase in the expectation of a firm either due to internal reasons or from the pressure of competitive environments. This assumption is made since it is empirically proved that external knowledge gained through collaboration, will benefit firms by providing faster results than if the firms get engaged in internal basic research instead (Fabrizio, 2009).

Amir-Aslani and Negassi (2006) argued that one of the few shared goals that biotechnology and pharmaceutical companies have is to bring new drugs into the market. Structuring strategic alliances provides them with a less costly, more certain, and more flexible way to acquire capabilities that they do not possess. The primary motivation behind entering alliances differs such that biotechnology companies desire to share risks and to access financial resources, whereas pharmaceutical companies intend to fill the gaps in their research pipelines. Hadjimanolis (1999) also argues that small firms use external expertise for innovation because of their lack of internal resources.

The competitive environment forces a firm to set higher goals in order to keep its competitive advantage. However, low productivity, high development time, the rising costs of R&D activities and the shortening of the product life cycle hinder their ability to develop new products on their own. Therefore, it is believed that mergers and acquisitions are a substitute strategy for increasing market demands and the immediate need for earning.

After considering the described dynamics of the system, it can be implied that when a firm falls behind its target knowledge, it will invest more in acquisition and partnership activities that can provide it with external knowledge to decrease the gap between the actual knowledge and the target knowledge. Consequently, the decision whether to invest

in R&D activities or to make more strategic alliances is made based on the value of performance gap.

The discussed relationships create our first balancing loop which is called B1 (see Figure 4.7). This loop reflects that a more positive gap leads to the firm concentrating more on external projects. This focus on external knowledge acquisition will result in the greater knowledge stock, which finally leads to the decrease in the gap between the target value of knowledge and the actual performance of the firm. However, making collaborative contracts depends on having sufficient absorptive capacity as well.

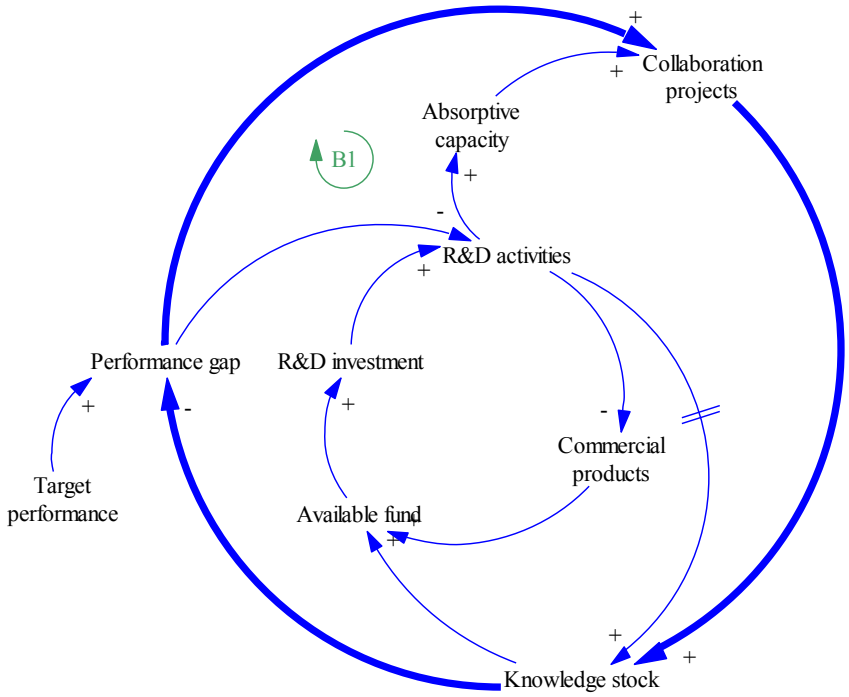


Figure 4.7 The first balancing loop B1

The first reinforcing loop is demonstrated in Figure 4.8 as R1. This loop demonstrates that if the firm exceeds its target then the performance gap is negative and the firm will concentrate on the internal R&D activities to introduce a newer and better product in order to create or maintain its competitive advantage among the other firms. Unlike in the case of the positive gap, the negative gap represents a situation where the firm has already achieved its goal, and thus there is no need to concentrate more on external knowledge. In this research, it is suggested that firms that achieve their desired performance should take the opportunity to focus on internal R&D activities. This allows them not only to generate new knowledge, but also to simultaneously enhance their ability to absorb and exploit existing knowledge in order to sustain their competitive advantage within a highly competitive environment.

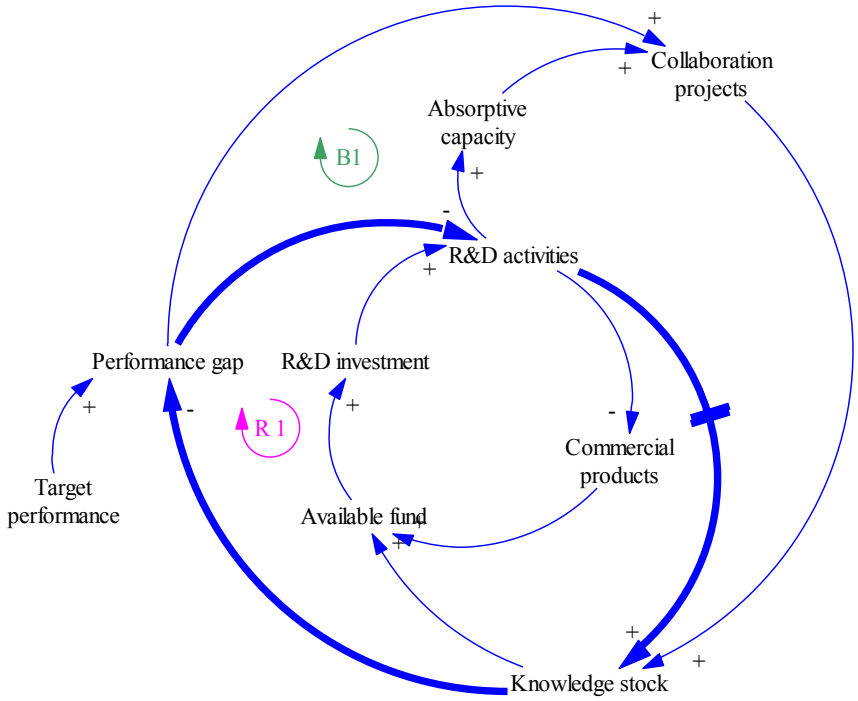


Figure 4.8 The first reinforcing loop R1

4.2.3. Allocation decision

In the simulation model, these relationships lead us to the conclusion that the fraction of investment on R&D activities or on external knowledge, *Indicated Fraction (IF),* is identified as a function of the performance gap. This variable, which has a value between 0 and 1, represents the ratio of external source of knowledge to internal source of knowledge. When the performance gap is zero, an equal amount of funding will be dedicated to each one. A nonlinear relationship is determined and modeled as an S-shaped curve, according to qualitative data derived from the literature. It is represented as follows:

$$Indicated\ Fraction\ (IF) = \frac{1}{1+exp(-Normalized\ parameter\ (g)*PG(t))} \quad (4\text{-}2)$$

PG(t) is the performance gap and the constant variable *Normalized parameter (g)* defines the slope of the S-shaped curved. *PG(t)*=0 is the inflection point where *Indicated Fraction (IF)* = 0.5, which shows that half of the investment is dedicated to the R&D activities and the other half is spent on generating knowledge through external knowledge.

However, a time delay exists from the moment of distinguishing the need for change to the time that the decision to change is actually applied. Thus, the allocation of funds is based on a perceived fraction, which is defined in our model by *Actual Fraction (AF)*, where *ATF (Adjustment Time for Fraction)* in the model is the time it takes to react to the *Indicated Fraction (IF)*. This delay and other similar delays are modeled here as an *exponential smoothing*. According to Sterman (2000), exponential smoothing means that the perceived value gradually adjusts to the actual value of the variable. The belief is constantly revised until the error is eliminated. This smoothing is necessary since the effect of changing a variable cannot be perceived instantly after measuring the actual value.

4.2.4. Knowledge of the firm

Each successful innovation project brings a value to the firm, either internally or externally. The amount of knowledge gained from each of these sources varies. As discussed earlier, R&D projects are inherently riskier than external projects, but have higher returns than external sources. The *Acquired Knowledge of Internal Innovation (AKII)* is the value of fraction of undertaken projects that are successful, and modeled here as follows:

$$\frac{dAKII}{dt} = CRP * RSR * VRD \quad (4\text{-}3)$$

CRP (Completed R&D Projects) is the numbers of completed R&D projects in each quarter, *RSR (R&D Success Rate)* is the success rate of R&D projects and *VRD (Value of R&D)* is the average value of R&D projects. Since *RSR* and *VRD* are typically constant, the variability in the knowledge acquired through internal innovation is a function of *CRP*.

Similarly, the knowledge obtained through external sources, *Acquired Knowledge of External Innovation (AKEI)* is the value of fraction of external projects that are successful, and modeled as follows:

$$\frac{dAKEI}{dt} = CEP*ESR*VEX \quad (4\text{-}4)$$

Where *CEP (Completed External Projects)* is the numbers of completed external projects in each quarter, *ESR (External Success Rate)* is the success rate of external projects and *VEX (Value of External)* is the average value of knowledge gained through external sources. Likewise, the *ESR* and *VEX* are constant and the variability in the knowledge acquired through external innovation is a function of *CEP*. It should be noted that *VRD* is greater than *VEX* but *RSR* is less than *ESR* because the R&D projects are much riskier than external projects.

The knowledge level of the firm is defined here as a stock, *Knowledge Value (KV),* and illustrated in Figure 4.9. The changes in the *Knowledge Value (KV)* stock depend on the knowledge acquired internally *(AKII)* and externally *(AKEI*) as its inflows.

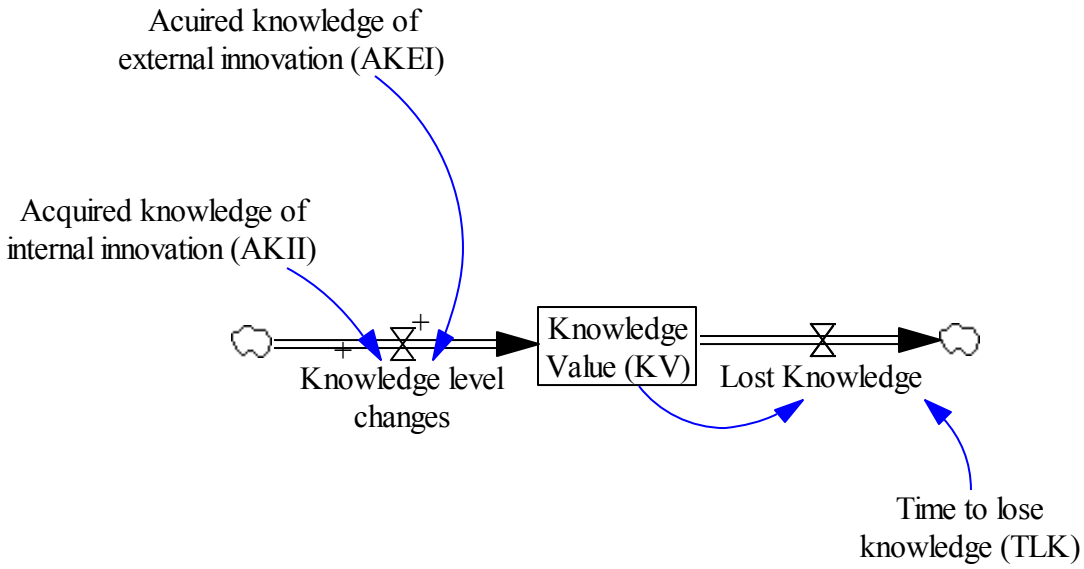


Figure 4.9 The dynamic model of Knowledge Value

The level of the firm's knowledge is also changing because of the knowledge loss. The outflow, *Lost Knowledge*, represents the fractional knowledge lost due to a variety of reasons, including not using the technology and saving it for the future, the departure of key employees, or even new technology replacing old technologies. The outflow is modeled as $\frac{KV(t)}{TLK}$, where *KV (t)* is the value of the firm's knowledge stock and *TLK (Time to Lose Knowledge)* is a constant representing the length of time in quarters in which knowledge is lost. The total knowledge stock value at time *t* is illustrated by the following equation:

$$KV(t) = \int_{t0}^{t} \frac{dAKII}{dt} + \frac{dAKEI}{dt} - \frac{KV(t-1)}{TLK} + KV(0) \quad (4\text{-}5)$$

4.2.5. External and Internal projects

At each quarter, the firm undertakes *External Projects* (*EP*), and *R&D Innovation Projects* (*RIP*). *RIP* is a function of the funds available for research activities such that

$$RIP = \frac{IFA}{ACR} \tag{4-6}$$

Where *ACR (Average cost of R&D)* is a constant which equals the average cost of a R&D project, and *IFA (Internal Fund Allocation)* is the function of *Fund For Research (FFR)* and *Actual Fraction (AF)* that represents the available funds for conducting in-house R&D activities.

$$IFA = Fund\ for\ research\ (FFR) * (1 - Actual\ Fraction\ (AF)) \tag{4-7}$$

The number of external projects *(EP)* are acquired by the firm is also dependent on the firm's absorptive capacity. Therefore, it is defined as follows:

$$EP = \frac{EFA}{ACE} * Absorptive\ Capacity\ (AC) \tag{4-8}$$

Where *ACE (Average Cost of External)* is a constant which equals the average cost of a project that is obtained from outside of the firm and *EFA (External Fund Allocation)* is the function of *Fund For Research (FFR)* and *Actual Fraction (AF)* that represents the available funds for obtaining external knowledge.

$$EFA = Fund\ For\ Research\ (FFR) * Actual\ Fraction\ (AF) \tag{4-9}$$

Moreover, the average time required for completing or gaining R&D projects and external projects are different. Thus, they are modeled in the system as *TR (Time to*

complete a R&D project) and *TE (Time to complete an external project)* for internal projects and external projects, respectively.

4.2.6. Financial resources

As it can be seen in Figure 4.10, the second reinforcing loop is R2. This loop shows that as the firm generates more knowledge, the firm will have more access to venture capital either by licensing their patents or signalling venture capital investors where there is an avenue for further development in which they can invest (Niosi, 2000). By having access to a greater source of funds, the firm is able to spend more on research activities. Therefore, with some delay, the firm's effort leads to an increase in its knowledge stock.

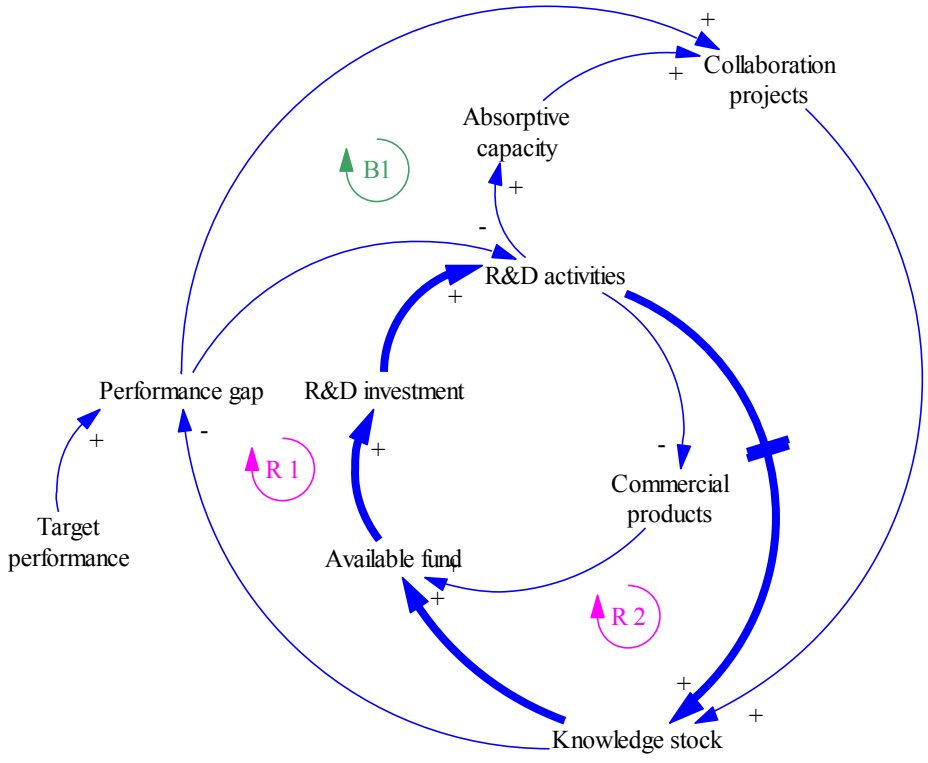


Figure 4.10 The second reinforcing loop R2

Although the system based on the characteristics of the reinforcing loop, desires to keep investing on its own R&D, the financial resources are limited and the investment on R&D activities cannot last for the long term. As the firm invests more in R&D, it will have less money to introduce a new product into the market, which causes a decrease in available funds and subsequently impacts the amount of investment for future research (Khilji *et al*., 2006). These relationships are represented in Figure 4.11 by loop B2.

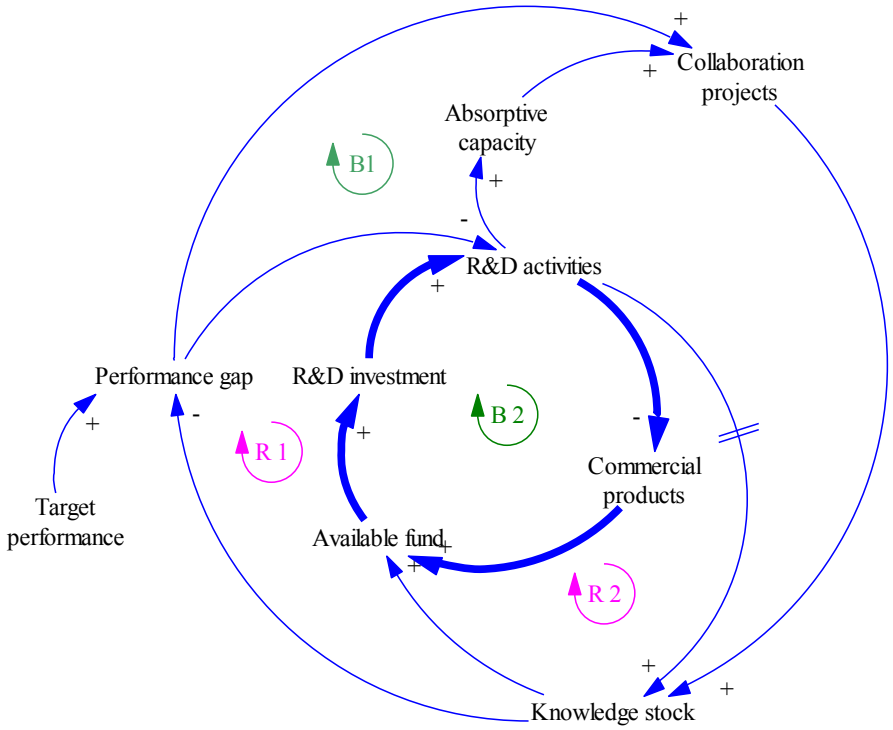


Figure 4.11 The second balancing loop B2

Therefore in the simulation model, the required funds for performing the discovery stage, (i.e. the early stage), *Fund For Research (FFR)*, are modeled as a stock (see Figure 4.12). These funds are used both for conducting in-house research and for knowledge acquisition from external resources. The inflow to this stock is called *Investment For Research (IFR)* and is defined as follows:

$$\frac{dIFR}{dt} = SI\ (t) * \ actual\ FI \tag{4-10}$$

$$SI\ (t) = II*KSE \tag{4-11}$$

Where *SI (Standard Investment)*, the funds that the firm can acquire in each quarter, is a function of the *Initial Investment (II)* and *the Knowledge Stock Effect (KSE). II* is a constant and is defined as the quarterly standard fund available for the discovery stage and *KSE* is a function of the knowledge value, *KV (t). KSE* represents that the firm in addition to gaining benefit from external sources of funds, such as the government and venture capital, can earn revenue from its stock of knowledge.

The limitation of R&D activities in the simulation model is applied by the variable called *Fractional Investment*. However, since the effect of this reduction is not immediate, the *actual FI* is used in the model by considering exponential smoothing delay, where *In. Adjustment Time (IAT)* in the model is the time delay of realization of this decrease in the financial resources (see Figure 4.12). The *Fractional Investment* is formulated as follows.

$$FI = MI + (1\text{-}MI) * \\ 1/\ (1+EXP\ (Normalized\ parameter\ (g2)*(CCF - AF))) \tag{4-12}$$

Where *Min Investment fraction (MI)* is a constant that determines the minimum percentage of investment on the whole research process either internally, or otherwise externally if the firm focuses all its attention on the external resources. The constant variable *Normalized parameter (g2)* defines the slope of the S-shaped curve and *Critical*

Collaboration Fraction for reinvestment (CCF) is also a constant that represents the fraction of allocation in which the investment for research activities starts declining.

The outflow of this stock models the allocation of available funds to internal and external projects:

$$EFA = \frac{FFR * AF}{Td} \tag{4-13}$$

$$IFA = \frac{FFR * (1 - AF)}{Td} \tag{4-14}$$

Where *FFR* (*Fund For Research)* is the total funds available for investing in both internal and external projects, *AF (Actual Fraction)* is a function of the performance gap as previously defined and *Td (Time to Deplete)* is the time delay in using the available fund.

Thus, the *Fund For Research (FFR)* stock at time *t* is demonstrated by the following equation:

$$FFR\,(t) = \int_{t0}^{t} \frac{dIFR}{dt} - \frac{(1 - AF) * FFR(t-1)}{Td} - \frac{AF * FFR(t-1)}{Td} + FFR(0) \tag{4-15}$$

These relationships in the simulation model are illustrated in Figure 4.12.

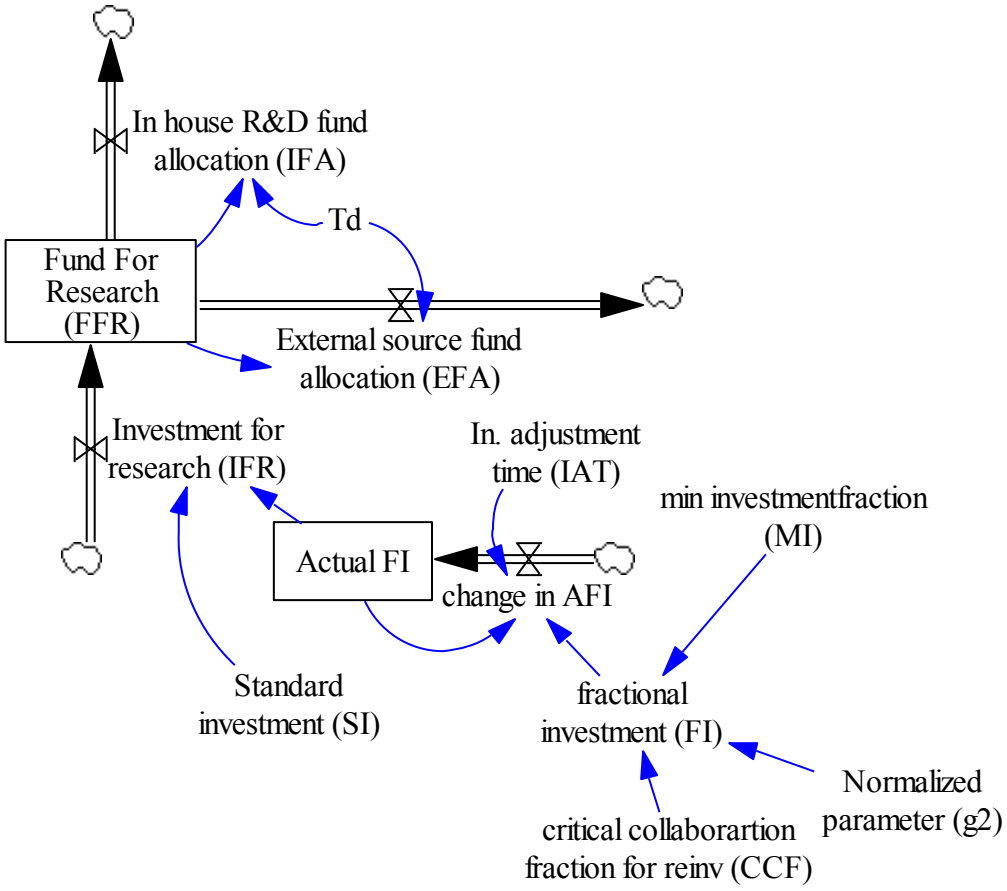


Figure 4.12 The dynamic model of Fund for Research

4.2.7. Absorptive capacity

R&D activities, in addition to being a major source of knowledge, provide the firm with the ability of absorbing external sources of knowledge. This creates our third reinforcing loop, which is called R3 (see Figure 4.13), and demonstrates that more investment in internal R&D leads to an increase in absorptive capacity. Absorptive capacity is regarded as an important factor for absorbing external knowledge (Cohen and Levinthal, 1990), and here it is thus considered to be an essential element for building the

ability of the firm to get involved in alliances and in collaboration activities that ultimately yield knowledge for the firm.

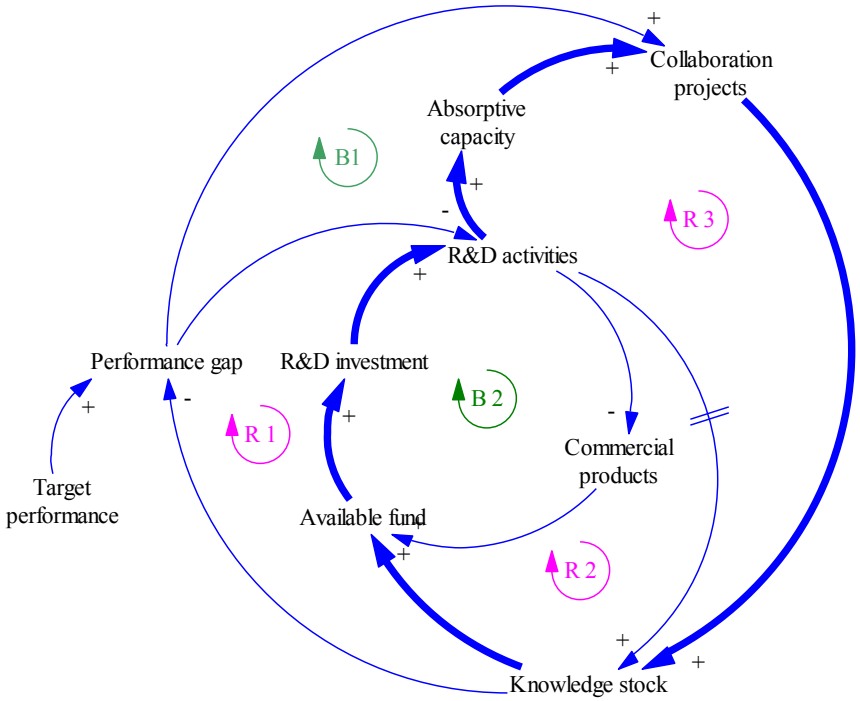


Figure 4.13 The third reinforcing loop R3

Absorptive capacity in this model is modeled as a function of *Actual Fraction (AF)* and has a value between 0 and 1. When the performance gap is zero, the *AF* is 0.5 and the *Absorptive Capacity (AC)* is 0.97. This high value for *AC* is set because the firm at the initial condition has no gap in the system, which means that the firm initially has enough absorptive capacity to identify, assimilate, and exploit knowledge outside of the firm. Focusing more on external resources and less on internal activities leads to a steady decline in the absorptive capacity. However, the slope and the amount of this decrease vary for each firm depending on the firm's skills and number of employees. Absorptive capacity in the simulation model is formulated as follows:

$$Actual\ Absorptive\ Capacity\ (AAC) = \frac{1}{1+exp(\beta*(Fac*Actual\ Fraction\ (AF))} \quad (4\text{-}16)$$

Where β and F_{ac} are constants that determine the slope and the shape of the *AC* versus *AF*. However, by increasing or decreasing the level of R&D activities, the absorptive capacity will not go up or down right away, respectively. In the real situation, there is a smoother response to the changes in R&D activities. By adding an exponential smoothing delay (perception delay), the absorptive capacity can be adjusted gradually over time (*TAC* in the model), which is showed in the model by *Absorptive Capacity (AC)*. The full list of the equations of the Vensim model is available in Appendix A.

Chapter 5

5. Discussion of the findings

5.1. Base Model

As it was mentioned by Sterman (2000), the process of model testing involves controlled experimentation. In this regard, models should be initialized in a *balanced equilibrium.* Equilibrium means that all stocks in the system are unchanging. For having an equilibrium for a stock, the net rate of change must be zero, it means that their inflows and outflows to be equal. In the present model, equilibrium of *Knowledge Value (KV)* stock requires the following:

$$Knowledge\ level\ change = Lost\ knowledge \tag{5-1}$$

Hence, the initial value of the *Knowledge Value (KV)* is set as follows:

$$Initial\ knowledge\ value\ (KV^*) = TLK * \left(\frac{(1-Normal\ Frac)*II*VRD*RSR}{ACR} + \frac{(Normal\ Frac)*II*VEX*ESR*Initial\ AC}{ACE}\right) \tag{5-2}$$

Where the description of the variables are as follows:

Parameter	***Definition***
Normal Frac	The initial allocation ratio
II	Initial investment
VRD	Value of R&D projects
RSR	R&D project success rate
ACR	Cost of R&D projects
VEX	Value of external projects
ESR	External project success rate
Initial AC	Initial value of absorptive capacity
ACE	Cost of external projects
TLK	Time for knowledge to become lost

From the equilibrium function, it can be concluded that the equilibrium knowledge value is high if the values and success rates of external and internal projects are high. The initial absorptive capacity of the firm, as well as the funds allocated for the discovery stage, also have a direct impact on the equilibrium knowledge value. However, the high R&D expenditure and the high cost of external projects leads to the low knowledge value in equilibrium.

In order to capture the dynamics of the model, after setting the equilibrium values, we first need to initiate the model without any exogenous influences. The *base case* model, which is illustrated in Figure 5.1 and Figure 5.2, represents the behaviour of the model in this situation for the *Performance Gap* and *Actual Fraction* variables. The base case is tested assuming that the *Target knowledge value* is the same as *Initial knowledge value*, where ultimately the *Performance Gap* is zero. This means that the fraction of funds allocated to either R&D activities or external knowledge is the same and is equal to 0.5 for each. It is also hypothesized that there is enough absorptive capacity to acquire knowledge from external resources (the value is near to 1).

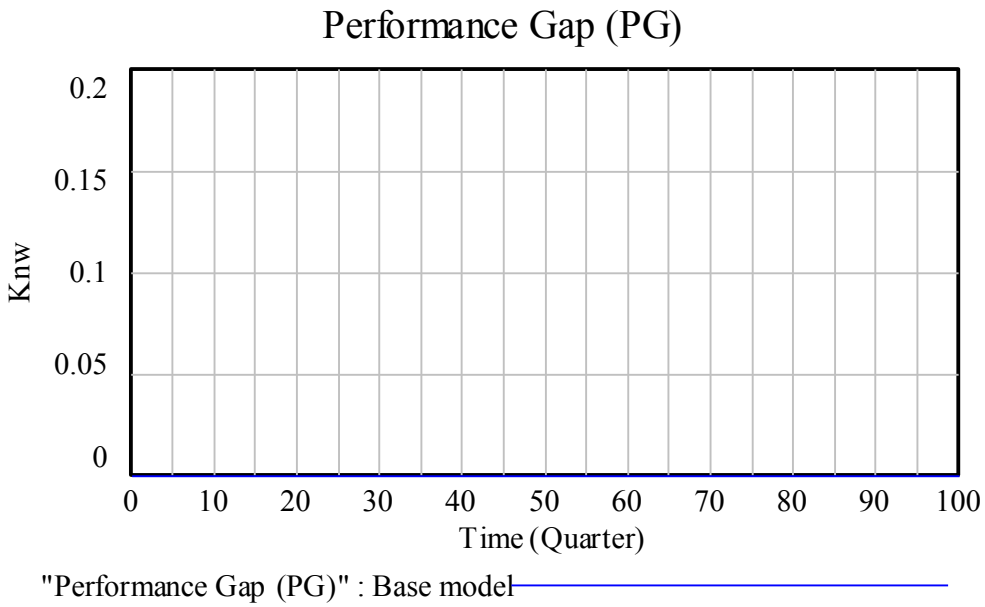


Figure 5.1 Base case: *Performance Gap* of the base case model

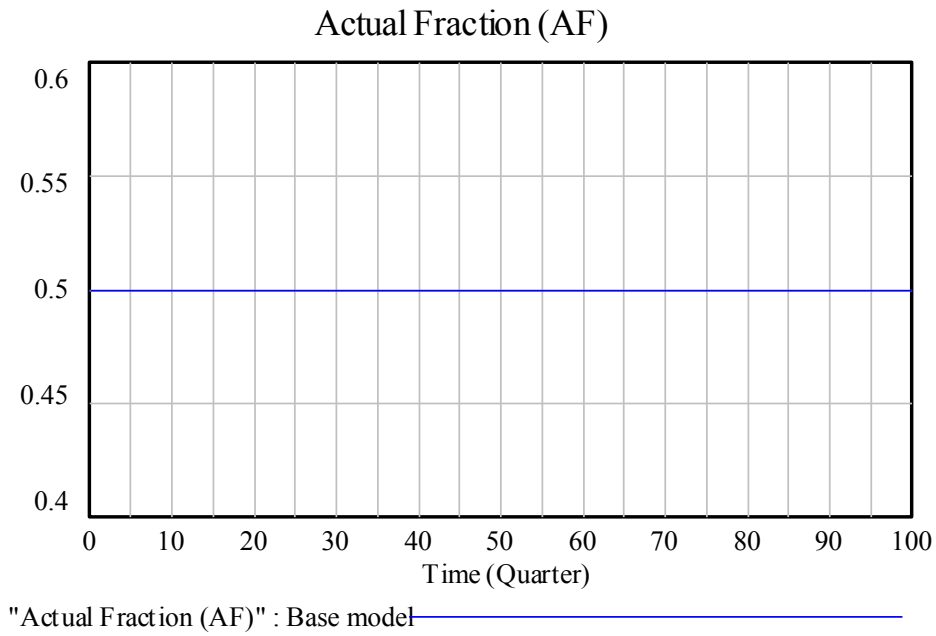


Figure 5.2 Base case: *Actual Fraction* of the base case model

For testing different scenarios in the model, a two years equilibrium period (eight quarters) is set, where financial resources are equally allocated between obtaining

knowledge through in house activities and acquiring knowledge from external resources. After this point in unit time, the firm decides which sources of knowledge to focus on based on the value of the *performance gap* variable. As it was stated previously, in the case of positive the performance gap, the greater attention is paid on acquiring knowledge from external sources. In this model we investigate through simulation runs the effect of using external knowledge and establishing the strategic alliances on the knowledge performance gap. In the following parts the effect of size of the gap, R&D expenditures and the firm's initial orientation towards using external resources of knowledge on the firm's policy decision are examined and the results are interpreted.

5.2. Increase in target by 10%, 30% and 50%

To see how the model reacts to different amounts of increase in the performance target, the target is increased by 10%, 30% and 50% in the time 8 (quarters) in three sets of runs. The proportional results of these runs for *Performance Gap* variable are shown in Figure 5.3.

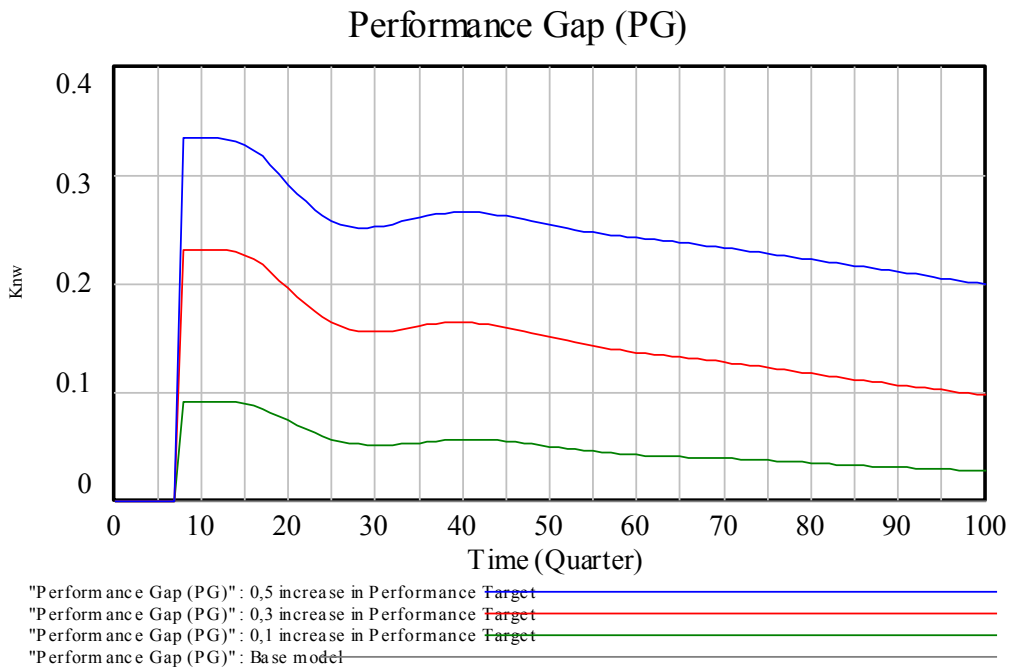


Figure 5.3 *Performance Gap* for 10%,30% & 50% increase in target

The model is simulated over a time period of 100-quarters, where the target knowledge value is increased by 10%, 30% and 50% and they can be distinguished by green, red and blue lines, respectively. It can be seen that the firm is able to gradually reduce the generated gap because of the increase in the target by acquiring its required knowledge through utilizing external acquisition and partnership with other firms and research institutes.

By increasing the target (i.e. 10% to 50%), the *Performance Gap* becomes positive (i.e. 0.08 to 0.35). In order to bridge the gap as soon as possible the firm will focus more on the fast and certain strategy of exploiting knowledge from external resources. In this situation, the system instantly responds to this increase in target by allocating more financial resources to acquire external knowledge rather than conducting in house R&D activities. However, it takes time to make some collaboration contracts or acquire relevant knowledge, which is why the gap is steady until the time of 15 quarters. After this point in unit time, the required knowledge will come into the firm and feed into the *Knowledge Value (KV)* stock and this leads to shrinking the observed gap between the actual knowledge and the target knowledge.

In Figure 5.3, a very smooth oscillation is noticed in the trend of changes for the *Performance Gap*, which can be justified by the relation of *Performance Gap* and *Actual Fraction (AF)*. Once the firm observes that the gap is lessened, it will allocate little more funds to the internal activities and since they pay off late, the gap slightly increases. However, this increase is not significant and does not affect the decision of allocating more on acquiring external knowledge, and ultimately the gap starts declining.

To conclude this experiment, **the firm which is in need of the gain of additional knowledge, it can gain the required knowledge through focusing on the fast and less risky strategy of the knowledge acquisition from external sources. i.e. it will search for collaboration partners to forge strategic alliances.**

5.3. Increase in target by 100%

The model is also tested when the target is doubled compared to the base case. The result is shown in Figure 5.4 in comparison to 50% increase in the target.

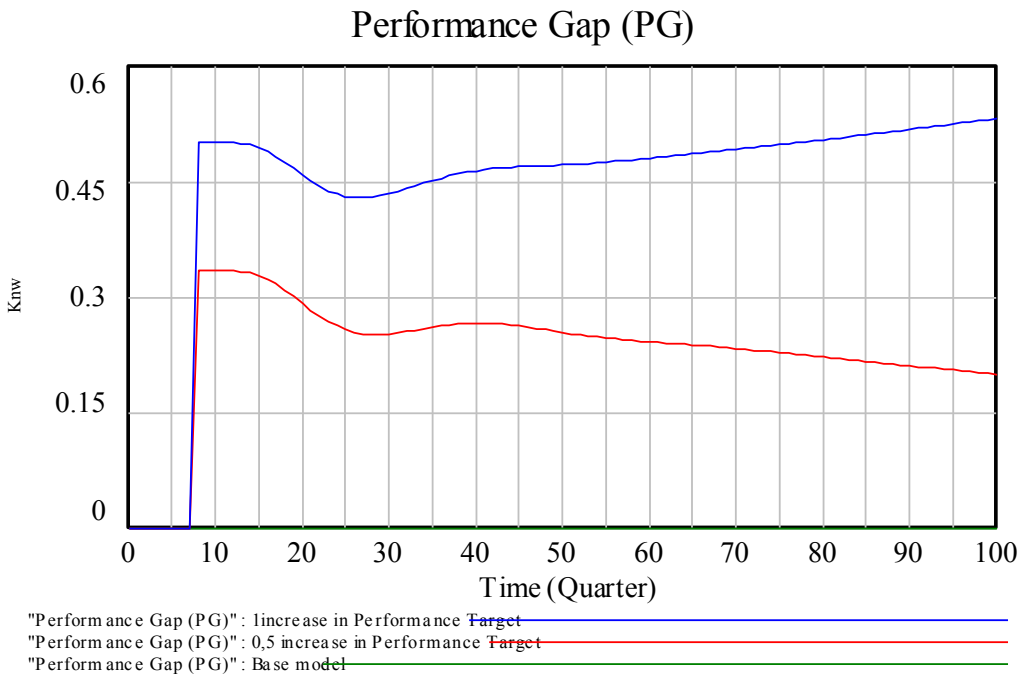


Figure 5.4 *Performance Gap* for 50% & 100% increase in target

Once the target is doubled, it was expected that the system will put in more effort into acquiring knowledge through external resources to fulfill its immediate need of new information and knowledge. Figure 5.4 represents this situation. Initially, the gap starts closing until the time of 26 quarters, but then the performance gap grows. By doubling the target, the firm needs more knowledge from external resources, and then it will allocate more money to acquire this knowledge. The increase in the allocation to external source of knowledge is shown in Figure 5.5.

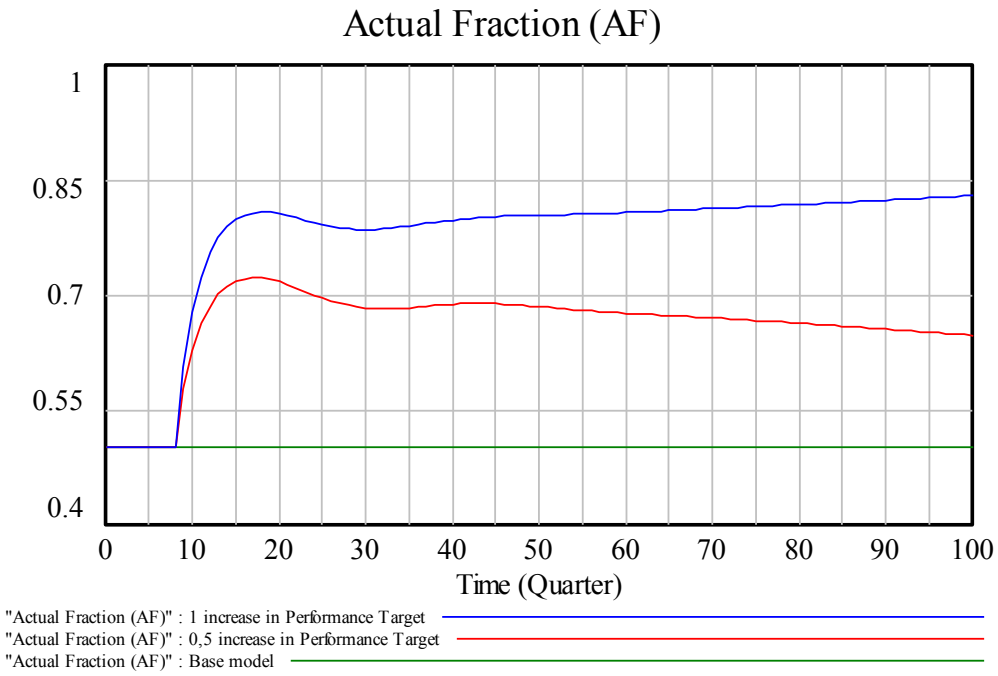


Figure 5.5 *Actual Fraction* for 50% & 100% increase in target

Therefore, the firm will have less money to invest in R&D activities and this leads to a gradual decrease in the absorptive capacity, as demonstrated in Figure 5.6. The results is also consistent with the study conducted by Deeds and Hill (1996), in which structuring strategic alliances initially benefits the firm by providing it with a quick set of complementary assets, but as a result of focusing more on this strategy, there is some diminishing and negative returns at some points. This model shows (see Figure 5.4) that for the short term, using external knowledge and partnership can reduce the gap (around 25 quarters), but putting more emphasis on this strategy leads to a considerable distance between the actual knowledge of the firm and its desired gap in the long term.

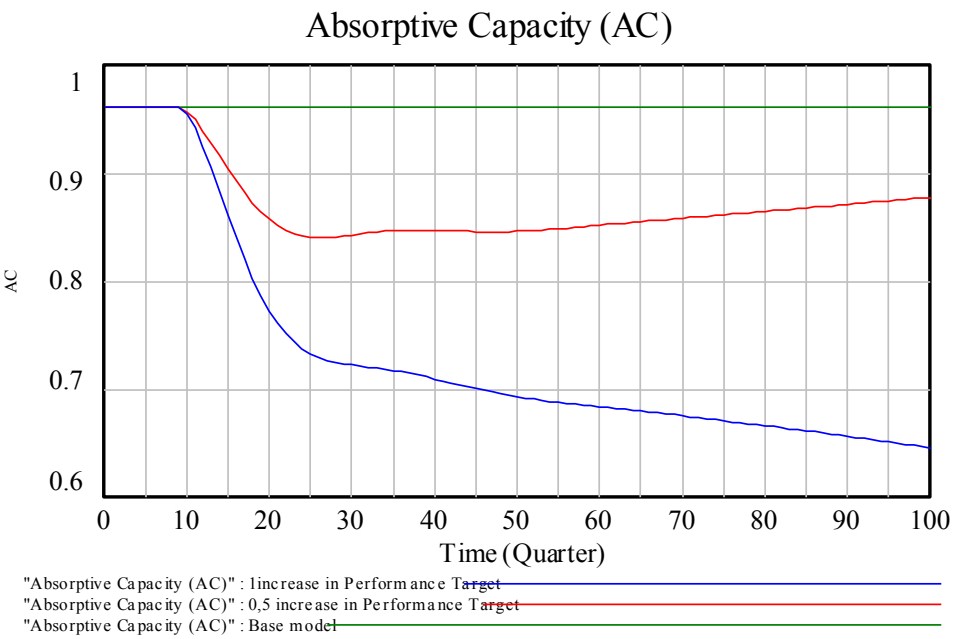


Figure 5.6 *Absorptive Capacity* for 50% & 100%increase in target

The observed decrease in *Absorptive Capacity* (see Figure 5.6) means that the firm cannot use the external knowledge efficiently, so the number of projects will decrease as demonstrated in Figure 5.7. It can be inferred that since the gap is too large, a great *Knowledge Value* is required to reduce the *Performance Gap*. Although acquiring external knowledge is less risky and has quicker return, it has lower value and cannot resolve this difference. On the other hand, not paying enough attention to the internal R&D activities leads to decrease in *Absorptive Capacity* level, which is very important for obtaining external knowledge. Hence, the combination of these two situations results in a wider gap. Therefore, the decrease in the knowledge level will be misunderstood by focusing more on the external knowledge, which ultimately leads to the dramatic increase in the size of the gap and the gap will not be closed in the long term (see blue line in Figure 5.4).

The main conclusion stemming from this exercise is that **the external knowledge strategy is effective for a small amount of increase in the innovation target, but it is not a suitable strategy when the firm needs to gain a substantial amount of knowledge for large scale innovative plans.**

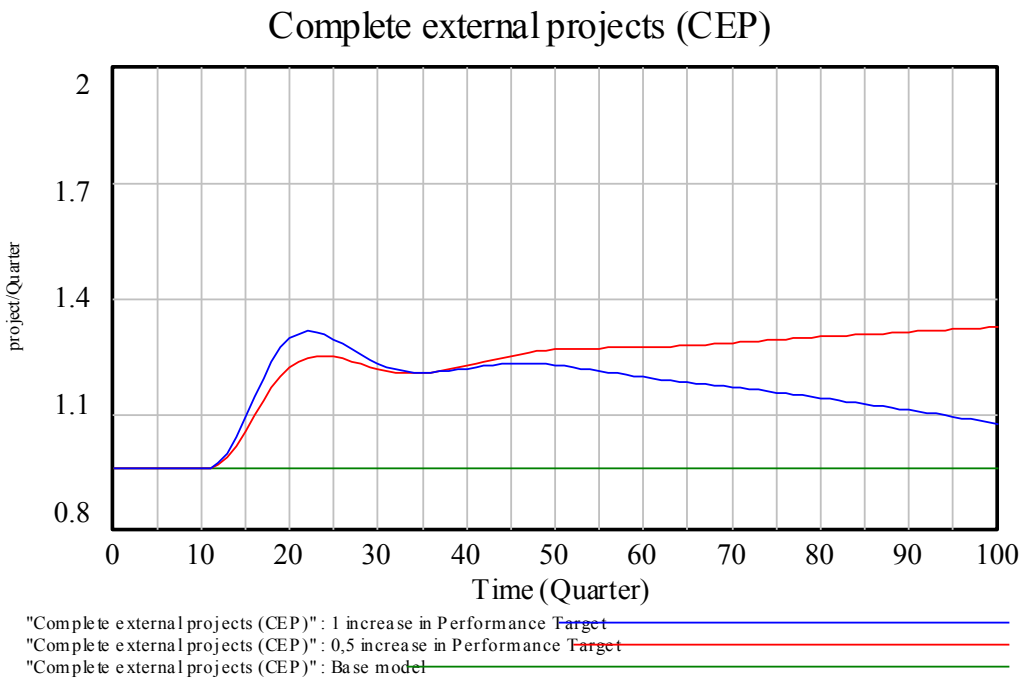


Figure 5.7 Quarterly *Complete External Projects* (CEP)

5.4. The response of the gap to the R&D cost changes

The effectiveness of the external knowledge acquisition strategy cannot only be judged by the amount of increase in the performance target. As Figure 5.8 demonstrates, the same increase of 60% in the target was tested for both the initial condition (condition of the base case model) and when the R&D activities cost less for a firm. This is usually the case of large firms, where they have a lower R&D expenditure due to the economies of scale, which results in a higher return for the firm (Van Moorsel *et al*., 2007). As can be seen in Figure 5.8, adopting external policy is not effective for long term when the

R&D expenditure decreases. It can be observed from the simulation results that when the ratio of the cost of R&D (*ACR*) to the value of R&D (*VRD*) projects is approximately close to the ratio of the cost of external (*ACE*) to the value of external (*VEX*), focusing on external resources is not beneficial.

The growing gap can be justified through the equilibrium equation of *Knowledge Value (KV*) stock (equation 5-2). Considering the cost of R&D *(ACR),* which is given in the denominator of the fraction, the *KV** goes up by decreasing this cost, bearing in mind that we did not change the knowledge acquired by external innovation. Thus, by increasing the target even more, the firm should put more effort into its external sources to compensate the gap. By focusing more on knowledge acquisition and partnership, the firm will lose its *Absorptive Capacity (AC)* and turns into a negative feedback loop, where focusing on knowledge acquisition from outside of the firm results in a larger gap.

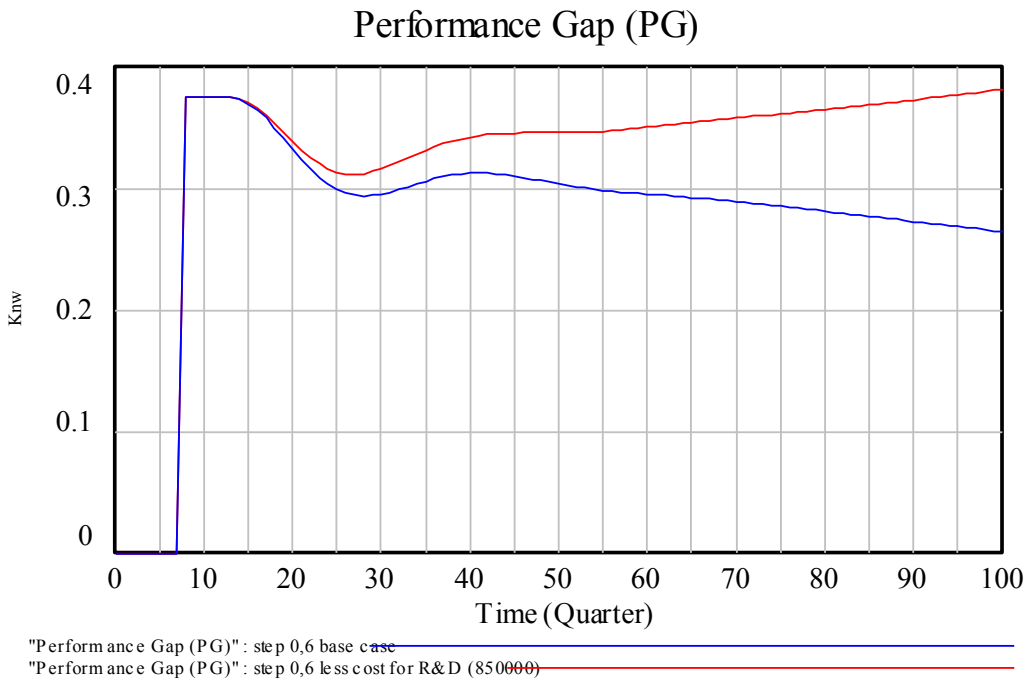


Figure 5.8 The effect of cost of R&D on the *Performance Gap*

Figure 5.9 illustrates that even when the increase in target is low (20%) and the R&D expenditures are low (around half compared to the base case model), concentrating on strategic research alliances and outside knowledge in the long term leads to an increase in the generated gap of actual knowledge and performance gap (green line). This led to the conclusion that the cost of the R&D projects (*ACR*) also can affect the decision making in terms of the preference for the external resources when the firm falls behind its knowledge target. Therefore, **when the cost of R&D projects is low and their return is high, the acquisition and partnership is not an effective policy and for adopting this policy other parameters should be taken into account.**

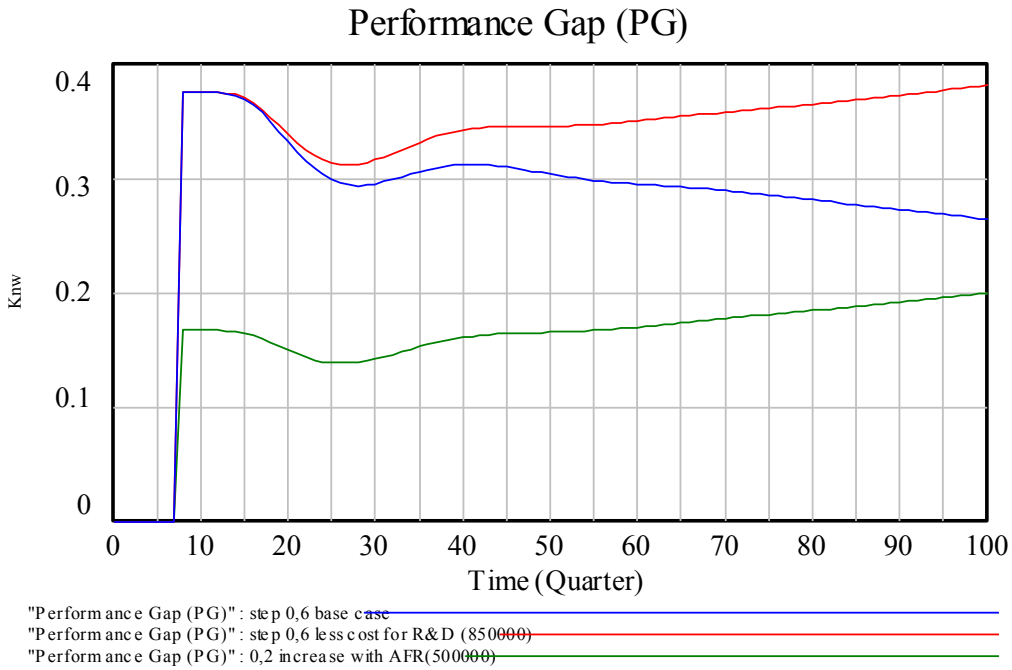


Figure 5.9 The effect of lower cost of R&D on the *Performance Gap*

5.5. Resource allocation between external & internal

To see the effect of the firm's initial policy towards allocation of funds for R&D activities and acquiring external knowledge, the model is tested for two sets of scenarios:

(1) a firm with high R&D intensity (75% of its available funds are allocated to in-house research activities); (2) a firm with low R&D intensity (30% of its available funds are allocated to in-house research activities).

5.5.1. Scenario (1)

Figure 5.10 displays the *Performance Gap* for the 20% and 60% increase in the performance target for both base cases: when the initial fraction of R&D activities is 0.5 and for scenario (1): where the initial fraction of R&D is 0.75. The *Absorptive Capacities* (AC) of these runs are also shown in Figure 5.11.

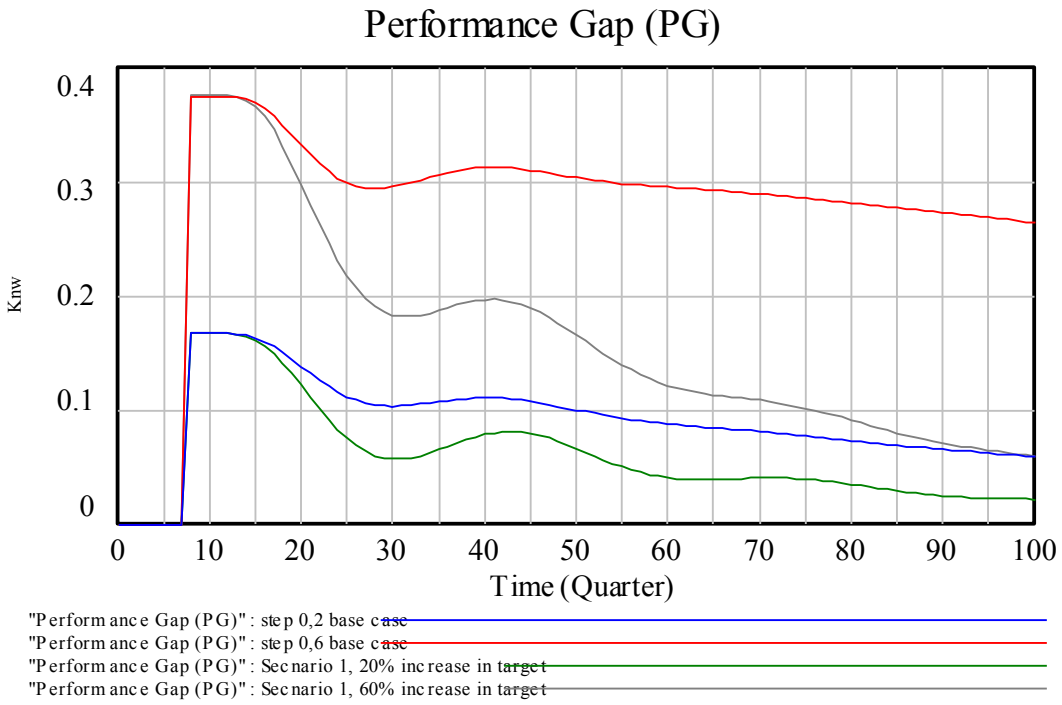


Figure 5.10 *Performance Gap* trend for scenario (1) and the base case

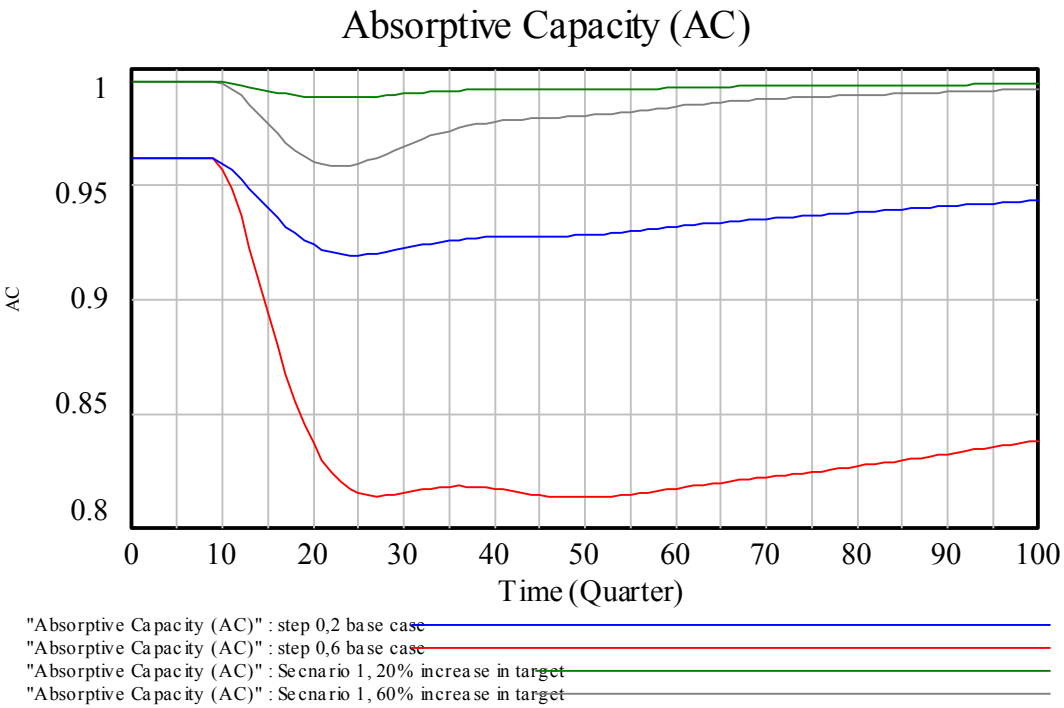


Figure 5.11 *Absorptive Capacity* for scenario (1) and the base case

As seen in Figure 5.11 (green and gray lines), the firm which has already invested most of its funds in R&D activities, has accumulated a vast pool of knowledge and hence a high *Absorptive Capacity (AC).* This accumulated knowledge and absorptive capacity provide the firm with the capability to exploit the outside knowledge effectively. Therefore, the higher range of external knowledge can be exploited to close the gaps, which ultimately results in a faster response. Therefore, it can be concluded that **when there is an increase in target, investing more in the external sources of knowledge for firms with a high R&D intensity brings fast results, even for a larger performance gap.** The steeper slopes of the green and gray line in Figure 5.10 shows this quick decline is the *Performance Gap*. Since these firms already sustain their place in the market and have a valuable source of knowledge with great scientists to utilize

external knowledge or structure collaboration partnerships, they can compensate a sudden increase in target by relying more on external knowledge.

5.5.2. Scenario (2)

Figure 5.12 illustrates the *Performance Gap* for the 20% and 60% increase in the performance target for both base cases: when the initial fraction of R&D activities is 0.5, and for scenario (2): where the initial fraction of R&D is 0.3. The *Absorptive Capacity* (AC) of scenario (2) is set the same as the base case and they both start from one point, which is 0.97. The *Absorptive Capacity* graphs are also shown in Figure 5.13.

The graphs show that there is not a significant difference between the initial condition (50% allocation of fund to R&D activities) and this scenario. From these results, we can infer that **when the firm has already spent more than 50% of its funds on establishing collaborative agreements and acquiring external knowledge, it can close small gaps in its knowledge performance by pursuing this strategy. However, as previously explained, this strategy is only efficient for small gaps, while for larger gaps, further use of external knowledge leads to increase in the gap.**

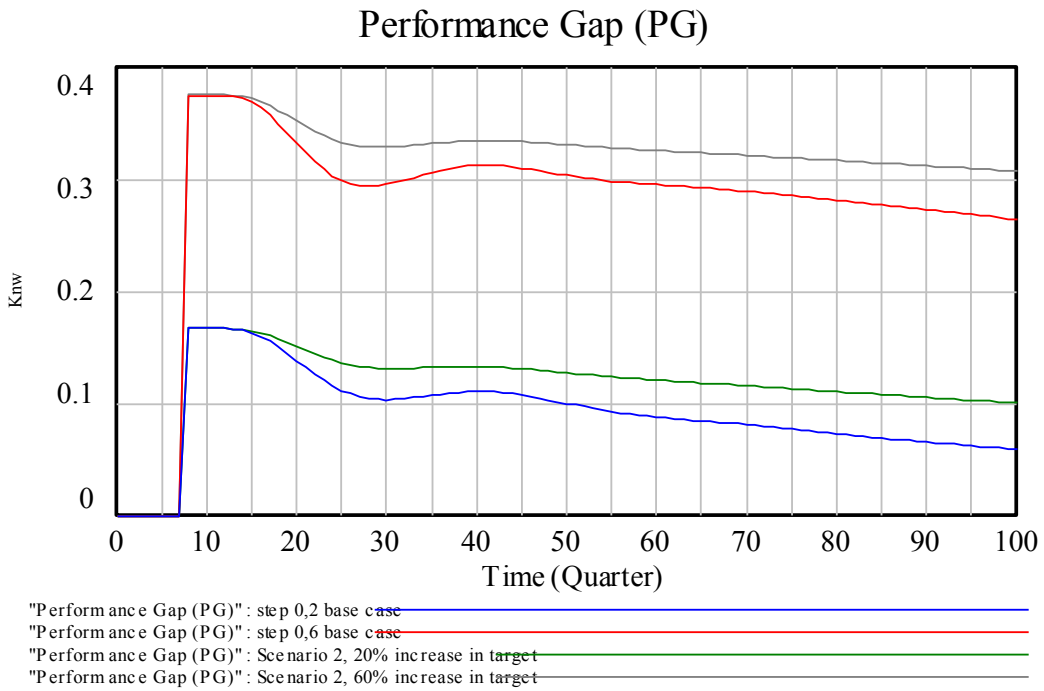


Figure 5.12 *Performance Gap* trend for scenario (2) and the base case

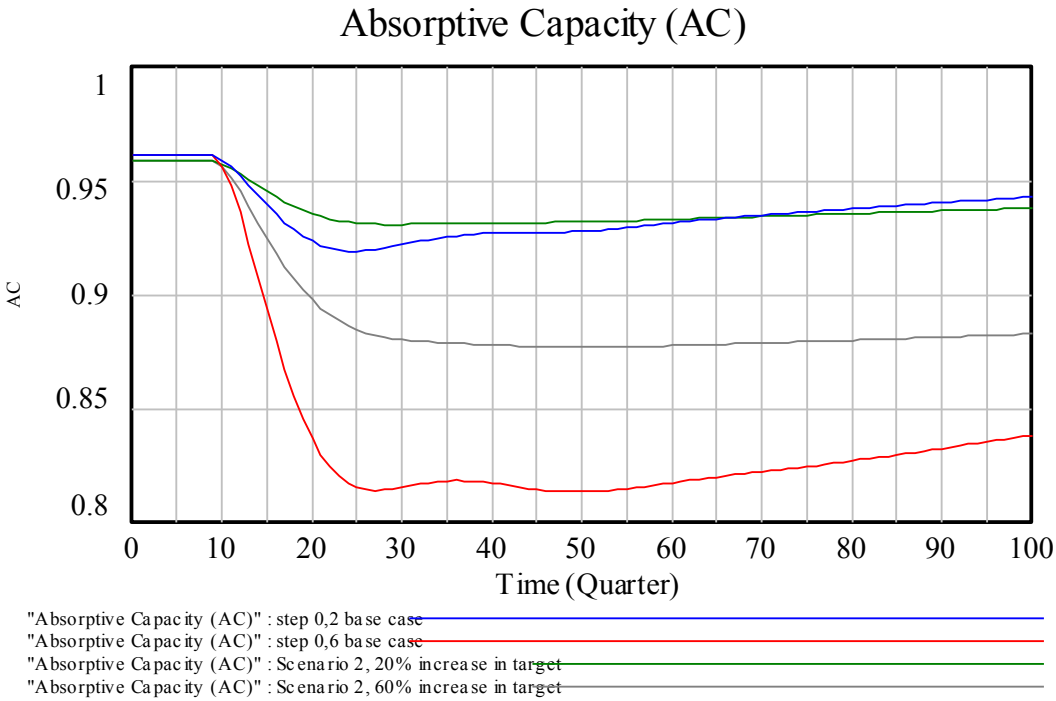


Figure 5.13 *Absorptive Capacity* for scenario (2) and the base case

5.6. Combination of initial resource allocation and R&D expenditure

To improve our understanding of the system's responses to the firm's initial policy towards allocating funds for internal R&D and external sources of knowledge, the simulation model was tested for the following scenarios:

- Scenario (3): high R&D intensity and low cost of R&D
- Scenario (4): high R&D intensity and high cost of R&D
- Scenario (5): low R&D intensity and low cost of R&D
- Scenario (6): low R&D intensity and high cost of R&D

5.6.1. Scenario (3): The combination of high R&D intensity and low cost

The 20% and 60% increase in target was examined for the condition in which the initial fraction of R&D is 0.75, which means that the firm has a high R&D intensity and the R&D expenditure is lower compared to scenario (1). Figure 5.14 illustrates the *Performance Gap* of the 20% and 60% increase in target for this initial condition and previously explained scenario (1). Blue and red lines represent the trend of *Performance Gap* for a 20% and 60% increase in target, respectively.

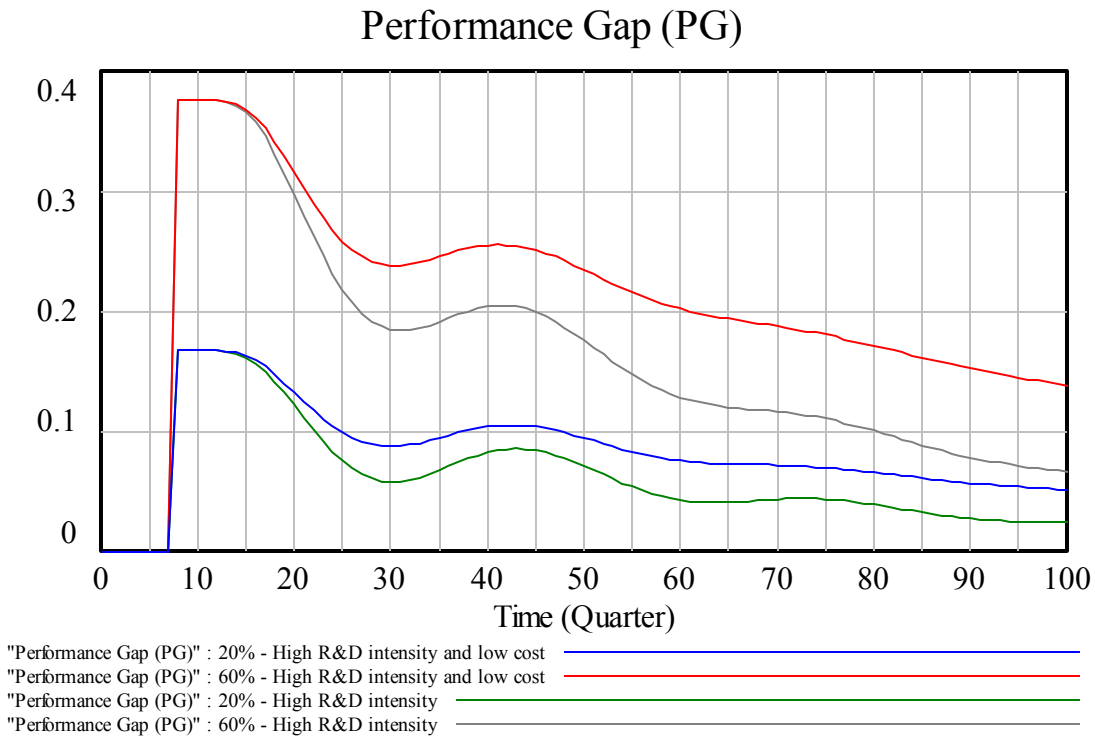


Figure 5.14 *Performance Gap* for scenario (3) and scenario (1)

As seen in Figure 5.14, the firm can compensate the generated gap by focusing more on the external source of knowledge, even in a situation with a lower cost of R&D. However, the level of changes is shifted higher compared to scenario (1) (grey and green lines). Generally, for a high R&D intensive firm, the firm can gradually close the gap by allocating more money to external sources.

In fact, the firm already has an appropriate stock of internal knowledge (See Figure 5.15) the value which is greater than the stock of external knowledge (See Figure 5.16). Thus, the firm is able to satisfy its need for extra knowledge by allocating little more funds to external activities. Furthermore, while the performance gap starts closing, the firm can return to its earlier policy which was focusing on R&D.

This synthesis results in an effective combination of R&D activities and collaborative efforts, which leads to a faster response to the gap even if the lower R&D cost slightly shifts this behaviour. It should be noted that if the cost is very low, the gap will start growing. However, this case does not usually happen since the R&D expenditure in biotechnology is inherently high.

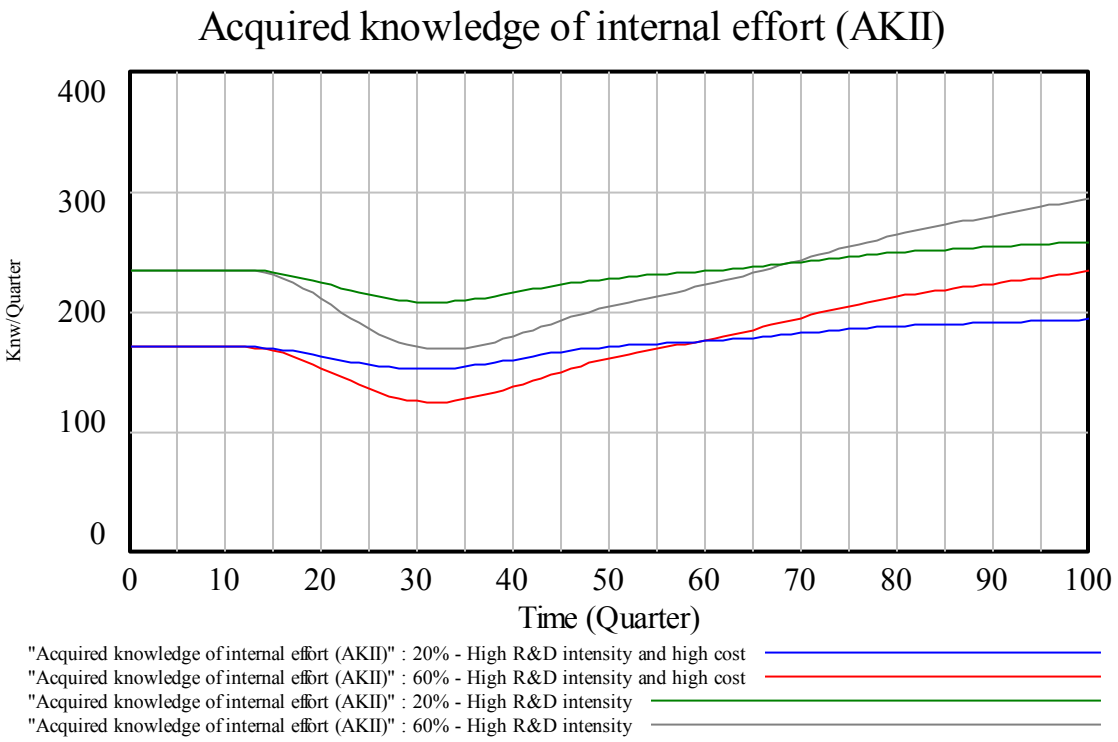


Figure 5.15 Knowledge acquired by internal R&D for scenario (3) and scenario (1)

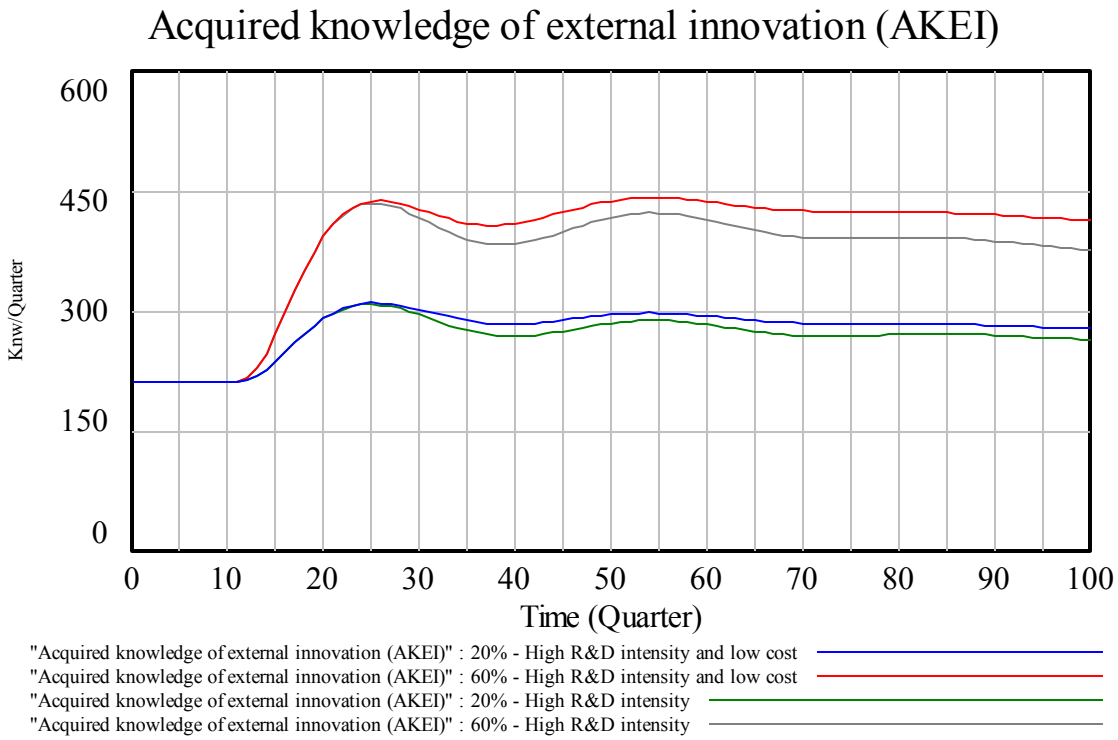


Figure 5.16 Knowledge acquired by external resources for scenario (3) and scenario (1)

This leads to the conclusion that **when there is an increase in target, even with a low R&D cost, investing more in external sources of knowledge for firms with a high R&D intensity brings faster results, even for a larger performance gap.**

5.6.2. Scenario (4): The combination of high R&D intensity and high cost

Figure 5.17 demonstrates the *Performance Gap* for a 20% and 60% increase in target for the condition in which the initial fraction of R&D is 0.75, which means that the firm has a high R&D intensity, and the R&D expenditure is higher in comparison to scenario (1).

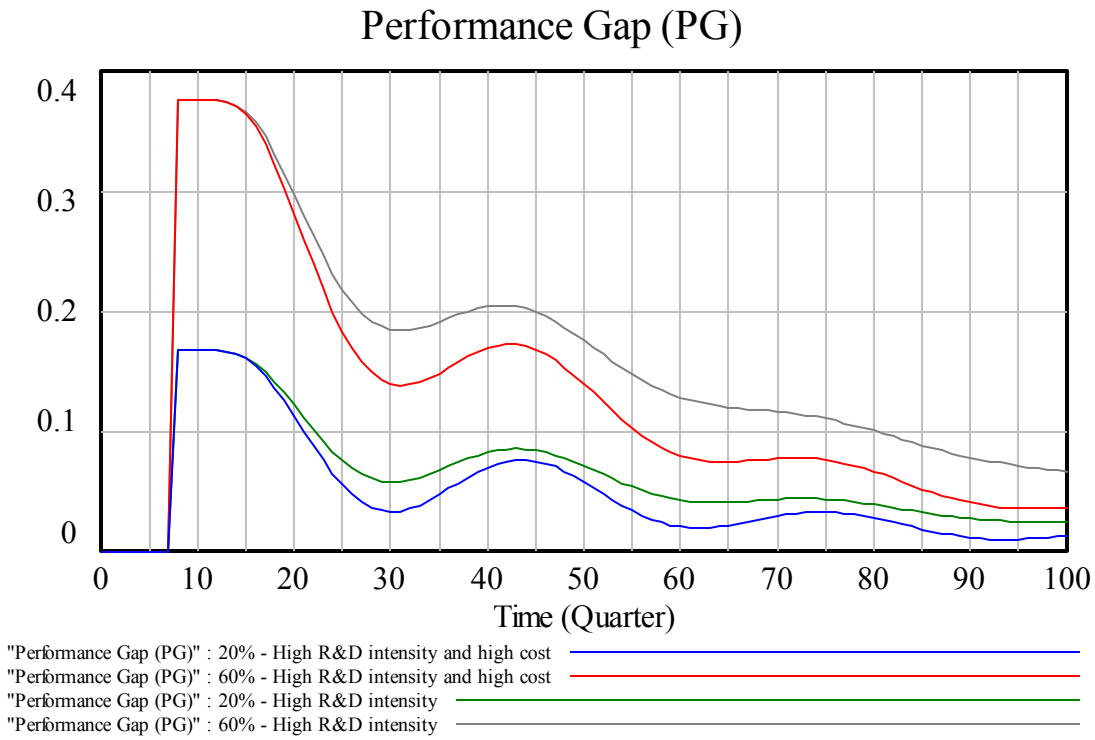
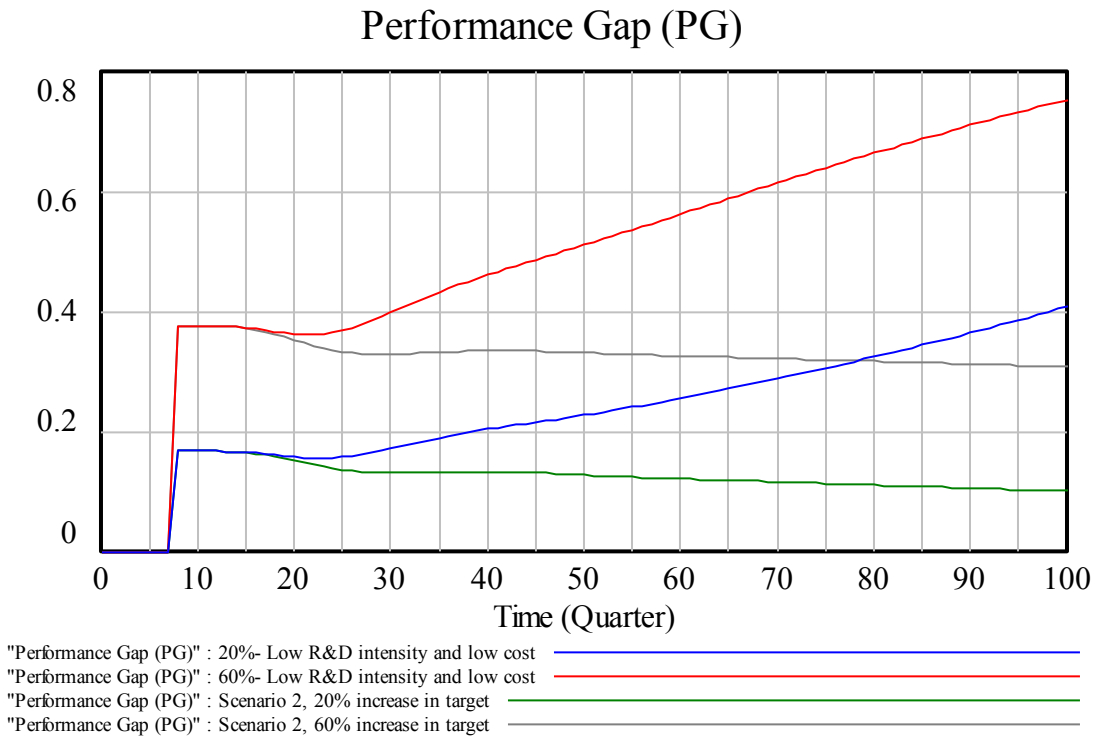


Figure 5.17 *Performance Gap* for scenario (4) and scenario (1)

As shown by the red line and blue line in Figure 5.17, there is a steeper drop in the gap compared to scenario (1), when there were no changes to the R&D cost. It can be concluded that **when the cost of R&D is high and the firm is highly R&D intensive, there are more benefits to acquiring knowledge from outside of the firm, even for the larger gap.** However, we can see a rather soft oscillation behaviour in the *Performance Gap* trend, which is the result of shifting focus from R&D to external and vice versa, but overall this leads to a decrease in the performance gap.

5.6.3. Scenario (5): The combination of low R&D intensity and low cost

Figure 5.18 shows the *Performance Gap* for a 20% and 60% increase in target for the condition in which the initial fraction of R&D is 0.3, which represents a firm with low R&D intensity, and the R&D expenditure is lower in comparison to scenario (2).



. Figure 5.18 *Performance Gap* for scenario (5) and scenario (2)

As observed from the simulation results in Figure 5.18, when the firm initially allocates smaller amounts of funds to the R&D activities while the R&D cost is low, it cannot reduce the generated gap by focusing more on its former policy, which was acquiring knowledge externally. Even for a slight increase in target (20%), the firm is not able to reduce the gap by collaboration policy, and as a result the gap steadily grows.

5.6.4. Scenario (6): The combination of low R&D intensity and high cost

Figure 5.19 shows *Performance Gap* in two sets of tests for a 20% and 60% increase in target for low R&D intensity firms that have a low R&D cost (scenario 5) and a high R&D cost (scenario 6).

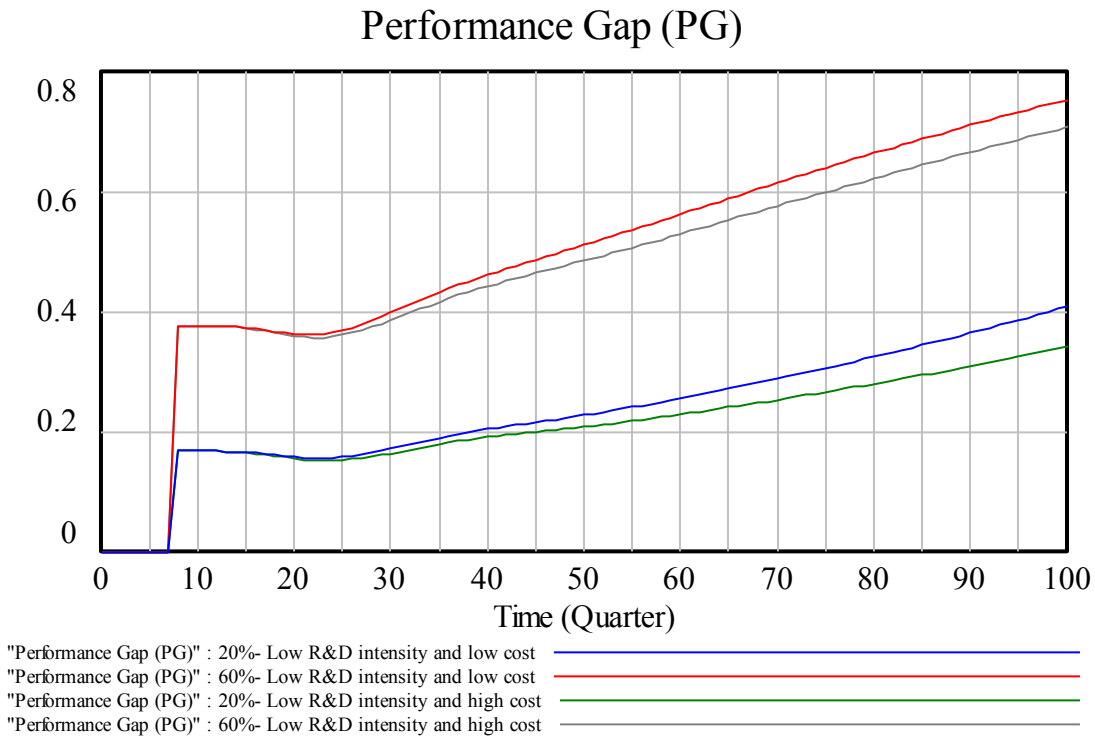


Figure 5.19 *Performance Gap* for scenario (5) and scenario (6)

As shown in Figure 5.19, there is only a slight difference between the low R&D cost and high R&D cost in the test runs and the gap ultimately grows for both of them.

It must be taken into consideration that in a low R&D intensity environment, the firm has a lower stock of R&D knowledge. Therefore, no matter whether the cost of R&D is low or high, the firm is not able to manage the generated gap by directing more efforts towards the gain of external knowledge.

On the one hand, the knowledge value brought by external acquisition is not high enough to close this gap, and on the other, the firm is unable to make these collaborations due to its low level of internal knowledge and *Absorptive Capacity (AC)*. In the other words, the firm does not have a strong research and product development platform to attract other companies and institutes to make collaborative agreements. This is also consistent with several studies that have shown that there is a positive correlation between higher levels of R&D spending and a higher level of collaboration (Hall and Baghchi-Sen, 2007; Bagchi-Sen, 2004; Deeds and Hill, 1996; Freeman, 1991). Companies with strong research and developmental capabilities have a greater potential to become partners and collaborate more effectively (Arora and Gambardella, 1994; Nambisan, 2002). Conversely, it can be argued that in firms with little in house research knowledge, the opportunity to develop collaborations and absorbing external knowledge is not easily available.

This in-depth analysis for the different scenarios of the simulation model reveals that **the acquisition of knowledge is not an efficient strategy for firms with a low R&D intensity, i.e. when the firm spends less than 50% of its fund on R&D activities, no matter whether the cost of R&D is high or low for the firm and for adopting this policy other parameters should be considered.**

5.7. Validation methods in system dynamics

Barlas and Kanar (2000) argued that the validation of the system dynamics model involves two components: *structure* validation and *behaviour* validation. *Structure* validation evaluates whether the relationships developed in the model adequately demonstrate the real relationships. *Behaviour* validation means that we want to make the behaviour of the model as close as possible to the anticipated behaviour of the real system.

The *structure* validation can be applied by two ways; (a) *direct* structure testing *(b) indirect structure (or structure-oriented behaviour).* In *direct* structure validity tests, the model is compared to the real system structure. In this test, the mathematical equations or other forms of the relationship are evaluated against the real system. Since these tests are qualitative, simulation is not involved. On the other hand, *Structure-oriented* behaviour tests indirectly evaluate the validity of a model through applying certain behaviour test on a model that involves simulation. For example, one of the methods is *extreme condition* testing, in which the extreme values are assigned to the selected parameters. Then, the generated behaviour of model will be compared to the expected behaviour of the real system under the same extreme conditions.

5.7.1. Validation of the current model

As mentioned above, validation can be performed from two different perspectives: validation of the structure of the model or validation of the behaviour of the model. Regarding the structural validation of the model in this study, all of the elements of the

model are retrieved from the available literature. Thus, the model equations and their relationships are developed based on the existent literature.

Considering the behavioural validation, three sets of condition have been tested in the model: (a) the condition in which the firm is ahead of its target, (b) the condition in which the firm is ahead of its target and there are unlimited financial resources due to more focus on R&D and (*extreme condition* method) (c) the condition in which the firm has more access to financial resources.

To test condition (a), a negative gap, which means that the firm performs well and is ahead of the target was imposed on the system to check the model-generated behaviour. It was expected that the firm initially focuses more on internal activities since it is ahead of its schedule and can invest in a new product to create and sustain the competitive advantage. However, after a while its financial resources become limiting because of the long-run return of R&D activities and the lack of commercial products during this time. Therefore, both internal and external projects decline due to the lack of available fund and as a result the firm's performance is affected and leads to a fall in its knowledge stock.

The model's results satisfied our expectations. The results of the model are shown in comparison with the positive gap. As it shown in Figure 5.20 (blue line) , the *Performance Gap* was negative at first but as the time passes, the number of ongoing projects decreases due to the reduction in the financial resources. The knowledge they bring to the firm gradually diminishes (see Figure 5.21 and 5.22) and this leads to an approximately zero gap.

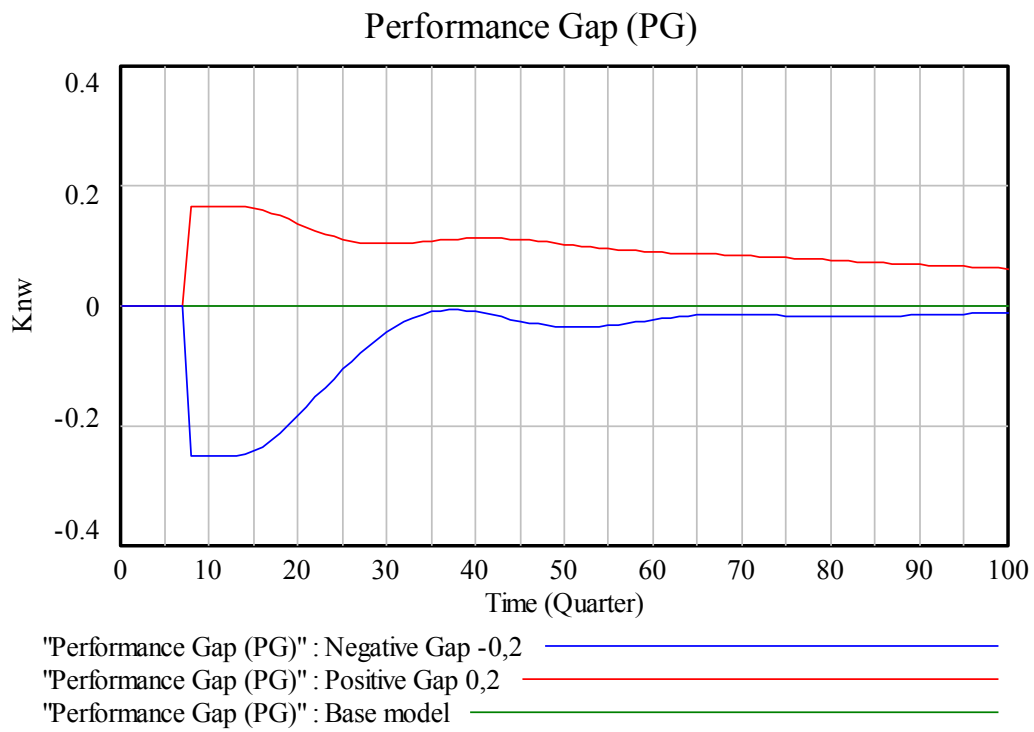


Figure 5.20 *Performance Gap* of condition (a)

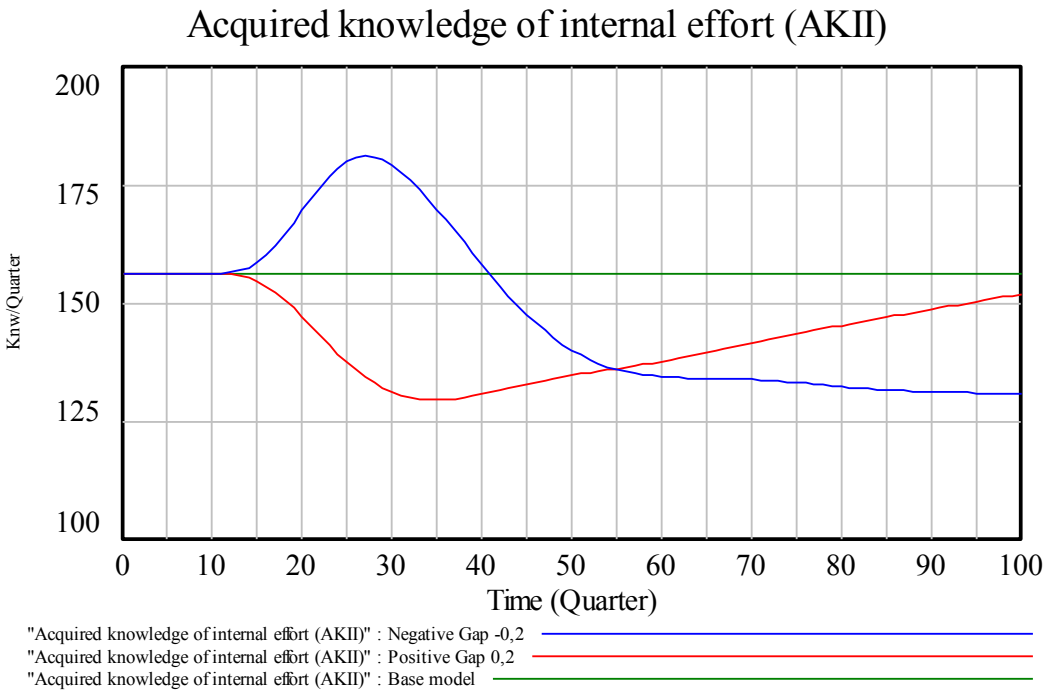


Figure 5.21 Acquired Knowledge of internal innovation for condition (a)

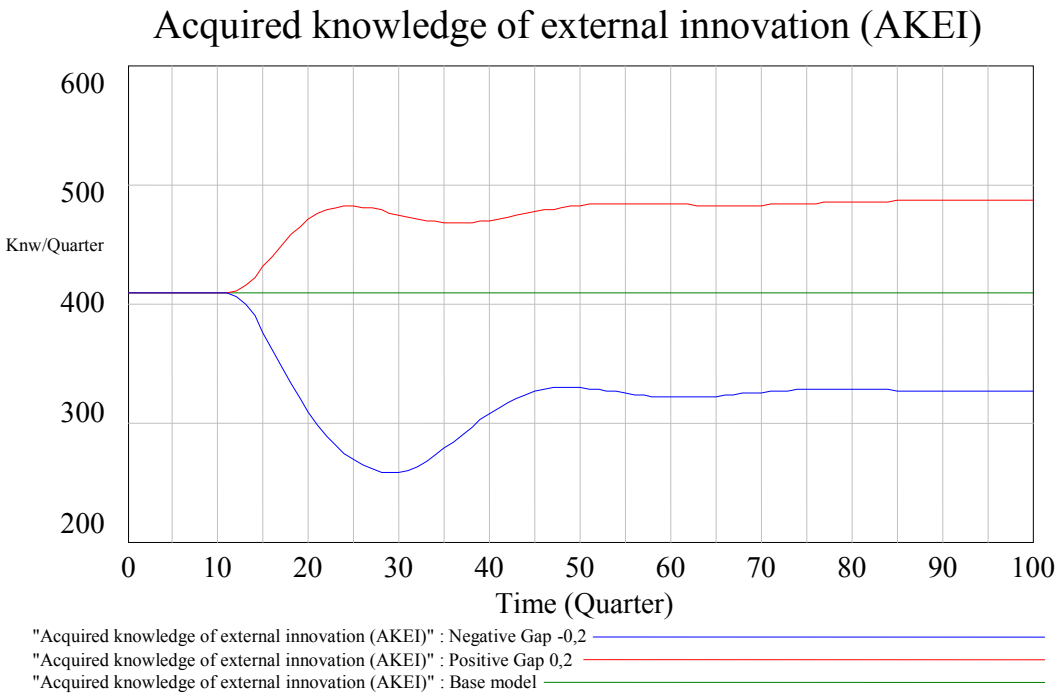


Figure 5.22 Knowledge gained by external innovation for condition (a)

Condition (a) and condition (b) only differ in terms of the limitations of financial resources. Condition (b) tests the situation in which there is no shortage of the financial resources created as a result of spending most of the available funds on R&D activities. The anticipated behaviour is that the firm would mainly maintain this strategy since it results in a higher return without making any constraints for the firm. As demonstrated in Figure 5.23, when the firm performance is negative, the firm will invest more in internal innovation and since there are no limitations in the funding resources, the firm intends to focus more on the R&D. As shown in Figure 5.23, it can keep this difference for a long term. However, this decrease in the knowledge level is due to the long term return of R&D projects.

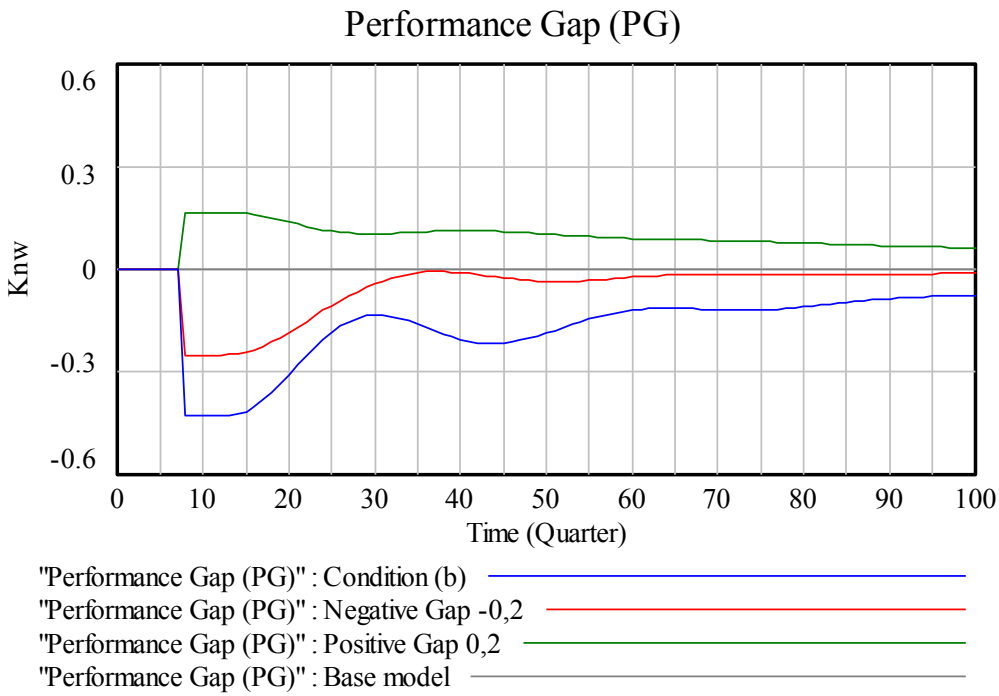


Figure 5.23 *Performance Gap* of condition (a)

In condition (c), it was expected that when the firm has more access to the financial resources, it can perform more projects and can exceed its target to make the gap negative. Figure 5.24 demonstrates that by increasing the standard investment (SI) by 20%, the number of projects, either internal or external, will also go up. The knowledge level of the firm also increases and the firm performance is improved. The increases in the knowledge gained internally and externally are shown in Figure 5.25 and 5.26, respectively. This test represents the importance of financial resources in the biotechnology innovation.

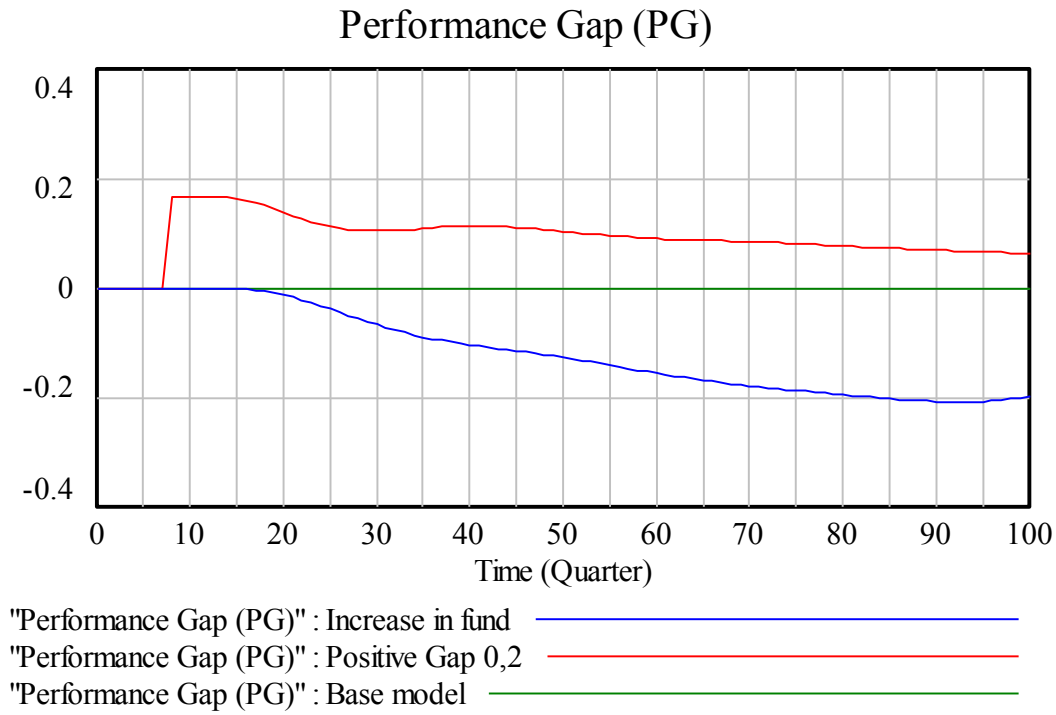


Figure 5.24 *Performance Gap* of condition (c)

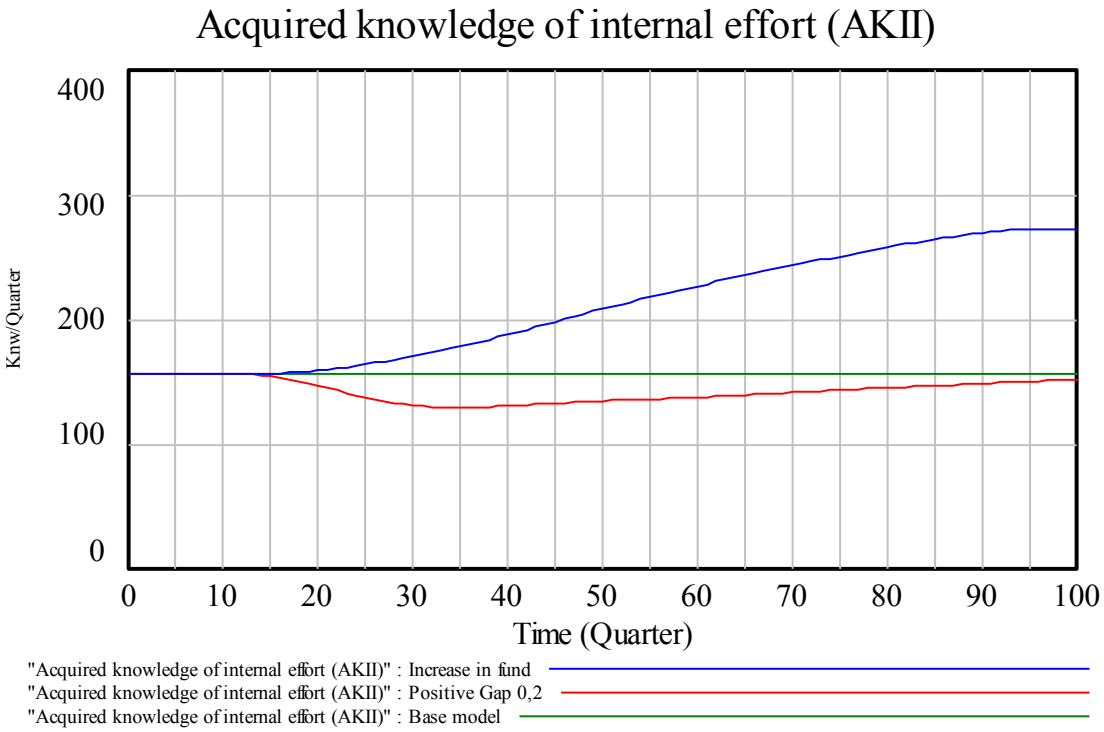


Figure 5.25 Knowledge gained by internal innovation for condition (c)

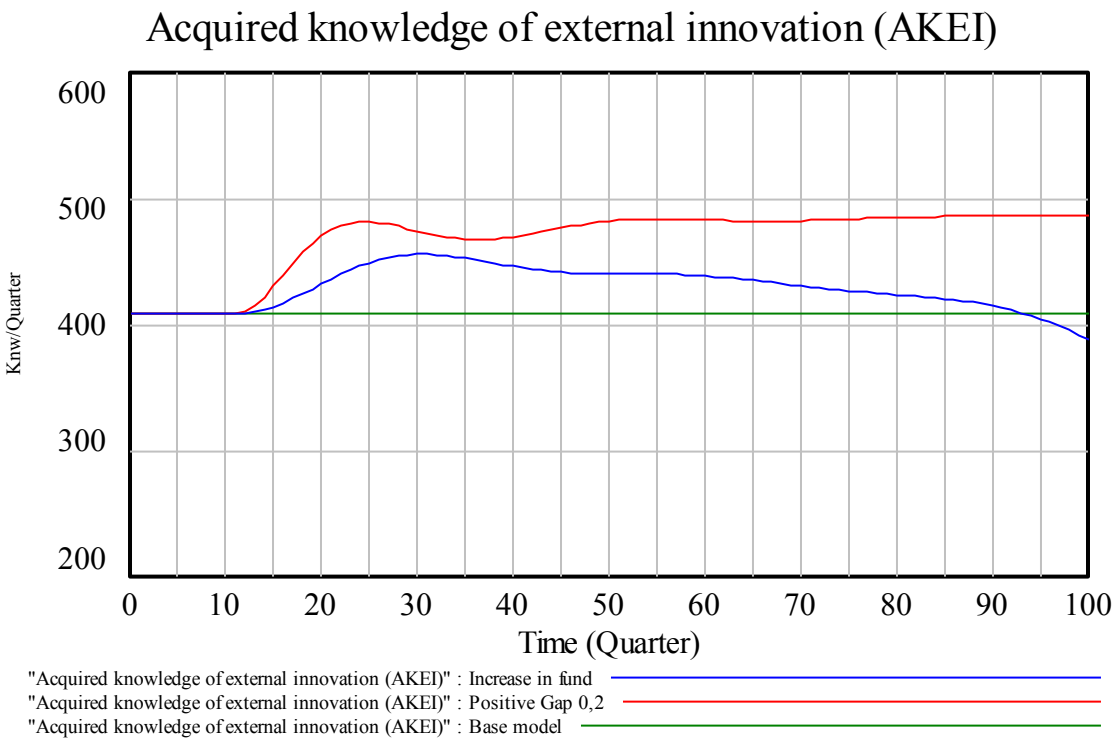


Figure 5.26 Knowledge gained by external innovation for condition (c)

Chapter 6

6. Conclusion

In this research, system dynamics methodology is employed to describe and formalize the relationships between critical factors in the early stage of the innovation process in biotechnology. In order to accomplish this objective, relevant literature was reviewed first. This helped us find the most influential factors that shape the early stage of the innovation process in biotechnology. Afterwards using the system dynamics approach, the relationships and interactions among these factors were examined and a series of causal loop diagrams illustrating their dynamics and the feedback mechanisms were developed. These causal models were then transformed to a computer simulation model, which enabled us to observe the behaviour of the whole system. The developed model presents an exploratory and rather detailed view of the factors influencing decisions made by a biotechnology corporation in the early stage of the innovation process. This research contributes to the advancement of knowledge by providing a better understanding of (a) the structure of the system, including elements and their relationships, and (b) the behaviour of the system in the early stage of innovation.

In this regard, this thesis introduces five causal loops as the main pillars of the interactions among these components: knowledge creation, knowledge accusation, capital raising, venture capital investment, and R&D lock-in. Internal R&D activities and external sources of knowledge (such as knowledge acquisition and partnership) provide knowledge for innovation in the biotechnology firms. It is widely recognized that scientific and research capabilities have a significant impact on the biotechnology innovative performance.

R&D activities play an important role in the creation and enhancement of biotechnology professional competences by providing firms with both the essential source of innovation and the firm's ability to learn. On the other hand, the presence of external networks, the existence of markets for certain technologies, growth barriers and the absorptive capacity all have an important impact on the process' effectiveness. This emphasizes the significant role which external sources of knowledge play in competitive conditions. In addition to considering both the external and internal sources, it is also important to take into account the balance between these sources. In this regard, the main objectives of the research pertain to how the biotechnology firm can maintain the right balance between adopting in house activities vs. structuring external collaboration and how it can execute its innovation plans while using the appropriate combination of these different sources of knowledge.

To achieve these objectives, the initial status of the computer simulation model is set in order to observe the system's behaviour under various settings of the model's factors. This thesis investigates the critical factors influencing the firm's decisions and polices regarding the employment of the most suitable combination of the internal and external sources of knowledge in order to increase the firm's innovative productivity. Our findings are summarized below:

- To maintain performance expectations, a firm should utilize distinct strategies for acquiring knowledge, depending on the firm's innovative goals and other internal factors.
- For a firm that initially allocates the available funds for research equally between internal and external sources of knowledge, an increase in its innovative target

should lead to an increased focus on the exploitation of external sources of knowledge. This means that the firm should commit the available funds to the establishment of collaborative agreements. However, if the firm's innovative goals are too ambitious and hence its knowledge target is too high, exploiting external sources of knowledge appears to be a suitable short-term strategy but may not be effective in the long run. Another factor influencing the fund allocation decision is the cost of R&D projects for a firm. For a firm with a relatively low cost of R&D, external sources may not be effective anymore, since R&D projects are cheaper and thus create higher returns for a firm than the external sources of knowledge can generate.

- In a highly competitive environment in which introducing a new product is required, focusing on the external knowledge acquisition is a highly efficient strategy for high R&D intensity firms. Since these firms initially spend the majority of their available funds on internal R&D activities, they manage to build a high level of absorptive capacity. As a consequence, they are able to quickly and easily absorb external knowledge, to integrate it with their prior knowledge efficiently and to generate a great innovative potential needed for the new product development.
- For low R&D intensity firms who spend less than 50% of their available funds on in house R&D activities, the strategy of focusing primarily on external knowledge sources and seeking numerous collaborative agreements requires a very careful assessment. A short-sighted policy of exploiting mostly external knowledge, without taking into account the firm's absorptive capacity level, may

prevent a firm from ever reaching its expected innovative goals, even if there are some temporary improvements in the beginning.

The findings of this research have could also be used as normative suggestions for decision makers in the companies. Although this research provides the general insights for policy makers, there is still a need for a customized model that is based on the specific characteristics of a biotechnology firm in order to develop effective policies. Therefore, one future research direction can involve an empirical study for a specific biotechnology firm.

Several other future research directions are recommended based on the results of this study. First, the allocation process is based only on funding resources, neglecting other resources such as human resources. Therefore, future research can be focused on other aspects of the resources, such as scientists, since their importance is extremely emphasized by existent literature in the success of biotechnology firms. Second, the effectiveness of involvement in the external scientific community is only investigated through the value of the knowledge they bring to the firm, but there may be other reasons why external sources are valuable that our model did not demonstrate. Thus, a future study can focus on other reasons such as empowering the external communication channels or seeking new paradigms of technology. Third, the only independent variable evaluated in our model was the increase in the innovation goal. The rate of change in the market place and the change in the required type of innovation are other factors that may greatly influence the R&D versus external sources focus. These factors can be considered as the independent variables throughout other future studies.

References

Afuah, A. (2002). Mapping technological capabilities into product markets and competitive advantage: The case of cholesterol drugs. *Strategic Management Journal, 23*(2), 171-179.

Albino, V., Garavelli, A., & Schiuma, G. (2001). A metric for measuring knowledge codification in organisation learning. *Technovation, 21*(7), 413-422.

Amir-Aslani, A., & Negassi, S. (2006). Is technology integration the solution to biotechnology's low research and development productivity? *Technovation, 26*(5-6), 573-582.

Arora, A., & Gambardella, A. (1994). Evaluating technological information and utilizing it: Scientific knowledge, technological capability, and external linkages in biotechnology. *Journal of Economic Behavior & Organization, 24*(1), 91-114.

Arvanitis, S. (1997). The impact of firm size on innovative activity–an empirical analysis based on swiss firm data. *Small Business Economics, 9*(6), 473-490.

Axelrod, A. (2008). *Edison on innovation: 102 lessons in creativity for business and beyond* Jossey-Bass.

Bains, W. (2004). Failure rates in drug discovery and development-will we ever get any better? *DDW DRUG DISCOVERY WORLD, 5*(4), 9-19.

Baker, A. (2003). Opinion piece: Biotechnology's growthinnovation paradox and the new model for success. *Journal of Commercial Biotechnology, 9*(4), 286-288.

Balachandra, R., & Friar, J. H. (1997). Factors for success in R&D projects and new product innovation: A contextual framework. *Engineering Management, IEEE Transactions on, 44*(3), 276-287.

Balconi, M. (2002). Tacitness, codification of technological knowledge and the organisation of industry* 1. *Research Policy, 31*(3), 357-379.

Banbury, C. M., & Mitchell, W. (1995). The effect of introducing important incremental innovations on market share and business survival. *Strategic Management Journal, 16*(S1), 161-182.

Barlas, Y., & Kanar, K. (2000). Structure-oriented behavior tests in model validation. *18th International Conference of the System Dynamics Society, Bergen, Norway,* 33–34.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management, 17*(1), 99.

Benner, M. J., & Tushman, M. (2002). Process management and technological innovation: A longitudinal study of the photography and paint industries. *Administrative Science Quarterly, 47*(4), 676-709.

Brem, A., & Voigt, K. I. (2009). Integration of market pull and technology push in the corporate front end and innovation management--insights from the german software industry. *Technovation, 29*(5), 351-367.

Burgelman, R. A. (1983). A process model of internal corporate venturing in the diversified major firm. *Administrative Science Quarterly,* , 223-244.

Chang, Y. C., & Chen, M. H. (2004). Comparing approaches to systems of innovation: The knowledge perspective. *Technology in Society, 26*(1), 17-37.

Cockburn, I., Henderson, R., & Stern, S. (2000). Untangling the origins of competitive advantage.

Cockburn, I. M., & Henderson, R. M. (1998). Absorptive capacity, coauthoring behavior, and the organization of research in drug discovery. *The Journal of Industrial Economics, 46*(2), 157-182.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly,* , 128-152.

Coombs, J. E., & Deeds, D. L. (2000). International alliances as sources of capital:: Evidence from the biotechnology industry. *The Journal of High Technology Management Research, 11*(2), 235-253.

Coombs, R., Richards, A., Saviotti, P. P., & Walsh, V. (1996). *Technological collaboration: The dynamics of cooperation in industrial innovation* Edward Elgar Pub.

Cooper, R. G. (1990). Stage-gate systems: A new tool for managing new products. *Business Horizons, 33*(3), 44-54.

Cooper, R. G. (1999). *Product leadership: Creating and launching superior new products* Basic Books.

Cooper, R. G. (2008). The stage-gate idea-to-launch process–update, what's new, and NexGen systems. *Journal of Product Innovation Management, 25*(3), 213-232.

Cooper, R. G., & Kleinschmidt, E. J. (1988). Resource allocation in the new product process. *Industrial Marketing Management, 17*(3), 249-262.

Cooper, R. G., & Kleinschmidt, E. J. (1990). New products: The key factors in success.

Cooper, R. G. (1988). Predevelopment activities determine new product success. *Industrial Marketing Management, 17*(3), 237-247. doi:DOI: 10.1016/0019-8501(88)90007-7

Cooper, R. G., & Kleinschmidt, E. J. (1994). Screening new products for potential winners. *IEEE Engineering Management Review, 22*(4), 24-30.

Coyle, R. G. (1996). *System dynamics modelling: A practical approach* Chapman & Hall/CRC.

Damanpour, F. (1991). Organizational innovation: A meta-analysis of effects of determinants and moderators. *Academy of Management Journal, 34*(3), 555-590.

Dangelico, R. M., Garavelli, A. C., & Petruzzelli, A. M. (2010). A system dynamics model to analyze technology districts' evolution in a knowledge-based perspective. *Technovation, 30*(2), 142-153.

De Carolis, D. M. (2003). Competencies and imitability in the pharmaceutical industry: An analysis of their relationship with firm performance. *Journal of Management, 29*(1), 27.

de Jong, J. P. J., & Freel, M. (2010). Absorptive capacity and the reach of collaboration in high technology small firms. *Research Policy, 39*(1), 47-54.

De Luca, L. M., Verona, G., & Vicari, S. (2010). Market orientation and R&D effectiveness in High‐Technology firms: An empirical investigation in the biotechnology industry*. *Journal of Product Innovation Management, 27*(3), 299-320.

Deeds, D. L. (2001). The role of R&D intensity, technical development and absorptive capacity in creating entrepreneurial wealth in high technology start-ups. *Journal of Engineering and Technology Management, 18*(1), 29-47.

Deeds, D. L., Decarolis, D., & Coombs, J. E. (1997). The impact of firmspecific capabilities on the amount of capital raised in an initial public offering: Evidence from the biotechnology industry. *Journal of Business Venturing, 12*(1), 31-46.

della Valle, F., & Gambardella, A. (1993). 'Biological'revolution and strategies for innovation in pharmaceutical companies. *R&D Management, 23*(4), 287-302.

Dickson, M., & Gagnon, J. P. (2004). Key factors in the rising cost of new drug discovery and development. *Nature Reviews Drug Discovery, 3*(5), 417-429.

Dodgson, M., & Rothwell, R. (1994). *The handbook of industrial innovation* Edward Elgar Publishing.

Drucker, P. F. (1985). The discipline of innovation. *Harvard Business Review, 63*(3), 67-72.

Edquist, C. (1997). *Systems of innovation: Technologies, institutions, and organizations* Routledge.

Edwards, M. G., Murray, F., & Yu, R. (2003). Value creation and sharing among universities, biotechnology and pharma. *Nature Biotechnology, 21*(6), 618-624.

Fabrizio, K. R. (2009). Absorptive capacity and the search for innovation. *Research Policy, 38*(2), 255-267.

Feldman, M. P. (1999). The new economics of innovation, spillovers and agglomeration: A review of empirical studies. *Economics of Innovation and New Technology, 8*(1-2), 5-25.

Ford, D. N., & Sterman, J. D. (1998). Dynamic modeling of product development processes. *System Dynamics Review, 14*(1), 31-68.

Forrester, J. W. (1968). *Principles of systems* Cambridge, MA: Productivity Press.

Freeman, C. (1987). *Technology, policy, and economic performance: Lessons from Japan* Pinter Publishers London.

Freeman, C., & Soete, L. (1997). *The economics of industrial innovation* Routledge.

Galanakis, K. (2006). Innovation process. make sense using systems thinking. *Technovation, 26*(11), 1222-1232.

Galbreath, J. (2005). Which resources matter the most to firm success? an exploratory study of resource-based theory. *Technovation, 25*(9), 979-987.

Gans, J. S., & Stern, S. (2003). Managing ideas: Commercialization strategies for biotechnology. *ICFAI Journal of Intellectual Property Rights, 2*(2), 17-28.

Garcia, R., Calantone, R., & Levine, R. (2003). The role of knowledge in resource allocation to exploration versus exploitation in technologically oriented organizations*. *Decision Sciences, 34*(2), 323-349.

García-Muiña, F. E., Pelechano-Barahona, E., & Navas-López, J. E. (2009). Making the development of technological innovations more efficient: An exploratory analysis in the biotechnology sector. *The Journal of High Technology Management Research, 20*(2), 131-144.

Gerwin. D., & Tarondeau. J.C. (1982). Case studies of computer integrated manufacturing systems: A view of uncertainty and innovation processes. *Journal of Operations Management, 2*(2), 87-99.

Glassman, B. (2009). *Improving idea generation and idea management in order to better manage the fuzzy front end of innovation.* (Ph.D., Purdue University). , 350. . (3378749)

Greis, N. P., Dibner, M. D., & Bean, A. S. (1995). External partnering as a response to innovation barriers and global competition in biotechnology. *Research Policy, 24*(4), 609-630.

Griliches, Z. (1979). Issues in assessing the contribution of research and development to productivity growth. *Bell Journal of Economics, 10*(1), 92-116.

Hadjimanolis, A. (1999). Barriers to innovation for SMEs in a small less developed country (cyprus). *Technovation, 19*(9), 561-570.

Hall, L. A., & Bagchi-Sen, S. (2002). A study of R&D, innovation, and business performance in the canadian biotechnology industry. *Technovation, 22*(4), 231-244.

Hall, L. A., & Bagchi-Sen, S. (2007). An analysis of firm-level innovation strategies in the US biotechnology industry. *Technovation, 27*(1-2), 4-14.

Heinonen, L. (2009). Measuring performance in biopharmaceutical product development process: What counts63. *International Journal of Technology Intelligence and Planning, 5*(4), 357-372.

Henderson, R., & Cockburn, I. (1994). Measuring competence? exploring firm effects in pharmaceutical research. *Strategic Management Journal, 15*(S1), 63-84.

Herstatt, C., & Verworn, D. I. B. (2001). The "Fuzzy front end" of innovation. working paper no. 4. Department of Technology an Innovation Management, Technical University of Hamburg.

Hill, C. W. L., & Deeds, D. L. (1996). The importance of industry structure for the determination of firm profitability: A neo-Austrian perspective. *Journal of Management Studies, 33*(4), 429-451.

Hitt, M. A., Ireland, R. D., & Hoskisson, R. E. (2007). *Strategic management: Competitiveness and globalization* South-Western Pub.

Hu, J. L., & Hsu, Y. H. (2008). The more interactive, the more innovative? A case study of south korean cellular phone manufacturers. *Technovation, 28*(1-2), 75-87.

Hüsig, S., & Kohn, S. (2003). Factors influencing the front end of the innovation process: A comprehensive review of selected empirical NPD and explorative FFE studies. *Proceedings of the 10th International Product Development Management Conference,* 10-11.

HÜSIG, S., KOHN, S., & POSKELA, J. (2005). The role of process formalisation in the early phases of the innovation process. *12th Int. Prod. Development Conf. Copenhagen,*

Imai, K., Nonaka, I., & Takeuchi, H. (1985). Managing the new product development process: How japanese companies learn and unlearn. *The Uneasy Alliance: Managing the Productivity-Technology Dilemma,* , 337–375.

Kang, K. N., & Lee, Y. S. (2008). What affects the innovation performance of small and medium-sized enterprises (SMEs) in the biotechnology industry? an empirical study on korean biotech SMEs. *Biotechnology Letters, 30*(10), 1699-1704.

Khilji, S. E., Mroczkowski, T., & Bernstein, B. (2006). From invention to innovation: Toward developing an integrated innovation model for biotech firms. *Journal of Product Innovation Management, 23*(6), 528-540.

Khurana, A., & Rosenthal, S. R. (1997). Integrating the fuzzy front end of new product development. *Sloan Management Review, 38*(2), 103.

Khurana, A., & Rosenthal, S. R. (1998). Towards holistic "front ends" in new product development. *Journal of Product Innovation Management, 15*(1), 57-74. doi:DOI: 10.1016/S0737-6782(97)00066-0

Kim, J., & Wilemon, D. (2002). Strategic issues in managing innovation's fuzzy front-end. *European Journal of Innovation Management, 5*(1), 27-39.

Koc, T. (2007). Organizational determinants of innovation capacity in software companies. *Computers & Industrial Engineering, 53*(3), 373-385.

Koen, P., Ajamian, G., Burkart, R., Clamen, A., Davidson, J., D'Amore, R., . . . Johnson, A. (2001). Providing clarity and a common language to the" fuzzy front end". *Research-Technology Management, 44*(2), 46-55.

Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science,* , 383-397.

Lane, P. J., & Lubatkin, M. (1998). Relative absorptive capacity and interorganizational learning. *Strategic Management Journal, 19*(5), 461-477.

Lane, P. J., Salk, J. E., & Lyles, M. A. (2001). Absorptive capacity, learning, and performance in international joint ventures. *Strategic Management Journal, 22*(12), 1139-1161.

Lichtenthaler, E., Savioz, P., Birkenmeier, B., & Brodbeck, H. (2004). Organisation of the early phases of the radical innovation process. *International Journal of Technology Intelligence and Planning, 1*(1), 100-114.

Lin, C. H., Tung, C. M., & Huang, C. T. (2006). Elucidating the industrial cluster effect from a system dynamics perspective. *Technovation, 26*(4), 473-482.

Loch, C. (2000). Tailoring product development to strategy: Case of a european technology manufacturer. *European Management Journal, 18*(3), 246-258.

Lundvall, B. Å. (1992). National innovation systems: Towards a theory of innovation and interactive learning. *London: Pinter,*

Maani, K. E., & Cavana, R. Y. (2000). *Systems thinking and modelling: Understanding change and complexity* Prentice hall.

Malerba, F. (1992). Learning by firms and incremental technical change. *The Economic Journal, 102*(413), 845-859.

Markham, S. K., Ward, S. J., Aiman-Smith, L., & Kingon, A. I. (2010). The valley of death as context for role theory in product innovation. *Journal of Product Innovation Management, 27*(3), 402-417.

Marsh, D., & Oxley, L. (2005). Modelling innovative activity in the new zealand biotechnology sector. *Mathematics and Computers in Simulation, 69*(1-2), 103-112.

Matson, J. V. (1996). *Innovate or die: A personal perspective on the art of innovation* Paradigm Press (Royal Oak, Mich.).

Matusik, S. F. (2002). An empirical investigation of firm public and private knowledge. *Strategic Management Journal, 23*(5), 457-467.

McEvily, S. K., & Chakravarthy, B. (2002). The persistence of knowledge‐based advantage: An empirical test for product performance and technological knowledge. *Strategic Management Journal, 23*(4), 285-305.

Milling, P. M. (2002). Understanding and managing innovation processes. *System Dynamics Review, 18*(1), 73-86.

Moenaert, R. K., De Meyer, A., Souder, W. E., & Deschoolmeester, D. (1995). R&D/marketing communication during the fuzzy front-end. *Engineering Management, IEEE Transactions on, 42*(3), 243-258.

Montoya-Weiss, M. M., & O'Driscoll, T. M. (2000). From experience: Applying performance support technology in the fuzzy front end. *Journal of Product Innovation Management, 17*(2), 143-161.

Morecroft, J. D. W. (1985). Rationality in the analysis of behavioral simulation models. *Management Science,* , 900-916.

Mowery, D. C., Oxley, J. E., & Silverman, B. S. (1996). Strategic alliances and inter firm knowledge transfer. *Strategic Management Journal, 17*, 77-91.

Munson, F., & Pelz, D. (1979). The innovating process: A conceptual framework. *Univ.Michigan, Ann Arbor, Working Paper,*

Murphy, S. A., & Kumar, V. (1997). The front end of new product development: A canadian survey. *R&D Management, 27*(1), 5-15.

Muscio, A. (2007). The impact of absorptive capacity on SMEs' collaboration. *Economics of Innovation and New Technology, 16*(8), 653-668.

Nelson, R. R. (1982). The role of knowledge in R&D efficiency. *The Quarterly Journal of Economics, 97*(3), 453.

Nicholls‐Nixon, C. L., & Woo, C. Y. (2003). Technology sourcing and output of established firms in a regime of encompassing technological change. *Strategic Management Journal, 24*(7), 651-666.

Nieto Antolín, M. (2001). *Bases para el estudio del proceso de innovación tecnológica en la empresa* Universidad de León.

Niosi, J. (2000). *Explaining rapid growth in canadian biotechnology firms [electronic resource]* Ottawa: Statistics Canada. Science and Technology Redesign Project.

Nobelius, D., & Trygg, L. (2002). Stop chasing the front end process--management of the early phases in product development projects. *International Journal of Project Management, 20*(5), 331-340.

Oliver, R. W. (2003). *The biotech age: The business of biotech and how to profit from it* McGraw-Hill Companies.

Penrose, E. T. (1959). *The theory of the growth of the firm*, J. Wiley & Sons.

Peteraf, M. (1993). The cornerstones of competitive advantage: A resource-based view. *Resources, Firms, and Strategies: A Reader in the Resource-Based Perspective,* , 187-203.

Pisano, G. P. (2006). Can science be a business? lessons from biotech. *Harvard Business Review, 84*(10), 114-24, 150.

Porter, M. E. (1990). The competitive advantage of nations. *Harvard Business Review,*

Poskela, J., Dietrich, P., Berg, P., Artto, K. A., & Lehtonen, T. (2005). Integration of strategic level and operative level front-end innovation activities. Paper presented at the *PICMET, Portland, OR, Paper Presented at Portland International Conference on Management of Engineering and Technology,*

Poskela, J., & Martinsuo, M. (2009). Management control and strategic renewal in the front end of innovation. *Journal of Product Innovation Management, 26*(6), 671-684.

Prager, D. J., & Omenn, G. S. (1980). Research, innovation, and university-industry linkages. *Science, 207*(4429), 379.

Rainey, D. L. (2005). *Product innovation: Leading change through integrated product development* Cambridge Univ Pr.

Reid, S. E., & de Brentani, U. (2004). The fuzzy front end of new product development for discontinuous innovations: A theoretical model. *Journal of Product Innovation Management, 21*(3), 170-184.

Rosenberg, N. (1990). Why do firms do basic research (with their own money)? *Research Policy, 19*(2), 165-174.

Rothwell, R. (1994). Towards the fifth-generation innovation process. *International Marketing Review, 11*(1), 7-31.

Rothwell, R., & ZEGUELD, W. (1985). «Reindustrialisation and Technology»—Longman ed. *Chap.«The Role of Technology—Based Small Firms in the Emergence of New Technologies,*

Scherer, F. M. (2002). The economics of human gene patents. *Academic Medicine, 77*(12, Part 2), 1348.

Schroeder, R. G., Bates, K. A., & Junttila, M. A. (2002). A resource‐based view of manufacturing strategy and the relationship to manufacturing performance. *Strategic Management Journal, 23*(2), 105-117.

Schroeder, R. G., Van de Ven, A. H., Scudder, G. D., & Polley, D. (1989). The development of innovation ideas. *Research on the Management of Innovation: The Minnesota Studies,* , 107-134.

Shan, W., & Song, J. (1997). Foreign direct investment and the sourcing of technological advantage: Evidence from the biotechnology industry. *Journal of International Business Studies,* , 267-284.

Shan, W., Walker, G., & Kogut, B. (1994). Inter firm cooperation and startup innovation in the biotechnology industry. *Strategic Management Journal, 15*(5), 387-394.

Smith, P. G., & Reinertsen, D. G. (1991). *Developing products in half the time* Van Nostrand Reinhold New York.

Sterman, J. D. (1987). Testing behavioral simulation models by direct experiment. *Management Science, 33*, 1572-1592.

Sterman, J. D. (2000). *Business dynamics: Systems thinking and modeling for a complex world* Irwin McGraw-Hill.

Stoneman, P. (1995). *Handbook of the economics of innovation and technological change* Blackwell.

Sundbo, J. (1998). *The theory of innovation: Enterpreneurs, technology and strategy* Edward Elgar Pub.

Tang, H. (1998). An integrative model of innovation in organizations. *Technovation, 18*(5), 297-309.

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal, 18*(7), 509-533.

Tidd, J. (2001). Innovation management in context: Environment, organization and performance. *International Journal of Management Reviews, 3*(3), 169.

Tidd, J., Bessant, J., & Pavitt, K. (1997). *Managing innovation* John Wiley and Sons, Inc.

Todtling, F., & Trippl, M. (2007). Knowledge links in high-technology industries: Markets, networks or milieu? the case of the vienna biotechnology cluster. *International Journal of Entrepreneurship and Innovation Management, 7*(2), 345-365.

Tollman, P., Guy, P., Altshuler, J., Flanagan, A., & Steiner, M. (2001). A revolution in R&D. *How Genomics and Genetics are Transforming the Biopharmaceutical Industry.Boston Consulting Group,*

Traore, N. (2004). Canadian biotech firms' creative capacity: On the role of absorptive capacity, relational capital, learning, and firm characteristics. *International Journal of Biotechnology, 6*(1), 1-19.

Utterback, J. M. (1994). *Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change* Harvard Business School Press Boston, MA, USA.

Valle, F., & Gambardella, A. (1993). 'Biological' revolution and strategies for innovation in pharmaceutical companies. *R&D Management, 23*(4), 287-302.

Van de Ven, A. H. (1986). Central problems in the management of innovation. *Management Science, 32*(5), 590-607.

Van Moorsel, D., Cranfield, J. A. L., & Sparling, D. (2007). Factors affecting biotechnology innovation in canada: Analysis of the 2001 biotechnology use and development survey. *International Journal of Biotechnology, 9*(1), 39-59.

Van Moorsel, D., Cranfield, J. A. L., & Sparling, D. (2007). Factors affecting biotechnology innovation in canada: Analysis of the 2001 biotechnology use and development survey. *International Journal of Biotechnology, 9*(1), 39-59.

Verganti, R. (1997). Leveraging on systemic learning to manage the early phases of product innovation projects. *R&D Management, 27*(4), 377-392.

Verworn, B., Herstatt, C., & Nagahira, A. (2008). The fuzzy front end of japanese new product development projects: Impact on success and differences between incremental and radical projects. *R and D Management, 38*(1), 1-20.

Verworn, B. (2009). A structural equation model of the impact of the "fuzzy front end" on the success of new product development. *Research Policy, 38*(10), 1571-1581. doi:DOI: 10.1016/j.respol.2009.09.006

Vinding, A. L. (2006). Absorptive capacity and innovative performance: A human capital approach. *Economics of Innovation and New Technology, 15*(4-5), 507-517.

Wu, D. D., Kefan, X., Hua, L., Shi, Z., & Olson, D. L. (2010). Modeling technological innovation risks of an entrepreneurial team using system dynamics: An agent-based perspective. *Technological Forecasting and Social Change, 77*(6), 857-869.

Zahra, S. A., & George, G. (2002). Absorptive capacity: A review, reconceptualization, and extension. *Academy of Management Review,27,* 185-203.

Zahra, S. A., & Nielsen, A. P. (2002). Sources of capabilities, integration and technology commercialization. *Strategic Management Journal, 23*(5), 377-398.

Zaltman, G., Duncan, R., & Holbek, J. (1973). *Innovations and organizations,* John Wiley & Sons.

Zhang, Q., & Doll, W. J. (2001). The fuzzy front end and success of new product development: A causal model. *European Journal of Innovation Management, 4*(2), 95-112.

Zott, C. (2003). Dynamic capabilities and the emergence of intraindustry differential firm performance: Insights from a simulation study. *Strategic Management Journal, 24*(2), 97-125.

Zucker, L. G., & Michael, R. (1998). Intellectual human capital and the birth of US biotechnology enterprises. *The American Economic Review, 88*(1), 290-306.

Appendix A- Lists of Vensim model equations

---

(01) "Absorptive Capacity (AC)"= INTEG (Change in AC level,
"actual AC value (AAC)")
Units: AC [0,1,0.01]
The ability of firm in recognizing the value of external knowledge and apply it to commercial end

(02) ACE= 250000
Units: $
Average fund required for conducting each collaborative project

(03) "Acquired knowledge of internal effort (AKII)"="succeeded R&D projects (SIP)"*"Value of R&D projects (VRD)"
Units: Knw/Quarter
Amount of knowledge gained each quarter by R&D projects

(04) ACR=1.2e+006
Units: $/project
Average fund required for conducting each R&D project

(05) "actual AC value (AAC)"=1/(1+EXP(Beta*(F ac-"Actual Fraction (AF)")))

(06) Actual FI= INTEG (change in AFI, "fractional investment (FI)")

(07) "Actual Fraction (AF)"= INTEG (change in F, "Indicated fraction (IF)")

(08) "Acquired knowledge of external innovation (AKEI)"="succeeded external projects (SEP)"*"Value of collaboration projects (VEX)"
Units: Knw/Quarter
Amount of knowledge gained each quarter by partnership projects

(09) "adjustment time (ATF)"=3
Units: Quarter

(10) Beta=-8

(11) Change in AC level=("actual AC value (AAC)"-"Absorptive Capacity (AC)")/"Time to adjust AC (TAC)"
Units: AC/Quarter
Change in Ac level

(12) change in AFI= ("fractional investment (FI)"-Actual FI)/"In. adjustment time (IAT)"

(13) change in company performance=("Indicated knowledge stock effect (IKSE)"-"Knowledge stock effect (KSE)")/"Time to adjust company performance (TACP)"

(14) change in F=("Indicated fraction (IF)"-"Actual Fraction (AF)")/"adjustment time (ATF)"

(15) "Complete external projects (CEP)"= DELAY3("External Projects (EP)", "T External (TE)")
Units: project/Quarter
Number of complete and successful R&D projects

(16) "Complete R&D projects (CRP)"= DELAY3("R&D innovation Projects(RIP)", T R)
Units: project/Quarter
Complete successful R&D projects

(17) "critical collaboration fraction for reinv (CCF)"= 0.35

(18) Desired number of external projects="External source fund allocation (EFA)"/ACE

(19) "External Projects (EP)"=Desired number of external projects*"Absorptive Capacity (AC)"
Units: project/Quarter
Number of partnership projects undertake in each quarter

(20) "External source fund allocation (EFA)"=("Fund For Research (FFR)"*"Actual Fraction (AF)")/Td
Units: $/Quarter

(21) "External success rate (ESR)"=0.85
Units: Dmnl [0,1]
Fractional rate of success for collaborative projects

(22) F ac=0.9

(23) FINAL TIME = 100
Units: Quarter
The final time for the simulation.

(24) "fractional investment (FI)"="min investmentfraction (MI)"+(1-"min investmentfraction (MI)")*1/(1+EXP("Normalized parameter (g2)"*("critical collaboration fraction for reinv (CCF)" -"Actual Fraction (AF)")))
Units: Dmnl

(25) "Fund For Research (FFR)"= INTEG ("Investment for research (IFR)"-("External source fund allocation (EFA)"+

"In house R&D fund allocation (IFA)"), Td*"Initial Investment (II)")
Units: $

(26) "In house R&D fund allocation (IFA)"= ("Fund For Research (FFR)"*(1-"Actual Fraction (AF)"))/Td
Units: $/Quarter

(27) "In-house Projects (IP)"= INTEG ("R&D innovation Projects(RIP)"-"Complete R&D projects (CRP)", "R&D innovation Projects(RIP)"*T R)
Units: projects
Number of in house R&D projects

(28) "In. adjustment time (IAT)"= 4

(29) "Indicated fraction (IF)"=1/(1+EXP("Normalized parameter (g)"*"Performance Gap (PG)"))

(30) "Indicated knowledge stock effect (IKSE)"="Knowledge Value (KV)"/Initial knowledge value

(31) initial AC=1/(1+EXP(Beta*(F ac-Normal Frac)))

(32) "Initial Investment (II)"=500000

(33) Initial knowledge value="Time to lose knowledge (TLK)"*((1-Normal Frac)*"Initial Investment (II)"/ACR)*("Value of R&D projects (VRD)"*"R success rate (RSR)")+ ("Time to lose knowledge (TLK)"*(Normal Frac*"Initial Investment (II)"/ACE)*initial AC*"Value of collaboration projects (VEX)"*"External success rate (ESR)")

(34) INITIAL TIME = 0
Units: Quarter
The initial time for the simulation.

(35) Input=1+STEP(Step Height, Step Time)

(36) "Investment for research (IFR)"="Standard investment (SI)"*Actual FI
Units: $/Quarter

(37) Knowledge level changes="Acquired knowledge of external innovation (AKEI)"+"Acquired knowledge of internal effort (AKII)"
Units: Knw/Quarter
Knowledge gained by firm either by R&D or Collaboration in each quarter

(38) "Knowledge stock effect (KSE)"= INTEG (change in company performance,1)

(39) "Knowledge Value (KV)"= INTEG (Knowledge level changes-Lost Knowledge, Initial knowledge value)
Units: Knw
Amount of knowledge gained by firm

(40) Lost Knowledge="Knowledge Value (KV)"/"Time to lose knowledge (TLK)"
Units: Knw/Quarter
Knowledge lost

(41) "min investmentfraction (MI)"= 0.5

(42) Normal Frac=0.5

(43) "normal performance target K (NPT)"= Initial knowledge value

(44) "Normalized parameter (g)"=-3
Units: Dmnl
Normalized parameter to adjust R&D and collaboration ratio

(45) "Normalized parameter (g2)"=200

(46) "Number of projects through external (EP)"= INTEG ("External Projects (EP)"-"Complete external projects (CEP)","External Projects (EP)"*"T External (TE)")
Units: projects
Number of firm's projects that are co-authored with other firms and research institutes

(47) "Performance Gap (PG)"=("Performance Target knowledge (PT)"-"Knowledge Value (KV)")/"Performance Target knowledge (PT)"
Units: Knw
THe gap which exists between the actual performance and target performance

(48) "Performance Target knowledge (PT)"= "normal performance target K (NPT)"*Input
Units: Knw
an initial value of firm's target in the early stage

(49) "R success rate (RSR)"=0.5
Units: Dmnl [0,1]
Fractional success rate of R&D projects

(50) "R&D innovation Projects(RIP)"="In house R&D fund allocation (IFA)"/ACR
Units: project/Quarter
Number of R&D projects undertake in each quarter

(51) SAVEPER = TIME STEP
Units: Quarter [0,?]
The frequency with which output is stored.

(52) "Standard investment (SI)"="Initial Investment (II)"*"Knowledge stock effect (KSE)"

(53) Step Height=0
Units: Dmnl
Height of step input for performance gap

(54) Step Time=8
Units: Quarter
Time for change

(55) "succeeded external projects (SEP)"="Complete external projects (CEP)"*"External success rate (ESR)"

(56) "succeeded R&D projects (SIP)"="Complete R&D projects (CRP)"*"R success rate (RSR)"

(57) "T External (TE)"=8
Units: Quarter
Average time for completing collaborative projects

(58) T R=16
Units: Quarter
Average time required to complete R&D projects

(59) Td=12
Units: Quarter

(60) TIME STEP = 1
Units: Quarter [0,?]
The time step for the simulation.

(61) "Time to adjust AC (TAC)"=8

(62) "Time to adjust company performance (TACP)"=5
Units: Quarter

(63) "Time to lose knowledge (TLK)"=8
Units: 1/Quarter
Amount of knowledge which is lost in each quarter

(64) "Value of collaboration projects (VEX)"=500

Units: Knw/project
Value of knowledge acquired by undertaking joint project with other firms and universities and research institutes

(65) "Value of R&D projects (VRD)"=1500
Units: Knw/project
The amount of knowledge gained by each R&D project

Vensim simulation model