An investigation of the innovation performance in the capital goods sector in Colombia: using the System Dynamics approach

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M.Phil. Thesis

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I have been impressed with the urgency of doing.
Knowing is not enough; we must apply.
Being willing is not enough; we must do.

Leonardo da Vinci

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ACKNOWLEDGEMENTS

Once, something was given to me: an opportunity. *After sometime* such opportunity brought countless benefits into my life, benefits that I dare to summarize into: new knowledge and self-satisfaction.

Thanks to those who gave me the opportunity to come to Bergen and to those who supported me, academically and emotionally, along this experience.

ABSTRACT

The innovation performance of a firm within the capital goods sector in Colombia is addressed using the System Dynamics method. The problem that motivated this study can be stated as the lack of a comprehensive theory that explains both the poor innovation performance of the Colombian industry and its scarce level of the technological capabilities. Although there are a number of attempts to explain the problem, their causal structures are not fully specified and the results of these have not been evaluated with regard to whether they altogether constitute a coherent and consistent theory of the underlying causes explaining the observed dynamics. Robledo's (1997) research on the innovation process of the Colombian capital goods industry is examined in detail. Robledo's research is formalized to investigate how well the theory accounts for the phenomena its author set out to explain. We tested that the dynamics that Robledo (1997) describes can be produced by the causal factors he postulates. In particular, we demonstrate that given the intangible nature of capabilities and its effect on the innovation process, the actors making up the system of innovation maybe reluctant to invest in R&D. This fact highlights that industrialists, academics and policy-makers need to do both acknowledge that innovation is a learning process and estimate the intangible benefits of R&D. In particular, academics and policy-makers should encourage the industrialists to consider R&D investments at the core of its business strategy.

Key words—capabilities, capital goods, innovation, and system dynamics.

CHAPTER 1
Research Overview

Introduction

In this chapter we will offer an overview of this thesis, stating the research theme, the enquiries that gave rise to this research, the hypothesis on which it is based, and the research method employed. The main findings will also be summarized so as to offer the reader a general idea of our line of argument. Finally, the organization of this thesis is presented.

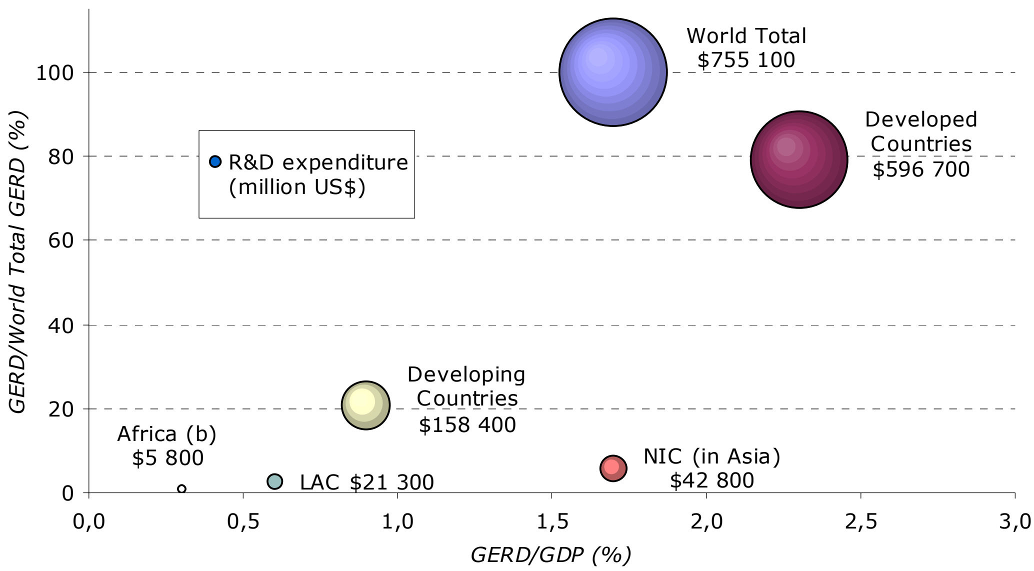
The research theme

In this thesis we address the innovation performance of a firm within the capital goods sector in Colombia. For this purpose we apply the System Dynamics method. The problem that motivated this study can be stated as the lack of a comprehensive theory that explains both the low level of the technological capabilities, of the Colombian industry, required to carry out innovation activities and its poor innovation performance. Although there are a number of attempts to explain the problem, the causal structures proposed are not fully specified and the results of these have not been evaluated with regard to whether they altogether constitute a coherent and consistent theory of the underlying causes explaining the observed dynamics (behaviour).

In this thesis, we examine a particular theory in detail, formalizing it to investigate how well the theory accounts for the phenomena that its author set out to explain. Our focus is Robledo's (1997) research on the innovation process of the Colombian capital goods industry, in which Government Institutions (GIs) and Higher Education Institutions (HEIs) play a key role. Because nonlinearity, delays and feedback are central to the innovation process, a causal modelling approach suitable for capturing dynamics is required; hence Robledo's verbal descriptions of causal relationships are formalized in the form of a System Dynamics model. It is expected that this approach will improve our understanding of the accumulation of the capabilities affecting the innovation performance observed at micro and macro level; and, as a result, will improve decision making and future policy design.

Science and technology indicators of Latin America and the Caribbean region

Figure 1
Gross expenditure in research and development (GERD) in 2000



Source: UNESCO (2004)

Gross expenditure in research and development (GERD) and intensity (represented by the ratio between GERD and Gross Domestic Product (GDP)) are two of the key indicators used to monitor resources devoted to science and technology (S&T) worldwide. In Figure 1, three indicators are displayed; GERD as a percentage of GDP (horizontal axis), GERD as percentage of world total expenditure (vertical axis) and GERD in million US dollars (represented by the bubble size). New industrialized countries (NIC) of South-East Asia are responsible for pulling up the developing countries average GERD intensity from 0.7% in 1990 to 0.9% in 2000.

One of the main characteristics of Latin America and the Caribbean region (LAC) system of innovation is its very low GERD intensity which is ranked below the developing countries average. In 2000, LAC region's GERD amounted to US$21.3 billion, which constitutes 2.82% of the total world expenditure. GERD intensity was 0.60% of its GDP, still falling short of the target of 1% suggested in various S&T policy documents and international declarations for over 30 years (UNESCO 2004). It is widely recognized in the literature the importance of R&D investment in order to develop abilities not only to innovate but also to benefit from new knowledge developed elsewhere (UN 2005, Kneller and Stevens 2002; Griffith, Redding and Van Reenen 2000).

Table 1

Gross expenditure in research and development from 1980 to 2000

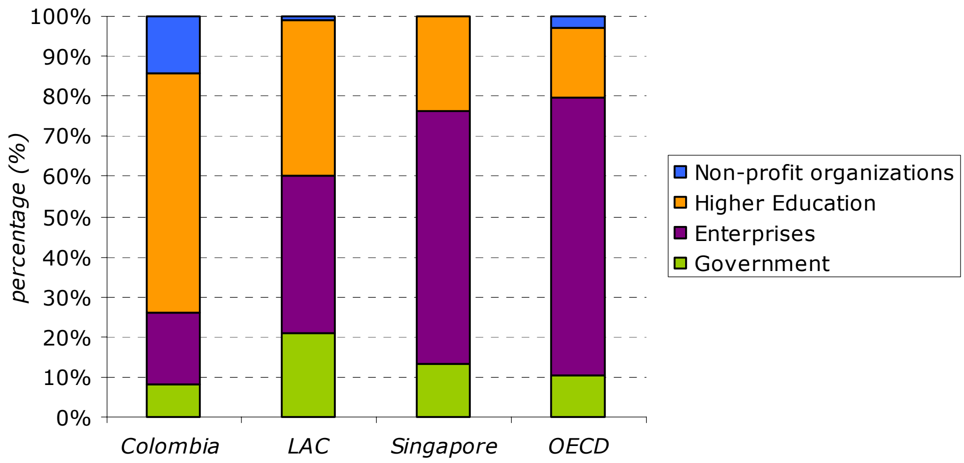
	1980	1985	1990 (a)	1994 (a)	1999/2000 (a)
As percentage of GDP					
World Total	1,85	2,22	1,80	1,50	1,70
Developed Countries	2,22	2,62	2,30	2,10	2,30
Developing Countries	0,52	0,54	0,70	0,50	0,90
LAC	0,44	0,43	0,50	0,50	0,60
Africa (b)	0,28	0,25	0,60	0,20	0,30
NIC (in Asia)			1,60	0,90	1,70
Structure (%)					
World Total	100,00	100,00	100,00	100,00	100,00
Developed Countries	93,97	95,21	89,78	86,56	79,02
Developing Countries	6,03	4,79	10,25	13,44	20,98
LAC	1,74	1,13	2,76	3,13	2,82
Africa (b)	0,52	0,34	1,27	0,88	0,77
NIC (in Asia)			2,00	1,53	5,67
Million US Dollars					
World Total	$208 370	$271 850	$409 800	$478 500	$755 100
Developed Countries	$195 798	$258 834	$367 900	$414 200	$596 700
Developing Countries	$12 571	$13 016	$42 000	$64 300	$158 400
LAC	$3 635	$3 062	$11 300	$15 000	$21 300
Africa (b)	$1 081	$921	$5 200	$4 200	$5 800
NIC (in Asia)			$8 200	$7 300	$42 800

(a) In purchasing power parity terms
(b) Only Sub-Saharan Africa until 1985
Source: Data for 1980-1985 from Alcorta and Peres (1998) and other data from UNESCO (2004)

Table 1 shows overall trends in GERD over the period from 1980 to 2000. Developed countries' leadership in research and development expenditures has declined slightly. Their GERD expenditure as a percentage of world total expenditure drop from 94% to 79% in two decades. Moreover, LAC's GERD almost doubled in absolute terms from 1990 to 2000, but as percentage of GDP it increased slightly from 0.5% to 0.6%. In terms of the Technology Achievement Index which measures creation of technology, diffusion of recent and earlier innovation, and human skills, there is a significant gap between the LAC region, the G7 and NIC (Hansen et al 2002, 4).

Figure 2

R&D expenditure by sector of performance in 2001



Source: RICYT and OECD

Figure 2 illustrates the percentage of GERD conducted by the government, business enterprises, HEIs and non-profit organizations for particular countries. In Colombia and the LAC region in general, most of the research and development expenditure is financed by the government and undertaken by HEIs. In contrast, in the OECD countries and Singapore, research and development (R&D) is mainly both financed and conducted by enterprises. Note that it is important that research collaboration and diffusion among agents should be strong enough so as to guarantee that industry will benefit from R&D investments carried out within the country. Unfortunately, evidence supports the fact that in the LAC there is little collaboration among firms as well as between HEIs and firms. De Ferranti et al (2003, 5, emphasis added) states that[1];

> Not only does Latin America lag in terms of the total amount of R&D relative to GDP, but ***a relatively large share of that R&D is undertaken by the public sector and has less spillover on private R&D than in other latitudes***. As a consequence, R&D spending in Latin America is not only small, but is less concentrated in applied research and development and has less effect on patents and productivity growth than what we observe in

[1] See also the studies carried out by Robledo (1997), Alcorta and Peres (1998), Durán, Salazar and Ibañez (2000), Vargas, Malaver and Zerda (2003).

> OECD countries and in the Asian tigers even when benchmarked by their respective average per capita income.

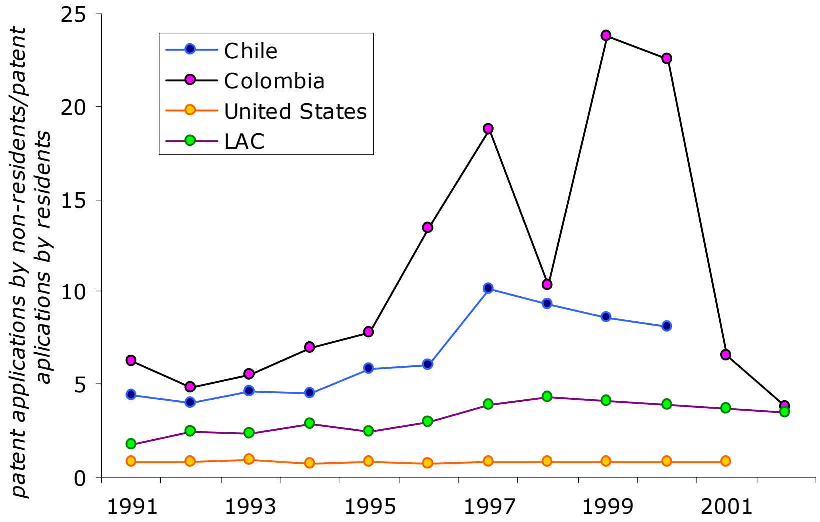
In Colombia, although the average GERD for the LAC region increased over the same period, the role played by enterprises contributing to GERD declined from 30% in 1996 to 18% in 2001 (RICYT 2005). In addition, total investments in S&T have declined since 1995 as a percentage to GDP. While in 1995 the government invested as much as the business enterprises, in 2003, these investments constituted 0.23% and 0.8% of GDP, respectively (DNP 2005). Over the period form 1995 to 2003, the role played by business enterprises in R&D decreased. This probably was due to the slow down of the Colombian economy during that period, and also because of the lack of confidence by business enterprises on R&D as a strategic path of development (Vargas, Malaver and Zerda 2003; Robledo 1997).

The data reported thus far is a useful representation of the scale and direction of R&D. However, indicators of the benefits of R&D investments are needed to complement this documentation. Statistics on the effect of R&D are far more difficult to define and produce; technology balance of payments, patent dependency rate and data on publications are some options (OECD 2002). Although the benefits of R&D investments cannot be entirely assessed by these output indicators, we offer the patent dependency rate and the average publications in SCI index as an illustration of the pervasive problem faced by the Colombian innovation system.

Technology dependency measured by the ratio between patent applications by non-residents and patent applications by residents is shown in figure 3; the higher the number, the more dependent the country is on acquisition of foreign technology. Once again, we observe that Colombia's performance is not only inferior to the LAC average, but also that, in 2001, the dependency rate was at the same level as ten years before. This means that the country depends on foreign technology innovations just as much as it did in 1991. In 2002, the decrease in the dependency rate was due to a decline in non-resident patent applications rather than to an increase in resident patent applications (RICYT 2005). This fact is consistent with Hansen et al (2002) who pointed out that foreign technology dependency, few resources allocated to R&D activities and slow economic growth are common features of the developing countries.

Figure 3

Dependency rate

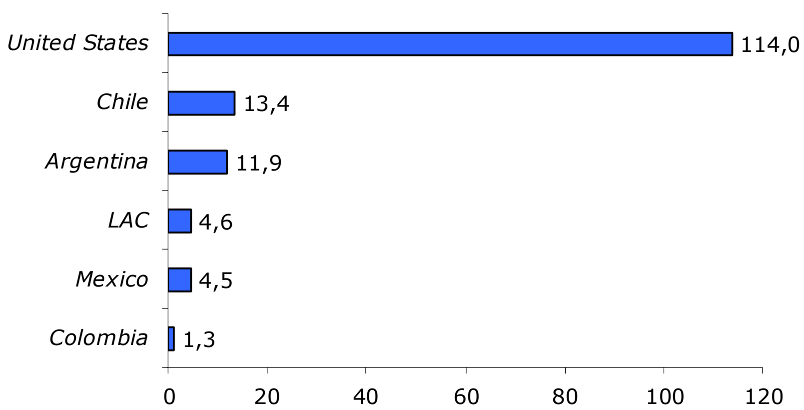


Source: RICYT

The number of publications per capita reported by Colombia in the Science Citation Index (SCI) increased from 0.6 in 1993 to 1.9 in 2002; however the country’s performance with respect to this indicator is lagging behind the LAC region average (figure 4).

Figure 4

Average publications in SCI index per capita over 1993-2002



Source: RICYT

A survey of technological development, carried out in 1996 in the Colombian industry, collected detailed information regarding innovation processes within the country over the period from 1989 to 1996. The assessment of S&T performance of the Colombian industry did thus far, lead to the following findings (Durán, Salazar and Ibañez 2000)[2]:

- Formal R&D activity is a source of innovation in 20% of the enterprises in the survey.
- The design and the acquisition of embodied technology, machinery and equipment with a technological content connected to either product or process innovations introduced by the firm, is among the more common science and technology activities, carried out in 60% of the enterprises covered by the survey. This fact is consistent with the level of technology dependency rate explained earlier.
- 24% of the enterprises conducted R&D projects between 1989 and 1996.
- An assessment of the enterprises' technological condition compared to the national market was undertaken by 58% of the enterprises in the survey. This percentage drops, however, to 22% when one compares the enterprises' technological condition to the international market.

Summing up, our aim in this section was to document that Colombia has an evident disadvantage with regard to S&T compared to other countries in the LAC region and to the NIC. Moreover, we wanted to point out the need of more accurate research in the S&T field in order to support future policy design.

[2] According to Robledo (2004), when interviewing Colombian entrepreneurs, it was found that they were not prepared to answer questions about technology and innovation. Therefore, there is considerable uncertainty about the results of such a survey. It might have reported overestimated statistics.

Prior research

Many theorists assert that innovation is the engine of economic growth[3]. There is a significant body of empirical and theoretical evidence that support such a statement: considering the history of economy since the industrial revolution, it is relatively obvious how growth has been triggered by innovations.

Actually, as a point of departure for this thesis, we call attention to the fact that theories pretending to explain the causal relationship between the factors that drive innovation and the resulting innovation itself might fail to explain innovation in industries different to those used to gather evidence; as is claimed by several theorists:

> […] literature on this subject [economic development] has emphasized the positive contributions of science and technology to development. This optimistic view must be tempered by the realization that ***the science and technology of developed nations is not, in the main, the kind that is required in underdeveloped countries***; the part that is required in not usually available under favourable conditions, and if it is, there is often a lack of competence to use it (Sagasti 1973, 55, emphasis added).
>
> ***
>
> So far, research on the subject has been mostly focused on gathering evidence from the developed economies, and building theories based on that evidence. However, there are few indications on the extent to which those theories may explain innovation elsewhere. What we need is ***more research grounding on questions and variables reflecting the reality of developing economies*** as well (Da Silveira 2001, 767, emphasis added).
>
> ***
>
> The majority of theoretical reflection about science and technology has been done by intellectuals from developed countries. Such analyzes pretend to have universal validity, at least when they address firms' behaviour in a

[3] The literature on this subject is vast. See in particular: Solow, Robert, 1994. Perspectives on growth theory. *Journal of Economic Perspectives* 8 (1): 45-54; Romer, Paul, 1994. The origins of endogenous growth. *Journal of Economic Perspectives* 8 (1): 3-22; Aghion, Philippe and Peter Howitt, 1999, *Endogenous growth theory,* 694p; Nelson, R. and H. Pack. 1998. The Asian miracle and modern growth theory. *Policy Research Working Paper* 1881. The World Bank Development Research Group. 44p.

> relatively competitive environment; however, ***there are striking differences when these analyzes are compared to evidence from developing countries*** (Vargas, Malaver and Zerda 2003, 21, our translation and emphasis).

There are other assertions that claim the general theories to be inappropriate when applied to developing economies; as is explained by Lall (2001, 132, original emphasis):

> Technological capabilities do not appear as a determinant of comparative advantage in theories of trade. In fact, *technological activity in any form* has no role in the conventional analysis of comparative advantage in developing countries. Developing countries are technological 'followers', for whom, it is assumed, technology is easy to find, transfer, use and upgrade….There is no difference between acquiring *capacity* (the physical plant, equipment and blueprints) and *capability* (the ability to use these efficiently).

The application of general theories on innovation could lead us to erroneous problem interpretations and, as a consequence, to recommending misleading policies. We do not assert that theories on innovation should not be taken into account when analyzing the innovation process in a developing country. On the contrary, we could draw on and adapt it whenever appropriate. Several theorists have been aware of the need to adjust theories to developing economies and have undertaken empirical studies with the aim to gather information and to provide clues as to explain innovation performance in developing countries; such empirical studies are reviewed in what follows. Regardless of the approach to the innovation process, the literature reviewed comprises studies pointing to the underlying causes responsible for the poor performance of the LAC in terms of science and technology.

In order to identify the factors that are associated with a decision to license technology and to demonstrate the existence of a technological dependence syndrome due to the relationship between licensing and future technological dependence, Mytelka (1978) investigated the metalworking and chemical industries from three Andean Countries: Colombia, Ecuador and Peru. According to Mytelka (1978, 105), the term "technological dependence" refers to a firm's inability to produce its own technology for the new or allied products it plans to introduce in the near future. He concludes that the ownership structure and the product sector, as well as the firm size, are related to the firm's decision to obtain technology by licensing rather than by generating it autonomously or obtaining it through other means (Mytelka 1978, 101).

As Mytelka (1978) points out, the developing countries' seem to have an inability to benefit from technology developed elsewhere. Developing countries should benefit not only from the access to foreign technology, but also from the opportunity to modify, extend or generate new technology. The policy of the Andean Group aiming, at that time, to motivate the diffusion of technology through licensing[4], produced a counterintuitive effect: licensing, at least in the firms surveyed, proved to be a factor inhibiting the development of a capacity to innovate within the firm. Technological dependence was thus reinforced; the firms in the Andean Group, once having chosen to license technology, hardly engaged in research and development activities any longer. Sagasti (1973) also identified such counterintuitive effect and describes it clearly:

> [...] Such equipment [complex and advanced capital equipment] was usually provided from abroad, because their incipient scientific and technological infrastructure has no capacity to provide the know-how needed in productive activities. These conditions have led to an increasing dependence on foreign technology, thereby intensifying technological dominance. [...] ***Thus in some cases the efforts to begin industrialization have led to increased technological dependence*** (Sagasti 1973, 51, emphasis added).

Despite the interesting results found by Mytelka up to 1978, we consider that he failed to provide a concrete explanation to the firms' tendency to rely on imported technology and to why firms get used to that fact. He denotes some underlying causes but his analysis keeps focus on the problem symptom: the technological dependence syndrome; we observe that in his following conclusion (Mytelka 1978, 134, emphasis added):

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[4] The above mentioned policy refers to the Decision 24 of the Andean Group on "The Common Treatment for Foreign Capital, Trademarks, Patents, Licensing Agreements and Royalties" (Mytelka, 1978, p.101-102).

> ***Whether derived from legal or psychological conditions***, it thus appeared that within the context of Andean dependence and underdevelopment, with its resultant pattern of ownership structure and product choice, the relationship between licensing and technological dependence found in this study could best be explained in terms of loss of opportunity for "learning by doing".

Several case studies addressing the local processes of learning and accumulation of innovative capabilities in Brazil were carried out and reported by Cassiolato, Lastres, and Maciel (2003) drawing on some policy lessons. It is worth mentioning the case about the metal-mechanic production system in Espírito Santo which Villaschi and dos Santos (2003) described in the chapter 21 of their book. It brings evidence towards the major role played by the interaction between companies, suppliers and supporting institutions in facilitating the firms' learning process and, as a result, in the process of increasing the capability to innovate. Nonetheless, such capability building only went as far as process y/or product improvement.

Cassiolato, Villaschi, and Ramos (2003, 578) conclude, among other things, that due to neo-liberal policies implemented in Brazil in the last 20 years (as in most Latin American countries), "technology, innovation and knowledge were assumed to be 'globalized commodities' that could be acquired under market conditions and brought by new Foreign Direct Investment". As a result, instead of fostering local capabilities, policies were aimed at opening the economy and attracting the foreign investment. They suggest that firms should advance, both individually and collectively, towards the production of technologically more complex goods, with the aid of the establishment of virtuous technical and economic relations (Cassiolato, Villaschi, and Ramos 2003, 579).

Alcorta and Peres (1998, 867) assert that firms from Latin America and the Caribbean (LAC) invest little in innovation and illustrate several sets of exploratory explanations provided by empirical literature in the region. They regard the work done by Macario (1995) as the first set of explanations and mention that:

> [...] firms in these countries [Chile, Jamaica, Mexico and Venezuela] when confronted with a critical situation are likely to react by emphasizing commercial and financial solutions, not technological ones. The reason for this is that there is a much larger managerial capacity in commercialization and financial areas [...] (Alcorta and Peres 1998, 868).

The second set explanations to the little investments in innovation in LAC comprise the lack of knowledge regarding the importance of innovation and its main elements. The third set explanations, which is drawn from the work of Pirela (1993), and Pirela et al (1991a, b), focuses on entrepreneurs' lack of medium and long-term vision. Finally, the last set of explanations refers to entrepreneurs' own interest in developing new products as the main motivation to innovate (Waisbluth et al 1992).

Maloney (2002) argues that the causes of Latin America's underperformance and acute sense of dependency can be found in barriers to technological adoption and innovation with deep historical roots (Maloney 2002, 1). The first barrier is the deficient human capital and networks of institutions that facilitate the adoption and creation of new technologies (Maloney 2002, 10). The barriers to trade and investment that comprised the inward-looking policies implemented after the Great Depression stand as the second impediment to the transition to an innovation-based economy (Maloney 2002, 16).

In Colombia, Vargas, Malaver and Zerda (2003) carried out several case studies within the metal-mechanic and petrochemical industry. Their aim was threefold:

- To characterize the innovation processes, finding out whether innovation is embedded within the firm's strategic planning or it is the outcome of not planned decisions;
- To identify the internal and external factors influencing innovation;
- To assess the impact of innovation on firm's competitive and economic behaviour, and on technological capabilities development.

They report that the bulk of firms in the analyzed industries do not see innovation as a source of competitive advantage. Technology plays a supporting role to the firm's strategy, in other words, technology management is neither informal, nor systematic or planned. This situation hinders the creation and accumulation of high complex technological capabilities necessary for the development of innovations with high scope and novelty level. Also, firms have poorly developed linkage capabilities, and as a result, firms' relationships with other agents within the National System of Innovation are weak (Vargas, Malaver and Zerda 2003, 583-589). The most important conclusions reached by Vargas, Malaver and Zerda (2003) were reported by Robledo (1997) as well[5].

Robledo (1997) identifies the main factors and underlying causes explaining the poor innovation performance of the Colombian capital goods industry and how this performance has been influenced by the role played by Higher Education Institutions (HEIs) and the Government Institutions (GI) in the process of accumulation of innovation capabilities. He demonstrated that:

> The dominant innovation paradigm presently pertaining in Colombia is one of the major underlying causes explaining the low level of innovation capabilities accumulated by the Colombian capital goods innovation system. The poor innovation performance of the capital goods industry would be a way in which this low level of innovation capabilities becomes apparent (Robledo, 1997, 20).

In his study, Robledo (1997) states the key role played by the capital goods industry in introducing and diffusing technological change within the economy. He describes the visible expressions of the paradigm and the effect that the paradigm exerts on the agents' decisions regarding innovation investments. In brief, he concludes that the Colombian capital goods innovation system is trapped in a "vicious cycle"[6] which impedes the accumulation of innovation capabilities necessary for an effective innovation performance.

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[5] Similar facts and policy suggestions are reported in Cassiolato, Lastres, and Maciel (2003) for Brazilian case.

[6] This expression is examined in chapter 5.

So far, the literature reviewed offered evidence and suggested hypothesis about the underlying causes responsible for the innovation performance in the Colombian industry. In particular, Robledo proves a straightforward relationship between the dominant innovation paradigm and the innovation performance observed in the capital goods industry. Although the research done by Robledo might be right within its methodological domain, it reminds to be investigated whether the industry structure laid down by him in his thesis can explain as a theory the behaviour of the Colombian innovation system.

The research purpose

We intent to translate into a formal model, the main factors and underlying causes claimed by Robledo (1997) to be responsible for the poor innovation performance of the Colombian capital goods industry; and to test, using computer simulation, whether Robledo's theory actually leads to the particular behaviour he describes. To examine the policies suggested by Robledo is beyond the scope of this thesis.

This research does not deal with the innovation performance of a specific firm, partly because the product development process is usually firm specific, therefore better dealt with at the appropriate level, and because Robledo draws its conclusions from the empirical research he conducted[7] . This research emphasizes that the role that industrial firms can play in innovation and social well-being depends largely on both the internal skills they have at their disposal and the firm's interaction with HEIs and GIs.

In responding to the challenges posed by the Millennium Development Goals, and the fact that science, technology and innovation underpin every one of these goals, we expect to make a significant contribution to the UN (2005) recommendations about the role played by HEIs and GIs in innovation and the role of the industrial firm as a locus of learning.

[7] Robledo conducted an empirical research based on data from a representative sample of firms in the Colombian capital goods industry.

In addition, we appreciate the contribution of this thesis to the discussion in the literature about the innovation process in Colombia as being threefold: 1. it should offer a comprehensive theory that attempts to explain both the poor innovation performance of the Colombian industry and its scarce level of the technological capabilities; 2. it should improve the understanding of the accumulation of the capabilities affecting the innovation performance observed both at the firm level and at higher education and government institutions; and 3. it should increase the accessibility of Robledo's research to entrepreneurs, science and technology decision makers and other researchers.

The hypothesis

As indicated above, based on the research done by Robledo (1997), we will seek to build a formal model of the underlying causes explaining the innovation performance of the capital goods industry in Colombia. We are particularly interested in showing whether Robledo's description of the problem actually follows logically from the causes Robledo claims. Robledo found, as we already pointed out, that the dominant paradigm affecting innovation activities has a great bearing on the specific direction of development followed by the Colombian capital goods innovation system. In what follows we present Robledo's findings which are adopted as a hypothesis for this study.

First of all, we present briefly the concept of paradigm adopted by Robledo. In his study, Robledo supports the hypothesis that technological innovation and institutional change are interdependent; and he asserts that a paradigm is a particular kind of institution which, as said by Johnson (1992, 26), is a set of habits, routines, rules, norms and laws, regulating the relations between people, and shaping human interaction. Moreover, paradigms act pervasively at the level of the awareness and decision making functions in organisations, strongly affecting the development of the innovation process in firms and the accumulation of innovation capabilities in the whole industrial innovation system (Robledo 1997, 236).

There are visible expressions of the cumulative effect of the dominant paradigm present in the Colombian capital goods innovation system; as is described by Robledo (1997, 49):

> […] the Colombian capital goods innovation system:
> 1) Has disregarded innovation as a valid development alternative;
> 2) Has internalised conceptions which are akin to traditional economics, characterised by identifying 'knowledge' with 'information', by reducing the benefits of R&D to their direct results, and by assuming that innovations can easily be adopted, provided that the respective 'best practices' are introduced;
> 3) Has failed to accumulate research capabilities for innovation, by focusing almost exclusively on accumulating imitation capabilities for production;
> 4) Has created barriers to collaboration which hinder the establishment of innovation networks among users, producers, and research organisations.

The manifestation of the paradigm through such particular elements has created an intricate problem; the little generation and accumulation of innovation capabilities within the system's organisations impedes a shift in the dominant paradigm, thus the inability to develop skills is reinforced all over again. This is clearly a vicious cycle as Robledo (1997, 48) denotes it:

> […] the Colombian capital goods innovation system is trapped in a Gordian knot which inhibits the generation and accumulation of innovation capabilities within the system. This Gordian knot is formed by three entwined vicious circles: the first one keeps firms from accumulating innovation capabilities which otherwise could be accumulated through a synergistic relationship with institutions and other firms; as a result, the fundamental contribution of firms to establish a successful innovation system is not realised. The second vicious circle is responsible for the inadequate development of the research function in the Higher Education System, thereby preventing HEIs from creating and re-creating knowledge which is relevant to the Colombian society and productive sectors. As for the third vicious circle, it results in a government failing to foster industrial innovation and the accumulation of innovation and research capabilities in industrial firms and organisations.

Besides the identification of effect that the paradigm exerts on the innovation system, Robledo investigated the facts determining the paradigm formation as well as the role that HEIs and Government Institutions (GIs) might play in the process of paradigm shift. Notwithstanding the importance of these latter issues in explaining Robledo's research purpose and in the conclusions he attained, we will emphasize on the effect that the paradigm exerts on the development of the innovation process and the development of innovative capabilities within firms.

As the Oslo Manual (OECD, 1992) and the Millennium Project (UN, 2005) explain, and to be consistent with Dosi et al (1994) and Nelson and Winter (1982) cited by Alcorta and Peres (1998) we consider important to focus our analysis on the firm because:

> Within organisations, however, firms play a central role in the NSI [National System of Innovation]. It is they which are responsible for innovating. They must develop the competencies in product design and production, in overall management and assessment of consumer needs and in linking to upstream and downstream suppliers and distributors. It is they that must search, develop R&D 'routines' and further engage in the learning processes for innovation (Alcorta and Peres 1998, 860).

As far as the role of HEIs and GIs is concerned, our analysis addresses the influence exerted by the interaction between the firm and these agents on the rate and direction of development of innovative capabilities within the whole innovation system.

The research methodology

Several theorists have pointed out innovation as a systemic phenomenon, a nonlinear process which is governed by uncertainty, delays and feedback among different functions and participants. This description leads us easily to conclude that innovation is a complex process:

> The attributes of R&D activity are non-specifities [it is not-product specific and not firm-specific], lags [delays], uncertainty [business, technological and market uncertainty] and costliness (Kay 1988, 282).

***

> [...] the process of innovation is complex, since it involves many variables, the technical properties and interactions (and economic usefulness) of which are understood only very imperfectly (Griliches and Klette 1990, 28-29).

***

> It is a complex, diversified activity with many interacting components [...] furthermore, innovation is not a linear process and there may be important loops back in the system (OECD 1992).

***

> It has to consider values and goals and the conflicting interests of decision makers. It deals with soft and hard variables; it involves risk taking and large sums of capital investment; and it has to deal with feedback. It is a highly complex system—a challenge to understand and difficult to manage (Milling 2002, 85).

In order to cope with innovation, firms need to generate and accumulate knowledge and skills through time. Thus, sometimes the effect of policy solutions, aimed at improving the innovation performance, and the policies themselves are distant in time (delay) and space (perception). This has been the case of the countries making up the Andean region (Mytelka 1978; Robledo 1997). Based on this evidence we suggest counterintuitive behaviour as another feature of innovation.

In order to examine the consistency of the causal explanation laid out in Robledo's research, we shall look for a methodology suitable for the type of problem we are focus on and for the analysis of both the innovation process and the development of innovative capabilities. In addition, it must allow us to test Robledo's theory intended to explain the innovation development problem of the Colombian economy.

Qualitative models might properly represent complex feedback structures; nevertheless, they omit parameters, functional forms, external inputs, and initial conditions needed to fully specify the structure of a system, understand their dynamics, and test the model itself. System dynamics offers the ability to bring a model to life, to see the consequences of structural assumptions, to try out "what-ifs", and to challenge managerial intuition (Vennix and Gubbels 1994, 139). As Sterman (2000) asserts, formalizing qualitative models and testing them via simulation often leads to radical changes in the way we understand reality. Likewise, Forrester states that verbal statements need to be clarified by translating them into less ambiguous forms and into a form that will allow us to experiment with the implications of the statements already made (Forrester 1961, 44).

It follows that innovation becomes an object of research suited for the system dynamics methodology which is a tool for simulating complex, nonlinear, multi-loop feedback systems. As indicated by Sterman (1991, 2000), it is a powerful method that maybe applied to gain useful insight into situations of dynamic complexity.

A system dynamics model reflects the physical constrains and social goals, rewards and pressures that cause people to behave the way they do and to generate cumulatively the dominant dynamic tendencies of the total system (Meadows 1980, 31). Actually, system dynamics has been used to study topics such as product development (Ford and Sterman 1998), innovation management (Forrester 1964; Senge 1986; Milling 2002), innovation implementation (Repenning 2002) among others, at the micro level; and innovation and the dynamics of economic growth (Forrester 1979, 1981; Graham and Senge 1980; Senge 1986) at the macro level.

We want to call attention to the concept of ‘mental model’ which has been widely addressed in system dynamics. Sterman (2000, 16) states that a “mental model” includes our beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model (which variables are included and which are excluded) and the time horizon we consider relevant-our framing or articulation of a problem. We consider the term ‘mental model’ akin to the concept of paradigm adopted by Robledo. The paradigm as well as the mental model might determine the way organizations consider the R&D activity as an alternative path of economic development. In the Colombian context, as Robledo suggest, the understanding of the poor innovation performance likely resides in the stage in which firms become aware of a problem or an opportunity, and they make either innovation favouring or innovation avoiding decisions.

System dynamics greatest potential for improvement comes when the modelling process changes deeply held mental models (Sterman, 42).

It is worth mentioning that data given by Robledo (1997) is not a sufficiently complete basis for translating his research findings into a system dynamics model. Thus, we draw on theory and have searched for other types of data to fill in the gaps between the statements he makes and the structural relationships. The validity of the model is assessed following the guidelines for validation of system dynamics type of simulation models suggested in Barlas (1996).

Main Findings

A weak system of innovation, make up by Higher Education Institutions (HEIs), government institutions (GIs) and industrialist, in which neither GIs accumulate sufficient capabilities necessary to design effective science and technology policies nor HEIs accumulate the research capabilities necessary to interact with the industry, will not encourage the private firm to allocate resources to R&D early on its life span. As a result, the firm does not develop its innovation capability either and it is unable to support the development of capabilities at the other agents. It is in this sense that the accumulation of capabilities in the system of innovation is caught in a vicious cycle. This situation has significant economical consequences when the firm copes with high performance standards in the market place. The sooner the firm is encouraged to invest in R&D the better. Otherwise, the firm will recognize new opportunities; neither will it have the economic resources to undertake R&D investments. The vicious cycle is reinforced all the way around.

Robledo concludes that a minimum level of capabilities is required for the virtuous cycle of development to gain momentum. This fact was clearly observed in the simulations. Unless none capability has been accumulated in HEIs or GIs until the present time, the interactive learning between the firm, HEIs and GIs will necessarily trigger the development of their capabilities. If the system of innovation has accumulated little capabilities so far, the further development of capabilities will evolve at a very slow pace. As a result, when the level of capabilities will be sufficient to encourage the firm to invest in R&D, it might be late and probably the firm will have not survived in the meanwhile, since it failed to develop the capabilities necessary to compete in the market.

The interaction between HEIs and GIs reinforces the development of their own capabilities rather independent from the firm's capability evolution. This fact reflects the crucial role that they have to play in the firm's innovation process. However, this is not consistent with the conclusions attained in the literature regarding the system made up by government, HEIs and industry. According to the literature on the triple-helix model of university, industry, and government relations (Etzkowitz and Leydesdorff 2000), every actor plays a key role in the innovation process. In fact, in some cases each actor can take the role of the other despite the different tasks they have to perform.

The actors making up the system of innovation have to understand that the interdependence among the system actors is not "good" or "bad" per se as long as every actor is aware of the system structure and its own role. Each actor has to understand that within a system of innovation not only the benefits of accumulating capabilities spill over the other actors, but also the negative aspects. A better understanding of the system structure is clue for a more efficient policy-design (Sterman 2000; Forrester 1994). This is particularly important for the Colombian system of innovation since, as Robledo claims, there are inherent time lags in conveying the insights of innovation analysts to policy-makers making up the system.

In reality, and relating this research to studies regarding the technology dependence of developing countries, we found a key explanation or verification of previous conclusions reached in the literature (Hansen et al 2002; Nelson and Pack 1998; Pack 1986; Contractor 1983; Buckley 1979; Mytelka 1978). When a firm is unable to innovate it has to license products developed else where. As a result, the firm does not have the possibility to develop the capability necessary to neither produce the products already licensed nor to improve their quality. Furthermore, in case that it is cheaper to pay for licenses than investing in R&D, the firm will stay far from the possibility to develop the capabilities necessary not only to develop new products but also to interact with the GIs and HEIs.

The direct benefits of R&D are not significant soon after the investments took place; even though, the intangible benefits of R&D actually seem to be important. For instance, if the firm invests in R&D since its start up, it takes 6 years to increase slightly the number of designs in production. However, the innovation capability is significantly high compared to its initial value; it is 1.5 times greater. This accumulated capability forms the technological base that will allow the firm to speed up its product development process after 6 years. The delay between the time that R&D investments take place and the time when direct benefits are perceived is significant. This delay is not only due to the regular delays in the product development but also due to the inertia involved in the learning process originating the capabilities.

We recognizes that given the intangible nature of capabilities and its effect on the innovation process, the actors making up the system of innovation maybe reluctant to invest in R&D. This fact highlights that industrialists, academics and policy-makers need to do both acknowledge that innovation is a learning process and estimate the intangible benefits of R&D. In particular, academics and policy-makers should encourage the firm to consider R&D investments at the core of its business strategy.

Robledo refers indistinctly to two different patterns of behaviour when the accumulation of capabilities is governed by the “vicious circle”. It follows that it is either trivial to distinguish them as different patterns of development and Robledo uses the expression “vicious circle” just to denote a general closed loop of causal influences, or it is difficult to infer the emergent behaviour of the intertwined relationship among the agents making up the system of innovation (HEIs, GIs and the firm). In either case, the need to translate verbal statements into a less ambiguous form is obvious.

This thesis made a formal representation of the research done by Robledo. This first model can be questioned by the actors making up the system of innovation itself -industrialists, academics and policy-makers. They can examine the assumed relationships among the structure components and judge their plausibility. They can add also dynamics or assumptions that were omitted by both Robledo and us. Hence, this research might help to attain one of the purposes of Robledo's research: to highlight the roles that firms, HEIs and the government have to play in the performance of the system of innovation. This might be also the first step to improve policy-design regarding science and technology.

To finish off, this study suggest that a careful analysis of an existing theory can be very generative, helping to test and extend verbal theories and provide new explanations for empirical results about the complex phenomena of innovation within a developing economy.

Organization of the thesis

The thesis is organized into five chapters. Chapter 2 introduces the main factors and underlying causes identified by Robledo (1997) as responsible for the poor innovation performance of the Colombian capital goods industry. In Chapter 3, the dynamic hypothesis accounting for the problematic behaviour is provided as well as a description of the model built. After explaining the model, chapters 4 and 5 show the process followed to validate the model and the analysis of the simulation results, respectively. The thesis ends with a discussion about the conclusions attained by Robledo and those found by means of this thesis.

CHAPTER 2
Describing the Innovation Process

Introduction

We consider Robledo's research as very important to analyse the innovation performance of the Colombian industry. That is why we decided, as mentioned already, to formalize Robledo's research in order to investigate how well the theory accounts for the phenomena that its author sets out to explain. Our first step to accomplish this goal is to make a textual analysis of this research in order to identify constructs and relationships relevant for a formal model.

First we will introduce the main findings of Robledo's research; then we will present Robledo's findings by putting them into categories relevant for the formal modelling. This procedure is based on the method used by Sastry (1997). By the end of the chapter we expect to have shown the information we used and how did we use it to formalize verbal descriptions of causal relationships into formal equations. The analysis done in this chapter constitutes the basis for the definition of the dynamic hypothesis and for the construction of the model, which are explained in the next chapter.

Main findings of Robledo's research

Our focus is Robledo's research on the innovation process of the Colombian capital goods industry, and the role played by government institutions (GIs) and higher education institutions (HEIs) in this process. Before presenting Robledo's main research findings, we will introduce the reader to the capital goods industry and the great bearing it has on industrial development.

Capital goods industries have played a leading role in the industrialization process of developing countries, both the early-comers to the industrial scene such as United States and the relatively late-comers such as Japan.

As stated by the UN, the capital goods industry produces machinery and equipment for capital formation. Hence, these industries have not only determined the pace of capital accumulation, but have also acted as a decisive instrument for the generation and diffusion of technological change throughout the economy (UN 1985, xiv).

The capital goods sector develops skills and knowledge required for the assimilation, replication, adaptation and improvement of technology. This skills form the knowledge base upon which further technical progress so largely depends (Romijn 1997; Dilmus 1991).

The enterprises making up the capital goods industry have the ability to manufacture a very large range of products. These products may vary quite substantially in terms of the technical skills and knowledge required for their manufacture. Nonetheless, a given piece of capital equipment can be used to make a large number of items of varying degrees of manufacturing complexity (Romijn 1997, 361). It has been found that the differences observed among firms –within the capital goods industry- are not due to capital assets but to capabilities. This is stated by Romijn (1997, 363) as follows:

> "[…] differences in grade between firms can only emanate from the fact that some firms use their capital to manufacture products that require more advanced technical knowledge and skills than other firms which have exactly the same capital-set."

The relevance of the capital goods sector for industrial technological progress is well recognized by Robledo and constitutes one of the reasons why he selected this industry to carry out his research. This can be appreciated in the next statement:

> "it has been widely recognised that the capital goods industry shows important linkages with the rest of the productive sectors, which means that a weak capital goods industry may compromise the balanced development of the rest of a country's economy." (Robledo 1997, 25)

The following assumptions made by Robledo are relevant to understanding his research findings:

- Innovation is a learning process which proceeds cumulatively on the basis of innovation capabilities accumulated historically in the firm and its innovation environment. The development path of these capabilities is signposted by dominant innovation paradigms (Robledo 1997, 76-77).
- There are innovation capabilities supporting the innovation process. They play a key role both in the awareness and decision making function of the firm and in the implementation process giving place to innovation and/or production activities (Robledo 1997, 77).
- The accumulation of innovation capabilities depends largely on the interaction with HEIs and GIs, who also accumulate technological capabilities, i.e. HEIs accumulate research capabilities and GIs accumulates capabilities for science and technology policy-design. The interaction between the firm and both HEIs and GIs is governed by three feedback loops that form what the author calls a Gordian knot. As Robledo indicates it:

  > "[…] the Colombian capital goods innovation system is trapped in a Gordian knot which inhibits the generation and accumulation of innovation capabilities within the system. This **Gordian knot is formed by three entwined vicious circles**: the first one keeps firms from accumulating innovation capabilities which otherwise could be accumulated through a synergistic relationship with institutions and other firms; as a result, the fundamental contribution of firms to establish a successful innovation system is not realised. The second vicious circle is responsible for the inadequate development of the research function in the Higher Education System, thereby preventing HEIs from creating and re-creating knowledge which is relevant to the Colombian society and productive sectors. As for the third vicious circle, it results in a government failing to foster industrial innovation and the accumulation of innovation and research capabilities in industrial firms and organisations." (Robledo 1997, 48, emphasis added)

In his study, Robledo supports the hypothesis that technological innovation and institutional change are interdependent, and he asserts that a paradigm is a particular kind of institution which, as said by Johnson (1992, 26), is a set of habits, routines, rules, norms and laws, regulating the relations between people, and shaping human interaction. Moreover, paradigms act pervasively at the level of the awareness and decision making functions in organisations. The dominant paradigm affecting innovation activities is largely responsible for the specific development path followed by the Colombian capital goods innovation system.

Robledo identified several factors that gave rise to the industrial paradigm presently pertaining in the Colombian capital goods industry:

> "Although the evidence is not yet definitive in this respect, we suggest that the dominant industrial innovation paradigm in the Colombian case has been highly determined by:
>
> 1) Traditional economic models and analyses, whose disregard for innovation, have made firms and institutions fail to accumulate innovation capabilities as a long-term competitive advantage;
> 2) 'Myopic' business management style and practices which tend to disregard the accumulation of innovation capabilities as a strategic alternative to be selected during technological-related decision-making processes;
> 3) A notorious lack of specific concerns about national security and technological autonomy at all levels in the innovation system which are found to be powerful driving forces to foster innovation processes in other countries." (Robledo 1997, 48-49)

We do not intend to address the factors that originated the paradigm. Our aim is to demonstrate, as Robledo asserts, that given the influence of the paradigm and the structure underlying the system of innovation, the accumulation of innovation capabilities within the system has adopted evident habits regarding R&D. Robledo describes these practices as follows:

> "As a result of the dominant innovation paradigm, we will seek to demonstrate that the Colombian capital goods innovation system:
>
> 1) Has disregarded innovation as a valid development alternative;
> 2) Has internalised conceptions which are akin to traditional economics, characterised by identifying 'knowledge' with 'information', by reducing the benefits of R&D to their direct results, and by assuming that

innovations can easily be adopted, provided that the respective 'best practices' are introduced;

3) Has failed to accumulate research capabilities for innovation, by focusing almost exclusively on accumulating imitation capabilities for production;
4) Has created barriers to collaboration which hinder the establishment of innovation networks among users, producers, and research organisations." (Robledo 1997, 49)

The cumulative effect of these practices is responsible for the poor innovative performance of the Colombian capital goods industry. In fact, the innovation capabilities accumulated within the actors making up the system of innovation has not been sufficient to yield a proper economic development of the industry. As conceptualized by Arrow (1962), while some of these capabilities accumulate automatically over time as a result of learning by doing, for the most part it has to be actively acquired through "technological effort" –a purposive commitment of time, human and physical resources to activities leading to technological learning (Romijn 1997; Dilmus 1991).

As shown in chapter 1, the poor performance of Colombia in science and technology suggests that the problem perceived by Robledo up to 1997 is still active. This fact can also be easily noticed in the following quotation, which was taken from a survey, carried out in 2005, of the Colombian institutions for technological development:

> "The institutions for technological development face a lack of financial resources, a scarce demand for R&D projects from business enterprises, and competition with universities. For these institutions, the most concerning issue is the scarce demand for R&D projects; they claim that entrepreneurs simply do not understand the importance of innovation and technological development." (Dinero 2005, our translation)

The causal relationships between the factors that drive innovation and the resulting innovation itself, have been poorly understood in Colombia, and it might be also the case of other developing countries in the Latin American and the Caribbean region (Cassiolato, Lastres, and Maciel 2003). This fact can be noticed in both the description of the poor innovation performance of the Colombian industry and the research conclusions attained by Robledo, pointing to the Colombian industry's disregard of R&D as a mechanism required for innovation.

Furthermore, we consider that the description, as it is given down by Robledo, remains to be explained and diffused among researchers and decision makers in order to comply with his attempt to build on the discussion about innovation and to support policy design. As Robledo (1997, 344) states "for the transformation of the Colombian industrial innovation system to succeed, the complexity of the process of innovation must be explicitly and openly recognised and properly dealt with."

If the purposive commitment of resources by every actor making up the system of innovation is the only way to break the vicious cycle in which the innovation system is trapped into, then it is crucial to ease the comprehension of the role that every actor has to play in the system. Robledo's research indicate that the GIs, HEIs and industrialists misperceive the fact that by developing innovation related capabilities they support the accumulation of those capabilities at each other agent. Likewise, if one actor fails to develop its capabilities, the technological efforts made by others actors are futile.

Robledo concludes that HEIs and the government play a critical role in the innovation process, by helping industrialist to make the accumulation of capabilities possible and successful.

Although Robledo conducted an empirical research based on data from a representative sample of firms in the Colombian capital goods industry, his research is not conclusive. In addition, the data given by Robledo (1997) is not a sufficiently complete basis for translating his research findings into a system dynamics model, nonetheless, with the aid of theory and other types of data, it is possible to address his research using the system dynamics method and to fill in the gaps between the statements he makes and the structural relationships.

Translation into the System Dynamics language

We identified in Robledo's research statements describing constructs –variables- using the method developed by Sastry (1997) in order to formalize a theory into a model. We have collected into categories those statements that appeared to refer to the same construct, and analyzed statements describing relationships between the constructs.

Tables 2, 3, 4, and 5 summarize the variables that constitute the guiding posts for constructing the causal framework of the model. We have four categories: construct, definition, structure/relationship, and dynamic behaviour. The construct refers to the identified variable, for which it is important to track its behaviour. The definition is an explanation of the construct as it is set out by Robledo. In the structure/relationship category, a description of how one variable influences another is given. Finally, the dynamic behaviour describes the pattern of evolution over time of the identified variable. There are no clear relationships or behaviour patterns for all the variables that were included in the model.

Table 2

Robledo's description of capability

Category	Example*
Construct	Capabilities
Definition	"Capabilities are accumulated in industrial, education and government organizations…the basic nature of these capabilities is the same, in the sense that they are comprised of knowledge, skills, and internal and external relationships" (R: 223-224).
Structure / Relationship	"through interactive learning, then organizations augment or renew their stock of capabilities" (R: 224).
Dynamic Behaviour	"learning is a cumulative development process (R: 81)…as a result innovation capabilities are accumulated"…"it may give rise to a virtuous circle of accumulation of capabilities…or to a vicious circle where the accumulation of capabilities stops at a certain level" (R: 82).

* R refers to Robledo (1997).

Table 2 shows Robledo's description of the concept of capability, which is common to the specific capabilities accumulated at the actors making up the system of innovation –industrialist, HEIs and GIs.

Table 3 summarizes the main statements that Robledo uses to define the policy-design capability accumulated at GIs. According to the general definition of capability given in table 2, the GIs' policy-design capability is developed through interactive learning. In table 3, it is shown that the development of this capability depends on the strength of the link between GIs and both HEIs and the firm. If either HEIs or firms do not commit resources to building their technological capabilities, they do not support GIs to build its policy-design capability and as a result GIs fail to promote science and technology activities.

Table 3
Robledo's description of the GIs' policy-design capability

Category	Example*
Construct	GIs' Policy-Design Capability
Definition	"Government institutions should accumulate capabilities for efficient policy making" (R: 224).
Structure / Relationship	"efficient and effective policies are likely to emerge only from a very well informed policy-making process, which in turn requires continuous support from the HEIs in the form of provision of advanced knowledge and skills" (R: 224)...""firms have also failed to recognise the relevance of innovation, which has preventing them from interacting with the government in such a way that policies are questioned and a learning process takes place within the government itself" (R: 225).
Dynamic Behaviour	"lacking adequate policy-making capabilities, the Colombian government has never considered the accumulation of innovation capabilities a requirement of industrialization which deserves to be addressed by public policies" (R: 225).

* R refers to Robledo (1997).

Table 4 illustrates the description of the research capability accumulated at HEIs. The development of this capability depends on both the aid of the policies designed by the government and the strength of the link between HEIs and the firm. If HEIs do not perceive the policies from the government as efficient incentives to both carry out R&D activities and offer advanced training, HEIs are not willing to invest in R&D and as a result will not build their research capability. Likewise, if firms do neither allocate resources to R&D nor demand HEIs support, HEIs are unable to consolidate their research capability.

Robledo reports an evident lack of long term strategic thinking and action towards the creation of research capability in the Colombian HEIs, and he also found out that just 5 out of the 36 firms in his sample, reported to have been engaged in joint R&D projects with HEIs.

Table 4

Robledo's description of the HEIs' research capability

Category	Example*
Construct	HEIs' Research Capability
Definition	"HEIs should accumulate capabilities for research and advanced training" (R: 224).
Structure / Relationship	"[capabilities] are accumulated in HEIs through supportive policies from the government" (R: 224)…"HEIs do not accumulate research capabilities because they are not demanded by the productive sectors" (R: 273).
Dynamic Behaviour	"to the extent that [capabilities] have not been accumulated sufficiently…academic-industrial linkages are weak and fail to produce successful interactions which otherwise would lead to a cumulative development of the learning process" (R: 225)…"there are not allocated enough resources for carrying out research activities that, eventually, would consolidate…research groups" (R: 264).

* R refers to Robledo (1997).

Table 5 contains the description of the firm's innovation capability. It could be noticed by reading through tables 3, 4, and 5 that the evolution of each capability is related to each other.

The innovation capability refers to the skills necessary to support the product development process. Nonetheless, as Robledo explains, the Colombian capital goods industry associates innovation capability with skills necessary to adapt new technology to the production process. This belief is the result of the perception of innovation as a by-product of investments in production capacity; Robledo states:

> “Innovation is a euphemism for some sort of learning by doing change or, at most, for inexpensive or short-term profitable investment in new equipment or organizational practices.... It is necessary to achieve some degree of efficiency.” (Robledo 1997, 242)

Table 5

Robledo’s description of the firm’s innovation capability

Category	Example*
Construct	Firm's innovation capability
Definition	"[capability] needed to develop more advanced and complex product and processes" (R: 255)..."if some kind of technological capability is needed, it is the sort of capability required to adapt and improve the use of the technology employed in the productive process" (R: 240).
Structure / Relationship	“supposedly automatic and costless by-product of the first [production capacity] (R: 238)...Colombian industrial firms did not accumulate innovation capabilities... principally because innovation itself was not perceived as a valid pathway towards industrial development" (R: 250).
Dynamic Behaviour	"where firms lack such capabilities...it is impossible for them, or otherwise fruitless, to establish collaborative relationships with academic institutions and other firms" (R: 273)..."academic-industrial linkages are weak and fail to produce successful interactions which otherwise would lead to a cumulative development of the learning process" (R: 225)

* R refers to Robledo (1997).

The firm does not perceive R&D as a strategic development alternative since it perceives the policies from the government as ineffective incentives to carry out R&D activities. Likewise, the firm perceives that HEIs lack the capabilities necessary to offer research collaboration. As a result, the firm does not allocate resources to R&D and is unable to develop its innovation capability beyond the level it attains by merely adapting new technology to the production process.

To complement the statements included in table 5, Robledo also reports that firms do not make important efforts to create any organizational capacity for learning and skill acquisition (refer to the concept of absorptive capacity that is given in chapter 3) required for using the knowledge generated outside their organisations. In fact, one third of the firms in his survey reported that the product and process development was said explicitly to be carried out under senior management leadership, by integrating ad-hoc project teams comprised of personnel from production-oriented functions.

This early stage of the model building uncovered insights into Robledo's research; for instance, as we will discuss in detail in chapter 5, Robledo refers indistinctly to two different patterns of behaviour when he describes the vicious cycle dominating the accumulation of capabilities within the agents making up the system of innovation. Moreover, he does not define a clear time horizon for the perception of the problem. This time frame is crucial for the problem assessment and analysis.

The description of the problem contains many additional variables such as labour competence, marketing capability, absorptive capacity and product quality, which are also central to formalization of the causal theory as it is reported by Robledo. These variables make part of the dynamics governing the innovation process. However, Robledo does not describe in detail these variables so as to make a clear analysis of them as the one done for the variables represented in tables 2 to 4. Hence, as we illustrate in the next chapter, we draw on theory to formalize these variables and the causal relationships that they are part of into equations. To finish off, the analysis represented in tables 2 to 4 will be used for the definition of the dynamic hypothesis and the formulation of the model, the next steps in the formalization of Robledo's research.

CHAPTER 3
Formalizing the Innovation Process

Introduction

In chapter 2 we pointed out that, given both the paradigm influencing decisions regarding innovation and the structure governing the system of innovation, the learning capabilities of the Colombian firms are seriously impaired, and so are the possibilities for these firms to respond successfully to an increasingly changing and demanding environment (Robledo 1997, 222). In this chapter we pursuit our aim to translate Robledo's findings into a formal model.

We offer a dynamic hypothesis accounting for the problematic behaviour reported in this thesis. Then we make a description of the model built as well as the assumptions made to fill in the gaps between the evidence supporting this research and the model formulation we developed.

The dynamic hypothesis

The outcome of the modelling process is a dynamic hypothesis in which there is a degree of confidence that it represents the structure and observed behaviour of the problem situation (Oliva 2003, 553). The dynamic hypothesis makes a causal claim between structure and behaviour.

In dealing with the low level of innovation capabilities accumulated by the Colombian industrial innovation system and hence its poor innovation performance, Robledo (1997, 222) argues:

> [...] the Colombian capital goods innovation system is caught in a complex sequence of vicious circles that inhibit the development and accumulation of innovation capabilities, whose path-defining mechanism is a dominant

> innovation paradigm that acts forcefully at the level of the awareness and decision making processes, preventing organisations from accumulating innovation-related capabilities.

In what follows we propose a dynamic hypothesis (or conceptual model) accounting for this problematic behaviour. The formulation of this hypothesis is our second step to asses whether the dynamics that Robledo describes can be produced by the causal factors he postulates as the origin of the problem.

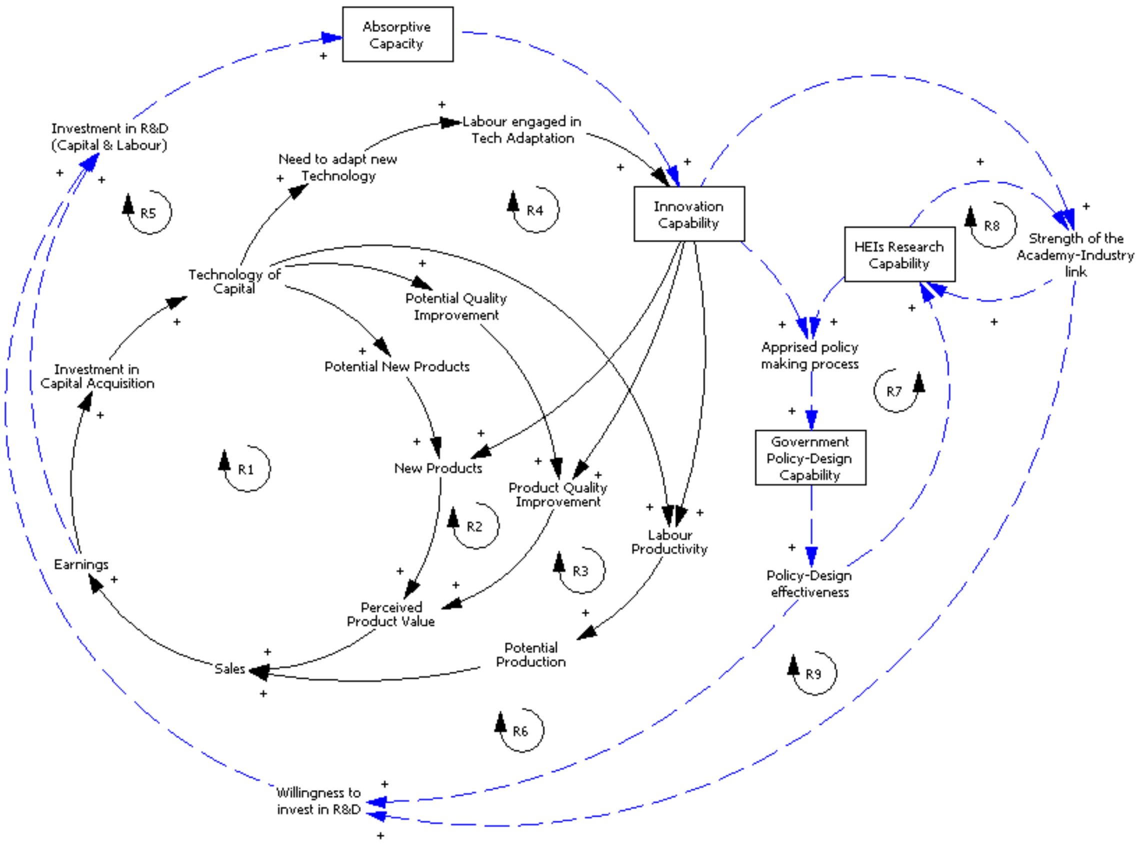
The dynamic hypothesis depicted as causal loop diagram is shown in Figure 5. As it was explained in chapter 1 (page 16), the dynamic hypothesis basically addresses the effect that the paradigm exerts on the development of the firm's innovative capabilities and the innovation process[8]. It also includes the influence exerted by the interaction between the firm and government institutions (GIs), and between Higher Education Institutions (HEIs) and GIs, on the rate and direction of the development of innovative capabilities within the firm.

We assume a firm invests in production capacity for two reasons; 1. to expand its current capacity; and 2. to replace the capital scrapped. Regardless of the reason, when the firm acquires new capital, the technology embedded in that capital has a higher technology level compared to the one existing in the current stock. As indicated by Robledo (1997), firms within the Colombian capital goods industry see innovation as a by-product and cost-less benefit of their investments in production capacity.

[8] The firm's innovative capability comprises knowledge, skills and internal and external relationships need to develop more advanced and complex products. This concept will be explained in detail in the next sections.

Figure 5

The dynamic hypothesis



Beginning with loops R1 and R2, new capital with a higher technology level, once it has been adapted to the product development process, gives the firm the possibility to develop new products or to improve the quality of its current products. Thus as more new products or quality improved products are launched into the market, the product value perceived by the customer increases. The higher the perceived product value, the greater are sales and, as a result, the more the earnings will be. The higher the earnings, the more future investments can be made. Thus closing the new product development loop R1 and the product quality improvement loop R2. Besides the effect of the technology level on the product development and quality, the technology embedded in the capital also affects the labour productivity. The higher the labour productivity, the greater is the production capacity of the firm and, as a result, the higher the sales may be. The higher the sales, the more earnings and more investments will be made in production capacity, thus closing the loop R3.

As mentioned before, firms within the Colombian capital good industry believe they can use technology as a mean to innovate. Robledo reports that firms allocate personnel from production oriented functions to the product development process in order to improve the firm's innovation capability, i. e. 1. to build the capability necessary to adapt technology to the production process; and 2. to gain the knowledge required to materialize the potential new products and quality improvements that, in the end, will increase the firm's earnings and hence the investments in production capacity (loop R4). Robledo claims that the innovation capability gained by moving personnel from production to the technology adaptation task is not sufficient to realize 1 and 2 above. Moreover, production tends to concentrate the attention of the team members to the detriment of product development. Also, the innovation process demands specific skills that are different from those required for production. It follows that direct investments in research and development (R&D) are needed in order to recognize the value of new, external information, assimilate it, and apply it to commercial ends. The greater the resources allocated to R&D, the greater is the knowledge absorption capacity of the firm and the higher its innovation capability. This enables the firm to translate potential innovation into real outcomes, thus closing the loop R5.

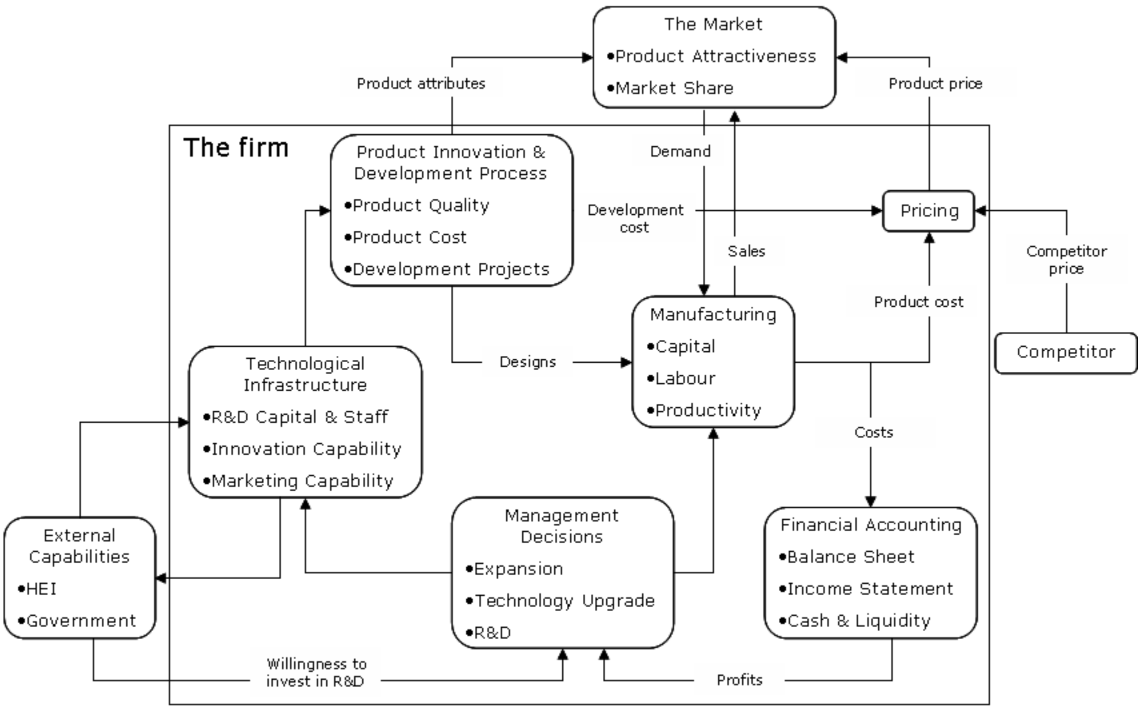
Higher Education Institutions (HEIs) and Government Institutions (GIs) significantly influence the firm's willingness to invest in R&D, according to the study done by Robledo. If the firm recognizes the relevance of innovation and invests in R&D in order to accumulate innovative capabilities, then it will be able to interact with the government in such a way that public policies regarding science and technology are questioned, and as a result, the government has the opportunity to improve upon his policy-design task; in other words, a learning process will take place within the government itself. The higher the innovation capability of the firm is, the stronger are the industry-government linkages. This may lead the government to improve its ability to design policies that encourage science and technology activities, thus increasing the firm's willingness to invest in R&D (loop R6). Likewise, the more effective the policy-design process is, the more the research (and training) capabilities accumulate in HEIs. This, in turn, support the policy design process by providing advanced knowledge and skills to the GIs, thus increasing the government policy design capability (loop R7).

Assuming that research and advanced training capabilities are accumulated sufficiently in HEIs, the academic-industrial linkages will be strong and they will succeed in their interactions, leading to a more intensive development of research capabilities at HEIs (R8). Assuming that innovative capabilities are accumulated sufficiently within industrial firms, and that the academy-industry linkages will be strong so that they succeed in their interactions, then this will encourage the firm to carry out direct investments in R&D (R9).

The dynamic hypothesis help us to understand that if firms fail to recognize the importance of investments in R&D and actually commit to such investments, they fail as well to develop the knowledge and skills needed in order to: 1. innovate; 2. support the government in its science and technology policy design process; and 3. interact with the academia in such a way that the firm will at the same time benefit from the knowledge developed at HEIs, and foster the learning process taking place at HEIs. Moreover, the capabilities accumulated within the HEIs and GIs affect the firm willingness to invest in R&D next time around. This circular set of causalities have been characterized by Robledo as a Gordian knot involving several reinforcing loops (denoted by the dash lines) that might lead to a pattern of behaviour in the form of virtuous or vicious cycle.

The causal loop diagram portraying the dynamic hypothesis help us understand how the variables are related. In figure 6 we illustrate the overall architecture of the model that is intended to materialize the hypothesis. Each major subsystem is represented along with the flows of goods and/or information coupling the subsystems with one another. For instance, the product innovation and development process subsystem accounts for the flow of projects from the potential product stage until the market release stage, when products are launched into the market place. Throughout this process, both product quality and development cost are dealt with. The output of this subsystem is the product launched and ready to be manufactured. Products have quality attributes that the market uses to asses the product value and that thus determine the product demand. In the next section the subsystems central to this thesis are described in detail; the remaining subsystems will be explained more briefly since their formulation is based on system dynamics common knowledge. These subsystems are documented in the model accompanying this thesis report.

Figure 6
Model overview



The model boundary

Table 6 include the very key endogenous and exogenous variables of the model along with those excluded. The model is documented in more detail in the next sections. The time horizon is 30 years and represents the average life of the companies of the capital goods industry (Durán, Salazar and Ibañez 2000). The time horizon enables us to capture the lengthy development of capabilities within each agent of the innovation system.

It is worth mentioning that in a different context, some exogenous variables might be considered endogenous variables; in the case of market size and competitor price, we consider that feedback most likely to be small since the firm we modelled does not play a dominant role in the market place and its competitive strategy is mainly based on the product differentiation. With regard to the tax rate and the loan interest rate, there is a feedback loop from the policy design at government institutions affecting those variables. However, to incorporate these dynamics is beyond the scope this thesis.

Table 6
Model boundary chart

Endogenous	**Exogenous**	**Excluded**
Product Innovation	Extramural knowledge	Process Innovation
Firm's capability for innovation	Technology cost	Firm's capability for investment assessment
Firm's capability for the establishment of links with the customers	Labour costs	Firm's capability for the establishment of links with suppliers and competitors
HEIs' research and training capability	Competitor price	Inventories
Government Institutions' policy-making capability	Market demand	
Product Price, Cost & Quality	Tax rate	
Product's market share	Loan Interest rate	
Capital & Technology Level		
Labour Force & Competence		

The reference mode

In order to contribute to the understanding of the poor innovation performance of the Colombian industry, our main objective is to asses whether the dynamics that Robledo describes can be produced by the causalities, i.e. causal relationships, which he postulates. Thus, as a reference mode we quote the following assertion:

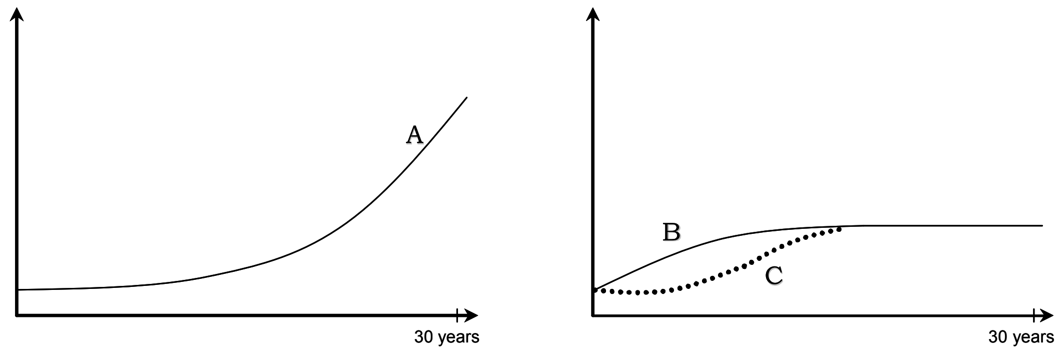
> [...] we suggest that the dynamics of the learning processes in industrial innovation systems may give rise to a virtuous circle of accumulation of capabilities if the right conditions are given. Conversely, if these conditions are not fulfilled, it is more likely that the industrial innovation system is caught in a vicious circle where the accumulation of capabilities stops at a certain level (Robledo 1997, 82).

As we will describe, the accumulation of capabilities for innovation is critical for the firms to accumulate other asset stocks such as products, product's quality and customers. Hence, innovative capabilities play a key role in the development of capabilities within HEIs and government institutions whose actions affect the firm's awareness of R&D investments as a strategic path of development.

Even though Robledo does not give a graphical representation of this reference mode, the phrase "virtuous circle" clearly suggests an exponential growth of capabilities, represented by the line A in figure 7. The phrase "vicious circle where the accumulation of capabilities stops at a certain level" suggests either a goal seeking (line B in figure 7) or an S-shaped behaviour (line C in figure 7), as stated by Robledo.

Figure 7

Reference mode



The model

The innovation process represents the confluence of technological capabilities and market needs within the framework of the innovating firm.

Roy Rothwell, 1992, 222

In general, the model we develop will constitute a transparent description of the causal theory described by Robledo (1997). By way of simulation, the model will enable us to generate a set of specific behaviour pattern overtime that allows us to investigate how well the theory accounts for the phenomena its author sets out to explain.

In what follows, we formalize the conceptual model described above by presenting the causalities that constitute the model structure as postulated by Robledo, along with the literature used to complement the formalization when this is required. The core of the model is the interplay between the firm's technological infrastructure and the product innovation and development process; these subsystems are highly dependant on the investment decision regarding research and development (R&D) made by firms. In this model the technological infrastructure and the product innovation and development process have been are integrated with generic system dynamics modules representing production and market.

The firm's technological infrastructure

Innovation involves processes of learning either through experimentation (trial and error) or through improved understanding (theory). Some, but not all, of this learning is firm specific (Pavitt 2003, 9). Such learning processes form the cumulatively augmented abilities and skills developed within the firm or, to be consistent with the literature on innovation, such learning processes form the innovative technological capabilities of the firm. These capabilities cannot be bought and sold; it does not imply that such skills are entirely immobile, they just cannot be entirely diffused either in the form of public or proprietary information (Dosi 1988, 1131).

Usually learning takes place through the reutilization of activities (learning-by-doing), but also because of the interactive relations established between the firm and its customers, suppliers or research institutions (learning-by-interacting) (López-Martinez and Piccaluga 2000, 59). A firm can develop several capabilities as a consequence of its innovation activity. Lall (1992) describes the technological capabilities as those capabilities necessary for the firm to survive in the market place and those capabilities developed as a function of the level of complexity of the activities performed by the firm. Lall (1992) classifies the technological capabilities in three groups: capabilities required to assess investment, capabilities required to produce and capabilities required to establish links with external agents. The production capabilities determine how good the firm is in absorbing technologies acquired or copied, and in using or improving such technologies. The linkage capabilities are necessary for acquire information, capabilities and technology from external agents such as suppliers, customers, research institutions and competitors.

According to Teece, Pisano and Shuen (1990), the competitive advantage of a particular enterprise is a function of its underlying core competences or capabilities, and its relationship with customers and suppliers. Warren (2002, 208; emphasis added) describes capabilities as "the effectiveness with which people and groups in the organization or its wider networks of collaborators achieve tasks that **are critical to accumulating other asset stocks** [...] they are clearly important contributors to performance over time, so some attempt must be made to grapple with them".

In this respect Robledo (1997) asserts that innovation capabilities are firm specific, specialized and differentiated in a wide range of functions (77); they play a key role in the awareness and decision making function of the firm and in the implementation process giving place to innovation and/or production activities. There are three kinds of capabilities that are accumulated within the innovation system (1997, 223-24; emphasis added):

> Capabilities are accumulated within industrial firms, HEIs and government organizations through cumulative development processes (learning processes) which depend critically on the interactions between the actors involved [...] firms should accumulate innovation capabilities which enable them to respond successfully to changes in the competitive environment. HEIs should accumulate capabilities for research and advanced training, while government institutions should accumulate capabilities for efficient policy-making. Nevertheless, **the basic nature of these capabilities is the same**, in the sense that they are comprised of knowledge, skills, and internal and external relationships.

Robledo regards capabilities as critical resources for the decision making process regarding innovation and for the implementation of decisions. We will explain, in what follows, how capabilities are built and the relationship between capabilities and the innovation development process.

In the model, we define a technological infrastructure that comprises both the in-house innovation capability and the marketing capability; these capabilities evolve (respectively) as a result of the firm's investments in: 1. research and development, and 2. customer relationships. These capabilities determine the firm's product development, manufacturing process and products' quality improvement.

In particular, the development of the capital goods sector requires the production of goods of increasing complexity, with a corresponding build-up of technological capacity in terms of machine-operating skills, manufacturing technology, product design, and research and development capabilities. In fact, it has been found that the differences observed among firms –within the capital goods industry- are not due to capital endowments but to capability endowments.

- The innovation capability

The innovation capability we model accounts for both product design capacity and research and development capacity. Product design capability is the ability to conceptualize, define and actually design a product that is acceptable to the market on both economic and technical grounds (UN 1985, 8). Research and development capability in the capital goods industries emphasizes, in most cases, the development work aimed at finding appropriate combinations of some extensions of already existing technical knowledge, with its scope closely bound by commercial feasibility (UN 1985, 9).

In the formulation of the *innovation capability* we apply two concepts postulated by Cohen and Levinthal (1989, 1990): the firm's stock of technical and scientific knowledge and the absorptive capacity; these concepts are frequently cited in the literature concerning technological change. As indicated by Cohen and Levinthal, the absorptive capacity is firm-specific and therefore cannot be brought and quickly integrated into the firm (1990, 135). This capacity refers not only to the acquisition or assimilation of information by an organization but also to the organization's ability to exploit it. It represents a sort of learning different from the concept of “learning by doing”:

> […] learning by doing typically refers to the automatic process by which the firm becomes more practiced, and, hence, more efficient at doing what it is already doing. In contrast, with absorptive capacity a firm may acquire outside knowledge that will permit it to do something quite different (1989, 570).

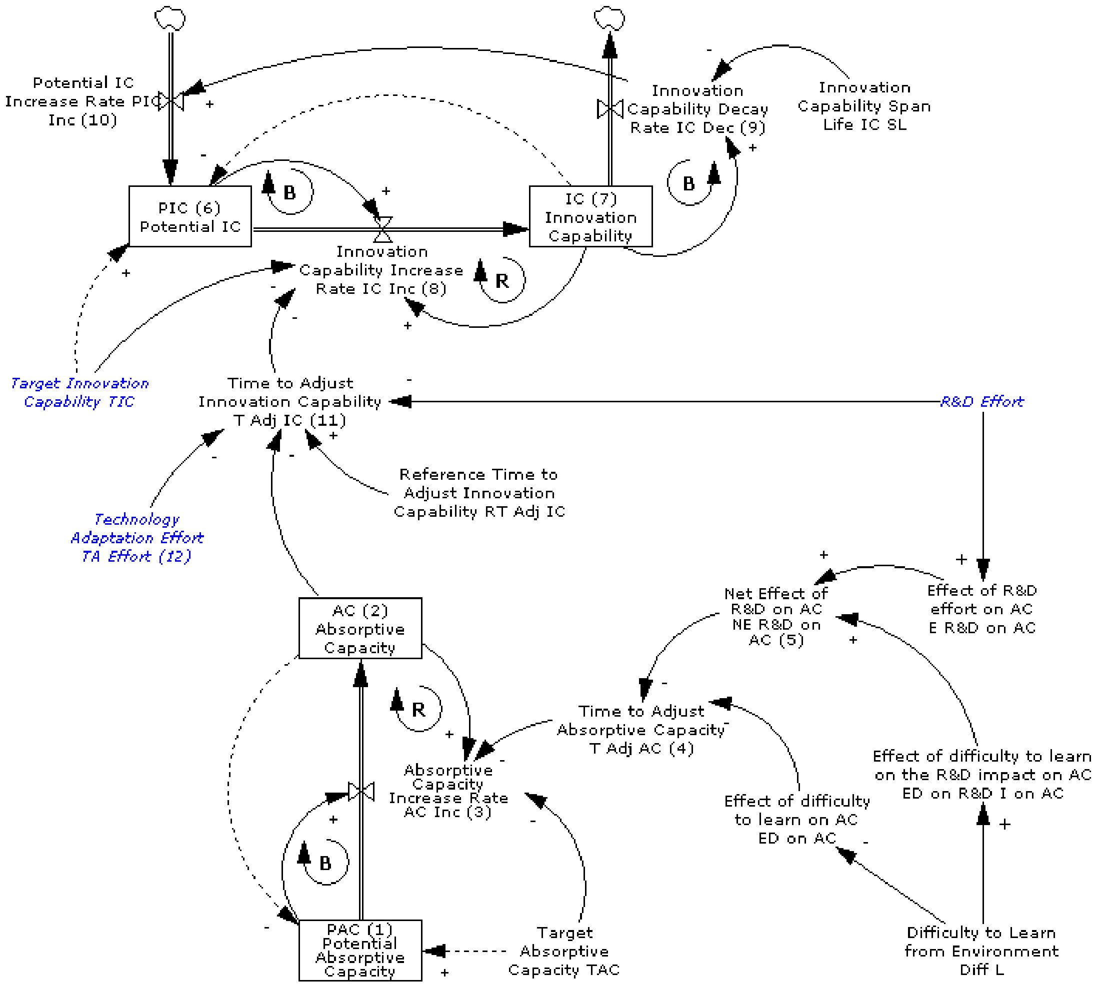
The formulation of the firm’s stock of technical and scientific knowledge, given by Cohen and Levinthal, is insightful since it establishes that the firm can neither assimilate what is not spilled out by other firms and research organizations nor can it passively assimilate externally available knowledge. The firm must invest in its own research and development (R&D) in order to absorb any of the R&D output of its competitors and the knowledge generated in the government institutions and universities. However, the formulation does not reflect that the knowledge absorbed by the firm from the environment cannot increase indefinitely, nor it considers the depletion of the stock. In addition, the formulation does not reflect the learning attribute of the absorptive capacity, which causes the absorptive capacity to accumulate.

In reality, the knowledge gain is constrained by the gap between the firm’s own stock of knowledge and the extramural knowledge. The stock of knowledge can decrease by knowledge loss. The accumulation of absorptive capacity facilitates subsequent development of absorptive capacity. We address these drawbacks by the formulation of the firm’s stock of technical and scientific knowledge that we use in this thesis.

The formulation of the *innovation capability* depicted as a stock and flow diagram is shown in figure 8 along with the variable name abbreviations and their equation numbers; the variables shown in *italics* are determined in other sectors of the model. Capabilities are stocks; they can either be accumulated or depleted over time. The *innovation capability* represents the stock of knowledge defined by Cohen and Levinthal (1989) and comprises the technological capacity required by the capital goods industry in order to support the product development process. There are three mechanisms used to accelerate the development of the innovation capability: the absorptive capacity, the R&D effort and the technology adaptation effort. In order to account for the learning and loss processes, both the inflow and the outflow of the capability depend on the current level of the capability itself. This formulation is consistent with the formulation of capabilities proposed by Warren (2002, chapter 9).

Figure 8

The innovation capability



The equations used for the formulation of the absorptive capacity are:

$$\text{PAC} = \textit{Integral}\,(-\ \text{AC Inc},\ \text{TAC} - \text{AC}_0) \qquad [1]$$

$$\text{AC} = \textit{Integral}\,(\text{AC Inc},\ \text{AC}_0) \qquad [2]$$

$$\text{AC Inc} = \text{PAC}^*(\text{AC}/\text{TAC})/\text{T Adj AC} \qquad [3]$$

T Adj AC = Ref T Adj AC / (NE R&D on AC * ED on AC) [4]

NE R&D on AC = E R&D on AC * ED on R&D I on AC [5]

ED on AC = *f* (Diff L)

E R&D on AC = *f* (R&D Effort)

ED on R&D Impact on AC = *f* (Diff L)

The formulation of the AC entails the definition of two stocks (figure 8): the stock of potential absorptive capacity (PAC) and the stock of absorptive capacity (AC). The PAC represents the amount of AC that is potentially exploitable by the firm. The AC represents the level of AC already acquired by the firm. Two loops can be identified in the formulation of the AC. The reinforcing learning loop and the balancing depletion loop. AC is developed as long as the firm has AC that facilitates the subsequent development of AC (reinforcing loop) and only if there is PAC to be transformed into AC. At the same time that this process takes place the PAC is depleted (balancing loop). This interaction between the PAC and the AC is formalized into the formulation of the absorptive capacity increase rate (equation 3).

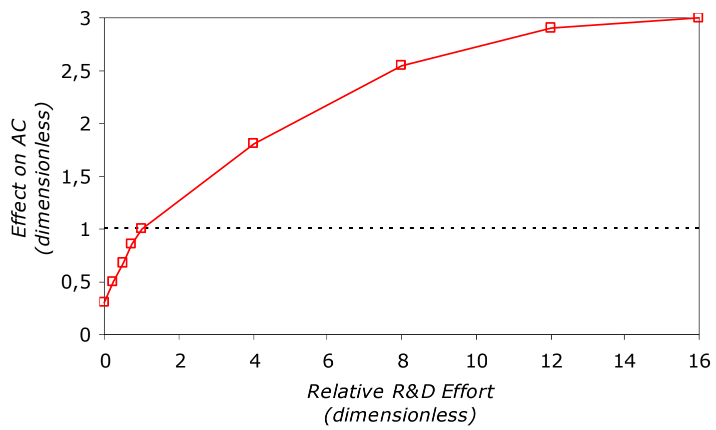
Since the AC is a measure of the firm's efficiency to absorb new knowledge, the AC takes values between 0 and 1. The formulation of the AC described so far captures its most fundamental characteristic: knowledge facilitates subsequent development of AC. As already mentioned, this formulation of the AC is not explicit in the formulation made by Cohen and Levinthal (1989).

In addition, the absorptive capacity (AC), as indicated by Cohen and Levinthal (1989), is a function of two variables: the firm's R&D effort and the difficulty to learn from the environment. These variables affect the pace at which the PAC is transformed into AC; hence the AC approaches the target absorptive capacity (TAC). We explain these variables in what follows:

- The firm's R&D Effort, represents the firm's own investments in R&D weighted by its revenues. The R&D Effort indirectly increases absorptive capacity, though at a decreasing rate. The higher the R&D Effort is, the less time that the firm will need to adjust its AC to the TAC (equation 4). In figure 8 this effect is represented by the variable named E R&D on AC. The table function for this effect is shown in figure 9. This function is normalized around the reference R&D effort.

Figure 9

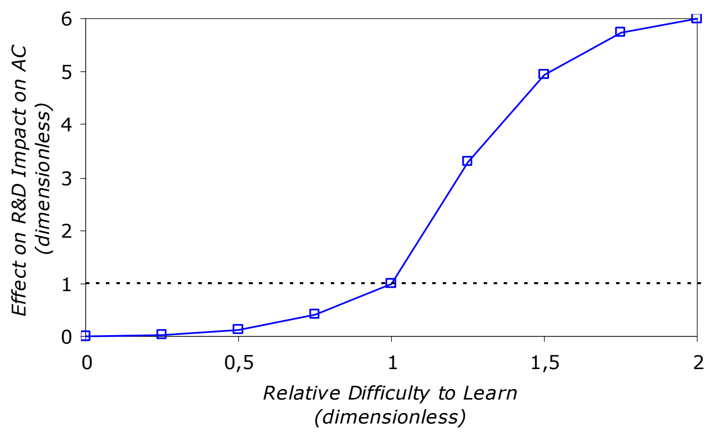
Effect of R&D effort on absorptive capacity



- The difficulty to learn from the environment (Diff L) includes the complexity of the knowledge to be assimilated, and the degree to which the outside knowledge matches the needs of the firm. This variable affects indirectly the AC in two ways.

Figure 10

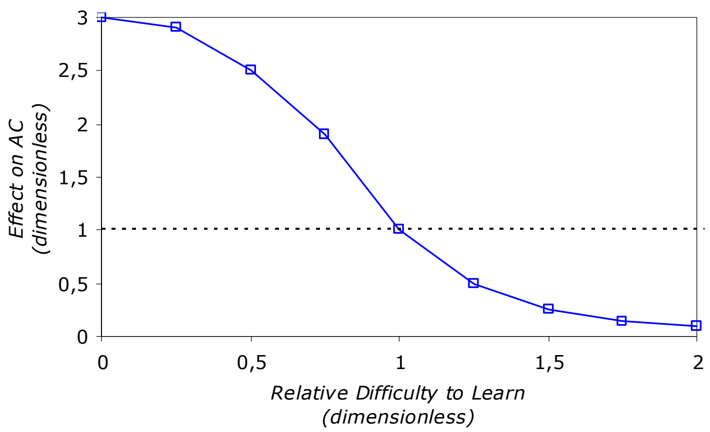
Effect of the difficulty to learn on R&D impact on absorptive capacity



First, the greater the difficulty to learn from the environment, the more significant is the marginal impact of the firm's own R&D on absorptive capacity. In other words, the firm's own R&D is more critical to the maintenance and development of the absorptive capacity. This effect is formulated in the variable ED on R&D Impact in AC, and affects the time that the firm needs to adjust its AC to the TAC (equation 4). The table function for this effect is represented in figure 10. Second, the greater the difficulty to learn from the environment is, the less external knowledge will the firm assimilate for a given R&D effort. This effect is formulated in the variable ED on AC, and affects also the time that the firm needs to adjust its AC to the TAC (equation 4). The table function for this effect is shown in figure 11. The functions represented in figures 10 and 11 are normalized around the reference difficulty to learn from the environment.

Figure 11

Effect of the difficulty to learn on absorptive capacity



The equations used for the formulation of the innovation capability's are:

PIC = *Integral* (PIC Inc – IC Inc, TIC –IC_0) [6]

IC = *Integral* (IC Inc – IC Dec, IC_0) [7]

IC Inc = PIC*(IC/TIC)/T Adj IC [8]

IC Dec = IC/IC SL [9]

PIC Inc = IC Dec [10]

T Adj IC = Ref T Adj IC/(AC + TA Effort + R&D Effort) [11]

PP Effort = TSTA/LF [12]

Like in the formulation of the absorptive capacity, the formulation of the innovation capability entails the definition of two stocks (figure 8): the stock of potential innovation capability (PIC) and the stock of innovation capability (IC). The PIC represents the amount of capability that the firm is potentially able to acquire. The IC represents the level of IC already accumulated by the firm. Three loops can be identified in the formulation of the IC. The reinforcing learning loop governing the acquisition of IC, and two balancing loops: one regulating the depletion of the PIC and the other regulating the loss of IC. The firm's IC is developed as long as the firm has a little IC that facilitates the subsequent development of IC (reinforcing loop) and only if there is PIC to be transformed into IC. At the same time that this process is taking place the PIC is being depleted (balancing loop). This interaction between the PIC and the IC is formalized into the definition of the innovation capability increase rate (equation 8).

It is possible that the IC of the firm decays. There is a loss of IC as technology and knowledge evolve overtime and render the IC of the firm obsolete. The IC decay rate is given by a first order delay; the IC decay is proportional to the stock of IC (equation 9). The loss of IC increases the gap between the firm's IC and the target IC. The gap represents space for further development of the firm's IC. As a result, the loss increases the potential innovation capability (equation 10).

The absorptive capacity, the R&D effort and the technology adaptation effort determine the pace at which the potential innovation capability (PIC) is transformed into innovation capability (IC); the higher these efforts are, the less time the firm will need to acquire IC (equation 11). Hence the IC approaches the target innovation capability (TIC).

The technology adaptation effort accounts for the belief, present in the Colombian capital goods industry, that innovation is a by product of investments in production capacity (see chapter 2, p.42-43). As indicated by Robledo, **when there is no formal R&D function within the firm**, the general practice is to allocate personnel from production oriented functions to the product development. This general practice does not seem to be successful among the firms that Robledo studied in his survey, since production itself tended to concentrate the attention of the team members to the detriment of product and process development and because the process demands specific skills and learning, different from those required for production (Robledo 1997, p.243-44). The technology adaptation effort represents the fraction of time that the employees spend in the product development process. This fraction is given by the ratio between the time spend in technology adaptation and the total labour force (both variables are measured in persons, equation 12). We model this third mechanism with the aim to represent the current practice in the Colombian capital goods industry, and to observe the development of the innovation capability when the firm does not invest in R&D and relies on the commitment of personnel from production to adaptation of technology as the only mechanism to build up its innovation capability.

- The marketing capability

The other capability included in the technological infrastructure module is the *marketing capability* which accounts for the firm's ability to establish links with the customer. It is worth mentioning that in the capital goods industry customers can play a key role in invention and early innovation (Dilmus 1991, 980). Rothwell (1992, 226, emphasis added) explains this as follows:

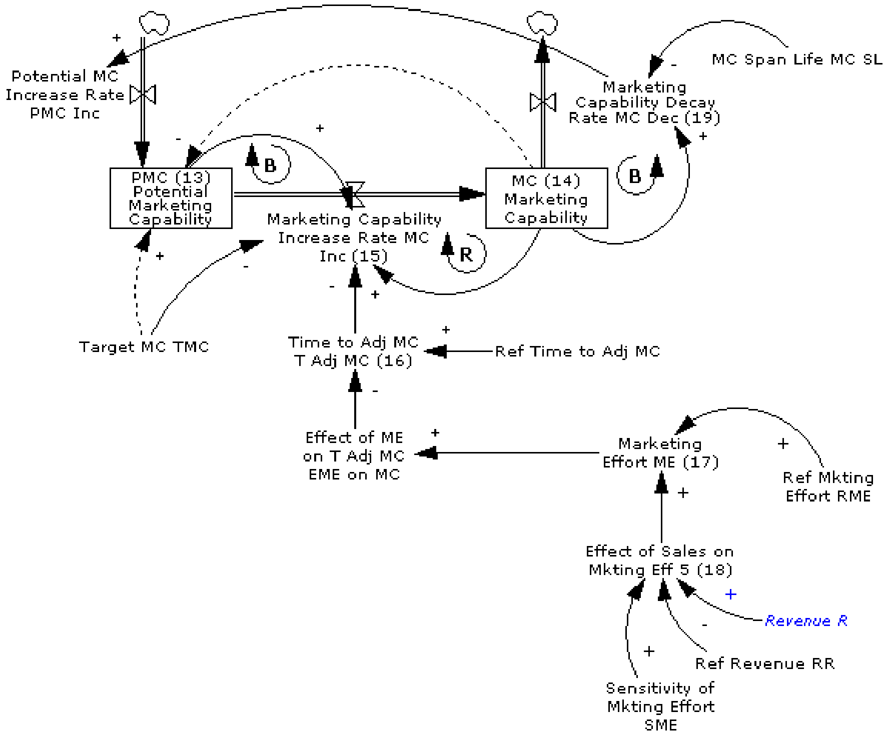
> In such markets, the role of marketing is to scan the market place in order to identify new and evolving customer requirements as a basis for initiating new product developments or modifications to existing products. **The customer is employed as an integral part of the development process.**

The equations used in the formulation of the marketing capability are:

PMC = Integral (PMC Inc – MC Inc, TMC-MC_0)	[13]
MC = Integral (MC Inc – MC Dec, MC_0)	[14]
MC Inc = PMC*(MC/TMC)/T Adj MC	[15]
T Adj MC = Ref T Adj MC/E ME on MC	[16]
E ME on MC = f (ME)	
ME = RME*E S on ME	[17]
E S on ME = (R/RR)^SME	[18]
MC Dec = MC/MC SL	[19]

The formulation of the *marketing capability* depicted as a stock and flow diagram is shown in figure 12 along with the variable name abbreviations and their equation numbers. The formulation of the marketing capability entails the definition of two stocks: the stock of potential marketing capability (PMC) and the stock of marketing capability (MC). The PMC represents the amount of capability that the firm is potentially able to acquire. The MC represents the level of MC already accumulated by the firm.

Figure 12
The marketing capability

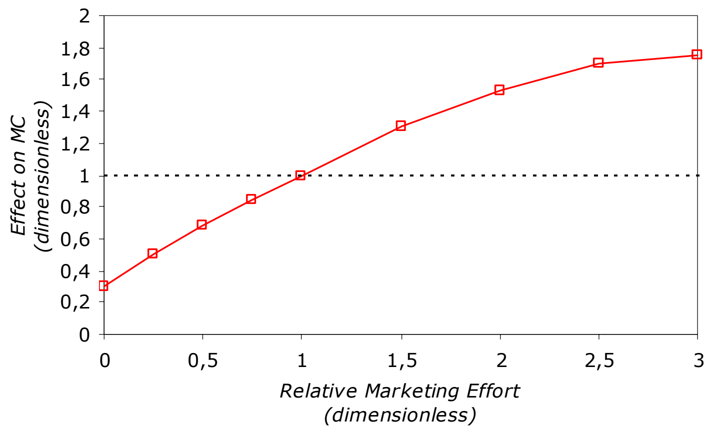


Three loops can be identified in the formulation of the MC: the reinforcing learning loop governing the acquisition of MC, and two balancing loops, one regulating the depletion of the PMC, and the other regulating the loss of MC. The firm's MC is developed as long as the firm has a little MC that facilitates the subsequent development of MC (reinforcing loop) and only if there is PMC to be transformed into MC. At the same time that this process is taking place the PMC is being depleted (balancing loop). This interaction between the PMC and the MC is formalized into the definition of the marketing capability increase rate (equation 15).

The firm's own marketing research endeavour, which is assessed by the ratio between the marketing research expenditure and the revenue, determines the pace at which the potential marketing capability (PMC) is transformed into marketing capability (MC); the higher the effort (EME on MC) is, the less time the firm will need to acquire MC (equation 16). The marketing effort affects the time to adjust the MC as described by the function represented in figure 13. This function is normalized around the reference MC.

Figure 13

Effect of marketing effort on marketing capability



The marketing effort accounts for firm's marketing research expenditure, which is one of the items in a firm's marketing budget and its aim is to yield information that allows the firm to identify and define market driven opportunities and problems. The marketing expenditure comprises the advertising expenditure, the marketing expenditure and the investments made to create customer relationships, as it is suggested by Dutta, Narasimhan and Rajiv (1999).

The formulation of the MC described thus far captures three fundamental characteristics: 1. the higher the firm's effort to gather information from the market, the greater is the ability to monitor customer needs; 2. prior skills facilitate subsequent development of capability; and 3. capabilities cannot be brought in and quickly integrated into the firm.

It is possible that the MC of the firm decays. There is a loss of MC as customer needs change overtime and render the MC of the firm obsolete. The MC decay rate is given by a first order delay; the MC decay is proportional to the stock of MC (equation 19). The loss of MC increases the gap between the firm's MC and the target MC. The gap represents space for further development of the firm's MC. As a result, the loss increases the potential marketing capability.

To sum up, the innovation capability and the marketing capability serve to enhance performance beyond the individual contribution of each of the individual capabilities (Griffin and Hauser 1996; Gatignon and Xuereb 1997). In the next section we show that the innovation capability and the marketing capability, described above, significantly influence the flow of product designs throughout the innovation and development process (Dutta, Narasimhan and Ibañez 1999). Moreover, the innovation capability affects the quality improvement of products and the adaptation of technology to the production process.

The innovation & development process

There are many definitions of technological innovation, and in this thesis we adopt the one proposed by Freeman (1974) and used by Rothwell (1992, 222-23), which describes innovation as follows:

> Innovation is a process which includes the technical, design, manufacturing, management and commercial activities involved in the marketing of a new (or improved) product or the first use of a new (or improved) manufacturing process.

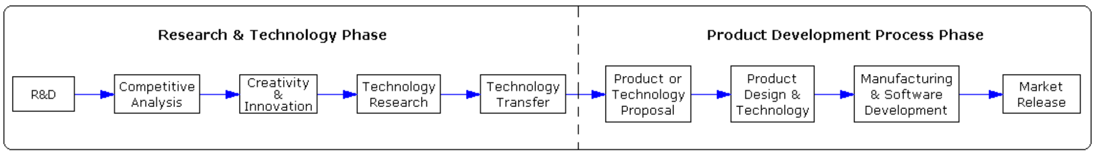
Innovation processes involve the exploration and exploitation of opportunities for a new or improved product, process or service, based either on an advance in technical practice, or a change in market demand, or a combination of the two; as Pavitt indicates it (2003), it is essentially a matching process[9]. Innovation is a techno-economic process by means of which firms increase their knowledge base to improve their operations,

[9] The classic paper on this subject is by Mowery and Rosenberg (1979).

processes, products or services. This new knowledge determines different types of benefits for the firms, the users of products and technologies, and the whole set of agents who participate in the process of innovation, and are reflected in economic terms in the last instance (López-Martinez and Piccaluga 2000, 2).

We want to call attention to three assumptions we made regarding the concept of technological innovation: 1. process innovation is excluded; 2. product innovation refers to the development of new products to the firm, which might not be new to the market; and 3. product innovation is possible thanks to the development of the firm's capabilities. In addition, the matching process between the supply and demand of innovations is indirectly addressed by means of the marketing capability which allows the firm to screen customer needs and translate them into the product innovation and development process.

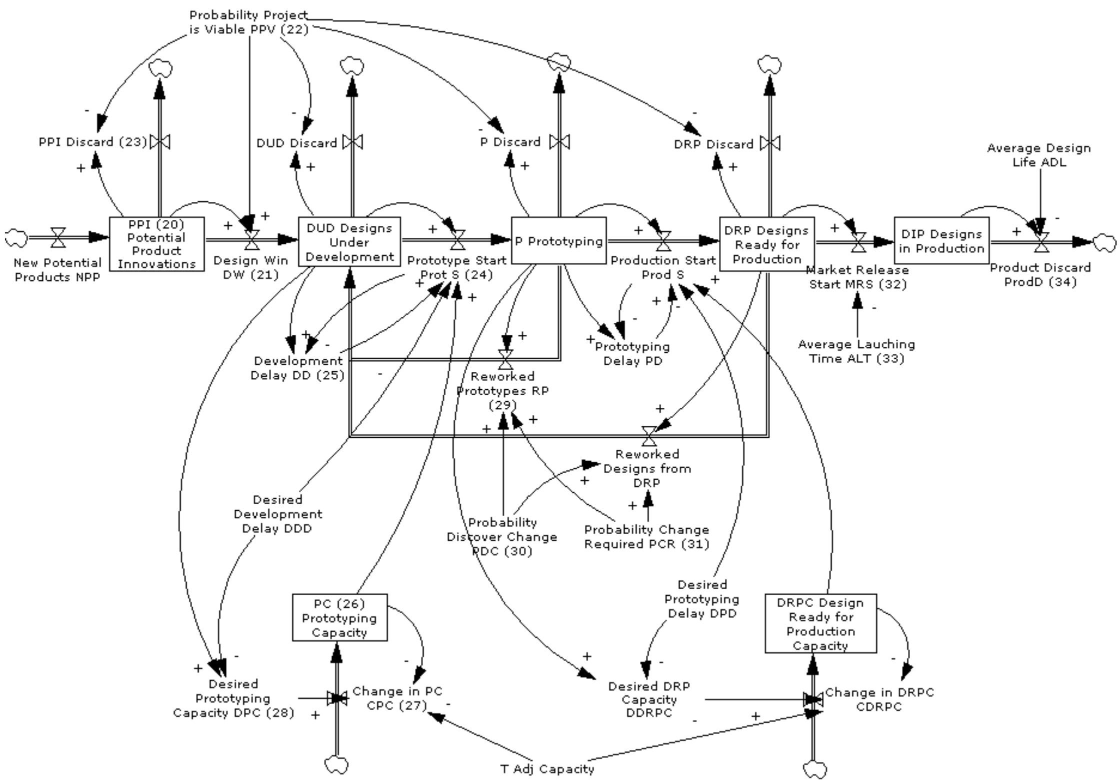
Figure 14
Product innovation & development process postulated by Gaynor (1996)



The capital goods sector is characterized by a wide range of products of varying degrees of technological complexity (in terms of design intensity). Although the innovation process is firm specific, we may draw a general picture of this process. We adopt the conceptual innovation and development process described by Gaynor (1996). The major functional steps of the process are shown in figure 14; as Gaynor (2.5) indicates, these steps are those used in the industrial sector and describe the technology and product strategy process employed in the development process.

This process is consistent with the chain link model postulated by Kline (1985) who describes the innovation process as a set of interdependent sub-processes which are closely linked with the research and development function and which interact with the firm's environment. This conception of the innovation process is reported on both Robledo's analysis of the innovation underperformance of the Colombian capital goods industry and on the study cases undertook by Vargas, Malaver and Zerda (2003) regarding the Colombian metal-mechanical industry which is a sub-sector of the capital goods industry. In addition, these researches regard innovation as learning processes that involve several agents whose decisions interplay to affect the industry performance.

Figure 15
Product innovation & development process



Since we aim to analyzing the interplay between the technological infrastructure described earlier and the product innovation and development process, the conceptual process postulated by Gaynor (1996) is reduced to the formalized structure of stocks and flows shown in figure 15 along with the variable name abbreviations and their equation numbers.

New potential products accumulate in a stock of potential product innovations. As the feasibility of potential innovations is being evaluated, the product's design development starts. After designs have been completed and reviewed, prototyping starts. Once prototypes have been successfully tested, products flow to the designs ready for production. Products accumulate in this stock until products are launched into de market place. After the market release, the stock of designs in production increases. Finally when the products reach the end of their life cycle, they are scrapped, thus decreasing the stock of designs in production.

The stock of potential product innovations (PPI) is increased by the flow of new potential products (NPP), and decreased by the design start (DS) and the designs discarded (PPI Discard) (equation 20). The flow of NPP represents design ideas that may potentially develop into innovations. NPP is assumed to be a constant rate of 10 designs per year. The DS is considered to be a function of the PPI multiplied by the probability (PPV) that a design is viable (feasible) both on commercial and technical grounds (equation 21). The PPV is the reference probability affected by those firm's capabilities that we assume have an effect on the design feasibility (equation 22). The Innovation Capability (IC) affects the probability that a design is viable (PPV) as described by the function represented in figure 16. This function is normalized around the reference IC. The assumption behind this nonlinear function is that since a probability of 1 implies perfection, there will be a diminishing scope for further improvement as the firm becomes better at defining and designing a product acceptable to the customer.

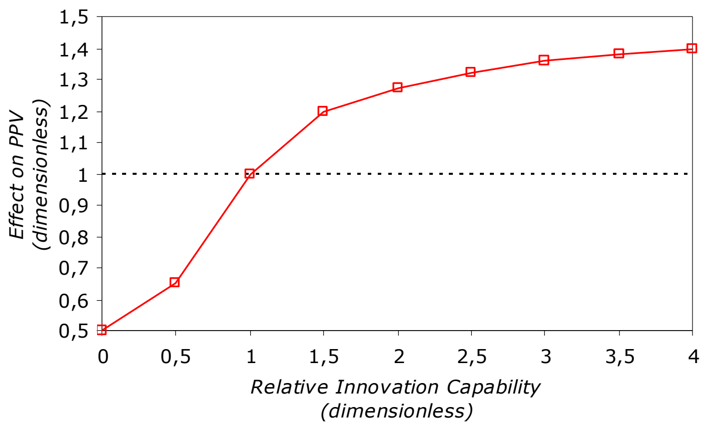
As mentioned, there is synergy between the innovation capability and the marketing capability that serves to improve the product development process. As a result, we assumed that both the innovation capability (IC) and the marketing capability (MC) affect PPV through the same function (figure 16). Thus, given a reference probability of 50% and given both the IC and the MC effects, the PPV may rise to a maximum of 98% for very high relative innovation and marketing skills. If the maximum PPV is 98%, it means that the maximum PPV is 96% greater than the reference probability. On the contrary, the PPV may decrease to a minimum of 13% for very low relative skills. If the minimum PPV is 13%, it means that the minimum PPV is 25% less than the reference probability. The higher PPV and the greater the stock of potential innovations (PPI), the greater the number of commercial and technical feasible designs flowing to the design development stage.

PPI = NPP – DW - PPI Discard	[20]
DW = PPI*PPV	[21]
PPV = RPPV*Effect of IC on PPV*Effect of MC on PPV	[22]
PPI Discard = PPI*(1-PPV)	[23]

A similar formulation governs the flow of discarded designs in every stage. Besides the effect of capabilities on PPV, it is assumed that PPV increases as the product flows downstream in the innovation and development process. This assumption is consistent with Kay (1988) who states that uncertainty tends to decrease as a project moves downstream through the various stages towards final innovation.

Figure 16

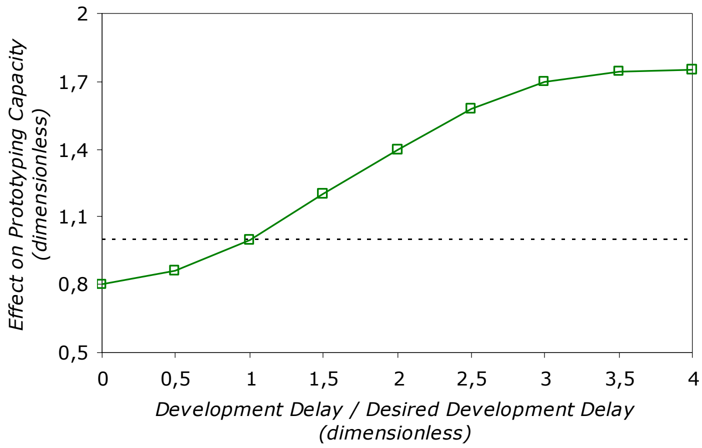
Capabilities' effect on PPV



The prototyping start rate (Prot S) accounts for the number of designs per year that flow from the development stage to the prototyping stage. Prot S is a function of the development delay (DD), desired development delay (DDD), prototyping capacity (PC) and the stock of designs under development (DUD). The DD accounts for the time period it takes for a product design to be developed. Both the current number of DUD divided by the perceived prototyping start rate determine the DD. The perceived prototyping start rate is assumed to be a third-order delay of the real rate (equation 24). DD affects PC as described by the function represented in figure 17; this function is normalized around DDD. The line y=1 represents the case in which the firm does not adjust its prototyping capacity in response to changes in the development delay. The 45° line represents a policy in which the prototyping capacity changes proportionally as the development delay changes. The nonlinear shape of the function that we decided to use is based on a simple assumption: the prototyping capacity cannot increase indefinitely. The assumed relationship saturates at a maximum for very high development delays. As a result, given the desired development delay, PC may rise to a maximum of 80% greater than the PC necessary to develop the desired designs accumulated in stock.

Figure 17

Effect of development delay on production capacity



The PC is a function of the desired prototyping capacity (DPC) and the time necessary to adjust the capacity itself, as it is formulated in equations 25-27. The DPC is given by the ratio between the DUD and the DDD. Once the variables PC, DD, DDD and DUD are given, the prototyping start (Prot S) rate is calculated as the minimum function between the prototyping capacity affected by the development delay and the greatest possible number of designs flowing from the DUD (equation 28). The assumption behind this formulation is that Prot S will be as great as possible, as much as the prototyping capacity allows it, but it is constrained by the availability of designs in the development stage ready to be passed on to the next stage. The production-start rate (Prod S) and the variables involved in its formulation follow a similar reasoning as the prototyping start rate. The production start rate is the inflow to the designs ready for production (DRP) stage.

DD = DUD/*Smooth3*(Prot S)	[24]
PC = CPC	[25]
CPC = (DPC - PC)/T Adj Capacity	[26]
DPC = DUD/DDD	[27]
Prot S = Min (PC*Eff of DD on PC, DUD/time step)	[28]

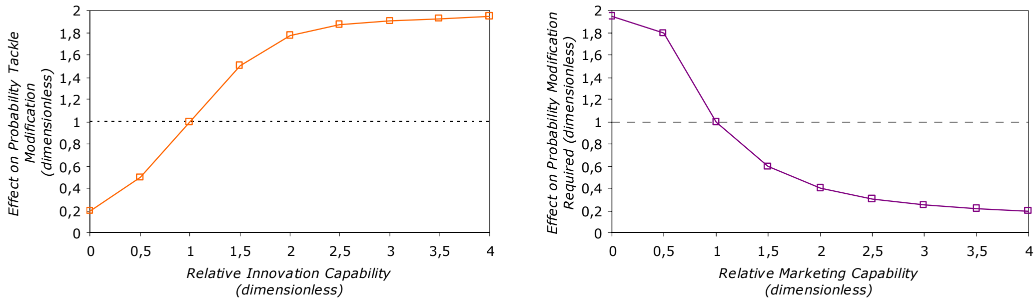
Before moving downstream into the product development process, a product in the prototyping stage might need design changes in order to comply with customer requirements. These reworked designs are taken into account in the reworked prototypes rate (RP) which feeds back into the DUD stage. To determine the RP, the stock of designs in prototyping (P) is multiplied by two probabilities (equation 29). First is the probability to tackle a modification, which represents the firm's ability to cope with problems along the innovation and development process instead of discarding projects in the face of problems. The second probability is the one that a modification be required. The probability to tackle a modification (PTM) is given by the reference probability (RPTM) affected by the influence of the firm's innovation capability (IC) (equation 30). This effect is shown on the left side of figure 18 and it is normalized around the reference IC. The PTM raises to a maximum of 97.5% for very high innovation skills; the maximum probability is 95% greater than the reference probability. On the contrary, the PTM decreases to a minimum of 10% for very low innovation skills; the minimum probability is 20% less than the reference probability. The idea underlying this nonlinear function is that since a probability of 1 implies perfection, there will be diminishing scope for further improvement.

RP = P*PTM*PMR	[29]
PTM = RPTM*Effect of IC on PTM	[30]
PMR = RPMR*Effect of MC on PMR	[31]

The probability that a modification is required (PMR) is given by the reference probability (RPMR) affected by the influence of the firm's marketing capability (MC) (equation 31). This effect is shown on the right side of figure 18. The reason behind this table function is that the higher the MC is the better is the firm at satisfying customer requirements. As a result, less modification may take place. Figure 18 (right side) shows PMR rising to a maximum of 97.5% for very low marketing skills; the maximum PMR is 95% greater than the reference probability. On the contrary, PMR decreases to a minimum of 10% for very high marketing skills; the minimum probability is 20% less than the reference probability. The scope for improvement diminishes as PMR reaches its minimum value. A similar formulation governs the rate of reworked designs ready for production (RDRP).

Figure 18

Capabilities' effect on reworked designs



The stock of designs in product (DIP) constitutes the last stage in the product innovation and development process. DIP is increased by the market release start rate (MRS) and decreased by the product discard (ProdD). The MRS is a function of the stock of designs ready for production (DRP) and the average time it takes for the firm to launch product designs into the market place (ALT) (equation 32). The ALT is given by the reference launching time (RALT) affected by the influence of the firm's marketing capability (MC) (equation 33). The marketing capability (MC) affects the average launching time (ALT) through the function shown in figure 19. The function is normalized by the reference MC. The line y=1 represents the case in which the average launching time of a product is independent of the firm's marketing skills. The nonlinear shape of the function that we decided to use is based on a simple assumption: the average launching time cannot decrease indefinitely. The assumed relationship drops to a minimum for high marketing skills; ALT declines to a minimum of 50% less than the reference ALT. In contrast, for low marketing skills, ALT rises to a maximum of 50% greater than the reference ALT. After some time, when products reach the end of their useful life they are discontinued according to the formulation shown in equation 34.

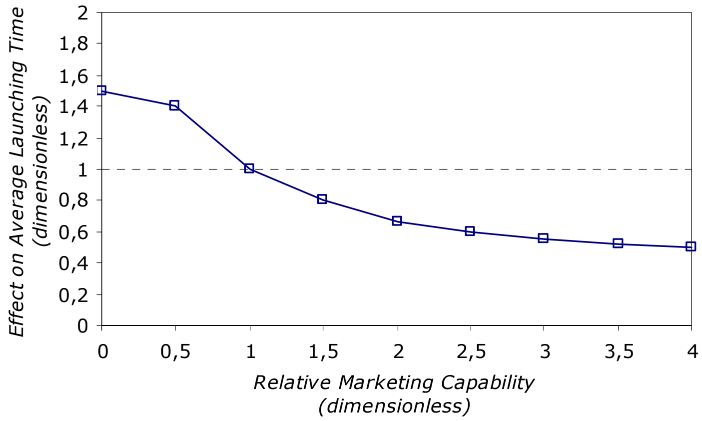
MRS = DRP/ALT [32]

ALT = RALT*Effect of MC on ALT [33]

ProdD= DIP/ADL [34]

Figure 19

Effect of the marketing capability on the product's average launching time



To finish off, the designs flowing throughout the product development process have two attributes: cost and quality[10]. These attributes determine the product cost and attractiveness, respectively. The product cost influences the product price. Based on the product price and the product quality, the customer assesses the product perceived value. This value affects the product attractiveness which determines the market share of the firm.

External knowledge infrastructure

In the previous section, we explained the firm's capabilities needed to support the innovation process. We will describe, in what follows, the design capability and the research capability developed by Higher Education Institutions (HEIs) and Government Institutions (GIs),

[10] These attributes are modeled as co-flows in the product development process.

respectively. These agents, together with the firm, make up the system of innovation.

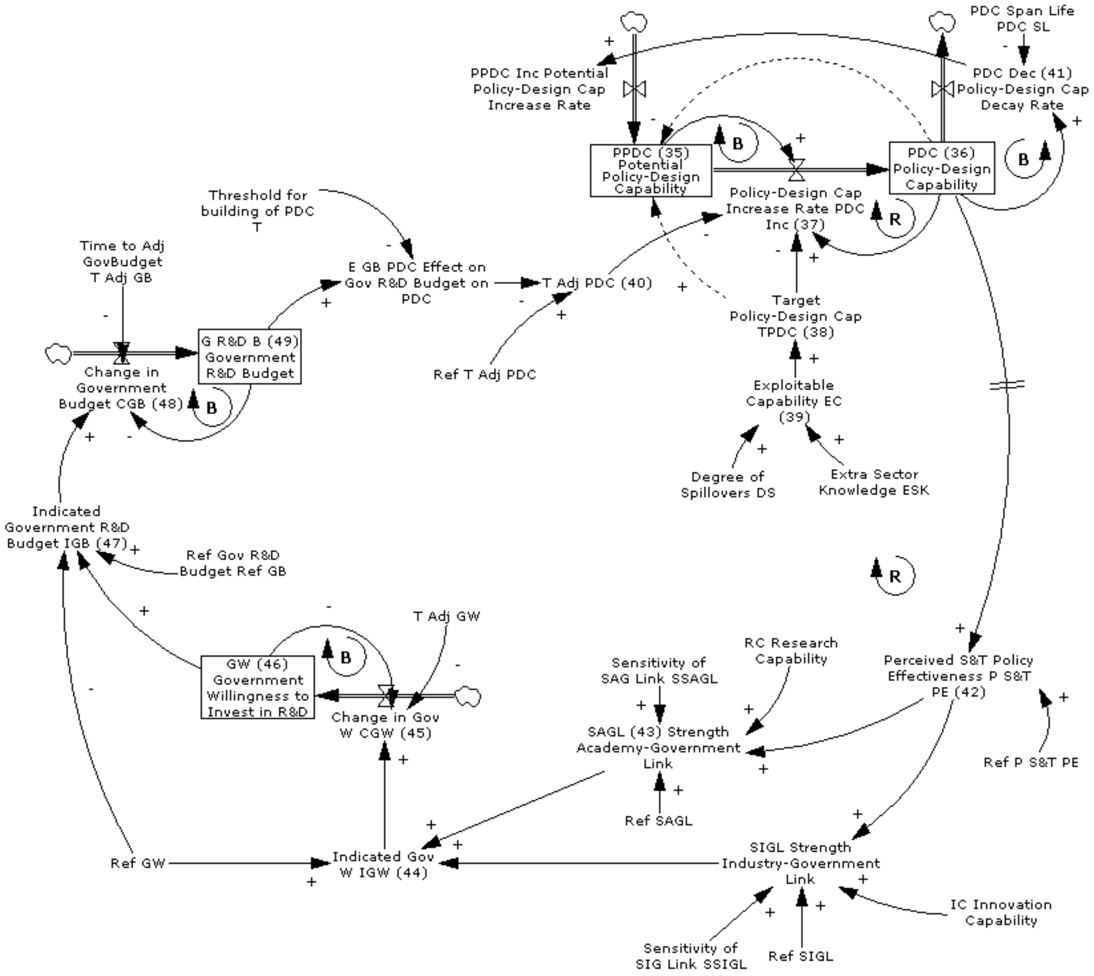
The development of both policy-design capability and research capability is influenced by the firm's innovation capability. In deed, the development of these three capabilities interacts through a reinforcing relationship (see the causal loop diagram in p. 47). For instance, the greater the firm's innovation capability, the stronger the industry-government link, and, as a result, the greater the capability accumulated at GIs. We will explain next the formulation of the GIs' policy-design capability with regard to science and technology.

The equations used in the formulation of the GIs' policy-design capability are:

PPDC = Integral (PPDC Inc – PDC Inc, TPDC-PDC_0) [35]
PDC = Integral (PDC Inc – PDC Dec, PDC_0) [36]
PDC Inc = PPDC*(PDC/TPDC)/T Adj PDC [37]
TPDC = EC [38]
EC = DS*ESK [39]
T Adj PDC = Ref T Adj PDC/E GB on PDC [40]
E GB on PDC = f (GB/T)
PDC Dec = PDC/PDC SL [41]

The formulation of the GIs' policy-design capability depicted as a stock and flow diagram is shown in figure 20 along with the variable name abbreviations and their equation numbers. The formulation of this capability entails the definition of two stocks: the stock of potential policy-design capability (PPDC) and the stock of policy-design capability (PDC). The PPDC represents the amount of capability that GIs are potentially able to acquire. The PDC represents the level of PDC already accumulated by the GIs.

Figure 20
GIs' policy-design capability for science and technology

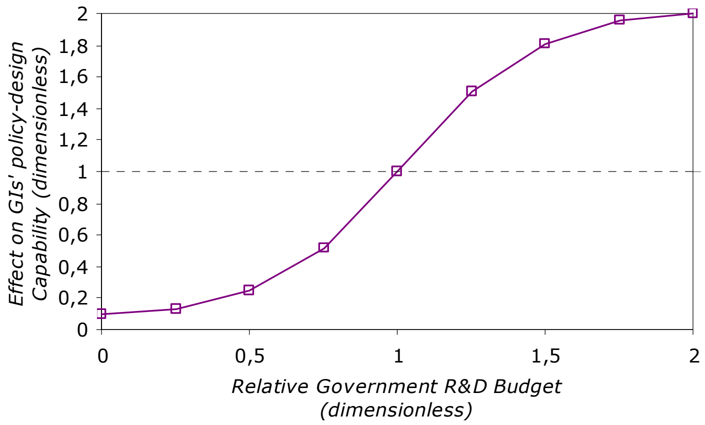


Three loops define the development of the PDC: the reinforcing learning loop governing the acquisition of PDC, and two balancing loops, one regulating the depletion of the PPDC, and the other regulating the loss of PDC. The GIs' PDC is developed as long as GIs have some PDC that facilitates the subsequent development of PDC (reinforcing loop) and only if there is PPDC to be transformed into PDC. At the same time that this process is taking place, the PPDC is being depleted (balancing loop). This interaction between the potential policy-design capability (PPDC) and the policy-design capability (PDC) is formalized into the formulation of the policy-design capability increase rate (equation 37).

The target policy-design capability (TPDC) also affects the policy-design increase rate. It is used as a reference for the initial PPDC and to asses the gap between the PPDC and the PDC. The TPDC is equal to the 'exploitable capability', which represents the stock of technological knowledge accessible to the agents making up the system of innovation (equation 38). The 'exploitable capability' is determined by the stock of external knowledge and the level of spillovers (equation 39). Economists use the term "spillover" to capture the idea that some of the economic benefits of R&D activities accrue to economic agents other than the party that undertakes the research (Jaffe 1996).

Figure 21

Effect of the government R&D budget on the GIs' policy-design capability



The government gross expenditure in R&D, as a percentage of GDP, determines the pace at which the potential policy-design capability (PPDC) is transformed into the policy-design capability (PDC). The government budget for R&D affects the time to adjust the PDC as described by the function represented in figure 21; the higher the GIs effort, the less time the GIs will need to acquire PDC (equation 40). This function is normalized around the threshold budget required for the capability development. This threshold is 1%, and has been reported by the UNESCO in various science and technology documents.

It is also possible that the PDC of the GIs decays. Like in the formulation of the firm's capabilities, the PDC decay rate is given by a first order delay (equation 41). The loss of PDC increases the gap between the GIs' PDC and the target PDC. The gap represents space for further development of the GIs' capability. As a result, the loss increases the potential policy-design capability.

The GIs' policy-design capability determines the GIs' policy-design effectiveness perceived by HEIs and the firm. This variable is assumed to be a first order delay of the GIs' policy-design capability itself (equation 42). The reason supporting this assumption is that, as GIs' capability increases, GIs become better at designing policies to support science and development activities. The better their policies are, the higher the effectiveness of those policies to assist the R&D investments carried out by the academy and industrialists. In addition, it takes time for industrialists and the academy to perceive that effectiveness.

The perceived GIs' policy-design capability affects the strength of the links that GIs have with the academy and industrialists. The capabilities of these actors also affect the strength of these links. For instance, the higher the HEIs' research capability and the higher the perceived GIs' policy-design effectiveness are, the greater is the effect that they exert on the reference strength of the academy-government link. Likewise, the higher the HEIs' research capability, the greater the strength of academy-government link will be (equation 43). The HEIs' research capability and the perceived GIs' policy effectiveness are each normalized around their reference values.

The strength of the academy-government link and the strength of the industry-government link determine the government's willingness to allocate resources to R&D investments (equation 45). The higher the government's willingness is, the greater the budget that the government will allocate to perform R&D activities.

PE = *Smooth1* (PDC) [42]
SAGL = Ref SAGL*((RC/Ref RC)*(PE/Ref PE))^SSAGL [43]
SIGL = Ref SIGL*((IC/Ref IC)*(PE/Ref PE))^SSIGL [44]
IGW = SAGL+SIGL [45]
CGW = (IGW-GW)/T Adj GW [46]
GW= Integral (CGW) [47]
IGB = Ref GB*(GW/Ref GW) [48]

CGB = (IGB – GB)/T Adj GB [49]

GB = Integral (CGB) [50]

The research capability accumulated within HEIs is formulated similar to the GIs policy-design capability. The difference lies in that the HEIs willingness to invest in R&D is influenced by the strength of the academy-government link and the strength of the academy-industry link. Both of them represent the intensity of the research collaboration between the agents involved in each link.

The two capabilities described above influence the firm's willingness to invest in R&D. The HEIs research capability influences the firm's willingness through the strength of the academy-industry link. The government S&T policy-design capability influences the firm's willingness through the strength of the government-industry link. The firm's willingness determines the decision to allocate resources to perform formal R&D activities. The investments in R&D are allocated to the acquisition of the capital and labour to be used only in R&D activities. This is consistent with the definition of R&D investments suggested in the Frascati Manual (OECD 2002).

Other model sectors

Since the firm invests in R&D to support the product development process, this investment should have a positive effect on the product quality. This is possible through the competence of the labour force that performs R&D activities. Their competence determines the product quality per new potential design and the quality added on each stage of the product development.

The technology of capital, which is formulated as a co-flow of the capital stock, affects the capital productivity and the consumption of material in the manufacturing process.

The core of the model is the interplay between the firm's technological infrastructure and the product innovation and development process; as a result, the formulation of the variables mentioned above, plus other variables necessary to measure the firm's economic performance, belongs to other model sectors not explained in this report. Nonetheless their formulation can be consulted in the annex comprising the model equations (p. 136).

The model is available in both Powersim Constructor and Vensim software.

CHAPTER 4
Model Validation

Good tests kill flawed theories; we remain alive to guess again.

Karl Popper

Introduction

In the previous chapter we described the model built to follow our research purpose. In what follows we report some of the tests we carried out to comply with the validation of a system dynamics model.

The model validation is a prolonged process that is distributed throughout each stage of the system dynamics method. A model is a simplification of the real system; thus, the model validity is the usefulness with respect to some purpose (Forrester 1961; Randers, 1980; Oliva, 2003). The validation process was done following Barlas' (1996) guidelines for model validation. It is worth mentioning that the research done by Robledo (1997) does not provide sufficient data to make a quantitative assessment of the model ability to reproduce the behaviour of the real system. Hence, the model validation is focused on testing the structure consistency of the model. We believe this is valid since the ultimate objective is to increase understanding of the underlying causes responsible for the poor innovation performance of the Colombian capital goods industry.

By the end of this chapter we aim to have established the model suitability to investigate if the description of the problem done by Robledo's follows logically from the causes he claims. The model validity allows us investigate that the model behaviour, which is analyzed in the next chapter, is obtained for the right reasons.

Direct structure test

This test assesses the validity of the model by direct comparison with knowledge and information about the real system (Forrester and Senge 1980). It comprises structural and parameter confirmation tests.

The structure of the model we built reflects the causal relationships asserted by Robledo as governing the firm's innovation process and the bearing that higher education institutions (HEIs) and government institutions (GIs) have on the accumulation of capabilities at the firm level. Furthermore, when the evidence offered by Robledo was not enough to formalize causality, the equations were built so as to conform to the general knowledge in the literature.

The model parameters have real world counter parts; they are conceptually and numerically valid. Most parameters were estimated using the qualitative description done by Robledo or the literature and surveys related to our research field. Table functions and some parameters values were assumed but checked for plausibility, for two reasons:

1. The data was limited for some of the parameters. The research done by Robledo did not have the purpose to gather data necessary to build a model; as a result, the system description does not comprise several variables and parameters important to formalize the causal relationships into equations. For instance, the time necessary for the firm to absorb and actually use new knowledge is a parameter that controls the rate at which the firm builds its innovation capability. This capability is crucial for the product development process, so we estimated it to an average of 3 years. The reason behind this estimation is that in case the firm has to use a new manufacture technique, for instance, it has to enrol one of its employees in a training program, which in Colombia, in an official education institution might take a minimum of 1 year.
2. There is no data that could have been used as proxy variables to estimate those parameters that are not directly addressed by Robledo in his work.

As a final direct structure test, using the dimensional analysis feature of the Vensim software, it was checked that each equation in the model is dimensionally consistent; equations are written in such a way that they appropriately represent the real world.

Structure oriented behaviour test

This test evaluates the validity of the structure indirectly, by applying certain behaviour tests on model generated behaviour patterns. These tests involve simulation. Although there are several test to be carried out (Barlas 1996; Forrester and Senge 1980), we performed just three of them: the extreme condition test, the behaviour sensitivity analysis and the phase relationship test.

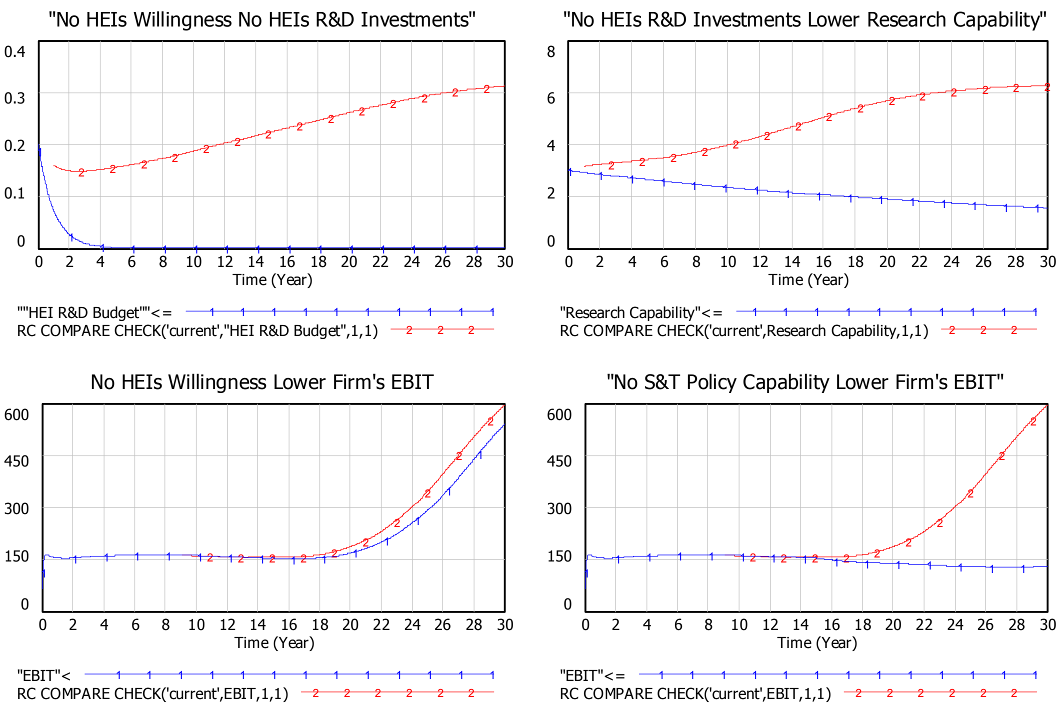
Extreme condition test

This test can provide information on potential structural flaws. It evaluates the validity of the model under direct extreme conditions such as zero capital, zero labour force or zero innovation capability. Although some values may not occur in real life, the model should be robust when subject to extreme shocks and parameters (Peterson and Eberlein 1994). For instance, zero innovation capability should indicate very few designs in production. This was taken in account during the modelling process; however, we used the Reality Check feature of the Vensim software to test if the model behaves expectedly. Not all but some variables are chosen to extreme values.

When the willingness of Higher Education Institutions (HEIs) to invest in research and development (R&D) is zero this means there are no indicated investments in R&D, and thus, no growth in its R&D budget. The HEIs R&D budget should be lower than in the base run and should decrease until it reaches the indicated budget which is zero (top left side in figure 22). Likewise, if HEIs do not allocate budget to R&D activities, there is not any possibility for them to build their research capability and the capability will decay from its initial value until its reaches zero (top right side in figure 22). The model behaves expectedly.

Figure 22

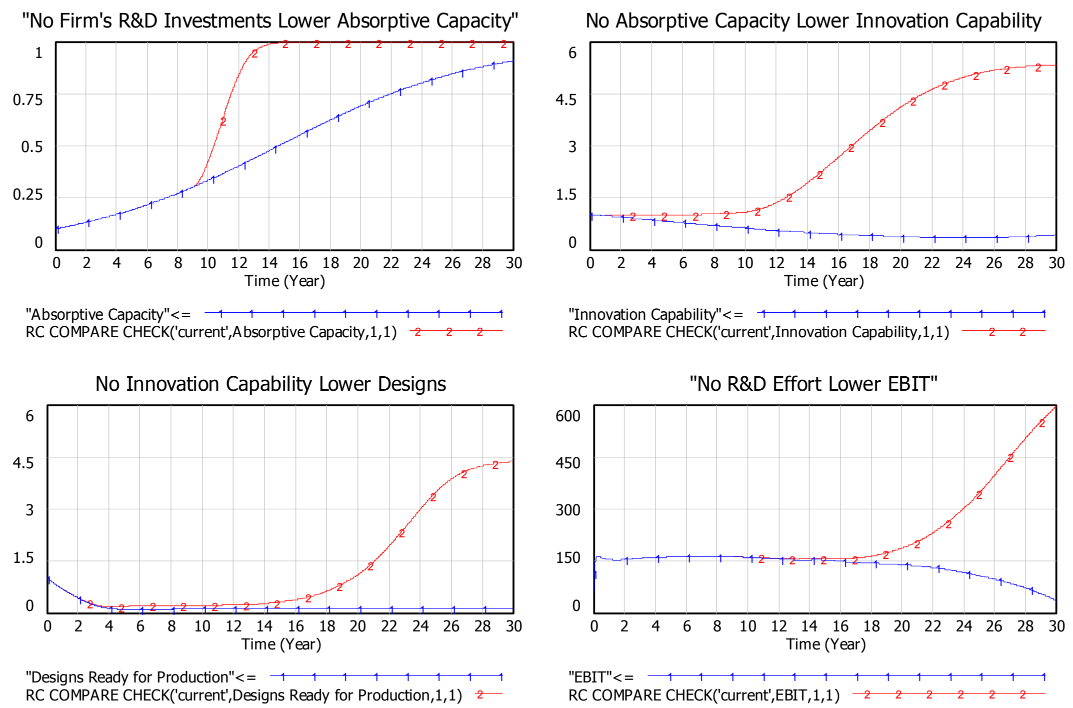
Reality Check for extreme condition test I



Since there is an interaction between the firm and HEIs, and the research capability supports the accumulation of innovation capability at the firm, we would expect to see lower earnings at the firm than if there had been any research capability accumulated at HEIs. Although the model behaves expectedly (bottom left side in figure 22), just at the end of the simulation time the firm's earnings are lower than the earnings in the base run. This reveals the delay that exists between the learning process giving rise to the accumulation of the firm's innovation capability and the research capability developed by HEIs. In other words, if HEIs do not have capabilities to foster the firm willingness to invest in R&D, the firm will not allocate resources to R&D and its performance will deteriorate sooner or later. Likewise, when there is no science and technology capability accumulated at the Government Institutions (GIs), the firm's earnings are lower, as we would have expected (bottom right side in figure 22).

Figure 23

Reality Check for extreme condition test II



When the firm does not allocate resources to R&D activities, it is delays the development of its absorptive capacity (top left side in figure 23) and thus its innovation capability will be lower than in the base run (top right side in figure 23). Likewise, zero innovation capability should indicate very low designs in production compared to the base run (bottom left side in figure 23). Therefore, we would expect to see lower earnings at the firm than if there had been any innovation capability accumulated at the firm. The model behaves expectedly (bottom right side in figure 23).

Behaviour sensitivity

This test consists of determining the relationships and parameters the modeller suspects are both highly uncertain and likely to affect the conclusions drawn from the model (Randers 1980; Forrester and Senge 1980). In the model of a real system, uncertainty associated with the values of parameters exists; thus, we should be more concerned about the behavioural sensitivity of the model than about its numerical sensitivity (Sterman 2000).

The initial GIs' policy-design capability, the time necessary for the firm to adjust new knowledge and the sensitivity of the product quality to the technological level are the parameters chosen for the sensitivity tests. In addition, the table function for the effect of the marketing capability on the product's average launching time and the table function for the effect of R&D effort on the absorptive capacity are also chosen for sensitivity tests. This is done in order to illustrate the type of test used to validate table functions all along the modelling process. Three scenarios are chosen for each variable and they are denoted by the numbers 1, 2 and 3. The simulation of each scenario is displayed in a figure and denoted by a line marker with its own number.

- Initial GIs policy-design capability

The parameter differences are as follows:

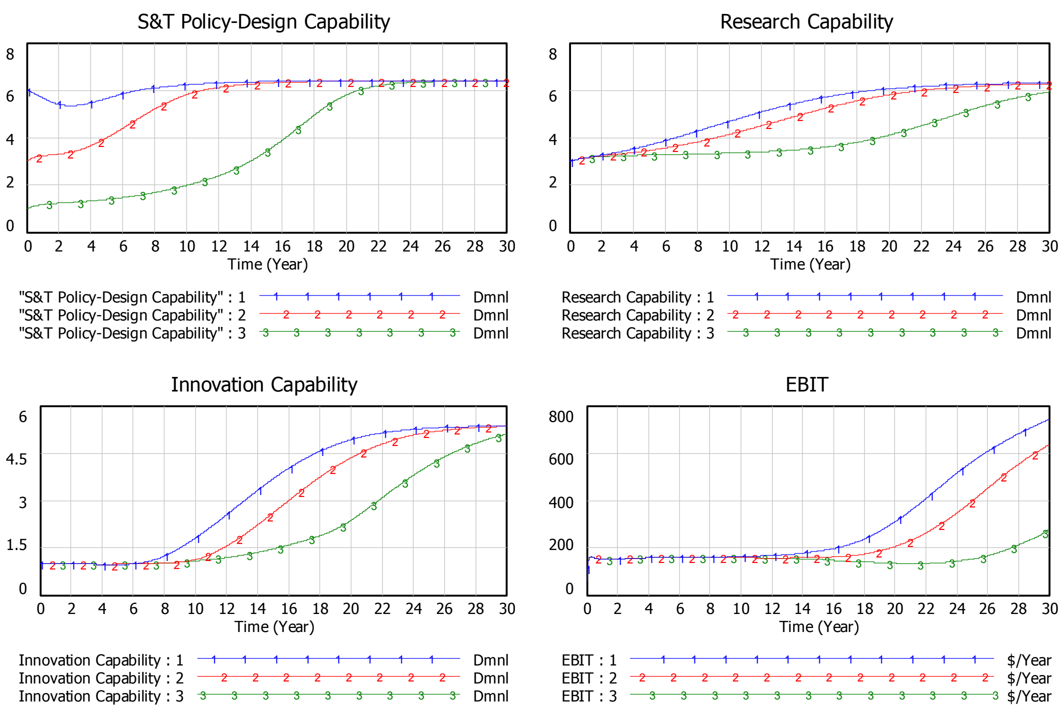
1: 6

2: 3

3: 1

Figure 24

Sensitivity analysis for the Initial GIs' policy-design capability



When the parameter value is increased, the capabilities accumulated at the different agents also increase (top side, and bottom left side in figure 24). This behaviour seems right because, earlier on, a higher GIs' policy-design capability speeds up the development of the capability itself. A higher GIs capability improves the policy effectiveness perceived by both HEIs and the private firm; this in turn fosters their willingness to invest in R&D. The higher the HEIs' and the firm' willingness to invest in R&D, the higher their investments in this field and thus the higher the capabilities they develop.

For the firm, in particular, higher capability creates more space for performance improvement, and, as a result, not only a higher capability reinforces its willingness to invest in R&D but also increases its R&D effort. Although the system behaves expectedly, this parameter causes drastic behaviour changes in the firm's earnings when altered (bottom right side in figure 24). When the GIs initial policy-design capability is very low, neither HEIs' nor the firm' are encouraged to invest in R&D. As a result, the development of their capabilities evolves slowly. Likewise, with regard to the initial HEIs willingness to invest in R&D, there are drastic behaviour changes when the parameter is altered.

- Reference time to adjust new knowledge

The parameter differences are as follows:

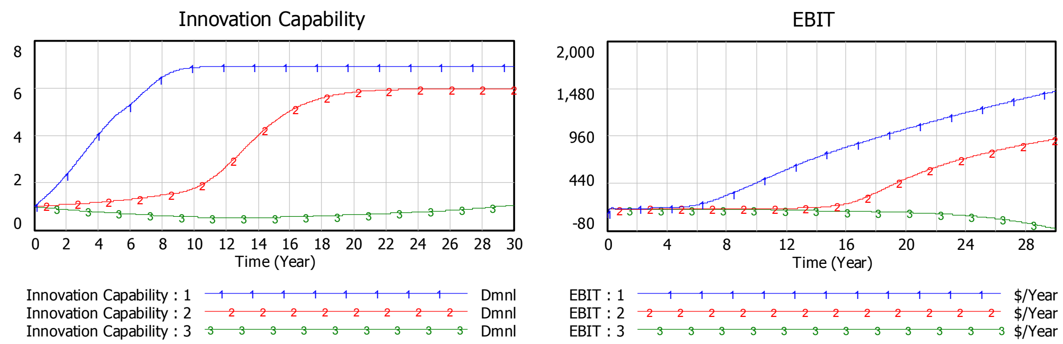
1: 0.5

2: 2

3: 8

Figure 25

Sensitivity analysis for the time to adjust new knowledge



The lowest firm's earnings occur when the time to adjust new knowledge is large. This behaviour seems right since as the new knowledge is not immediately assimilated, the development of the innovation capability unfolds slowly (left side in figure 25). The lower the firm's innovation capability, the lower its performance in terms of quality improvements and designs launched. Although this parameter shows significant behaviour changes when altered, the firm's earnings respond expectedly (right side in figure 25). The longer it takes to the firm to generate innovations, the worse its economic performance will be.

- Sensitivity of Quality

The parameter differences are as follows:

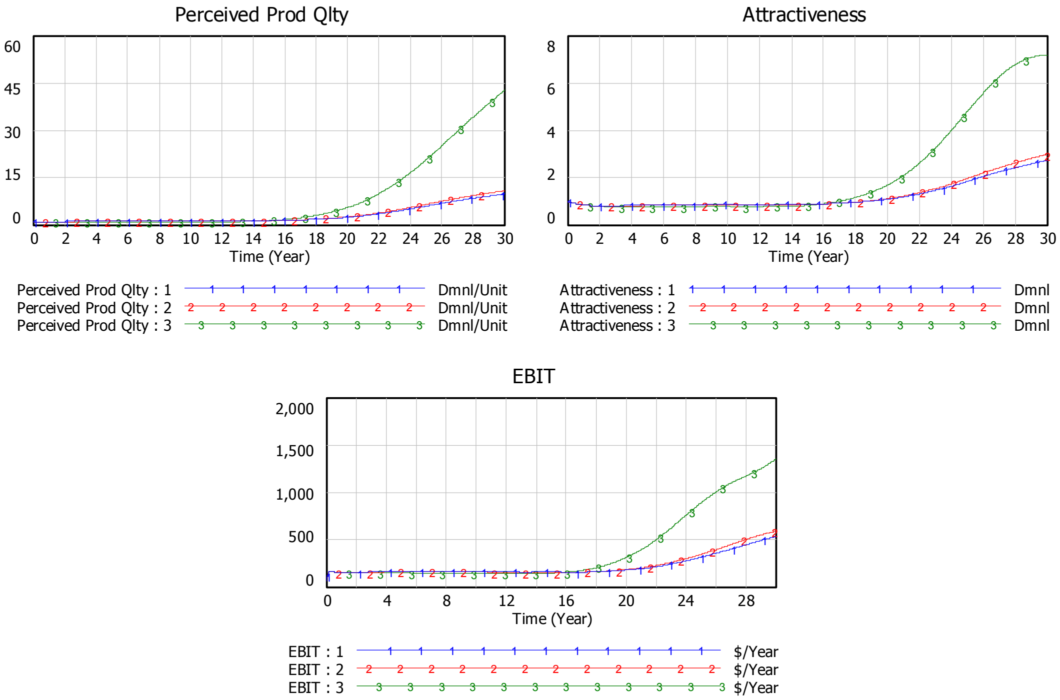
1: 0.1

2: 0.2

3: 1.25

Figure 26

Sensitivity analysis for the sensitivity of quality to the technological level

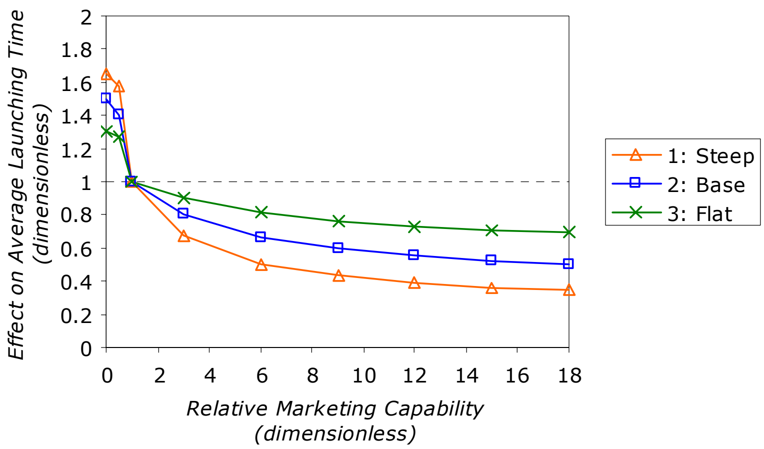


When the value of this parameter is increased, it means that the sensitivity of the product quality to changes in the technological level is higher. Thus, not only the positive effect of a rise in the technological level is amplified but also the negative effect of a decrease. The system behaves expectedly; the higher the sensitive of quality to the firm's technological level the greater the variation in both the product quality and the product attractiveness (top side in figure 26). A higher quality of the product not only increases the volume of sales but also enables the firm to charge a higher profit mark-up. The firm's earnings increase as we expected (bottom side in figure 26).

- Effect of the marketing capability on the product's average launching time

The alternative table functions for the effect of the marketing capability on the product's average launching time are shown in figure 27.

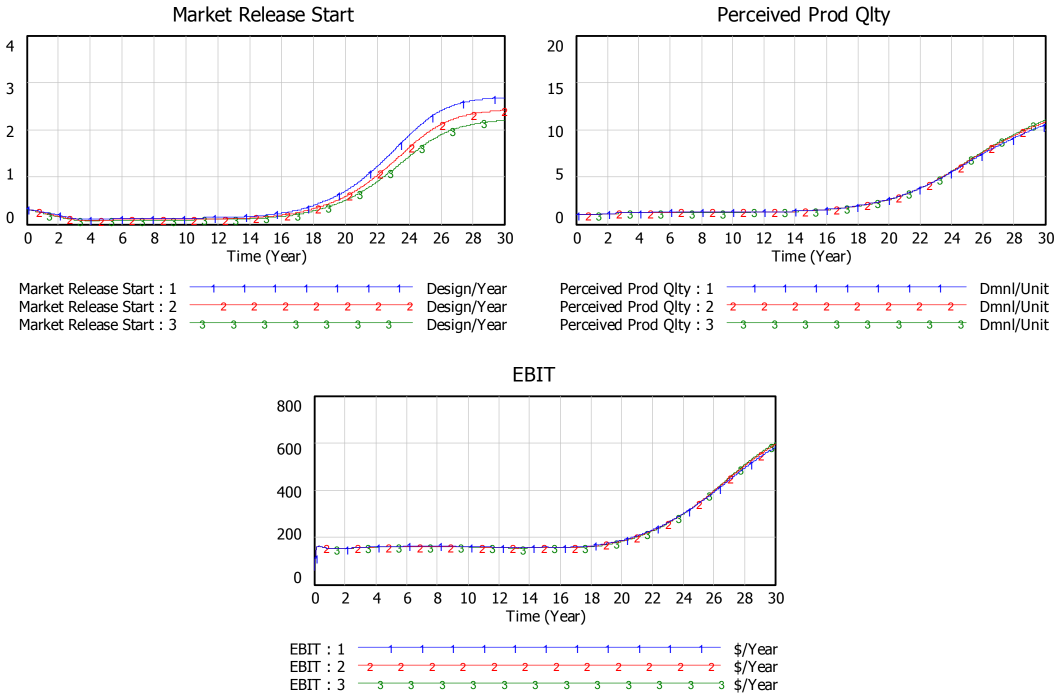
Figure 27
Table functions for the effect of the marketing capability on the product's average launching time



The assumed relationship drops to a minimum for high marketing skills. The steep case allows the average launching time (ALT) to be the 35% of the reference ALT. The flat case allows the average launching time (ALT) to be the 70% of the reference ALT. Both values are the minimum values that the ALT can take under each case. In contrast, for low marketing skills, the steep case allows the average launching time (ALT) to be 65% greater than the reference ALT; the flat case allows the average launching time (ALT) to be just 30% greater than the reference ALT (figure 27). These values are the maximum values that the ALT can take under each of the two cases. Unlike the flat case, the steep case varies significantly the responsiveness of the average launching time to the relative marketing capability. The relative marketing capability is the ratio between the marketing capability and the initial marketing capability.

Figure 28

Sensitivity analysis for the effect of the marketing capability on the product's average launching time



Under the steep case, the major responsiveness of the average launching time to the relative marketing capability increases the product's launching rate or market release start rate (top left side in figure 28). However, unless the firm's does not improve the quality added per new product developed, the average product quality decreases (top right side in figure 28). A lower quality of the product reduces the firm's earnings (bottom side in figure 28).

In contrast, under the flat case, the minor responsiveness of the average launching time to the relative marketing capability reduces the product's launching rate or market release start rate. As a result, the average product quality slightly increases as well as the firm's earnings.

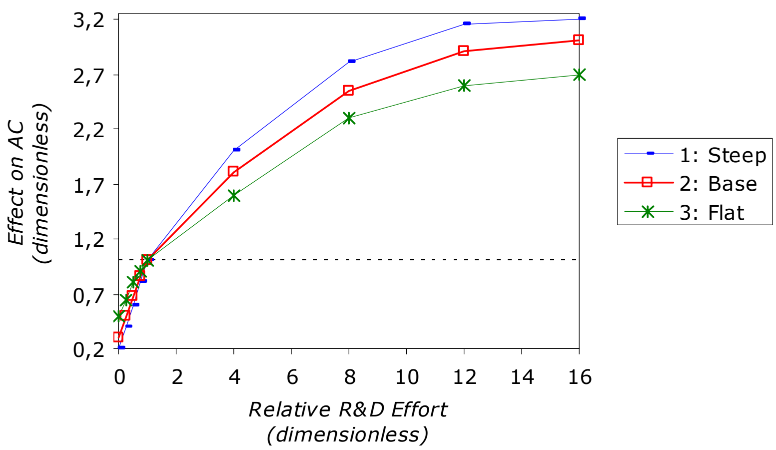
The model behaves expectedly under both the steep and flat cases. The effect of the marketing capability on the product's average launching time does not trigger significant behaviour changes when altered. In other words, the uncertainty in the assumed shape and values of the table function do not affect the conclusions drawn from the model.

- Effect of R&D effort on absorptive capacity

The alternative table functions for the effect of R&D effort on absorptive capacity are shown in figure 27.

Figure 29

Table functions for the effect of R&D effort on absorptive capacity

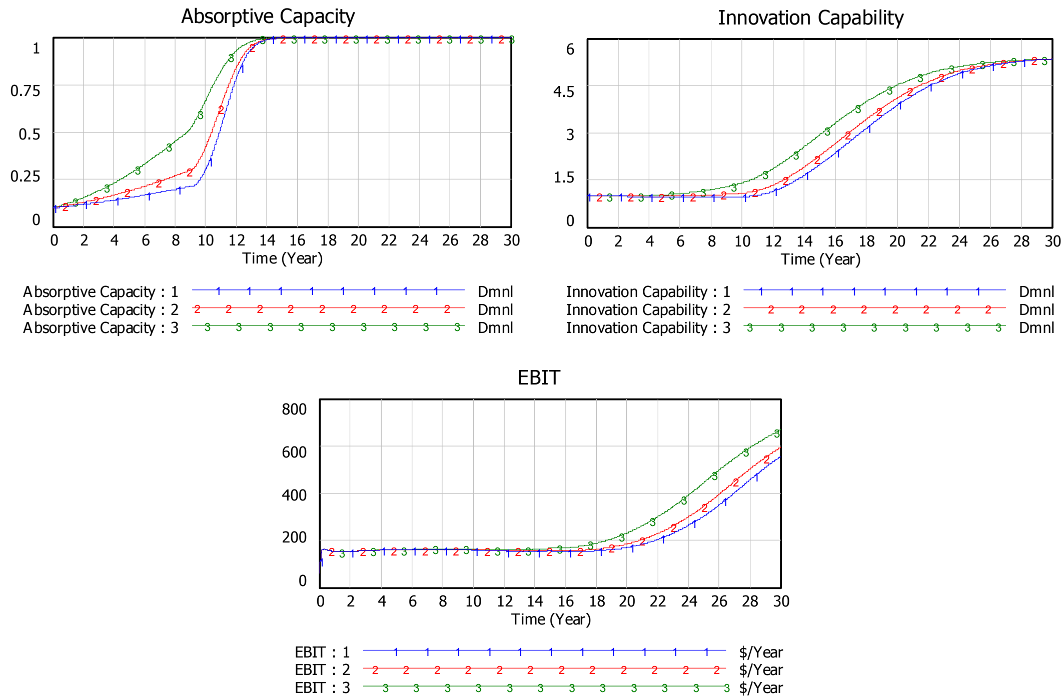


Unlike the flat case, the steep case varies significantly the responsiveness of the absorptive capacity to the relative R&D effort. The relative R&D effort is the ratio between the firm's R&D effort and the reference R&D effort. This reference value is 0.3% and was taken form Durán, Salazar and Ibañez (2000). The firm's R&D effort is given by the firm's own investments in R&D weighted by its revenues.

Under the steep case, the major responsiveness of the absorptive capacity to the relative R&D effort speeds up the development of the absorptive capacity itself (top left side in figure 30). The faster the development of the absorptive capacity is, the faster it is the development of the firm's innovation capability (top right side in figure 30). The higher the firm's innovation capability is, the better it is the product quality and the more designs are launched. As a result, the firm's earnings are higher than in the base case (bottom side in figure 30).

Figure 30

Sensitivity analysis for the effect of R&D effort on absorptive capacity



In contrast, under the flat case, the minor responsiveness of the absorptive capacity to the relative R&D effort slows the development of both the absorptive capacity and the firm's innovation capability. As a result the firm's earnings are lower than in the base case.

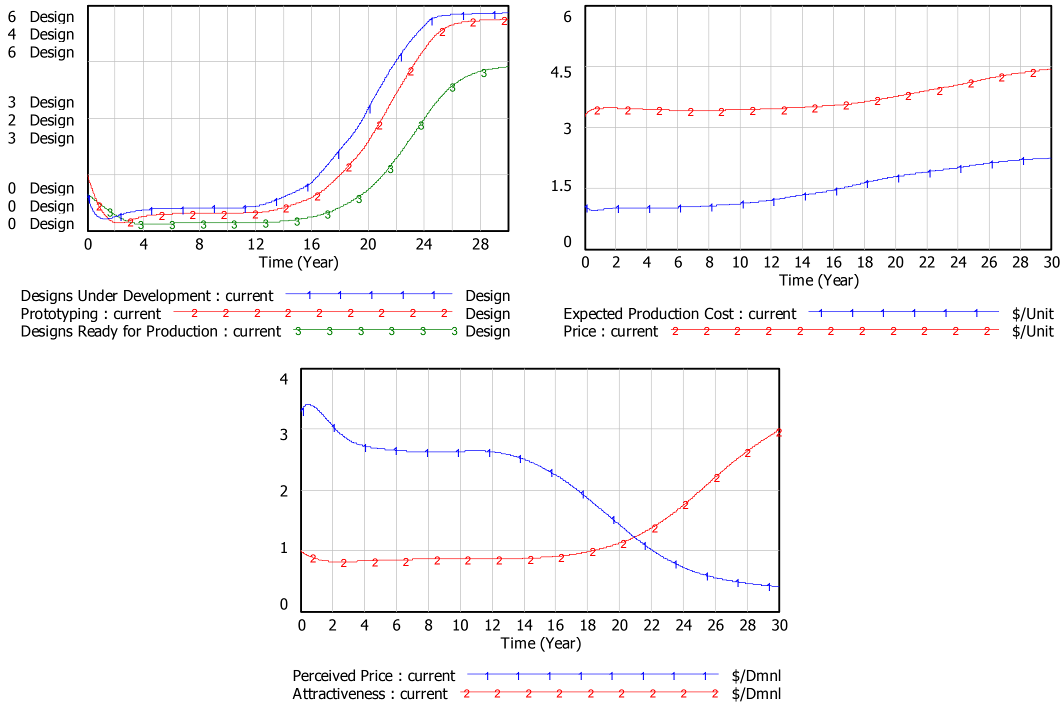
The model behaves expectedly under both the steep and flat cases. The effect of the R&D effort on the absorptive capacity does not trigger significant behaviour changes when altered. In other words, the uncertainty in the assumed shape and values of the table function do not affect the conclusions drawn from the model.

Phase relationship test

The phase relationships between pairs of cross-correlated variables in the model do not contradict the phase relationships that are expected from the real system. For instance, this phase lag is best seen between the stages of the product development process (top left side in figure 31), between the expected production costs and the product price (top right side in figure 31), and between the perceived product price and the product attractiveness (bottom side in figure 31).

Figure 31

Phase relationship test



Boundary adequacy test

We examine the boundary adequacy of the model as the last validation test. Once we have verified that the structure of the model is consistent and we have tested its behaviour sensitivity, we can have a better discussion regarding the appropriateness of the underlying assumptions about the model boundary and its feedback structure.

As we mention in Chapter 3 (p. 50-51), we omitted the effect of the dynamics governing tax rates, loan interest rates and labour cost on the firm willingness to undertake R&D investments. At some point in the modelling process and due to a survey on the technological development in Colombia (Durán et al 2000), reporting that decision makers consider cost and funding as two of the main barriers to undertake R&D investments, the variables mentioned above gained importance for the model purpose. As a result, we went back to analyse Robledo's research and we found that, although he does not clearly mention costs and funding as barriers on his research, he addresses them indirectly. According to his line of argument, it is likely that firms within the Colombian industry perceive R&D investments as an expensive investment option. Robledo reports that firms associate the benefits of R&D with its direct benefits, thus, the cost benefit relation of R&D projects might be in disadvantage compared to investments in the expansion of production capacity for example. In addition, although tax rates, loan interest rates and labour cost are variables clearly affected by the government policies, Robledo does not mention any dynamics governing these variables. Thus, to include these dynamics is beyond the purpose of this thesis.

Although frequently mentioned in the innovation literature, the dynamics associated with the development or improvement of technology by the firm for its own use in the product development and production processes is not included in the model. We recognize that the in-house developed technology might have an effect on the cost structure of the firm which in turn affects its economic performance. We would expect that the dynamics associated with the technology developed or improved in-house are as follows: once the firm has increased its capabilities at a certain level, it might be able to develop the technology they use; as a result, the investments in capital are cheaper compared to investments in capital with technology developed elsewhere. We consider that omitting these dynamics in our model do not alter the conclusions we attained to; furthermore these dynamics are not addressed by Robledo in his research.

By means of the sensitivity analysis we noticed that both the GIs' policy-design capability and the HEIs' research capability trigger significant behaviour changes when altered; in other words, they do play a key role in the firm innovation performance as Robledo asserts. The dynamics regarding the interaction between the firm and both GIs and HEIs were properly interpreted and transformed into the formal model. This conclusion will be addressed once more in the next chapter.

As a concluding remark, we consider the model as suitable to investigate how well Robledo's theory accounts for the behaviour he sets out to explain.

CHAPTER 5
Model Results and Discussion

How can I know what I think until I see what I say?

Karl Weick (cited by Richardson 1999, 238)

Introduction

In the previous chapter we got into more detail regarding the model built by showing how the equations were defined. In this chapter, we report and comment on selected results of the model simulation that serve our research purpose.

We take as a point of departure simple scenarios to illustrate the performance of the firm under a variety of assumptions. This is done in order to introduce the reader to and facilitate his understanding of the dynamic characteristics of the model leading to its replication of the reference mode. Subsequently, we examine more complex scenarios. For every scenario, we test the model response to a particular set of model parameter values. Our aim is to demonstrate under which circumstances (scenarios) the model reproduces the reference mode of behaviour and under which circumstances it does not do so. That way we improve our understanding of the dynamics responsible for the problem indicated by the reference mode and of how much enduring and pervasive the problem is.

At the end of the chapter we examine the contribution of this thesis to the discussion in the literature about the innovation process in Colombia. We intend this contribution to be threefold: 1. it should offer a comprehensive theory that accounts for the poor innovation performance of the Colombian industry and the scarce level of its technological capabilities; 2. it should improve our understanding of the accumulation of the capabilities that affect the innovation performance observed at the firm level as well as in

Higher Education and Government Institutions; and 3. it should increase the accessibility of Robledo's research to entrepreneurs, science and technology decision makers, and other researchers.

Initial tests

Based on the first set of simulations we examine whether the model behaviour is as expected if the firm is willing to directly invest in R&D at particular points in time over a period of 30 years. In these scenarios, the firm's willingness to invest in R&D is independent of the influence exerted by the environment. In other words, investment willingness is said to exist, regardless of the perceived government policy effectiveness and the strength of the link between the industry and the Higher Education Institutions (HEIs). With these scenarios, we want to illustrate the consequences of, with regard to the firm's capabilities and performance, delaying a readiness to invest in R&D.

We begin with a firm that invests in R&D at its start-up (scenario A1). This is represented in the model by setting the firm's willingness to invest in R&D at a higher level. Here, the model is initiated in undemanding conditions –the difficulty to learn from the environment is regular, thus the firm does not depend so much on its R&D effort to gain knowledge. In addition to that, the quality, productivity and growth targets are also low.

The second scenario (A2) is different from A1 in that the decision to invest in R&D is postponed until year 2. We expect the firm's innovation capability (IC) and marketing capability (MC) will exhibit exponential growth at first, but then gradually their growth will slow until the capabilities reach an equilibrium level. This reference point is given by a constant, the 'exploitable capability', which represents the stock of technological knowledge accessible to the agents making up the system of innovation. This behaviour mode should be observed in both A1 and A2 scenarios, but with a time lag between the two scenarios.

The third scenario (A3) represents a more demanding situation. Under this scenario the firm competes with other firms that have been investing in

R&D since their start-up (like under scenario A1). The firm is willing to invest in R&D only in year 7. As a result, the firm has to comply with higher performance targets, and has to cope with an environment that makes the firm depend more on its own R&D effort to gain the knowledge necessary for the product development.

We selected the following variables to represent the simulation results under the three scenarios –each scenario is represented by the line-marker 1, 2 or 3:

- The firm's innovation and marketing capabilities –figure 32 and figure 33, respectively.
- The firm's designs under production and the perceived product quality –figure 34 and figure 35.
- The firm's earnings before interests and taxes (EBIT) –figure 36.
- The firm's profitability and return on assets (ROA) –figure 37.

Figure 32
Firm's innovation capability under scenarios A1, A2 and A3

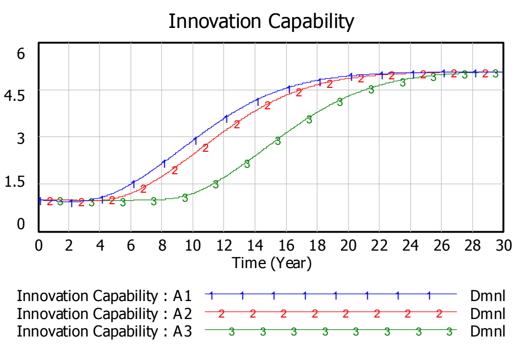


Figure 32 shows the resulting dynamics of the firm's innovation capability. There is a lag between the innovation capabilities obtained in each scenario. As expected, the sooner the firm starts to carry out R&D activities, the faster it develops its innovation capability. For instance, in year 8 the firm's innovation capability under scenario A1 is 1.23 times greater than under scenario A2 and 2.13 times greater than under scenario A3. The difference between scenarios is reduced as the capability approaches the equilibrium given by 'exploitable capability'.

This is evidence that the firm is learning by performing R&D activities. As the firm carries out R&D activities, it develops the absorptive capacity that enables it to gain the necessary knowledge for the product development.

Figure 33
Firm's marketing capability under scenarios A1, A2 and A3

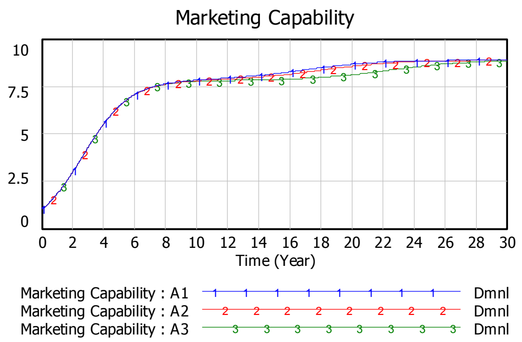
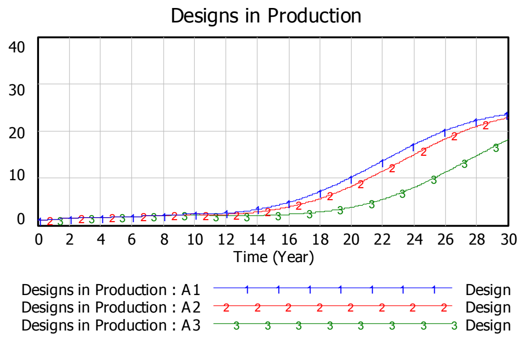


Figure 33 shows the resulting dynamics of the firm's marketing capability. There is also a lag between the marketing capabilities obtained in each scenario. Although there are not as significant differences across the three scenarios as with the innovation capability, the development corresponds to the expected behaviour. As long as the firm manages to stay in the market and sell some units, it will allocate resources to keep the linkage with the customer, and thus the firm will be able to increase its knowledge of the customer. At the beginning, the difference across scenarios is not significant since the development of the marketing capability depends on the volume of sales. The sales depend on the designs launched which, as we will see in the next figure, get the benefits from the R&D investments after some years; i.e.10 years under scenario A1. In figure 33, one can observe that under the conditions of scenario A3 it takes longer for the firm's marketing capability to catch up, over time, to the stable equilibrium given by the target marketing capability. This equilibrium is reached sooner under scenarios A1 and A2 than under scenario A3. In year 16 for instance, the marketing capability is 1.015 times greater under scenario A1 than under scenario A2 and 1.049 times greater than under scenario A3. These differences are reduced as the marketing capability approaches the target.

As explained in chapter 3, the marketing capability, together with the innovation capability, determine the product development process and its product quality component; these two variables are displayed in figure 34 and 35, respectively.

Figure 34

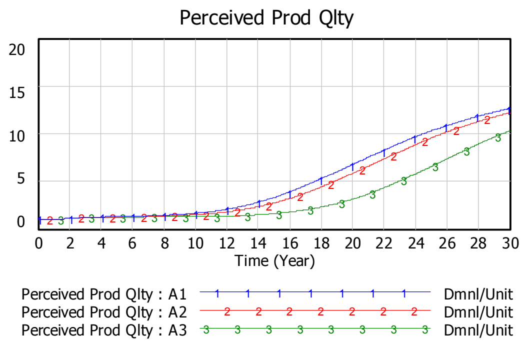
Firm's designs in production under scenarios A1, A2 and A3



The initial number of designs in production is the same in each scenario. We assumed that the firm first reaches the market place with one single product. In the first two scenarios the firm is willing to invest in R&D earlier than under scenario A3, and the firm develops faster its capabilities. As a result, it takes less time for the firm to launch new products under scenarios A1 and A2 than under scenario A3 (figure 34). In year 20, the number of designs in production is 1.23 times greater under scenario A1 than under scenario A2 and 2.66 times greater than under scenario A3. These differences are reduced as the designs in production come close to the stable equilibrium, which is attained at the maximum value of capabilities. This point is reached under scenarios A1 and A2 but is not reached under scenario A3.

Figure 35

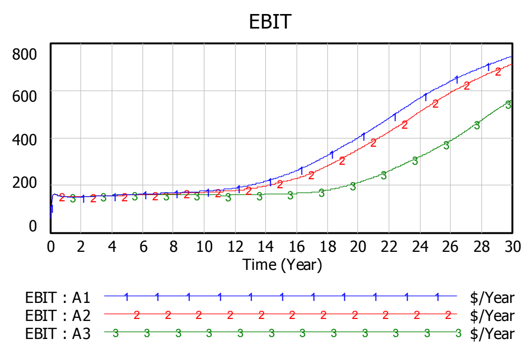
Perceived product quality under scenarios A1, A2 and A3



Likewise, the perceived product quality by the customer varies across the scenarios with a time lag (figure 35). Both the higher number of products launched and the higher product quality influence the sales, thus positively affecting the firm economic performance.

It is worth mentioning that although the direct benefits of R&D are not significant soon after the investments took place, the intangible benefits of R&D actually seem to be important. For instance, under scenario A1 the firm started to invest in R&D since it came into the market. After 6 years, the firm has slightly increased the number of designs in production (figure 34); however, the innovation capability is significantly high compared to its initial value (figure 32); it is 1.5 times greater. This accumulated capability forms the technological base that will allow the firm to speed up its product development process after year 6 (figure 34). The delay between the time that R&D investments take place and the time when direct benefits are perceived is significant. This delay is not only due to the regular delays in the product development but also due to the inertia involved in the learning process originating the capabilities.

Figure 36
Firm's EBIT under scenarios A1, A2 and A3

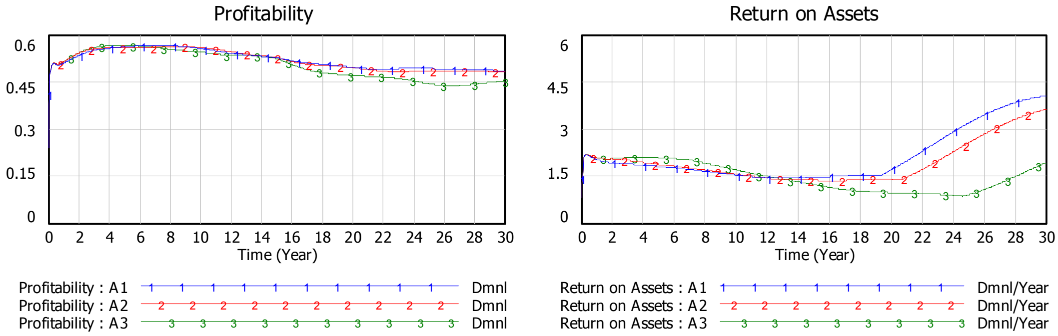


The EBIT (earnings before interests and taxes), a measurement of the firm's operating earnings, was chosen to asses the firm's economic performance. There is no significant difference in performance between scenarios A1 and A2. In contrast, the firm's performance is lower under scenario A3 than under the other two scenarios (figure 36).

The simulation results displayed for the firm's capabilities, its designs in production, and the product quality for the three scenarios illustrate that, the later the firm starts investing in R&D, the worse is its economic performance. For instance, in year 16, when the firm's EBIT under the three scenarios starts to grow apart from each other, the firm's EBIT is 1.14 times greater under scenario A1 than under scenario A2 and 1.57 times greater than under scenario A3. This result is confirmed by two indicators: 1. the firm's profitability, which is given by the ratio between the firm's EBIT and its revenues (left side in figure 37); and 2. the firm's return on assets (ROA), which is given by the ratio between the firm's EBIT and its total assets (right side in figure 37). Both the profitability and the ROA reflect the firm's lower performance under scenario A3.

Figure 37

Firm's profitability and ROA under scenarios A1, A2 and A3



The ROA clearly suggests that the longer the time before the firm starts investing in R&D, the lower are the earnings that the firm gets from the invested capital or in relation to the resources it has at its disposal. It is worth pointing out that if the firm invests in R&D early on, the firm's economic behaviour is not improved soon after the investments took place. However, this tendency switches into an increasing behaviour in the long run (right side in figure 37). To finish off, a better economic performance allows the firm to invest more resources in R&D, thus reinforcing the benefits of R&D investments.

Replication of the reference mode

As shown in chapter 3, we adopted the following statement as the reference mode:

> […] we suggest that the dynamics of the learning processes in industrial innovation systems may give rise to a virtuous circle of accumulation of capabilities if the right conditions are given. Conversely, if these conditions are not fulfilled, it is more likely that the industrial innovation system is caught in a vicious circle where the accumulation of capabilities stops at a certain level (Robledo 1997, 82).

Even though Robledo does not give a graphical representation of this reference mode, the phrase "virtuous circle" clearly suggests an exponential growth of capabilities. The phrase "vicious circle where the accumulation of capabilities stops at a certain level", suggests either a goal seeking or S-shaped growth behaviour (refer to figure 7 in chapter 3).

Before analyzing the model's replication of the reference mode, we consider important to examine what does the expression "vicious circle" (opposed to "virtuous circle") generally describe. Richardson (1999, 79) points out that:

> …the term [vicious circle] actually had its origins in formal logic. Starting from the notion of flawed, circular reasoning, the concept has come to represent an explicitly circular causal process, perceived as characteristically self-perpetuating and self-reinforcing.

One of the central concepts of the system dynamics method is that the system structure is responsible for its behaviour. A positive, or self-reinforcing, loop tends to amplify any disturbance and to produce exponential growth (Meadows 1980, 32). Furthermore, a positive loop can also create self-reinforcing decline[11].

[11] This behaviour might be produced, as well, by a multi-loop system with dominant positive feedback loops (Richardson 1995).

Regarding the system we are dealing with in this research, Robledo states the following structural relationship: "capabilities are accumulated within industrial firms, HEIs and government organizations (GIs) through cumulative development processes which depend critically on the interactions between the actors involved" (Robledo 1997, 223). This interdependence is clearly explained by Narula (2002, 795):

> …the firm –and its innovative activities- are part of a network of other firms and institutions that make up an SI [System of Innovation], and these, ceteris paribus, help determine the firm's behaviour (Narula 2002, 795)…this process is a self-reinforcing mechanism, and can lead to lock-in (796).

Ideally one would expect to observe the capabilities either grow exponentially or decay exponentially. In other words, the accumulation of capabilities among agents should follow either a virtuous or a vicious cycle. However, as it was quoted early on, Robledo claims that a vicious cycle of accumulation of capabilities is observed when the accumulation stops at a certain level[12].

A system that produces the vicious cycle stated above by Robledo is either a negative loop dominated system or a nonlinear system, at least, composed of two feedback loops (one positive and one negative) linked non-linearly. A negative, or goal-seeking, loop tends to move the system towards an equilibrium point or goal (Meadows 1980, 32). A nonlinear first-order system, for instance, represent a system exhibiting exponential growth at first, but then gradually its growth slows until the system reaches an equilibrium level (Sterman 2000); there are influences that shift the loop dominance between positive and negative loop processes (Richardson 1999, 55). This nonlinear first-order system represent a more realistic situation since no real quantity can grow (or decline) forever. There are always constraints that prevent a self-reinforcing process from expanding itself beyond all bounds (Richardson 1999, 54).

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[12] As it will be mentioned in the next sections, Robledo uses indistinctively two verbal expressions to denote the reference behaviour of a "vicious circle".

The behaviour of a nonlinear first-order system is not superior or poor per se. However, with regard to the performance of the Colombian industry, the fact that the accumulation of capabilities has stopped at a certain level seems to have a flawed connotation. The level of technological capabilities has not been sufficient to yield a proper economic development. It is in this sense that the system might be caught in a vicious cycle.

The structure of the model we built takes in account the fact that no quantity can grow without any limit. As a result, the model will exhibit neither a pure self-reinforcing growth nor a pure self-reinforcing decline in the accumulation of capabilities. On the contrary, we expect the capabilities to show an S-shaped growth.

Table 7

Parameter values for scenarios B1, B2, C1 and C2

Parameter	B1	B2	C1	C2
Initial Firm's Innovation Capability	1,0	1,0	1,0	1,0
Initial HEIs' Research Capability	3,0	3,0	6,0	6,0
Initial GIs' Policy-Design Capability	2,5	2,5	6,0	6,0
Quality Target	7,0	10,0	7,0	10,0
Productivity Target	0,3	0,5	0,3	0,5
Capital Growth	15 %	25 %	15 %	25 %
Difficulty to Learn from the Environment	0,3	1,0	0,3	1,0
Degree of Extra-sector Spillovers	0.7	0.7	0.9	0.9

In what follows, we present a set of simulations to examine the model's replication of the reference mode. This set of simulations comprises four scenarios. The parameter values changed across scenarios are summarized in table 7. Unlike in the previous section, in these scenarios the firm's willingness to invest in R&D is influenced by the learning taking place both at the GIs and at HEIs. This learning is perceived by the firm by means of the GIs policy-design effectiveness and the strength of the link between HEIs and firms.

Behaviour under scenarios B1 and B2

The scenarios B1 and B2 comprise similar assumptions to the ones made in scenarios A1 to A3. However, as we already mentioned, the firm's willingness to invest in R&D is endogenously determined in the model.

Scenarios B1 and B2, although they differ slightly from each other[13], represent the case of a new firm operating in a system of innovation with low initial science and technology capabilities. In other words, the GIs have not accumulated sufficient capabilities to design the science and technology policies necessary either to encourage business enterprises to carry out R&D investments or to encourage research activities at HEIs.

As we explained earlier, the structure governing the accumulation of capabilities at the firm, HEIs and GIs, is basically composed of two feedback loops. The positive loop represents learning as a cumulative process. The negative loop accounts for the limits to growth as the capability level approaches the 'exploitable capability'. We expect to observe that the low initial research capability accumulated at HEIs and the low policy-design capability accumulated at GIs will neither speed up the learning process governing the capabilities development nor will encourage the firm to invest in R&D early on its life span, thus negatively affecting the firm's overall performance.

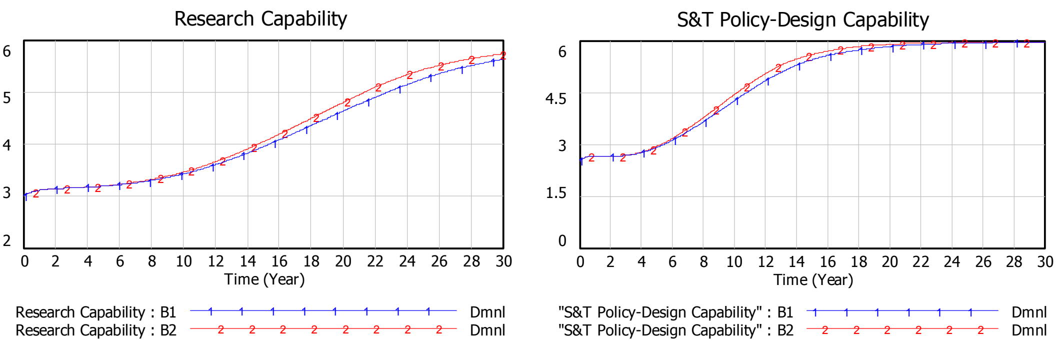
We selected the following variables to represent the simulation results under the two scenarios –each scenario is represented by the line-markers 1 or 2:

- The HEIs' research capability and the GIs' policy-design capability –figure 38.
- The firm's innovation capability –figure 39.
- The firm's designs in production –figure 40.
- The perceived product quality and price –figure 41.
- The firm's earnings before interests and taxes (EBIT) –figure 42.
- The firm's return on assets (ROA) –figure 42.

[13] We will describe the differences among these scenarios along with the description of the behaviour obtained.

Figure 38

HEIs' research and GIs' policy-design capabilities under scenarios B1 and B2

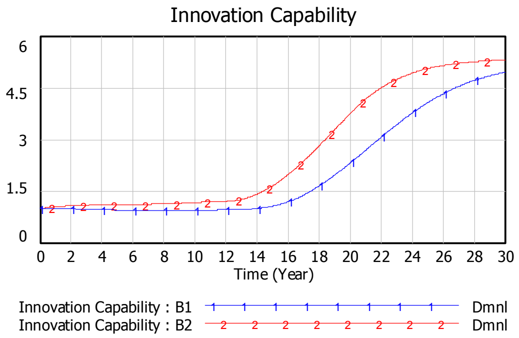


At first sight, we observe that both HEIs and GIs manage to increase their capabilities (figure 38); the firm also does. There is a lag between the developments of the capabilities under each of these two scenarios. Under scenarios B1, the firm is willing to invest in R&D in year 12; under scenario B2 the firm first invests in year 11. The reason for this late decision, under both scenarios, is that both HEIs and GIs fail to accumulate sufficient capabilities in order to encourage the firm to invest in R&D early on its life span. Furthermore, the low level of the firm's innovation capability does not speed up either the development of capabilities at the other agents.

After the firm starts investing in R&D, the development of the firm's innovation capability takes approximately 4 years under scenario B1 and 3 years under scenarios B2 (figure 39, next page). In fact, during the first 10 years, the positive feedback loop dominates the growth of the firm's innovation capability under scenario B1 causing the innovation capability to decay. Therefore, what or who is responsible for the change in the development path of the firm's innovation capability?

Figure 39

Firm's innovation capability under scenarios B1 and B2



Although the firm is not helping HEIs and GIs to develop their capabilities, the interaction between these two agents enables them to build up their capabilities to and beyond the threshold necessary to encourage the firm, after all, to invest in R&D. Once the firm starts to allocate resources to extend its innovation capability, the positive feedback loop still dominates the capability growth though, on this occasion, it makes the innovation capability to grow. Later on, as the innovation capability approaches its limits to growth, it goes through a nonlinear transition from exponential growth to equilibrium. The negative loop dominates the capability development thus slowing growth down until the innovation capability reaches the maximum quantity (figure 39).

The difference between the assumptions made under scenario B1 and B2 is the higher quality, productivity and capital expansion targets faced by the firm under scenario B2. In addition, the difficulty to learn from the environment is also greater under scenario B2 than under scenario B1. These differences are due to the fact that the firm might have to compete with multinational firms. These firms invest in R&D regardless of the level of capabilities accumulated by the national system of innovation within which the multinational branch operates. In fact, the branch does not necessarily invest in R&D since it can benefit from the investments made in branches located in other countries. Three main issues regarding the model behaviour under scenario B2 are worth explaining:

1. Unlike in scenario B1, the firm's innovation capability during the first 12 years does not decay. The capability seems to grow at a

decreasing rate; even though it is not possible to determine which loop dominates the behaviour (see figure 39). Before year 12 the firm's innovation capability is higher under scenario B2 than under scenario B1. This is due to the higher technology adaptation effort made under scenario B2 in order to comply with the performance targets. The effort helps to speed up the development of the innovation capability (chapter 3, p. 61)[14]. This advantage in the capability under scenario B2 is amplified by the reinforcing loop representing the learning process. For instance, in year 16, the firm's innovation capability is 1.66 times greater under scenario B2 than under scenario B1. It is reasonably logical to observe a faster evolution of the innovation capability under scenario B2 compared to scenario B1 (figure 39).

2. It is less difficult to learn from the environment under scenario B1 than under scenario B2. We might expect that the firm's environment under scenario B1 will ease the firm's accumulation of capabilities and will cause the firm's innovation capability to increase sooner than under scenario B2. This does not happen. On the contrary, the firm's innovation capability develops fast under scenario B2 (figure 39). As we explained in chapter 3, the reason behind this behaviour is that the ease with which learning may occur affects the firm's learning in two ways.

   First, the greater the difficulty to learn from the environment, the larger is the marginal impact of the firm's own R&D on the firm's absorptive capacity. In other words the firm's own R&D is critical to the maintenance and development of the capacity to absorb new knowledge. This is a positive effect.

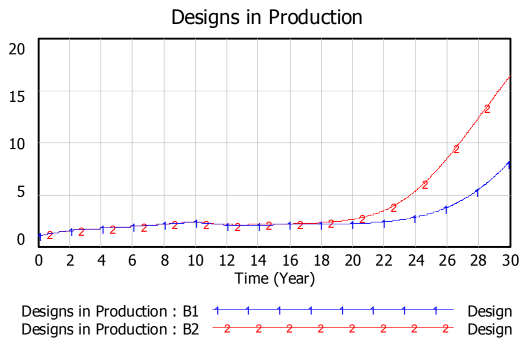
   Second, the greater the difficulty to learn from the environment, the less knowledge the firm assimilates of the external knowledge for a given R&D effort. This is a negative effect. Under scenario B2, the positive effect counteracts the negative effect of being within an

[14] This behaviour was also observed under scenario A3.

environment that hinders learning. Hence, the firm's innovation capability develops faster under scenario B2 than under scenario B1 (see figure 39).

Figure 40

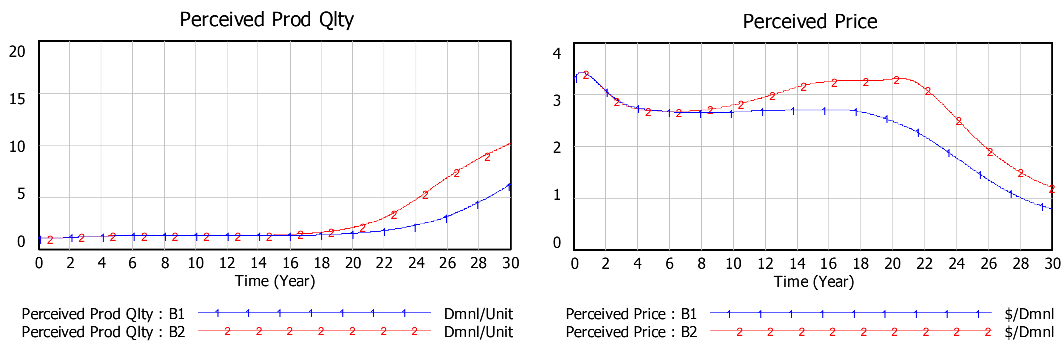
Designs in production under scenarios B1 and B2



3. The overall firm's behaviour, not only in the accumulation of capabilities but also in the designs in production (figure 40) and the product quality (left side in figure 41), is superior under scenario B2 than under scenario B1. However, the firm's economic performance, surprisingly, is worse under scenario B2.

Figure 41

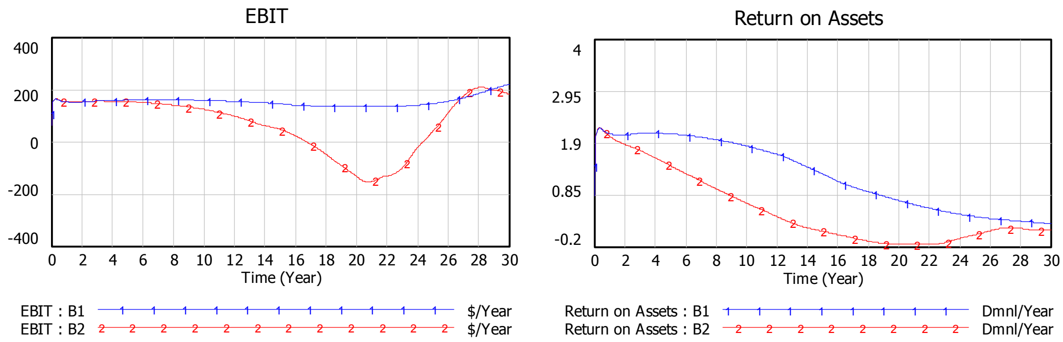
Perceived product quality and price under scenarios B1 and B2



Although the firm develops faster its innovation capability, it does not happen as early as the firm needs it to comply with the demanding conditions of the environment. Since under scenario B2, the quality, productivity and growth (capital expansion) targets are high, the firm has high operational costs. The perceived product price, which is given by the ratio between the product price and the product quality, reflects this fact. For instance, in year 16, the perceived product price is 1.2 times greater under scenario B2 than under scenario B1. The perceived product price is generally no lower under scenario B2 than under scenario B1 (right side in figure 41). Both the EBIT and the ROA also reflect the firm's lower performance (figure 42).

Figure 42

Firm's EBIT and ROA under scenarios B1 and B2



It follows that a firm that faces high performance standards and operates in a system of innovation with low science and technology capabilities, is at a higher risk to go out of business than if the same firm, embedded in the same environment, has to face less demanding conditions. The sooner the firm is encouraged to invest in R&D the better.

As a final comment, it is worth mentioning that we simulated other scenarios under which the system of innovation has lower innovation capabilities than under scenarios B1 and B2. Under those scenarios, the capabilities of the actors making up the system of innovation decay from their initial values. The rate of acquisition of new knowledge was lower than the rate at which knowledge becomes obsolete. As a result, we neither show nor analyze those scenarios. It is unlikely to observe that the innovation capabilities of the system of innovation decay from the level they already reached.

Behaviour under scenarios C1 and C2

Under scenarios C1 and C2, the firm's willingness to invest in R&D is also endogenously determined in the model. Although these scenarios differ slightly from each other[15], they represent the case of a new firm operating in a system of innovation with higher initial science and technology capabilities than under scenarios B1 and B2. In addition, the level of spillovers is also higher. This reflects the fact that in a system of innovation with high capabilities, the external benefits received free from research activities taking place at GIs and HEIs is high. The level of spillovers determines the 'exploitable capability'.

We expect to observe that the accumulation of capabilities at HEIs, GIs and the firm evolves faster and reaches a higher level under scenarios C1 and C2 than under scenarios B1 and B2. The fast development of the HEIs' and GIs' capabilities should encourage the firm to invest in R&D early on its life span, thus positively affecting the firm's overall performance.

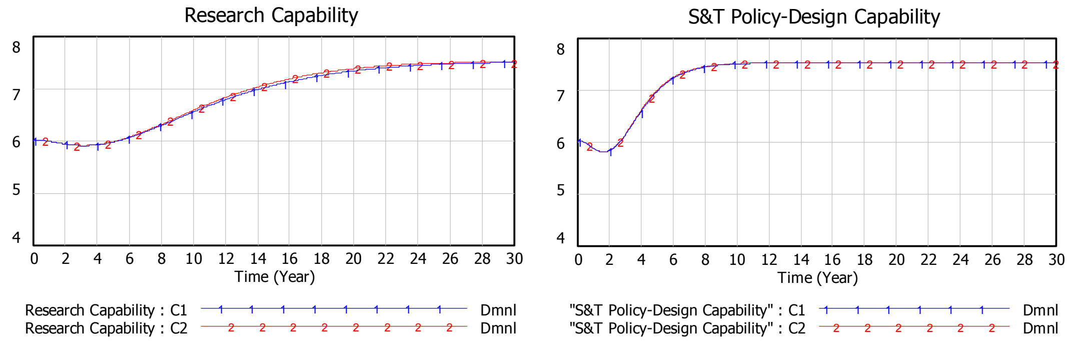
We selected the following variables to represent the simulation results under the two scenarios –each scenario is represented by the line-markers 1 or 2:

- The HEIs' research capability and the GIs' policy-design capability –figure 43.
- The firm's innovation capability –figure 44.
- The firm's designs in production and the perceived product quality –figure 45.
- The firm's earnings before interests and taxes (EBIT) and the perceived product price –figure 46.
- The firm's return on assets (ROA) –figure 47.

[15] We will describe the differences among these scenarios along with the description of the behaviour obtained.

Figure 43

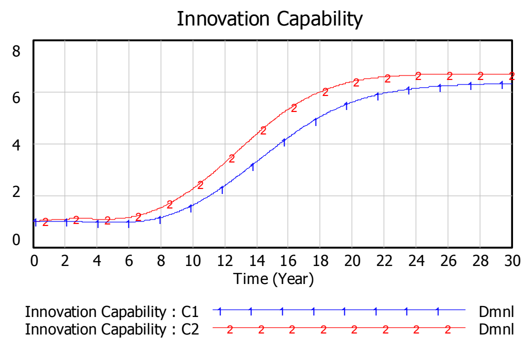
HEIs' research and GIs' policy-design capabilities under scenarios C1and C2



Given that, at the beginning of the simulation, HEIs and GIs have accumulated higher capabilities under scenarios C1 and C2 than under scenarios B1 and B2, the accumulation of capabilities unfolds faster. In other words, the technological base necessary for the further development of capabilities is bigger, thus the learning process regulating the accumulation of capabilities evolves more rapidly. The HEIs' research capability reaches the equilibrium -given by the exploitable capability- approximately in year 20 (left side in figure 44), which is more than 10 years earlier than under scenarios B1 and B2. The GIs' policy-design capability approaches the equilibrium approximately in year 8 (right side in figure 44), which is 8 years earlier than under scenarios B1 and B2.

Figure 44

Firm's innovation capability under scenarios C1 and C2



Surprisingly, the development of both the HEIs' capability and the GIs' capability does not seem to be sensitive to the differences in the firm's innovation capability across the two scenarios (figures 43 and 44)[16]. The interaction between HEIs and GIs is stronger in comparison to both the interaction between HEIs and the firm and between GIs and the firm. As a result, the interaction between HEIs and GIs reinforces the development of their own capabilities independent from the firm's capability evolution. In contrast, the development of the firm's innovation capability does depend on the evolution of the HEIs' and GIs' capabilities.

The fast development of the HEIs' and GIs' capabilities encourages the firm to invest in R&D early on its life span. The firm is willing to invest in R&D in year 3 under the two scenarios. After this year, the development of the firm's innovation capability takes approximately 7 years under scenario C1, and 5 years under scenario C2 (figure 44), which is sooner than under the scenarios B1 and B2 explained in the previous section.

There is a lag between the innovation capabilities obtained in each scenario (figure 44). During the first 6 years, the positive feedback loop dominates the growth of the firm's innovation capability under scenario C1, causing – as under scenario B1- the innovation capability to decay (figure 44). This fact does not occur under scenario C2.

The difference between the assumptions made under scenario C1 and C2 is the higher quality, productivity and capital expansion targets faced by the firm under scenario C2. In addition, the difficulty to learn from the environment is higher under scenario C2 than under scenario C1. These differences are due to the fact that the firm might have to compete with multinational firms (like under scenario B2). Three main issues regarding the model behaviour under scenario C2 are worth explaining:

1. Unlike in scenario C1, the firm's innovation capability is not significantly reduced before the firm starts investing in R&D. This is due to the higher technology adaptation effort made under scenario C2 in order to comply with the performance targets. The effort helps

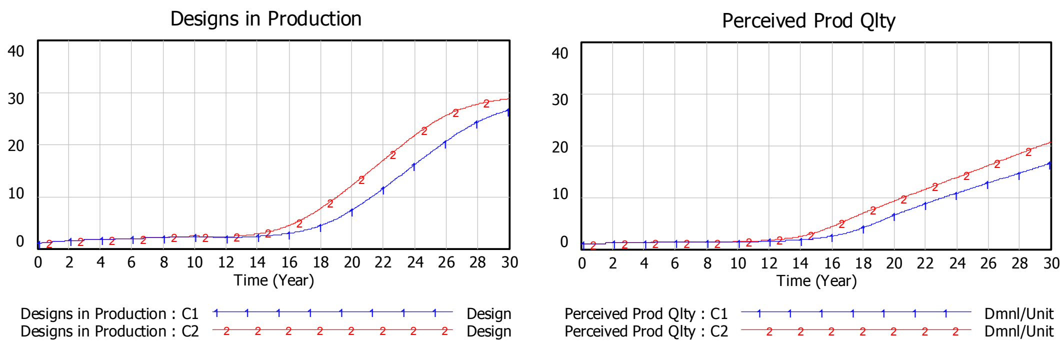
[16] However, the development of both the HEIs' capability and the GIs' capability behaves expectedly when the firm's innovation capability is zero. The development of both the HEIs' capability and the GIs' capability is sensitive to extreme conditions.

to speed up the development of the innovation capability. Before year 3 the firm's innovation capability is higher under scenario C2 than under scenario C1[17]. This advantage in the capability under scenario C2 is amplified by the reinforcing loop representing the learning process. It is reasonably logical to observe a faster evolution of the innovation capability under scenario C2 compared to scenario C1.

2. It is less difficult to learn from the environment under scenario C1 than under scenario C2. Under scenario C2, the positive effect counteracts the negative effect of being within an environment that hinders learning[18]. Hence, the firm's innovation capability develops faster under scenario C2 than under scenario C1 (figure 44).

Figure 45

Designs in production and perceived product quality under scenarios C1 and C2



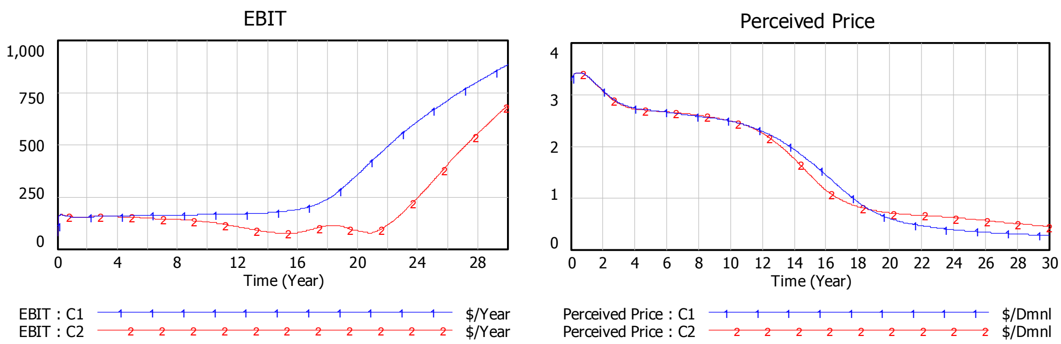
3. The overall firm's behaviour, not only in the accumulation of capabilities but also in the designs in production (left side in figure 45) and the product quality (right side in figure 45), is superior under scenario C2 than under scenario C1. According to the EBIT, the firm's economic performance is worse but it is positive under scenario C2 than under scenario C1 (left side in figure 48). Since the firm has to comply with high quality, productivity and growth (capital expansion) targets, the firm's operational costs sufficiently rise in the last third of the simulation so as to increase the perceived product price. For instance, in year 24, the perceived product price is 1.62

[17] This behaviour is also observed under scenario B2.
[18] These effects were explained in the previous section for scenarios B1 and B2.

times greater under scenario C2 than under scenario C1. The perceived product price is shown in the right side of figure 46.

Figure 46

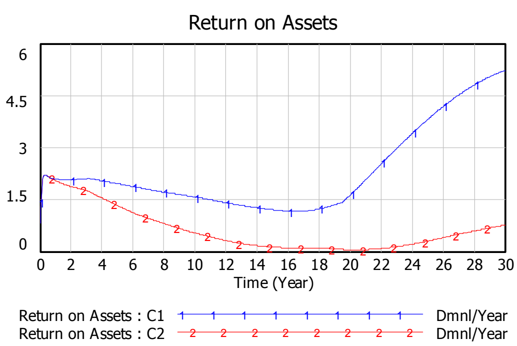
Firm's EBIT and perceived product price under scenarios C1 and C2



Regarding the ROA, the firm's economic performance under scenario C1 is better than under scenario C2 (figure 47). This indicates that the earning the firm gets in comparison to the resources that it has at its disposal are lower under scenario C2 than under scenario C1. If the firm has to comply with high performance standards, it is less efficient to generate earnings under scenario C2 than under scenario C1. This might not be the case of every firm operating within a system of innovation with higher initial science and technology capabilities and facing high performance standards. The simulation results we obtained represent the case of a company that has to comply with the performance targets described by the set of parameter values of scenario C2.

Figure 47

Firm's ROA under scenarios C1 and C2



Comparison between scenarios B2 and C2

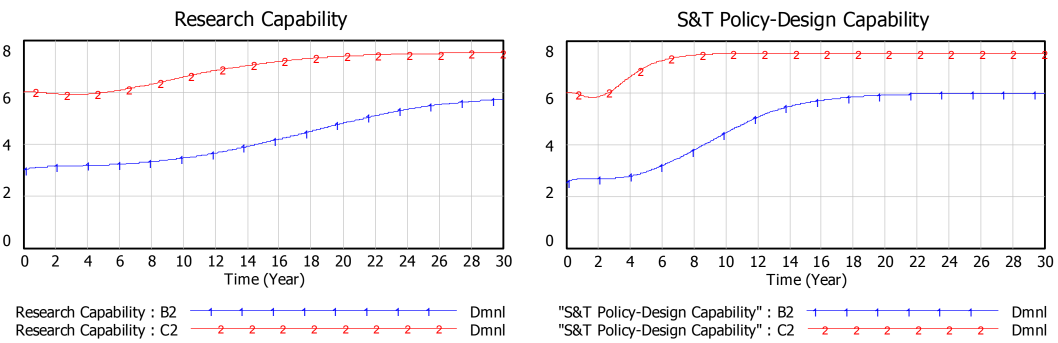
As mentioned in the previous sections, under both scenarios B2 and C2, the firm has to comply with demanding conditions –the difficulty to learn from the environment is high; thus the firm's own R&D is critical to the maintenance and development of the capacity to absorb new knowledge. In addition to that, the quality, productivity and growth (capital expansion) targets are also high. However, scenario B2 and C2 differ in that scenario B2 represents the case of a new firm operating in a system of innovation with lower initial science and technology capabilities than scenario C2. In addition, the level of spillovers is lower in scenario B2 than in scenario C2.

We selected the following variables to represent the comparison between the simulation results under these two scenarios –scenario B2 and C2 are represented by the line-markers 1 and 2, respectively:

- The HEIs' research capability and the GIs' policy-design capability –figure 48.
- The firm's innovation and marketing capabilities –figure 49.
- The firm's earnings before interests and taxes (EBIT) –figure 50.
- The firm's return on assets (ROA) –figure 51.

Figure 48

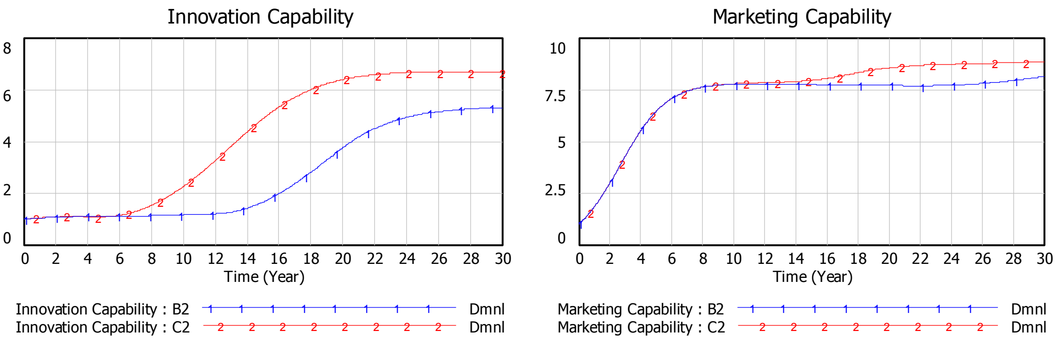
HEIs' research and GIs' policy-design capability under scenarios B2 and C2



Given that, at the beginning of the simulation, HEIs and GIs have accumulated higher capabilities under scenario C2 than under scenario B2, the development of capabilities unfolds faster. In fact, since the level of spillovers is higher under scenario C2 than under scenario B2, both the HEIs' research capability (left side in figure 48) and the GIs' capability (right side in figure 48) also reach a higher level under scenario C2 than under scenario B2. For instance, at the end of the simulation time, when the difference between the capabilities under the two scenarios is smallest, the HEIs' research capability is 1.30 times greater under scenario C2 than under scenario B2. The GI's policy-design capability is 1.26 times greater under scenario C2 than under scenario B2.

Figure 49

Firm's innovation and marketing capabilities under scenarios B2 and C2



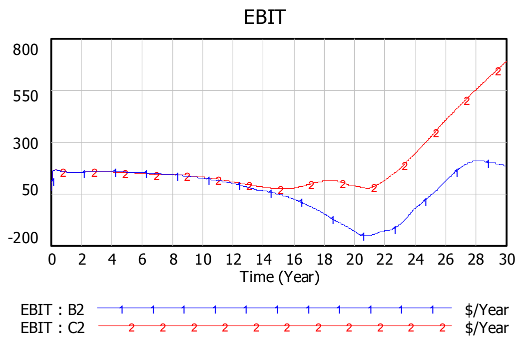
The fast development of the HEIs' and GIs' capabilities under scenario C2 encourages the firm to invest in R&D early on its life span. The firm first invest in R&D in year 3 under scenario C2, which is 6 years earlier than under scenario B2. After this, the development of the firm's innovation capability takes approximately 3 years under scenario C2 (left side in figure 49). The capability development is accomplished 6 years earlier than under scenario B2. This advantage in the development of the innovation capability under scenario C2 is amplified by the reinforcing loop representing the learning process. It is reasonably logical to observe a faster evolution of the innovation capability under scenario C2 compared to scenario B2. Also, since the capability evolves faster, it approaches the equilibrium sooner.

Regarding the marketing capability, in the right side in figure 49 one can observe that the difference between scenarios B2 and C2 is not as significant as with the innovation capability. However, the development corresponds to the expected behaviour. At the beginning of the simulation time, the difference between scenarios is not significant since the development of the marketing capability depends on the volume of sales. As we described in the previous sections, the sales depend on the designs launched which benefit from the R&D investments after some years. In figure 49, one can observe that under the conditions of scenario B2, it takes longer for the firm's marketing capability to catch up, over time, to the stable equilibrium given by the target marketing capability. This equilibrium is reached sooner under scenario C2 than under scenario B2.

The higher firm's innovation and marketing capabilities under scenario C2 influence both the number of products launched and the product quality, thus positively affecting the firm's economic performance. A better economic performance allows the firm to invest more resources in R&D and marketing, thus reinforcing the development of the firm's capabilities.

Figure 50

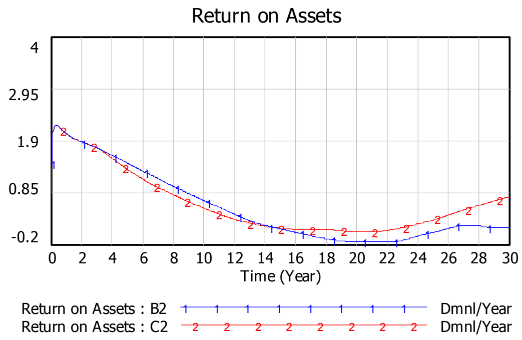
Firm's EBIT under scenarios B2 and C2



The overall firm's behaviour, not only in the accumulation of capabilities but also in the designs in production and the product quality, is superior under scenario C2 than under scenario B2. The firm's EBIT reflects the firm's superior performance under scenario C2 over the entire simulation time (figure 50). At the end of the simulation time, when the difference between the firm's EBIT under the two scenarios is greatest, the firm's EBIT is 3.7 times greater under scenario C2 than under scenario B2. The firm's ROA (figure 51) shows that the firm's economic performance is better under scenario C2 just towards the end of the simulation time.

Figure 51

Firm's ROA under scenarios B2 and C2



The comparison between scenarios B2 and C2 illustrates that a weak system of innovation, in which neither GIs accumulate sufficient capabilities necessary to design effective science and technology policies nor HEIs accumulate the research capabilities necessary to interact with the industry, will not encourage the private firm to allocate resources to R&D early on its life span. As a result, the firm does not develop its innovation capability either and it is unable to support the development of capabilities at the other agents. It is in this sense that the accumulation of capabilities in the system of innovation is caught in a vicious cycle. This situation has significant economical consequences when the firm copes with high performance standards in the market place. The sooner the firm is encouraged to invest in R&D the better.

Research contribution

As mentioned before, we appreciate the contribution of this thesis to the discussion in the literature about the innovation process in Colombia as being threefold: 1. it should offer a comprehensive theory that attempts to explain both the poor innovation performance of the Colombian industry and its scarce level of the technological capabilities; 2. it should improve the understanding of the accumulation of the capabilities affecting the innovation performance observed both at the firm level and at higher education and government institutions; and 3. it should increase the accessibility of Robledo's research to entrepreneurs, science and technology decision makers and other researchers.

First contribution: it should offer a comprehensive theory

Richardson (1999, 295) claims that "feedback scholars…have in fact argued for formal models on the grounds that even words can be an inappropriate representation, leading to false conclusions about the underlying causes of the behaviour of complex systems". Furthermore, as Forrester indicates (1961, 44), "verbal statements need to be clarified by translating them into less ambiguous forms and into a form that will allow us to experiment with the implications of the statements already made".

Robledo forcefully argues that the understanding of the poor innovation performance of the Colombian industry resides in the awareness or decision-making stage of the innovation process. In other words, in the stage in which firms become aware of a problem or an opportunity, and they make either innovation favouring or innovation avoiding decisions.

The value of this thesis lies in the insights gained by transforming a verbal model into a quantified simulation model with the aid of the system dynamics method. We found that system dynamics serves as a framework to organize and filter knowledge thus leading to a better understanding of complexity. It is in this sense that this thesis offers an extensive comprehension of both the poor innovation performance of the Colombian industry and its scarce level of the technological capabilities. It is expected that a better understanding of the problem will improve decision making and future policy design regarding R&D.

The qualitative model offered by Robledo points out two important issues: 1. the innovation paradigm influences the willingness of the system of innovation to carry out R&D as a strategic path of development; and 2. the structure of the system of innovation is characterized by the interactions among HEIs, GIs, and the industry. Their interactions comprise four feedback loops and yield the learning process through which the three agents accumulate innovation related capabilities.

As we mentioned, Robledo asserts that innovation favouring decisions will produce a "virtuous circle" of accumulation of capabilities within the system of innovation. In contrast, innovation avoiding decisions produce a "vicious circle" that either prevents the organizations from accumulating capabilities or causes the accumulation to stop at a certain level[19]. Furthermore, the level of capabilities influences the R&D decision itself.

Robledo refers indistinctly to two different patterns of behaviour when the accumulation of capabilities is governed by the "vicious circle". It follows that it is either trivial to distinguish them as different patterns of development and Robledo uses the expression "vicious circle" just to denote a general closed loop of causal influences, or it is difficult to infer the emergent behaviour of the intertwined relationship among the system's agents. In either case, the need to translate verbal statements into a less ambiguous form is obvious. As they are expressed by Robledo, the verbal expressions characterizing "vicious circle" in the accumulation of capabilities leave open questions such as: Under which conditions each pattern of behaviour takes place? Are they produced by the same underlying structure? Which reasons confer a flawed connotation to either pattern of behaviour? The translation of a verbal model into a formal model forces us to make a distinction between the two types of behaviour and to determine the structure originating them.

As mentioned earlier in this chapter, with the aid of the system dynamics method, we identified the following issues regarding the relationship between structure and behaviour:

- A positive, or self-reinforcing, loop produces exponential growth and can also create self-reinforcing decline. Thus, both a virtuous and a vicious cycle can be produced by a positive feedback loop.
- The accumulation of a quantity that stops at a certain level, is produced either by a negative loop dominated system or a nonlinear system, at least, composed of two feedback loops (one positive and one negative) linked non-linearly. For instance, a nonlinear first-order

[19] Although Robledo uses indistinctly both sentences to denote the emergent behaviour of a vicious cycle, we adopt the second expression "accumulation stops at a certain level" as the reference mode of the vicious cycle (see chapter 3). The reason to have chosen the second expression is that Robledo uses it more often than the first one.

system displays S-shaped growth and represents a more realistic situation than a positive dominated loop, since no real quantity can grow (or decline) forever. Nonetheless, the behaviour of a nonlinear first-order system is not superior or poor per se.

With regard to the innovation performance of the Colombian industry, it is not plausible to observe neither pure exponential growth nor pure exponential decay in the accumulation of innovation capabilities. There are factors that constraints a self-reinforcing process from expanding the accumulation of capabilities beyond all bounds either linked to a developing economy, such as the accessibility of information and the educational level, or akin to the properties of knowledge such as tacitness and obsoleteness. As a result, the structure of the model we built takes in account the fact that no quantity can grow without any limit.

We consider that both the pace of and the limits to growth in the development of capabilities are the reasons that confer a flawed connotation to the evolution of the innovation related capabilities of a system of innovation. In the Colombian case, both the pace and the level reached by the technological capabilities have not been sufficient to yield a proper economic development of the industry. It is in this sense that the system might be caught in a vicious cycle.

To finish off, it is important to mention that Robledo does not define a clear time frame for the perception of the problem. This time frame is crucial for the problem assessment and analysis. For instance, regarding the non-linear system underlying the accumulation of capabilities, we can observe pure exponential growth if the time horizon is sufficiently short so as to prevent us to perceive how the capability growth slows down as the capability approaches its maximum value. Furthermore, we can witness a stagnant development of capabilities just after the learning process was initiated. The formalization of the verbal model made necessary the definition of a time horizon.

Second contribution: it should improve the understanding of the problem

Robledo defines innovation as a learning process that benefits not only from the firm's internal learning process underlying the accumulation of capabilities but also from the firm's interaction with HEIs and GIs. Furthermore, he asserts that the low level of innovation capabilities accumulated by the Colombian industrial innovation system, the fact that firms are not willing to invest in R&D and the interactive learning regulating the accumulation of capabilities are inhibiting the further development and accumulation of innovative capabilities.

This thesis illustrates that the low level of innovation capabilities accumulated within the system of innovation is actually delaying its own development. As a result, the threshold of accumulated capabilities at HEIs and GIs needed in order to encourage the private firm to invest in R&D might take decades to be reached, as we showed in the previous sections. This fact is indirectly suggested by Narula (2002, 798) when he discusses about the linkages among the actors of a system of innovation:

> "Such linkages [linkages within the SI] are both formal and informal, and will probably have taken years –if not decades- to create and sustain.

Although the low level of capabilities has delayed its own development, the learning process underlying the accumulation of capabilities is currently taking place. As we examined with the different scenario simulations performed, the positive loop dominating the early development of capabilities has the ability to amplify any disturbance or any initial capability developed by the system of innovation.

Robledo concludes that a minimum level of capabilities is required for the virtuous cycle of development to gain momentum. This fact was clearly observed in the simulations. The interactive learning system between the firm, HEIs and GIs will necessarily trigger the development of their capabilities if some capability has been accumulated in HEIs or GIs until the present time. If the system of innovation has accumulated little capabilities so far, their further accumulation will evolve at a very slow pace. As a result, when the level of capabilities will be sufficient to encourage the firm to invest in R&D, it might be late and probably the firm will have not survived in the meanwhile, since it failed to develop the capabilities necessary to compete in the market.

In addition, we found that among the four feedback loops that, according to Robledo, govern the interactions among HEIs, GIs, and the industry, the interaction between HEIs and GIs is stronger in comparison to both the interaction between HEIs and the firm and between GIs and the firm. As a result, the interaction between HEIs and GIs reinforces the development of their research capability and policy-making capability rather independent from the firm's capability accumulation. In contrast, the development of the firm's innovation capability does depend on the evolution of the HEIs' and GIs' capabilities.

The fact that the interaction between HEIs and GIs reinforces the development of their own capabilities rather independent from the firm's capability evolution reflects the crucial role that they have to play in the firm's innovation process. However, this is not consistent with the conclusions attained in the literature regarding the system made up by government, HEIs and industry. According to the literature on the triple-helix model of university, industry, and government relations (Etzkowitz and Leydesdorff 2000), every actor plays a key role in the innovation process. In fact, in some cases each actor can take the role of the other despite the different tasks they have to perform.

The actors that make up the system of innovation have to be aware not only of the role they play in the interactive learning regulating the accumulation of capabilities but also of the inertia embedded in the learning process itself. The role that HEIs and GIs have to play in the firm's willingness to invest in R&D is crucial, as well as the support –through policies- that they have to give to firms in order to sustain the firm's willingness to invest in R&D until a long time has elapse and the firm gets the benefits from their investments in R&D. This fact reflects one of the conclusions reached by Robledo (1997, 348), as he denotes it:

> "The need for a learning approach to innovation and technological change *must* be recognised by key actors of the innovation process (industrialists, academics and policy-makers). The obvious condition to learn is to recognise the need to do so and to be willing to make the sustained efforts that learning requires".

In addition, the actors have to understand that the system interdependence is not "good" or "bad" per se as long as every actor is aware of the system structure and its own role. Each actor has to understand that within a system of innovation not only the benefits of accumulating capabilities spill over the other actors, but also the negative aspects. A better understanding of the system structure is clue for a more efficient policy-design (Sterman 2000; Forrester 1994). This is particularly important for the Colombian system of innovation since, as Robledo claims, there are inherent time lags in conveying the insights of innovation analysts to policy-makers making up the system.

We consider that if innovation is a learning process closely linked with the development of capabilities different to those necessary for the production process, it is logical to observe that the firm will fail to develop any capability to support innovation unless it makes direct investments in R&D. In reality, and relating this research to studies regarding the technology dependence of developing countries, we found a key explanation or verification of previous conclusions reached in the literature (Hansen et al 2002; Nelson and Pack 1998; Pack 1986; Contractor 1983; Buckley 1979; Mytelka 1978). When a firm is unable to innovate it has to license products developed else where. As a result, the firm does not have the possibility to develop the capability necessary to neither produce the products already licensed nor to improve their quality. Furthermore, in case that it is cheaper to pay for licenses than investing in R&D, the firm will stay far from the possibility to develop the capabilities necessary not only to develop new products but also to interact with the GIs and HEIs. The sooner the firm is encouraged to invest in R&D the better; actually this is even more convenient if the firm has to comply with high performance standards.

As a final comment, we pointed out in the previous sections that the delay between the time that R&D investments take place and the time when direct benefits are perceived is significant. As a result, we recognizes that given the intangible nature of capabilities and its effect on the innovation process, the actors making up the system of innovation maybe reluctant to invest in R&D. This fact highlights that industrialists, academics and policy-makers need to do both acknowledge that innovation is a learning process and estimate the intangible benefits of R&D.

Third contribution: it should increase the accessibility of Robledo's research

Although the relationship between R&D and economic development is highly unquestioned (Aghion and Howitt 1999; Nelson and Pack 1998; Solow 1994; Romer 1994), the attributes of that relationship is a matter not yet clarified. Based on the research done by Robledo (1997) we established an initial formal model of the underlying causes explaining the poor innovation performance of the Colombian capital goods industry and the role played by Higher Education Institutions (HEIs) and the Government Institutions (GI) in the process of accumulation of innovation capabilities. By proposing formal relationships between the variables making up the verbal description of the problem we leave the relationships exposed to be questioned by other researchers beyond the qualitative statements. As said by Forrester (1994, 63), "assigning a number does not alter the accuracy of the original statement, but it does create a much more explicit basis for communication".

Likewise, this first formal representation of the research done by Robledo could be questioned by the actors that make up the system of innovation itself - industrialists, academics and policy-makers. They could examine the assumed relationships among the structure components and judge their plausibility. They could add also dynamics or assumptions that were omitted by both Robledo and us. Hence, this research might help to attain one of the purposes of Robledo's research: to highlight the roles that firms, HEIs and the government have to play in the performance of the system of innovation. This might be also the first step to improve policy-design regarding science and technology.

To finish off, this study suggest that a careful analysis of an existing theory can be very generative, helping to test and extend verbal theories and provide new explanations for empirical results about the complex phenomena of innovation within a developing economy.

CONCLUSIONS

We intended to translate into a formal model, the underlying causes claimed by Robledo (1997) to be responsible for the poor innovation performance of the Colombian capital goods industry; and to test, using computer simulation, whether Robledo's theory actually leads to the particular behaviour he describes.

The conclusions we reached refer not only to this purpose but also to the challenges we cope with during the research process. These challenges might be opportunities for further research.

We found that Robledo refers indistinctly to two different patterns of behaviour when the accumulation of capabilities is governed by the "vicious circle". It follows that it is either trivial to distinguish them as different patterns of development, and Robledo uses the expression "vicious circle" just to denote a general closed loop of causal influences, or it is difficult to infer the emergent behaviour of the intertwined relationship among the agents making up the system of innovation (HEIs, GIs and the firm). In either case, the need to translate verbal statements into a less ambiguous form was evident. Indeed, the translation of a verbal model into a formal model uncovered relationships not yet studied, but necessary to be analyzed in the Colombian context. Among the important relationships, especially relevant were the relationship between the high competence of the labour force and product quality improvements, the learning curves present in the capital good industry, measurement or estimation of intangible assets, like capability, labour competence, which are closely linked to the innovation process.

This thesis made a formal representation of the research done by Robledo. This first formal model can be questioned by the actors (HEIs, GIs and industrialist) making up the system of innovation itself. They can examine the assumed relationships among the structure components and judge their plausibility. They can also add dynamics or assumptions that were omitted by both Robledo and us. Hence, this research might help to attain one of the purposes of Robledo's research: to highlight the roles that firms, HEIs and the government have to play in the performance of the system of innovation. This might be also the first step to improve policy-design regarding science and technology.

Robledo claims the Colombian capital goods innovation system to be trapped in a Gordian knot, formed by three vicious circles, which inhibit the generation and accumulation of innovation capabilities within the system. In our intent to test, using computer simulation, whether Robledo's theory actually leads to the particular behaviour he describes, we found that a weak system of innovation will not encourage the private firm to allocate resources to R&D early on its life span. A weak system of innovation is one in which neither GIs accumulate sufficient capabilities necessary to design effective science and technology policies nor HEIs accumulate the research capabilities necessary to interact with the industry. As a result, the firm does not develop its innovation capability and is unable to support the development of capabilities at the other agents.

We believe that it is in this sense, of a weak system in which firms do not invest in R&D, that the accumulation of capabilities in the system of innovation is caught in a vicious cycle, as Robledo describes it. This situation has significant economical consequences when the firm copes with high performance standards in the market place. The sooner the firm is encouraged to invest in R&D the better. Otherwise, the firm will not recognize new opportunities neither will it have the economic resources to undertake R&D investments. The vicious cycle is reinforced all the way around.

Robledo concludes that a minimum level of capabilities is required for the virtuous cycle of development to gain momentum. This fact was clearly observed in the simulations of the model we have built. The interactive learning system between the firm, HEIs and GIs will necessarily trigger the development of their capabilities if some capability has been accumulated in HEIs or GIs until the present time. If the system of innovation has accumulated little capabilities so far, their further accumulation will evolve at a very slow pace. As a result, when the level of capabilities will be sufficient to encourage the firm to invest in R&D, it might be late and probably the firm will have not survived in the meanwhile, since it failed to develop the capabilities necessary to compete in the market.

We recognize the fact that given the intangible nature of capabilities and its effect on the innovation process, the actors making up the system of innovation maybe reluctant to invest in R&D. This fact highlights that industrialists, academics and policy-makers need to both acknowledge that innovation is a learning process and estimate the intangible benefits of R&D. In particular, academics and policy-makers should encourage the firms to consider R&D investments at the core of their business strategy.

The purposive commitment of resources by every actor making up the system of innovation is the only way to break the vicious cycle in which the innovation system is trapped. Hence, it is crucial to ease the comprehension of the role that every actor has to play in the system. The simulations we did showed that the interaction between HEIs and GIs reinforces the development of their own capabilities rather independent from the firm's own capability accumulation. This reinforcement reflects the crucial role that HEIs and GIs have to play in the firm's innovation process. Likewise, if one of the three actors fails to develop its capabilities, the technological efforts made by the others are futile. This supports the recommendations regarding the role played by HEIs and GIs in the innovation and the role of the industrial firm as a locus of learning, posed by the Millennium Development Goals (UN 2005).

The data given by Robledo (1997) is not a sufficiently complete basis for translating his research findings into a system dynamics model. Nonetheless, with the aid of theory and surveys related to our research field, we made it possible to address his research using the system dynamics method and to fill in the gaps between the statements he makes and the system's structural relationships. In addition, we recognized that it is necessary to carry out fieldwork, not only for this research but also to make Robledo's research conclusive. For instance, we dealt with the fact that there is still no suitable set of indicators by which capabilities can be measured objectively, and which could serve as a basis for a systematic assessment of the contribution of this variable to the innovation and development process. The lack of measurement does not undermine the validity of research so far, but it reduces its usefulness.

We dealt with the difficulty to integrate the micro level represented by the firm and the macro level represented by GIs and HEIs. This difficulty has been also highlighted by Nelson and Winter (1982). In particular, the difficulty we faced had to do with two issues: 1. the comprehensive definition of capabilities, which in the majority of cases are firm specific, and 2. the characterization of the interaction among the agents making up the system of innovation. It would be valuable to carry out further research regarding these two issues in order to improve the understanding of the Colombian system of innovation.

In a first attempt to further validate the model built, the author attended panel discussions regarding the economic development of the second large city in Colombia, Medellín, and the role played by science and technology in the economic development of the city. The experts described the industry's disregard for R&D. It is worthy investigating whether the reasons underlying this attitude are still those reported by Robledo in 1997 or not. Is it just a matter of risk aversion? Or do industrialists misperceive the system structure they are embedded in?

People often attach an intrinsic value to their current business strategy and can therefore not easily change it. Sometimes people also lack the ability to reflect upon their R&D strategies; they are constrained by their own competences, budget, time or competitors. There is a great potential in Colombia to change mental models regarding R&D investment, with the aid of simulation.

The value of this thesis lies in the insights gained by transforming a verbal model into a quantified simulation model with the aid of the system dynamics method. It is in this sense that this thesis offers an extensive comprehension of both the poor innovation performance of the Colombian industry and its scarce level of the technological capabilities. It is expected that a better understanding of the problem will improve decision making and future policy design regarding R&D.

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ANNEX

Model Equations

The equations given here are in order of auxiliary, constant, level, rate and reality check.

```
********************************************************
	.Auxiliary
********************************************************~
	|

Expansion[Production]=
	MAX(0,Investment in Capital for Production-Replacement[Production]) ~~|
Expansion[Research]=
	MAX(0,"Investment in R&D"-Replacement[Research])
	~	CapUnit/Year
	~	It comprises new capital units due to investments in capital expansion.
	|

Aux 1=
	Designs Under Development-DUD Discard*TIME STEP
	~	Design
	~		|

Aux 2=
	Prototyping-DUProt Discard*TIME STEP
	~	Design
	~		|

Aux 3=
	Designs Ready for Production-DRProd Discard*TIME STEP
	~	Design
	~		|

Average Cost of DIProd=
	ZIDZ(Cost from DIProd, Designs in Production)
	~	$/(Year*Design)
	~		|

Average Cost of DIProt=
	ZIDZ(Cost from Prototyping, Prototyping)
	~	$/(Year*Design)
	~		|

Average Cost of DRProd=
	ZIDZ(Cost from DRProd, Designs Ready for Production)
	~	$/(Year*Design)
	~		|

Average Cost of DUD=
	ZIDZ(Cost from DUD, Designs Under Development)
	~	$/(Year*Design)
	~		|

Average Experience[Production]=
	IF THEN ELSE(Labour Force[Production]<Min LF,Labour Experience[Production]/Min LF,ZIDZ\
		(Labour Experience[Production], Labour Force[Production])) ~~|
Average Experience[Research]=
	IF THEN ELSE(Labour Force[Research]<Min LF,Labour Experience[Research]/Min LF,ZIDZ( \
		Labour Experience[Research], Labour Force[Research
	]))
	~	Week
	~	It indicates the average experience per employee.
	|

Average Labor Requirements[Capital Types]=
	ZIDZ(Labour Force[Capital Types], Capital[Capital Types])
	~	Person/CapUnit
	~		|

Average Lauching Time=
	Ref ALT*Effect of MC on ALT
	~	Year
	~		|

Average Qlty of DIProd[Quality]=
	ZIDZ(Qlty from DIProd[Quality], Designs in Production)
	~	Dmnl/Design
	~		|

Average Qlty of DIProt[Quality]=
```

```
	ZIDZ(Qlty from Prototyping[Quality], Prototyping)
	~	Dmnl/Design
	~		|

Average Qlty of DRProd[Quality]=
	ZIDZ(Qlty from DRProd[Quality], Designs Ready for Production)
	~	Dmnl/Design
	~		|

Average Qlty of DUD[Quality]=
	ZIDZ(Qlty from DUD[Quality], Designs Under Development)
	~	Dmnl/Design
	~		|

Average Qlty of NPP[Quality]=
	ZIDZ(Qlty from NPP[Quality], Potential Product Innovations)
	~	Dmnl/Design
	~		|

"Average R&D Spending"=
	DELAY1I("R&D Spending", Time to Avg, "R&D Spending")
	~	$/Year
	~		|

Average Tech Level[Labour,Capital Types]=
	IF THEN ELSE(Capital[Capital Types]<1,Avg Tech for Min Capital,ZIDZ( Technology Level\
		[Labour,Capital Types], Capital[Capital Types])) ~~|
Average Tech Level[Other Resources,Capital Types]=
	IF THEN ELSE(Capital[Capital Types]<1,Avg Tech for Min Capital,ZIDZ( Technology Level\
		[Other Resources
	,Capital Types], Capital[Capital Types]))
	~	Dmnl/CapUnit
	~	It is the average technology level per capital unit.
	|

Average Total Assets=
	(Total Assets+Last Period TA)/2
	~	$
	~		|

Capital Capacity=
	Capital[Production]*Capital Productivity
	~	Unit/(Design*Week)
	~	It is the maximum production possible of the capital.
	|

Capital Expense=
	Indicated Capital Expense*Effect of Liq on Capital Expense
	~	$/Year
	~	It accounts for the actual investments in capital for both production and \
		R&D. The liquidity determines whether the projected investments are made \
		or not.
	|

Capital Intensity[Production]=
	Initial Capital Intensity[Production]*Relative Tech Level[Labour,Production] ~~|
Capital Intensity[Research]=
	Initial Capital Intensity[Research]*Relative Tech Level[Labour,Research]
	~	CapUnit/Person
	~	It is the amount of capital present in relation to labour.
	|

Capital Productivity=
	Ref Capital Productivity*min(Effective Rel Tech Level[Labour,Production],Effective Rel Tech Level\
		[Other Resources,Production])
	~	Unit/(CapUnit*Design*Week)
	~	It indicates the amount of output created (units) per CapUnit per design \
		per week.
	|

Capital Upgrade Investment[Technology,Capital Types]=
	Desired Investment in CapUpgrade
	~	$/Year
	~		|

CapUpgradeInvest Productivity[Technology,Production]=
	Ref CapUpgradeInvest Prod[Technology,Production]*MAX(0,(Max Avg Tech Level[Technology\
		,Production]-Average Tech Level[Technology,Production]))/Max Avg Tech Level[Technology\
		,Production] ~~|
CapUpgradeInvest Productivity[Technology,Research]=
	Ref CapUpgradeInvest Prod[Technology,Research]*MAX(0,(Max Avg Tech Level[Technology,\
		Research]-Average Tech Level[Technology,Research]))/Max Avg Tech Level[Technology,Research\
		]
	~	Dmnl/$
	~		|

Change in C Intensity=
	XIDZ((Capital Intensity[Production]-Last Year C Intensity), Last Year C Intensity,1)
	~	Dmnl
	~		|

Debt to Assets Ratio=
	Debt/Total Assets
	~	Dmnl
	~	It indicates the proportion of debt the company is using to finance its \
		assets.
	|

Demand=
```

Industry Demand*Market Share
~ Unit/Year
~ It is the firm's demand.
|

Depreciation Expense=
SUM(Depreciation[Capital Types!])
~ $/Year
~ It is the expense accounting for the value lost by depreciation of assets.
|

Design Expense=
Total Design Expense
~ $/Year
~ It is the product development cost.
|

Desired Cash=
Perceived Expected Exp*Normal Pmt Coverage
~ $
~ It is the desired money in the form of bills, coins and bank deposits.
|

Desired DRP Capacity=
Prototyping/Desired Prototyping Delay
~ Design/Year
~ |

"Desired Invesment in R&D"=
"R&D Strategy Indicator"*Capital Expense*min(1,ZIDZ(Qlty Gap, Total Gap))
~ $/Year
~ It indicates the desired investment in capital for R&D. It depends on the \
ratio between the quality gap and the total gap.
|

Desired Investment in Capital for Production=
Capital Expense*min(1,ZIDZ(PC Gap, Total Gap))*(1-Weight on CapUpgrade)
~ $/Year
~ It indicates the desired investment in capital for production. It depends \
on the ratio between the production capacity gap and the total gap. It \
also depends on the weight given to investments in capital upgrade.
|

Desired Investment in CapUpgrade=
Capital Expense*min(1,ZIDZ(PC Gap, Total Gap))*Weight on CapUpgrade
~ $/Year
~ It indicates the desired investment in capital upgrade. It depends on the \
ratio between the production capacity gap and the total gap. It also \
depends on the weight given to investments in capital upgrade.
|

Desired Markup=
Ind Target Markup*Weight on Comptetitor Price+Ref Markup*(1-Weight on Comptetitor Price\
)
~ $/Unit
~ It is the desired markup to be added to the product variable cost. It is a \
weighted average between the Indicated Target Markup and the Reference \
Markup. The weights are given by the importance of the competitor price on \
the firm's price setting.
|

Desired Profit Markup Fract=
Ref DPMF*Min RPQ Perceived by Firm^Sensitivity of DPMF
~ Dmnl
~ It is the Desired Profit Fraction that the firm want to earn per unit.It \
is independent of the market share. It depends on the product's quality.
|

Desired Prototyping Capacity=
Designs Under Development/Desired Development Delay
~ Design/Year
~ |

Desired Shipment Rate=
Demand
~ Unit/Year
~ |

Desired Tech[Labour,Capital Types]=
Initial Average Tech Level[Labour,Capital Types]*Relative Labour to Tech Cost[Capital Types\
] ~~|
Desired Tech[Other Resources,Capital Types]=
Initial Average Tech Level[Other Resources,Capital Types]*Relative Resources to Tech Cost\
[Capital Types]
~ Dmnl/CapUnit
~ It indicates, for example, that the higher the relative labour to \
technolgy cost is, the higher is the desired technological level of the \
capital. In other words, the higher is the desired efficiency of the \
capital in terms of labour requirements.
|

Development Delay=
XIDZ(Designs Under Development,DELAY3I(Prototype Start, Time to Adj DD, Design Win),\
1)
~ Year
~ |

DIProd Discard=
Designs in Production*(1-Probability Project is Viable)/Perception Time

~ Design/Year
~ It indicates the number of designs discarded because they are not feasible \
either in commercial or technical grounds.
|

Down Time=
Capital Capacity*Fract of Employees Time Required for Maint
~ Unit/(Design*Week)
~ It represents the average time needed to give mantainance to the capital \
units.
|

DRProd Discard=
Designs Ready for Production*(1-0.75*Probability Project is Viable)/Perception Time
~ Design/Year
~ It indicates the number of designs discarded because they are not feasible \
either in commercial or technical grounds.
|

DUD Discard=
Designs Under Development*(1-0.25*Probability Project is Viable)/Perception Time
~ Design/Year
~ It indicates the number of designs discarded because they are not feasible \
either in commercial or technical grounds.
|

DUProt Discard=
Prototyping*(1-0.5*Probability Project is Viable)/Perception Time
~ Design/Year
~ It indicates the number of designs discarded because they are not feasible \
either in commercial or technical grounds.
|

EBIT=
Revenue-Expenses
~ $/Year
~ Firm's earnings before interests and taxes.
|

EBT=
EBIT-Interest Expense
~ $/Year
~ Firm's earnings before taxes.
|

Eff DD=
Eff DD function(Development Delay/Desired Development Delay)
~ Dmnl
~ |

"Eff of R&D 1"=
"Eff of R&D 1 function"("Normalized R&D Effort")
~ Dmnl
~ |

"Eff of R&D 2"=
"Eff of R&D 2 function"("Normalized R&D Effort")
~ Dmnl
~ |

Eff PD=
Eff PD function(Prototyping Delay/Desired Prototyping Delay)
~ Dmnl
~ |

Effect A=
Effect A function(Relative Innovation Capability)
~ Dmnl
~ |

Effect B=
Effect B function(Relative Innovation Capability)
~ Dmnl
~ |

Effect C=
Effect C function(Relative MC)
~ Dmnl
~ |

Effect D=
Effect D function(Relative MC)
~ Dmnl
~ |

Effect E=
Effect E function(Relative Innovation Capability)
~ Dmnl
~ |

Effect F=
Effect F function(Relative Innovation Capability)
~ Dmnl
~ |

Effect G=
Effect G function(Relative MC)
~ Dmnl
~ |

Effect H=
Effect H function(Relative MC)
~ Dmnl
~ |

Effect of Capital Intensity on LP=
Last Year Effect of Cap*(1+Change in C Intensity*Capital Elasticity[Production])
~ Dmnl
~ It indicates that the higher the capital intensity is, the higher is the \
labour productivity.
|

Effect of Competence on TL[Capital Types]=
Labour Competence[Capital Types]/Ref LC[Capital Types]
~ Dmnl
~ It indicates that the higher the labour competence is, the greater is the \
effective technology level.
|

Effect of Diff 1=
Effect of Diff 1 function(Normalized Diff to Learn)
~ Dmnl
~ |

Effect of Diff 2=
Effect of Diff 2 function(Normalized Diff to Learn)
~ Dmnl
~ |

Effect of Diff 3=
Effect of Diff 3 function(Normalized Diff to Learn)
~ Dmnl
~ |

Effect of Diff 4=
Effect of Diff 4 function(Normalized Diff to Learn)
~ Dmnl
~ |

"Effect of Diff on the effect of R&D Effort"=
IF THEN ELSE(Normalized Diff to Learn<=1,Effect of Diff 3,Effect of Diff 4)
~ Dmnl
~ It indicates that the greater the difficulty to learn from the \
environment, the more significant is the marginal impact of the firm's own \
R&D on absorptive capacity.
|

Effect of Diffulty to Learn on AC=
IF THEN ELSE(Normalized Diff to Learn<=1,Effect of Diff 1,Effect of Diff 2)
~ Dmnl
~ It indicates that the greater the difficulty to learn from the environment \
is, the less external knowledge will the firm assimilate for a given R&D \
effort.
|

Effect of Exp on LC[Capital Types]=
Relative Effective Exp[Capital Types]^LC Sensitivity to Exp
~ Dmnl
~ It indicates that the more experienced is an employee, the greater is his \
competence to perform a specific task.
|

Effect of Exp on LP=
(Relative Effective Exp[Production])^Strength of Learning
~ Dmnl
~ It indicates that the higher the labour experience is, the higher is the \
labour productivity.
|

"Effect of HEI R&D Budget on RC"=
"Effect of HEI R&D Budget on RC function"("HEI R&D Budget"/Threshold for Research Cap Building\
)
~ Dmnl
~ It indicates that the higher the HEIs R&D effort is, the less is the time \
needed to transform the potential research capability into actual research \
capability.
|

Effect of IC on LC=
IF THEN ELSE(Relative Innovation Capability=Min RIC, Min Eff of IC on LC, Relative Innovation Capability\
^LC Sensitivity to IC)
~ Dmnl
~ It indicates that the greater the innovation capability of an employee is, \
the greater is his competence to perform a specific task.
|

Effect of IC on PDC=
IF THEN ELSE(Relative Innovation Capability<=1,Effect A,Effect B)
~ Dmnl
~ It indicates that the higher the firm's ability to cope with problems \
along the innovation and development process is, the better is the firm at \
discovering design defects.
|

Effect of IC on PPV=
IF THEN ELSE(Relative Innovation Capability<=1,Effect E,Effect F)
~ Dmnl
~ The assumption behind this nonlinear function is that since a probability \

of 1 implies perfection, there will be a diminishing scope for further \
improvement as the firm becomes better at defining and designing a product \
acceptable to the customer.
|

Effect of Liq on Capital Expense=
Effect of Liq on Capital Expense function(Liquidity)
~ Dmnl
~ |

Effect of Liq on Debt Amortization=
Effect of Liq on Debt Amortization function(Liquidity)
~ Dmnl
~ |

Effect of Liq on Mkting Expense=
Effect of Liq on Mkting Expense function(Liquidity)
~ Dmnl
~ |

Effect of Liq on Training Exp=
Effect of Liq on Training Exp function(Liquidity)
~ Dmnl
~ |

Effect of LP Gap on Labour Engaged in TA=
Effect of LP Gap on Labour Engaged in TA function(Target LP Accomplishment)
~ Dmnl
~ It indicates that the higher the gap between the actual labour \
productivity and its target is, the greater is the time that employees \
spend in technology adaptation tasks (Robledo 1997).
|

Effect of MC on ALT=
Effect of MC on ALT function(Relative MC)
~ Dmnl
~ |

Effect of MC on PDR=
IF THEN ELSE(Relative MC<=1,Effect C,Effect D)
~ Dmnl
~ It indicates that the higher the marketing capability is, the better is \
the firm at satisfying customer requirements. As a result, less \
modification may take place.
|

Effect of MC on PPV=
IF THEN ELSE(Relative MC<=1,Effect G,Effect H)
~ Dmnl
~ The assumption behind this nonlinear function is that since a probability \
of 1 implies perfection, there will be a diminishing scope for further \
improvement as the firm becomes better at defining and designing a product \
acceptable to the customer.
|

Effect of ME on MC=
Effect of ME on MC function(Relative ME)
~ Dmnl
~ It indicates that the higher the marketing effort is, the less time the \
firm will need to acquire marketing capability.
|

"Effect of R&D Effort on AC"=
IF THEN ELSE("Normalized R&D Effort"<=1,"Eff of R&D 1","Eff of R&D 2")
~ Dmnl
~ It indicates that the higher the R&D Effort is, the less time that the \
firm will need to adjust its Aborptive Capacity.
|

Effect of Sales on Mkting=
(Sales/Ref Sales)^Sensitivity of Mkting Effort
~ Dmnl
~ |

Effect of Tech on Qlty=
min(Effective Rel Tech Level[Labour,Production],Effective Rel Tech Level[Labour,Research\
])^Sensitivity of Qlty+min
(Effective Rel Tech Level[Other Resources,Production],Effective Rel Tech Level[Other Resources\
,Research])^Sensitivity of Qlty
~ Dmnl
~ It indicates that the higher the effective technology level is, the \
greater is the product quality added per stage.
|

"Effect on Gov R&D Budget on S&TPC"=
"Effect of Gov R&D Budget on S&TPC function"("Government R&D Budget"/"Threshold for S&TPolicyCap Building"\
)
~ Dmnl
~ It indicates that the higher the GIs R&D effort is, the less is the time \
needed to transform the potential policy-design capability into actual \
capability.
|

Effective Capital Capacity=
Capital Capacity-Down Time
~ Unit/(Design*Week)
~ |

Effective Labour for Tech Adapt=

Time Spent in Technology Adaptation-Time Spent in Production Tasks
~ Person
~ |

Effective Rel Tech Level[Technology,Capital Types]=
Relative Tech Level[Technology,Capital Types]*Effect of Competence on TL[Capital Types\
]
~ Dmnl
~ It represent the advance in the technology embedeed in the capital.
|

Exp Cash Flow=
Revenue-Payments
~ $/Year
~ It is the amount of cash earned after paying all expenses and taxes. It \
does no include amortization nor depreciation.
|

Expected Demand=
DELAY1I(Demand, Time to Adj Exp Demand, Demand)
~ Unit/Year
~ It indicates the firm's demand expectations.
|

Expected Expenses=
MAX(Indicated Expenses,Payments)+Scheduled Amortization
~ $/Year
~ |

Expenses=
Depreciation Expense+Design Expense+Material Expense+Mkting Expense
+Wage Expense+SUM(Training Expense[Capital Types!])
~ $/Year
~ |

Exploitable Capability=
(Degree of Intra Sector Spillovers*Intra Sector K+Degree of Extra Sector Spillovers*\
Extra Sector K)
~ Dmnl
~ It represents the stock of technological knowledge accessible to the \
agents making up the system of innovation.
|

Extra Sector K=
9+Input Test for Scenarios B and C*Swich for Scenarios B and C
~ Dmnl
~ |

Fractional Change in Cost due to Learning=
IF THEN ELSE(Designs in Production/Ref Designs Launched=Min Ratio,Min Fraction, (Designs in Production\
/Ref Designs Launched)^Sensitivity of Cost
)
~ Dmnl
~ It represents the change in cost due to learning-by-doing.
|

Fractional Exp from Production Routine=
Reference Worked Weeks per Year*ZIDZ(Production Start Rate, Ref Production)
~ Week/Year
~ |

"Fractional Exp from R&D Routine"=
Reference Worked Weeks per Year*ZIDZ(Designs in Production,Ref Designs Launched)
~ Week/Year
~ |

"Ind Gov R&D Budget"=
"Ref Gov R&D Budget"*("Government Willingness to Invest in R&D"/Ref Gov W)
~ Dmnl/Year
~ |

"Ind HEI R&D Budget"=
"Ref HEI R&D Budget"*("HEIs Willingness to Invest in R&D"/Ref HEIs W)
~ Dmnl/Year
~ |

Ind Mkting Expense=
Marketing Effort*DELAY1I(Revenue, Time to Adj Revenue, Initial Avg Revenue)
~ $/Year
~ It is the projected marketing expense.
|

Ind Replacement[Capital Types]=
DELAY1I(Discard[Capital Types], Time to Perceive R, Discard[Capital Types])
~ CapUnit/Year
~ It is the projected replacement.
|

Ind Target Markup=
MAX(0,Target Price-Unit Variable Cost)
~ $/Unit
~ It is the indicated markup to be added to the product variable cost.
|

Ind Training Exp[Capital Types]=
Ref Training Exp[Capital Types]*MAX(0,(1-(min(Target Qlty Accomplishment[Lifetime],Target Qlty Accomplishment\
[Functionality]))))
~ $/Year
~ It is the projected training expense. It accounts for money invested in \

training the labour force regarding the tasks they perform. It depends on \
the gap between the target product quality and the actual product quality.
|

Indicated Attractiveness=
Ref Attractiveness*(Relative Perceived Price Ratio^Elasticity of Attrac to PP+Marketing Effort\
^Elasticity of Attrac to Mkting)
~ Dmnl
~ |

Indicated Capital Expense=
Total Assets*Goal Investment Growth Rate
~ $/Year
~ It is the projected capital expense.
|

Indicated Expenses=
Design Expense+Ind Mkting Expense+SUM(Ind Training Exp[Capital Types
!])+Indicated Capital Expense+Interest Expense+Material Expense+Taxes+Wage Expense
~ $/Year
~ It is the sum of the projected expenses.
|

Indicated Financing=
MAX(0,Indicated Financing from Liquidity-Exp Cash Flow)
~ $/Year
~ Indicated money to be borrowed after subtracting the firm's cash flow.
|

Indicated Financing from Liquidity=
(Desired Cash-Cash)/Time to Adj Ind Financing
~ $/Year
~ It indicates the surplus or defict of cash.
|

Indicated Firm W=
Ref Firm W*("S&T Policy Effectiveness"/Ref Policy Effectiveness+"Strength Academy-Industry Link"\
/Ref SAI Link)^Sensitivity of FW
~ Dmnl
~ |

Indicated Gov W=
Ref Gov W*("Strength Industry-Government Link"/Ref SIG Link+"Strength Academy-Government Link"\
/Ref SAG Link)
~ Dmnl
~ |

Indicated HEIs W=
Ref HEIs W*("S&T Policy Effectiveness"/Ref Policy Effectiveness+"Strength Academy-Industry Link"\
/Ref SAI Link)^Sensitivity of HEIs W
~ Dmnl
~ |

Indicated Labour Productivity=
Initial LP*Effect of Capital Intensity on LP*Effect of Exp on LP
~ Unit/(Week*Person*Design)
~ |

Indicated Markup=
MAX(Min Markup,Desired Markup)
~ $/Unit
~ It is the Indicated Markup to be added to the Unit Variable Cost. It is \
the maximum value between the Desired Markup and the Minimum Markup.
|

Indicated Price=
Unit Variable Cost+Indicated Markup
~ $/Unit
~ It is the Product Indicated Price. It is determined by the Unit Variable \
Cost and the Indicated Markup.
|

Initial Capital Intensity[Capital Types]=
XIDZ(Initial Capital[Capital Types], Initial Labour Force[Capital Types],1)
~ CapUnit/Person
~ |

Initial EPC=
Initial Unit Production Cost
~ $/Unit
~ |

Initial Perceived Expected Expenses=
INITIAL((Material Price+Initial Unit Production Cost)*(1+Desired Profit Markup Fract\
)*Initial Sales+Scheduled Amortization)
~ $/Year
~ |

Initial Production Cost= INITIAL(
Depreciation Expense+Design Expense+Ind Mkting Expense+SUM(Initial Labour Cost[Capital Types\
!])+Interest Expense)
~ $/Year
~ |

Initial Sales=
INITIAL(Sales)
~ Unit/Year
~ |

```
Initial Unit Production Cost=
		Initial Production Cost/MAX(1,Initial Sales)
	~		$/Unit
	~		|

Initial WIP=
		INITIAL(Production Start Rate*Manufacture Cycle Time)
	~		Unit
	~		|

"Input Test for Scenarios A1, A2, A3"=
		STEP(1,Step Time)
	~		Dmnl
	~		|

Interest Expense=
		Debt*Loan Interest Rate
	~		$/Year
	~		Interest payments.
	|

Interest Tax Shields=
		Interest Expense*Tax Rate
	~		$/Year
	~		It is the reduction in income taxes that results from the \
			tax-reductibility of interest payments.
	|

Internal Growth Rate=
		ZIDZ(Retained Earnings, Total Assets)
	~		Dmnl/Year
	~		It represents the growth generated by cash flows retained by the firm.
	|

Investment in Capital for Production=
		Desired Investment in Capital for Production/(Purchase Value of NC*Relative Tech Cost\
			)
	~		CapUnit/Year
	~		|

"Investment in R&D"=
		"Desired Invesment in R&D"/(Purchase Value of NC*Relative Tech Cost)
	~		CapUnit/Year
	~		|

Labour Capacity=
		Labour Force[Production]*Labour Productivity
	~		Unit/(Design*Week)
	~		It is the maximum production possible of the labour force.
	|

Labour Competence[Capital Types]=
		Ref LC[Capital Types]*Effect of Exp on LC[Capital Types]*Effect of IC on LC
	~		Dmnl
	~		It indicates the hability of the labour force to properly perform either \
			production activities or R&D activities.
	|

Labour Costs[Production]=
		Labour Force[Production]*Ref Labour Cost per Employee[Production]*Relative Labour Cost\
			[Production] ~~|
Labour Costs[Research]=
		Labour Force[Research]*Ref Labour Cost per Employee[Research]*Relative Labour Cost[Research\
			]
	~		$/Year
	~		|

Labour Intensity[Capital Types]=
		ZIDZ( 1, Capital Intensity[Capital Types])
	~		Person/CapUnit
	~		It is the number of labour present in relation to capital.
	|

Labour Req of New Capital[Capital Types]=
		Labour Intensity[Capital Types]
	~		Person/CapUnit
	~		|

Last Period Production=
		DELAY FIXED(Production Rate, TIME STEP, Production Rate)
	~		Unit/Year
	~		|

Last Period Sales=
		DELAY FIXED(Sales, TIME STEP, Sales)
	~		Unit/Year
	~		|

Last Period TA= DELAY FIXED (
		Total Assets, TIME STEP, Initial TA)
	~		$
	~		It is the total asset delayed one time step. It is used to calculate the \
			average total assets over a time step.
	|

Last Year C Intensity=
		DELAY FIXED(Capital Intensity[Production], TIME STEP, Initial Capital Intensity[Production\
			])
	~		CapUnit/Person
```

~ |

Last Year Effect of Cap=
DELAY FIXED(Effect of Capital Intensity on LP, TIME STEP, 1)
~ Dmnl
~ |

Liquidity=
1*(1-Switch for Accounting)+Switch for Accounting*(ZIDZ(Cash, Desired Cash)-1)
~ Dmnl
~ It indicates the proportion of cash the firm has compared to its desired \
cash.
|

Market Share=
Initial MS*ZIDZ(Attractiveness, Ref Attractiveness)
~ Dmnl
~ It represents the firm's market share.
|

Marketing Effort=
Ref Mkting Effort*Effect of Sales on Mkting
~ Dmnl
~ It represents the firm's own marketing research endeavour, which is \
assessed by the ratio between the marketing research expenditure and the \
revenue. It determines the pace at which the potential marketing \
capability is transformed into marketing capability.
|

Material Expense=
Sales*Unit Variable Cost
~ $/Year
~ Total cost of the material used in manufacture.
|

Material Price=
Ref Material Price*Relative Resources Price[Production]
~ $/Unit
~ It is the price of one unit of material.
|

Material Required=
XIDZ(Ref Material Req, Effective Rel Tech Level[Other Resources,Production],1)
~ Unit/Unit
~ It is the number of material units required to manufacture one unit \
(product). It is given by the Reference Material Required divided by the \
Technology Level.
|

Max Shipment Rate=
Inventory/Min Order Processing Time
~ Unit/Year
~ |

Min Markup=
(Expected Production Cost+Unit Variable Cost)*(1+Min Profit Markup Fraction)-Unit Variable Cost
~ $/Unit
~ It is the minimum markup to be added to the Unit Variable Cost. It is \
determined by the Min Profit Markup Fraction, the Unit Variable Cost and \
the Expected Production Cost.
|

Min Order Processing Time=
1/24
~ Year
~ |

Min RPQ Perceived by Firm=
min(ZIDZ(Average Qlty of DIProd[Lifetime], Initial Average Qlty of DIP[Lifetime]),ZIDZ\
(Average Qlty of DIProd[Functionality], Initial Average Qlty of DIP[Functionality])\
)
~ Dmnl
~ |

Mkting Expense=
Ind Mkting Expense*Effect of Liq on Mkting Expense
~ $/Year
~ It is the actual money spent in marketing.
|

Need to Adapt New Tech=
IF THEN ELSE(Relative Tech Level[Labour,Production]>1,1,IF THEN ELSE(Relative Tech Level\
[Other Resources,Production]>1,1,0))
~ Dmnl
~ |

Net Income=
EBT-Taxes
~ $/Year
~ It is the income that the firm has after subtracting expenses, interest \
payments and taxes.
|

Net Profit Margin=
ZIDZ((EBIT-Taxes-Interest Tax Shields), Revenue)
~ Dmnl
~ |

Normalized Diff to Learn=

Difficulty to Learn from Environment/Ref Difficulty to Learn
~ Dmnl
~ |

"Normalized R&D Effort"=
ZIDZ("R&D Effort", "Ref R&D Effort")
~ Dmnl
~ |

Order Fulfillment Ratio=
Order Fulfillment Ratio function(ZIDZ(Max Shipment Rate, Desired Shipment Rate))
~ Dmnl
~ |

Order Fulfillment Ratio function(
[(0,0)-(2,1)],(0,0),(0.2,0.2),(0.4,0.4),(0.6,0.58),(0.8,0.73),(1,0.85),(1.2,0.93),(1.4\
,0.97),(1.6,0.99),(1.8,1),(2,1))
~ Dmnl
~ |

Output Growth Rate=
XIDZ((Production Rate-Last Period Production), Last Period Production,1)
~ Dmnl
~ |

Payments=
Capital Expense+Design Expense+Interest Expense+Material Expense
+Mkting Expense+Taxes+SUM(Training Expense[Capital Types!])+Wage Expense
~ $/Year
~ It is the sum of the actual expenses.
|

PC Gap=
MAX(0,MAX(1-XIDZ(Production Capacity, Expected Demand, 1),Qlty Gap))
~ Dmnl
~ It indicates the gap between the firm's expected demand and its actual \
production capacity. In addition, when the firm does not invest in R&D, \
this variable also accounts for the gap between the product quality and \
its target.
|

Perceived Expected Exp=
DELAY1I(Expected Expenses, Time to Adj PExpExpenses, Initial Perceived Expected Expenses\
)
~ $/Year
~ |

Perceived Price=
XIDZ(Price, Perceived Prod Qlty, Price/Min PPQ)
~ $/Dmnl
~ It indicates the product value for the customer. It is the ratio between \
the product price and its quality.
|

Perceived Prod Qlty=
(DELAY1I(Average Qlty of DIProd[Lifetime], Time to Perceive PQ by Customer, Average Qlty of DIProd\
[Lifetime])*Weight Lifetime+DELAY1I(Average Qlty of DIProd[Functionality], Time to Perceive PQ by Customer\
,Average Qlty of DIProd[Functionality])*Weight Functionality)*Design per Unit
~ Dmnl/Unit
~ It is the perceived product quality by the customer.
|

Perceived Qlty per NPP[Quality]=
DELAY1I(Qlty per NPP[Quality], Time to Adj PQNPP, Initial PQNPP[Quality])
~ Dmnl/Design
~ |

Probability Change Required=
Ref PCR*Effect of MC on PDR
~ Dmnl
~ It is the probability that a modification be required
|

Probability Discover Change=
Ref PDC*Effect of IC on PDC
~ Dmnl
~ It is the probability to tackle a modification.
|

Probability Project is Viable=
Ref PPV*Effect of IC on PPV*Effect of MC on PPV
~ Dmnl
~ It represents the probability that a design is viable (feasible) both on \
commercial and technical grounds.
|

Production Capacity=
min(Labour Capacity,Effective Capital Capacity*Capacity Utilization)*Designs in Production\
*Reference Worked Weeks per Year
~ Unit/Year
~ It is the maximum production possible.
|

Production Cost=
Depreciation Expense+Design Expense+Interest Expense+Mkting Expense+SUM(Training Expense\
[Capital Types!])+Wage Expense
~ $/Year
~ Total production costs.
|

```
Profitability=
        ZIDZ(EBIT, Revenue)
        ~       Dmnl
        ~       It indicates how much the firm is earning compared to its revenue.
        |

Prototyping Delay=
        XIDZ(Prototyping, DELAY3I(Production Start, Time to Adj PD, Prototype Start), 1)
        ~       Year
        ~               |

Qlty Gap=
        MAX(0,(1-(min(Target Qlty Accomplishment[Lifetime],Target Qlty Accomplishment[Functionality\
                ]))))
        ~       Dmnl
        ~       It indicates the gap between the product's quality and its target value.
        |

Qlty per NPP[Quality]=
        Mean Qlty[Quality]*Effect of Tech on Qlty
        ~       Dmnl/Design
        ~       It is the average quality added per new potential product.
        |

"R&D Effort"=
        IF THEN ELSE( ZIDZ( "Average R&D Spending", Revenue)<=1,ZIDZ( "Average R&D Spending"\
                , Revenue)*100,100)
        ~       Dmnl
        ~       It represents the firm's own investments in R&D weighted by its revenues. \
                The R&D Effort indirectly increases absorptive capacity, though at a \
                decreasing rate.
        |

"R&D Spending"=
        "Desired Invesment in R&D"+Labour Costs[Research]
        ~       $/Year
        ~               |

"R&D Strategy Indicator"=
        IF THEN ELSE("Firm Willingness to Invest in R&D"<=Admissible Threshold, 0, 1)*(1-"Swich for Scenarios A1, A2, A3"\
                )+"Input Test for Scenarios A1, A2, A3"*"Swich for Scenarios A1, A2, A3"
        ~       Dmnl
        ~       It indicates whether the firm invest in R&D or not.
        |

Ref Markup=
        Expected Production Cost+(Expected Production Cost+Unit Variable Cost)*Desired Profit Markup Fract
        ~       $/Unit
        ~               |

Relative Effective Exp[Production]=
        ZIDZ( Average Experience[Production], Average Exp of New Hires[Production]) ~~|
Relative Effective Exp[Research]=
        ZIDZ( Average Experience[Research], Average Exp of New Hires[Research])
        ~       Dmnl
        ~               |

Relative Innovation Capability=
        ZIDZ( Innovation Capability, Ref IC)
        ~       Dmnl
        ~               |

Relative Labour to Tech Cost[Capital Types]=
        Relative Labour Cost[Capital Types]/Relative Tech Cost
        ~       Dmnl
        ~       It is the ratio between the relative labour cost and the relative \
                technology cost.
        |

Relative MC=
        Marketing Capability/Initial MC
        ~       Dmnl
        ~               |

Relative ME=
        Marketing Effort/Ref Mkting Effort
        ~       Dmnl
        ~               |

Relative Perceived Price Ratio=
        ZIDZ( Perceived Price, Ref PP)
        ~       Dmnl
        ~               |

Relative Resources to Tech Cost[Capital Types]=
        Relative Resources Price[Capital Types]/Relative Tech Cost
        ~       Dmnl
        ~       It is the ratio between the relative resources price and the relative \
                technology cost.
        |

Relative Tech Cost=
        Relative Tech Cost function(Time)
        ~       Dmnl
        ~       It is the price of technology in terms of a reference value.
        |

Relative Tech Level[Technology,Capital Types]=
```

ZIDZ(Average Tech Level[Technology,Capital Types], Initial Average Tech Level[Technology\
,Capital Types])
~ Dmnl
~ It represent the advance in the technology embedeed in the each capital \
unit.
|

Replacement[Capital Types]=
Ind Replacement[Capital Types]*Effect of Liq on Capital Expense
~ CapUnit/Year
~ It comprises new capital units due to investments to replace old capital.
|

Retained Earnings=
Net Income
~ $/Year
~ It represents the earnings kept for capital investments. It is equal to \
the net income since the firm does not pay dividends.
|

Return on Assets=
ZIDZ((EBIT-Taxes-Interest Tax Shields), Average Total Assets)
~ Dmnl/Year
~ It indicates how much profits the firm can get for each asset it has at \
its disposal.
|

Revenue=
Sales*Price
~ $/Year
~ |

Revenue to Assets Ratio=
ZIDZ(Revenue, Average Total Assets)
~ Dmnl/Year
~ It is the firm's operating profit margin. It indicates the firm's \
operational efficiency.
|

Reworked Designs from DRP=
Designs Ready for Production*Probability Change Required*Probability Discover Change\
/Perception Time
~ Design/Year
~ It accounts for the designs in the "designs ready for production" stage \
that need design changes in order to comply with customer requirements.
|

Reworked Prototypes=
Prototyping*Probability Change Required*Probability Discover Change/Perception Time
~ Design/Year
~ It accounts for the designs in the prototyping stage that need design \
changes in order to comply with customer requirements.
|

"S&T Policy Effectiveness"=
Ref Policy Effectiveness*("S&T Policy-Design Capability"/"Ref S&TPC")^Sensitivity of PE
~ Dmnl
~ It is the perceived science and technolgy (S&T) policy effectiveness to \
assist R&D investments carried out by the academy and industrialists.
|

Sales=
min(Production Rate,Demand)
~ Unit/Year
~ |

Sales Growth Rate=
XIDZ((Sales-Last Period Sales), Last Period Sales, 1)
~ Dmnl
~ |

Scheduled Amortization=
Debt*Amortization Fraction
~ $/Year
~ It is the planned debt amortization.
|

"Strength Academy-Government Link"=
Ref SAG Link*("S&T Policy Effectiveness"/Ref Policy Effectiveness*Research Capability\
/Ref RC)^Sensitivity of SAG
~ Dmnl
~ It indicates the strenght of the academic-government linkages. The \
stronger this link is, the more the academy and goverment institutions \
will succeed in their interactions, leading to a more intensive \
goverment's willingness to invest in R&D.
|

"Strength Academy-Industry Link"=
Ref SAI Link*(Innovation Capability/Ref IC*Research Capability/Ref RC)^Sensitivity of SAI
~ Dmnl
~ It indicates the strenght of the academic-industrial linkages. The \
stronger this link is, the more the academy and industrialist will succeed \
in their interactions, leading to a higher firm's willingness to invest in \
R&D.
|

"Strength Industry-Government Link"=
Ref SIG Link*(Innovation Capability/Ref IC*"S&T Policy Effectiveness"/Ref Policy Effectiveness\
)^Sensitivity of SIG

~ Dmnl
~ It indicates the strenght of the goverment-industrial linkages. The \
stronger this link is, the more the government institutions and \
industrialist will succeed in their interactions, leading to a more \
intensive goverment's willingness to invest in R&D.
|

Strength of Learning=
LN(1+Fractional Change in Productivity)/LN(2)
~ Dmnl
~ |

Target IC=
Exploitable Capability
~ Dmnl
~ |

Target Labour Productivity=
0.3
~ Unit/(Person*Design*Week)
~ |

Target LP Accomplishment=
ZIDZ(Labour Productivity,Target Labour Productivity)
~ Dmnl
~ It indicates the gap between the labour productivity and its target. A \
value of 1 indicates that the labour productivity equals the target.
|

Target Price=
Avg Competitor Price*Rel Target Price
~ $/Unit
~ |

Target Qlty Accomplishment[Quality]=
ZIDZ(DELAY1I(Average Qlty of DIProd[Quality], Time to Perceive PQ by Firm, Average Qlty of DIProd\
[Quality]), Target Product Qlty[Quality])
~ Dmnl
~ |

Target RC=
Exploitable Capability
~ Dmnl
~ |

"Target S&T Policy-Design Capability"=
Exploitable Capability
~ Dmnl
~ |

Taxes=
MAX(0,EBT*Tax Rate)
~ $/Year
~ Tax payments.
|

Technology Adaptation Effort=
Technology Adaptation Effort function(Time Spent in Technology Adaptation/Labour Force\
[Production])
~ Dmnl
~ It accounts for the belief, present in the Colombian capital goods \
industry, that innovation is a by product of investments in production \
capacity. It represents the fraction of time that the employees (from \
production) spend in the product development process.
|

Time Spent in Production Tasks=
Time Spent in Technology Adaptation*Fraction of Time Required for Production
~ Person
~ It indicates that employees are also occupied in production tasks when \
they are commited to the technology adaptation task (Robledo 1997).
|

Time Spent in Technology Adaptation=
(1-"R&D Strategy Indicator")*IF THEN ELSE(Need to Adapt New Tech=1,Labour Force[Production\
]*Fraction of Employee Time Required for Tech Adap*Effect of LP Gap on Labour Engaged in TA\
,0)
~ Person
~ It represents the fraction of time that people from production activities \
spend in technology adaptation tasks when there is not formal R&D \
investments.
|

Time to Adj AC=
Ref T Adj AC/("Effect of Diff on the effect of R&D Effort"*Effect of Diffulty to Learn on AC\
*"Effect of R&D Effort on AC")
~ Year
~ Time need to transform the Potential Absortive Capacity into Absortive \
Capacity.
|

Time to Adj Exp Demand=
1/2
~ Year
~ |

Time to Adj MC=
Ref T Adj MC/Effect of ME on MC
~ Year

~ |

Time to Adj New Knowledge=
Ref Time to Adj NK/(Min Effect+Absorptive Capacity+Technology Adaptation Effort+"R&D Effort"\
/100)
~ Year
~ |

Time to Adj RC=
Ref Time to Adj RC/("Min Effect of HEI R&D Budget on RC"+"Effect of HEI R&D Budget on RC"\
)
~ Year
~ Time need to transform the potential research capability into actual \
research capability.
|

"Time to Adj S&TPC"=
"Ref Time to Adj S&TPC"/("Min Effect on Gov R&D Budget on S&TPC"+"Effect on Gov R&D Budget on S&TPC"\
)
~ Year
~ |

Total Assets=
SUM(Assets[Capital Types!])
~ $
~ |

Total Design Expense=
Cost from DRProd+Cost from DUD+Cost from Prototyping
~ $/Year
~ |

Total Gap=
PC Gap+("R&D Strategy Indicator"*Qlty Gap)
~ Dmnl
~ |

Training Expense[Capital Types]=
Ind Training Exp[Capital Types]*Effect of Liq on Training Exp
~ $/Year
~ It is the actual training expense.
|

Training Productivity[Capital Types]=
Ref Training Productivity[Capital Types]*MAX(0,(Max Avg LExp[Capital Types]-Average Experience\
[Capital Types])/Max Avg LExp[Capital Types])
~ Week*Person/$
~ |

Unit Production Cost=
IF THEN ELSE(Sales>1, ZIDZ(Production Cost, Sales), Production Cost/Min Sales)
~ $/Unit
~ It is the production cost per unit.
|

Unit Variable Cost=
Material Price*Material Required
~ $/Unit
~ It is the variable cost of manufacturing one unit. It is the product of \
the material units required and the price per material unit.
|

Wage Expense=
SUM(Labour Costs[Capital Types!])
~ $/Year
~ It is the total wage expense. It includes the wage paid to both the \
production and R&D labour force.
|

****
.Constant
**~
|

Admissible Threshold=
0.5
~ Dmnl
~ |

Amortization Fraction=
1/10
~ Dmnl/Year
~ |

Av Cost per DIProt=
1
~ $/(Year*Year*Design)
~ |

Av Cost per DRProd=
1
~ $/(Year*Year*Design)
~ |

Av Cost per DUD=
3
~ $/(Year*Year*Design)
~ |

Average Cost per Design Win=
1
~ $/(Year*Design)
~ |

Average Design Life=
10
~ Year
~ |

Average Economic Life[Capital Types]=
10
~ Year
~ It is the length of time over which the asset is depreciated.
|

Average Exp of New Hires[Capital Types]=
1
~ Week
~ |

Average Qlty per DIProt[Quality]=
1
~ Dmnl/(Year*Design)
~ |

Average Qlty per DL[Quality]=
1
~ Dmnl/(Year*Design)
~ |

Average Qlty per DRProd[Quality]=
1
~ Dmnl/(Year*Design)
~ |

Average Qlty per DUD[Quality]=
1
~ Dmnl/(Year*Design)
~ |

Average Technical Life[Capital Types]=
15
~ Year
~ |

Avg Competitor Price=
5
~ $/Unit
~ Average competitor price.
|

Avg RC Span Life=
20
~ Year
~ |

"Avg S&TPC Span Life"=
8
~ Year
~ |

Avg Tech for Min Capital=
1
~ Dmnl/CapUnit
~ |

Capacity Adjustment Time=
2.5
~ Year
~ |

Capacity Utilization=
9/10
~ Dmnl
~ |

Capital Elasticity[Capital Types]=
0.47
~ Dmnl
~ This is the value estimated for Latin America. Henry, M., R. Kneller and \
C. Milner. 2003. Trade, technology transfer and national efficiency in \
developing countries. Research Paper 2003/50. The University of Nottingham.
|

Degree of Extra Sector Spillovers=
0.75
~ Dmnl
~ Represent... It takes values between 0 and 1. We assume that if the level \
of spillovers is in the range from 0.75 to 1, there is a good involvement \
of and support between agents of the system of innovation.
|

Degree of Intra Sector Spillovers=
0.5
~ Dmnl
~ |

Design per Unit=

1
~ Design/Unit
~ |

Desired Development Delay=
1
~ Year
~ |

Desired Prototyping Delay=
1
~ Year
~ |

Difficulty to Learn from Environment=
0.5
~ Dmnl
~ It includes the complexity of the knowledge to be assimilated, and the \
degree to which the outside knowledge matches the needs of the firm. It \
indicates the ease with which learning may occur. It could take values \
between 0 and 1. A value of 1 means that firm's ability to absorb \
knowledge is highly dependant on the firm own R&D effort.This variable \
affects indirectly the Absorptive Capacity in two ways.
|

Eff DD function(
[(0,0)-(5,2)],(0,0.8),(0.5,0.86),(1,1),(1.5,1.2),(2,1.4),(2.5,1.58),(3,1.7),(3.5,1.74\
),(4,1.75),(4.5,1.75),(5,1.75))
~ Dmnl
~ |

"Eff of R&D 1 function"(
[(0,0)-(1,1)],(0,0.3),(0.25,0.5),(0.5,0.68),(0.75,0.85),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

"Eff of R&D 2 function"(
[(1,1)-(20,6)],(1,1),(4,1.8),(8,2.55),(11,2.9),(16,3))
~ Dmnl
~ It is the table function used for input values between 1 and 16.
|

Eff PD function(
[(0,0.8)-(5,1.75)],(0,0.805),(0.5,0.86),(1,1),(1.5,1.29),(2,1.47),(2.5,1.58),(3,1.66\
),(3.5,1.71),(4,1.73),(4.5,1.75),(5,1.75))
~ Dmnl
~ |

Effect A function(
[(0,0.1)-(1,1)],(0,0.1),(0.25,0.13),(0.5,0.25),(0.75,0.52),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

Effect B function(
[(1,1)-(11,2)],(1,1),(2,1.258),(3,1.475),(4,1.633),(5,1.767),(6,1.846),(7,1.896),(8,\
1.929),(9,1.942),(10,1.95),(11,1.95))
~ Dmnl
~ It is the table function used for input values between 1 and 11.
|

Effect C function(
[(0,1)-(1,2)],(0,1.95),(0.25,1.933),(0.5,1.8),(0.75,1.525),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

Effect D function(
[(1,0.1)-(11,1)],(1,1),(2,0.728),(3,0.511),(4,0.38),(5,0.293),(6,0.238),(7,0.195),(8\
,0.167),(9,0.143),(10,0.132),(11,0.13))
~ Dmnl
~ It is the table function used for input values between 1 and 11.
|

Effect E function(
[(0,0.1)-(1,1)],(0,0.1),(0.25,0.13),(0.5,0.25),(0.75,0.52),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

Effect F function(
[(1,1)-(11,2)],(1,1),(2,1.258),(3,1.475),(4,1.633),(5,1.767),(6,1.846),(7,1.896),(8,\
1.929),(9,1.942),(10,1.95),(11,1.95))
~ Dmnl
~ It is the table function used for input values between 1 and 11.
|

Effect G function(
[(0,0.1)-(1,1)],(0,0.1),(0.25,0.13),(0.5,0.25),(0.75,0.52),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

Effect H function(
[(1,1)-(11,2)],(1,1),(2,1.258),(3,1.475),(4,1.633),(5,1.767),(6,1.846),(7,1.896),(8,\
1.929),(9,1.942),(10,1.95),(11,1.95))
~ Dmnl
~ It is the table function used for input values between 1 and 11.

|

Effect of Diff 1 function(
[(0,0)-(1,4)],(0,3),(0.25,2.9),(0.5,2.5),(0.75,1.9),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

Effect of Diff 2 function(
[(1,0)-(2,1)],(1,1),(1.25,0.5),(1.5,0.25),(1.75,0.15),(2,0.1))
~ Dmnl
~ It is the table function used for input values between 1 and 2.
|

Effect of Diff 3 function(
[(0,0)-(1,1)],(0,0),(0.25,0.04),(0.5,0.14),(0.75,0.43),(1,1))
~ Dmnl
~ It is the table function used for input values between 0 and 1.
|

Effect of Diff 4 function(
[(1,1)-(2,6)],(1,1),(1.25,3.32),(1.5,4.93),(1.75,5.74),(2,6))
~ Dmnl
~ It is the table function used for input values between 1 and 2.
|

"Effect of Gov R&D Budget on S&TPC function"(
[(0,0)-(2,2)],(0,0.1),(0.25,0.13),(0.5,0.25),(0.75,0.52),(1,1),(1.25,1.51),(1.5,1.81\
),(1.75,1.96),(2,2))
~ Dmnl
~ |

"Effect of HEI R&D Budget on RC function"(
[(0,0)-(2,2)],(0,0.1),(0.25,0.13),(0.5,0.25),(0.75,0.52),(1,1),(1.25,1.51),(1.5,1.81\
),(1.75,1.96),(2,2))
~ Dmnl
~ |

Effect of Liq on Capital Expense function(
[(0,0)-(2,1)],(0,0),(0.2,0.02),(0.4,0.1),(0.6,0.4),(0.8,0.8),(1,1),(1.2,1),(1.4,1))
~ Dmnl
~ |

Effect of Liq on Debt Amortization function(
[(0,0)-(0.6,1)],(0,0),(0.2,1),(0.4,1))
~ Dmnl
~ |

Effect of Liq on Mkting Expense function(
[(0,0)-(1,1)],(0,0),(0.1,0.3),(0.2,0.52),(0.3,0.7),(0.4,0.8),(0.5,0.87),(0.6,0.92),(\
0.7,0.96),(0.8,0.98),(0.9,1),(1,1))
~ Dmnl
~ |

Effect of Liq on Training Exp function(
[(0,0)-(2,1)],(0,0),(0.2,0.02),(0.4,0.1),(0.6,0.4),(0.8,0.8),(1,1),(1.2,1),(1.4,1))
~ Dmnl
~ |

Effect of LP Gap on Labour Engaged in TA function(
[(0,0)-(1,3)],(0,3),(0.25,1.35),(0.5,0.45),(1,0.15))
~ Dmnl
~ |

Effect of MC on ALT function(
[(0,0)-(20,2)],(0,1.5),(0.5,1.4),(1,1),(3,0.8),(6,0.66),(9,0.6),(12,0.55),(15,0.52),\
(18,0.5))
~ Dmnl
~ |

Effect of ME on MC function(
[(0,0)-(3,2)],(0,0.3),(0.25,0.5),(0.5,0.68),(0.75,0.85),(1,1),(1.5,1.3),(2,1.53),(2.5\
,1.7),(3,1.75))
~ Dmnl
~ |

Elasticity of Attrac to Mkting=
0.3
~ Dmnl
~ It is the elasticity of the product attractiveness to changes in the \
firm's marketing effort.
|

Elasticity of Attrac to PP=
-1
~ Dmnl
~ It is the elasticity of the product attractiveness to changes in the \
product's perceived price.
|

Fract of Employees Time Required for Maint=
0.01
~ Dmnl
~ |

Fraction of Employee Time Required for Tech Adap=
1/10
~ Dmnl
~ |

```
Fraction of Time Required for Production=
	1/10
	~	Dmnl
	~		|

Fractional Change in Productivity=
	0.1
	~	Dmnl
	~		|

Fractional Exp Decay Rate=
	1/10
	~	Dmnl/Year
	~		|

Goal Investment Growth Rate=
	0.15
	~	Dmnl/Year
	~		|

IC Span Life=
	10
	~	Year
	~		|

Industry Demand=
	10000
	~	Unit/Year
	~		|

Initial AC=
	0.1
	~	Dmnl
	~		|

Initial Assets[Production]=
	50 ~~|
Initial Assets[Research]=
	0
	~	$
	~		|

Initial Average Qlty of DIP[Quality]= INITIAL(
	Average Qlty of DIProd[Quality])
	~	Dmnl/Design
	~		|

Initial Average Tech Level[Technology,Production]=
	1 ~~|
Initial Average Tech Level[Technology,Research]=
	1
	~	Dmnl/CapUnit
	~		|

Initial Avg Revenue=
	0
	~	$/Year
	~		|

Initial Capital[Production]=
	5 ~~|
Initial Capital[Research]=
	0
	~	CapUnit
	~		|

Initial Cost=
	1
	~	$/Year
	~		|

Initial Debt=
	20
	~	$
	~		|

Initial Designs[Designs]=
	10,1,1,1,1
	~	Design
	~		|

Initial Effective Experience[Production]=
	25 ~~|
Initial Effective Experience[Research]=
	0
	~	Week*Person
	~		|

Initial Firm W=
	0.1
	~	Dmnl
	~		|

Initial Gov W=
	0.25
	~	Dmnl
	~		|
```

```
Initial HEIs W=
        0.5
        ~       Dmnl
        ~               |

Initial IC=
        1
        ~       Dmnl
        ~       It is estimated from Robledo (1997).
        |

Initial Inventory=
        0
        ~       Unit
        ~               |

Initial Labour Cost[Production]=
        INITIAL(Ref Labour Cost per Employee[Production]*Labour Force[Production]) ~~|
Initial Labour Cost[Research]=
        INITIAL(Ref Labour Cost per Employee[Research]*Labour Force[Research])
        ~       $/Year
        ~               |

Initial Labour Force[Production]=
        25 ~~|
Initial Labour Force[Research]=
        0
        ~       Person
        ~               |

Initial LP=
        1/8
        ~       Unit/(Design*Person*Week)
        ~               |

Initial MC=
        1
        ~       Dmnl
        ~               |

Initial MS=
        0.01
        ~       Dmnl
        ~               |

Initial PQNPP[Quality]=
        0
        ~       Dmnl/Design
        ~               |

Initial Price= INITIAL(
        (Unit Variable Cost+Expected Production Cost)*(1+Desired Profit Markup Fract))
        ~       $/Unit
        ~       It is the Initial Product Price
        |

Initial Qlty[Lifetime,Designs]=
        10,1,1,1,1 ~~|
Initial Qlty[Functionality,Designs]=
        10,1,1,1,1
        ~       Dmnl
        ~               |

Initial RC=
        3
        ~       Dmnl
        ~               |

"Initial S&TPC"=
        2.5
        ~       Dmnl
        ~               |

Initial TA=
        INITIAL(Total Assets)
        ~       $
        ~               |

Input Test for Scenarios B and C=
        RAMP(0.5, 1, 30)
        ~       Dmnl
        ~               |

Intra Sector K=
        1
        ~       Dmnl
        ~               |

LC Sensitivity to Exp=
        0.25
        ~       Dmnl
        ~               |

LC Sensitivity to IC=
        0.5
        ~       Dmnl
        ~               |

Loan Interest Rate=
```

0.03
~ Dmnl/Year
~ It is the interest rate a borrower pays over the period of one year.
|

Manufacture Cycle Time=
1/12
~ Year
~ |

Max Avg LExp[Capital Types]=
200
~ Week
~ |

Max Avg Tech Level[Technology,Capital Types]=
4
~ Dmnl/CapUnit
~ |

MC Span Life=
5
~ Year
~ |

Mean Qlty[Quality]=
1
~ Dmnl/Design
~ |

Min Eff of IC on LC=
0
~ Dmnl
~ |

Min Effect=
0.1
~ Dmnl
~ |

"Min Effect of HEI R&D Budget on RC"=
0.1
~ Dmnl
~ |

"Min Effect on Gov R&D Budget on S&TPC"=
0.1
~ Dmnl
~ |

Min Fraction=
0
~ Dmnl
~ |

Min LF=
1
~ Person
~ |

Min PPQ=
1
~ Dmnl/Unit
~ |

Min Profit Markup Fraction=
0.1
~ Dmnl
~ It is the minimum profit fraction that the firm earns per unit.
|

Min Ratio=
0
~ Dmnl
~ |

Min RIC=
0
~ Dmnl
~ |

Min Sales=
1
~ Unit/Year
~ Minimum volume of sales needed to calculate the unit production cost.
|

Normal Pmt Coverage=
1/4
~ Year
~ |

Perception Time=
1
~ Year
~ |

Purchase Value of NC=
10

~ $/CapUnit
~ It is the hypothetical average price per unit of new capital.
|

Ref ALT=
3
~ Year
~ |

Ref Attractiveness=
1
~ Dmnl
~ |

Ref Capital Productivity=
1
~ Unit/(CapUnit*Design*Week)
~ |

Ref CapUpgradeInvest Prod[Technology,Capital Types]=
0.1
~ Dmnl/$
~ |

Ref Designs Launched=
5
~ Design
~ |

Ref Difficulty to Learn=
0.5
~ Dmnl
~ |

Ref DPMF=
0.2
~ Dmnl
~ It is the Reference Desired Profit Fraction that the firm want to earn per \
unit.
|

Ref Firm W=
0.5
~ Dmnl
~ |

"Ref Gov R&D Budget"=
0.01
~ Dmnl/Year
~ |

Ref Gov W=
0.75
~ Dmnl
~ |

"Ref HEI R&D Budget"=
0.2
~ Dmnl/Year
~ |

Ref HEIs W=
0.75
~ Dmnl
~ |

Ref IC=
5
~ Dmnl
~ |

Ref Labour Cost per Employee[Capital Types]=
3,10
~ $/(Person*Year)
~ |

Ref LC[Capital Types]=
5,5
~ Dmnl
~ |

Ref Material Price=
1
~ $/Unit
~ It is the Reference Price of the materials used in the manufacture of one \
unit.
|

Ref Material Req=
1
~ Unit/Unit
~ It is the reference number of material units required to manufacture one \
unit (product).
|

Ref Mkting Effort=
1/10
~ Dmnl
~ |

```
Ref PCR=
          0.5
          ~          Dmnl
          ~                    |

Ref PDC=
          0.5
          ~          Dmnl
          ~                    |

Ref Policy Effectiveness=
          7.5
          ~          Dmnl
          ~                    |

Ref PP=
          1
          ~          $/Dmnl
          ~                    |

Ref PPV=
          0.5
          ~          Dmnl
          ~                    |

Ref Production=
          100
          ~          Unit/Year
          ~                    |

"Ref R&D Effort"=
          0.3
          ~          Dmnl
          ~          It is the average R&D effort reported by Durán et al 2000 for the capital \
                     goods industry.
          |

Ref RC=
          5
          ~          Dmnl
          ~                    |

"Ref S&TPC"=
          5
          ~          Dmnl
          ~                    |

Ref SAG Link=
          0.7
          ~          Dmnl
          ~                    |

Ref SAI Link=
          0.5
          ~          Dmnl
          ~                    |

Ref Sales=
          100
          ~          Unit/Year
          ~                    |

Ref SIG Link=
          0.7
          ~          Dmnl
          ~                    |

Ref T Adj AC=
          2
          ~          Year
          ~                    |

Ref T Adj MC=
          1
          ~          Year
          ~                    |

Ref Time to Adj NK=
          3
          ~          Year
          ~                    |

Ref Time to Adj RC=
          5
          ~          Year
          ~                    |

"Ref Time to Adj S&TPC"=
          2
          ~          Year
          ~                    |

Ref Training Exp[Capital Types]=
          2
          ~          $/Year
          ~                    |

Ref Training Productivity[Capital Types]=
```

0.001
~ Person*Week/$
~ |

Reference Worked Weeks per Year=
40
~ Week/Year
~ |

Rel Target Price=
1
~ Dmnl
~ |

Relative Labour Cost[Capital Types]=
0.75,1
~ Dmnl
~ It is the price of labour in terms of a reference value.
|

Relative Resources Price[Capital Types]=
0.75
~ Dmnl
~ It is the price of resources in terms of a reference value.
|

Relative Tech Cost function(
[(0,0)-(50,1)],(0,1),(25,0.5),(50,0.25))
~ Dmnl
~ |

Sensitivity of Cost=
-0.1
~ Dmnl
~ |

Sensitivity of DPMF=
0.5
~ Dmnl
~ It is the sensitivity of the Desired Profit Markup Fraction to changes in \
the product quality.
|

Sensitivity of FW=
0.5
~ Dmnl
~ |

Sensitivity of HEIs W=
0.5
~ Dmnl
~ |

Sensitivity of Mkting Effort=
1
~ Dmnl
~ |

Sensitivity of PE=
1
~ Dmnl
~ |

Sensitivity of Qlty=
0.2
~ Dmnl
~ |

Sensitivity of SAG=
0.5
~ Dmnl
~ |

Sensitivity of SAI=
1
~ Dmnl
~ |

Sensitivity of SIG=
0.5
~ Dmnl
~ |

Step Time=
0
~ Year
~ |

"Swich for Scenarios A1, A2, A3"=
0
~ Dmnl
~ |

Swich for Scenarios B and C=
0
~ Dmnl
~ |

Switch for Accounting=

1
~ Dmnl
~ It indicates whether the firm's liquidity influences its expenses or not.
|

Target AC=
1
~ Dmnl
~ It is assumed to its maximum value.
|

Target MC=
10
~ Dmnl
~ |

Target Product Qlty[Quality]=
7
~ Dmnl/Design
~ |

Tax Rate=
0.35
~ Dmnl
~ Income tax rate. It is set to 35% which is the actual rate in Colombia.
|

Technology Adaptation Effort function(
[(0,0)-(0.8,0.75)],(0,0),(0.15,0.4),(0.3,0.65),(0.45,0.73),(0.6,0.75),(0.75,0.75))
~ Dmnl
~ |

Threshold for Research Cap Building=
0.2
~ Dmnl/Year
~ |

"Threshold for S&TPolicyCap Building"=
0.01
~ Dmnl/Year
~ It is the value reported by UNESCO in various science and technology \
documents (2004).
|

Time Adj Firm W=
2
~ Year
~ |

Time Adj Gov W=
2
~ Year
~ |

Time to Adj Attractiveness=
1
~ Year
~ |

Time to Adj Capacity=
1
~ Year
~ |

Time to Adj DD=
1
~ Year
~ |

Time to Adj EPC=
1
~ Year
~ Time needed to adjust the expectations about the production cost per unit.
|

Time to Adj GovBudget=
1
~ Year
~ |

Time to Adj HEI Budget=
1
~ Year
~ |

Time to Adj HEIs W=
4
~ Year
~ |

Time to Adj Ind Financing=
1/4
~ Year
~ |

Time to Adj LP=
1
~ Year
~ |

```
Time to Adj PD=
	1
	~	Year
	~		|

Time to Adj PExpExpenses=
	1/4
	~	Year
	~		|

Time to Adj PQNPP=
	1
	~	Year
	~		|

Time to Adj Price=
	1
	~	Year
	~	It is the time needed to adjust the Product Price to the Indicated Price.
	|

Time to Adj Revenue=
	1/2
	~	Year
	~		|

Time to Avg=
	1
	~	Year
	~		|

Time to Perceive PQ by Customer=
	1
	~	Year
	~		|

Time to Perceive PQ by Firm=
	1/12
	~	Year
	~		|

Time to Perceive R=
	1
	~	Year
	~		|

Weight Functionality=
	0.5
	~	Dmnl
	~		|

Weight Lifetime=
	0.5
	~	Dmnl
	~		|

Weight on CapUpgrade=
	0.3
	~	Dmnl
	~	It indicates the importance given by the firm to investments in the \
		improvement of the technological level of the actual capital.
	|

Weight on Comptetitor Price=
	0.5
	~	Dmnl
	~	It represents the importance of the competitor price on the firm's price \
		setting.
	|

********************************************************
	.Control
********************************************************~
		Simulation Control Parameters
	|

FINAL TIME  = 30
	~	Year
	~	The final time for the simulation.
	|

INITIAL TIME  = 0
	~	Year
	~	The initial time for the simulation.
	|

SAVEPER  =
        TIME STEP
	~	Year [0,?]
	~	The frequency with which output is stored.
	|

********************************************************
	.Level
********************************************************~
	|

Absorptive Capacity= INTEG (
```

```
		AC Increase Rate,
			Initial AC)
	~		Dmnl
	~		It is a measure of the firm's efficiency to absorb new knowledge (Cohen \
			and Levinthal 1989; 1990).
	|

Accumulated Income= INTEG (
		Increase in AI,
			0)
	~		$
	~		|

Assets[Capital Types]= INTEG (
		+Investment[Capital Types]-Depreciation[Capital Types],
			Initial Assets[Capital Types])
	~		$
	~		It is the capital measured in monetary terms. It comprises both the \
			capital stock used in production and the capital used in R&D. It does not \
			include cash.
	|

Attractiveness= INTEG (
		Change in Attractiveness,
			Ref Attractiveness)
	~		Dmnl
	~		It indicates the product's attractiveness.
	|

Capital[Capital Types]= INTEG (
		+Acquisition[Capital Types]-Discard[Capital Types],
			Initial Capital[Capital Types])
	~		CapUnit
	~		It includes the capital units either used in production or R&D.
	|

Cash= INTEG (
		+Cash Inflow-Cash Outflow,
			Desired Cash)
	~		$
	~		It is money the firm has in the form of bills, coins and bank deposits.
	|

Cost from DIProd= INTEG (
		+Rise in Cost from MRStart-Decay in Cost from PD-Decrease in Cost from DIProd Discard\
			,
			Initial Cost)
	~		$/Year
	~		It is accumulated cost of the designs being produced.
	|

Cost from DRProd= INTEG (
		+Rise in Cost from ProdS+Increase in Cost from DRProd-Rise in Cost from MRStart-Decrease in Cost from DRProd Discard\
			-Rise in Cost from Reworked DRProd,
			Initial Cost)
	~		$/Year
	~		It is accumulated cost of the designs ready to be produced.
	|

Cost from DUD= INTEG (
		+Rise in Cost from DW+Increase in Cost from Develop+Rise in Cost from Reworked DRProd\
			+Rise in Cost from Reworked Prototypes-Rise in Cost from ProtStart-Decrease in Cost from DUD Discard\
			,
			Initial Cost)
	~		$/Year
	~		It is accumulated cost of the designs being developed.
	|

Cost from Prototyping= INTEG (
		+Rise in Cost from ProtStart+Increase in Cost from Prot-Rise in Cost from ProdS-Decrease in Cost from DUProt Discard\
			-Rise in Cost from Reworked Prototypes,
			Initial Cost)
	~		$/Year
	~		It is accumulated cost of the designs being tested.
	|

Debt= INTEG (
		+Borrowing-Amortization,
			Initial Debt)
	~		$
	~		Total money borrowed by the firm to finance its assets.
	|

Design Ready for Production Capacity= INTEG (
		Change in DRPC,
			1)
	~		Design/Year
	~		It represents the capacity needed to translate the designs in prototyping \
			to the designs ready for production.
	|

Designs in Production= INTEG (
		+Market Release Start-Product Discard-DIProd Discard*0,
			Initial Designs[DIP])
	~		Design
	~		It is the stocks of designs in production.
	|

Designs Ready for Production= INTEG (
```

```
	+Production Start-Market Release Start-Reworked Designs from DRP-DRProd Discard,
		Initial Designs[DRP])
	~	Design
	~	It is the stock of designs ready to be produced. These designs are waiting \
		to be launched.
	|

Designs Under Development= INTEG (
	+Design Win+Reworked Prototypes+Reworked Designs from DRP-Prototype Start-DUD Discard\
		,
		Initial Designs[DUD])
	~	Design
	~	It is the stock of designs being developed.
	|

Expected Production Cost= INTEG (
	Change in EPC,
		Initial EPC)
	~	$/Unit
	~	It represents the firm's expectation about the production costs per unit. \
		This expectation is based on the real Unit Production Cost.
	|

"Firm Willingness to Invest in R&D"= INTEG (
	Change in Firm W,
		Initial Firm W)
	~	Dmnl
	~	It indicates the firm's readiness to invest in R&D.
	|

"Government R&D Budget"= INTEG (
	Change in Government Budget,
		"Ref Gov R&D Budget")
	~	Dmnl/Year
	~	It is the proportion of the total budget that Goverment Institutions (GIs) \
		allocate to support R&D activities.
	|

"Government Willingness to Invest in R&D"= INTEG (
	Change Gov W,
		Initial Gov W)
	~	Dmnl
	~	It indicates the GIs' readiness to invest in R&D.
	|

"HEI R&D Budget"= INTEG (
	Change in HEI Budget,
		"Ref HEI R&D Budget")
	~	Dmnl/Year
	~	It is the proportion of the total budget that Higher Education \
		Institutions (HEIs) allocate to carry out R&D activities. In Colombia, \
		HEIs allocate its resources to three items: teaching, research and \
		extension activities.
	|

"HEIs Willingness to Invest in R&D"= INTEG (
	Change in HEIs W,
		Initial HEIs W)
	~	Dmnl
	~	It indicates the HEIs' readiness to invest in R&D.
	|

Innovation Capability= INTEG (
	+Innovation Capability Increase Rate-Innovation Capability Decay Rate,
		Initial IC)
	~	Dmnl
	~	It represents the stock of knowledge defined by Cohen and Levinthal (1989) \
		and comprises the technological capacity required by the capital goods \
		industry in order to support the product development process.
	|

Inventory= INTEG (
	+Production Rate-Shipment Rate,
		Initial Inventory)
	~	Unit
	~		|

Labour Experience[Production]= INTEG (
	+Increase in Exp from Hiring[Production]+Increase in Exp from OJT[Production]+Increase in Exp from Training\
		[Production]-Exp Decay Rate[Production]-Loss of Exp from Firing[Production],
		Initial Effective Experience[Production]) ~~|
Labour Experience[Research]= INTEG (
	-Exp Decay Rate[Research]+Increase in Exp from Hiring[Research]+Increase in Exp from OJT\
		[Research]-Loss of Exp from Firing[Research]+Increase in Exp from Training[Research\
		],
		Initial Effective Experience[Research])
	~	Week*Person
	~	It indicates the stock of labour experience gained from learning-by-doing, \
		training and hiring of new personnel.
	|

Labour Force[Production]= INTEG (
	+Hiring[Production]-Firing[Production],
		Initial Labour Force[Production]) ~~|
Labour Force[Research]= INTEG (
	+Hiring[Research]-Firing[Research],
		Initial Labour Force[Research])
	~	Person
	~	It includes the labour force either employed in production or R&D.
```

|

Labour Productivity= INTEG (
Change in Labour Productivity,
Initial LP)
~ Unit/(Week*Person*Design)
~ It indicates the amount of output created (units) per person per design \
per week.
|

Marketing Capability= INTEG (
+Marketing Capability Increase Rate-Marketing Capability Decay Rate,
Initial MC)
~ Dmnl
~ It accounts for the firm's ability to establish links with the customer.
|

Potential Absorptive Capacity= INTEG (
-AC Increase Rate,
Target AC-Initial AC)
~ Dmnl
~ It represents the amount of Aborptive Capacity that is potentially \
exploitable by the firm.
|

Potential IC= INTEG (
+Potential IC Increase Rate-Innovation Capability Increase Rate,
Target IC-Initial IC)
~ Dmnl
~ It represents the amount of Innovation Capability that is potentially \
exploitable by the firm.
|

Potential MC= INTEG (
+Potential MC Increase Rate-Marketing Capability Increase Rate,
Target MC-Initial MC)
~ Dmnl
~ It represents the amount of capability that the firm is potentially able \
to acquire.
|

Potential Product Innovations= INTEG (
+New Potential Products-PPI Discard-Design Win,
Initial Designs[PPI])
~ Design
~ It is the stock of potential innovations.
|

Potential RC= INTEG (
+Potential RC Increase Rate-RC Increase Rate,
Target RC-Initial RC)
~ Dmnl
~ It represents the amount of capability that HEIs are potentially able to \
acquire.
|

"Potential S&T Policy-Design Capability"= INTEG (
"Potential S&TPC Increase Rate"-"S&TPC Increase Rate",
"Target S&T Policy-Design Capability"-"Initial S&TPC")
~ Dmnl
~ It represents the amount of capability that GIs are potentially able to \
acquire.
|

Price= INTEG (
Change in Price,
Initial Price)
~ $/Unit
~ It is the Product Price. This price is adjusted to the Indicated Price \
with a time lag.
|

Prototyping= INTEG (
+Prototype Start-Production Start-Reworked Prototypes-DUProt Discard,
Initial Designs[DUP])
~ Design
~ It is the stock of designs being tested.
|

Prototyping Capacity= INTEG (
Change in PC,
1)
~ Design/Year
~ It represents the capacity needed to start testing the prototypes of the \
designs under development.
|

Qlty from DIProd[Quality]= INTEG (
+Rise in Qlty from MRStart[Quality]+Rise in Qlty from DIProd[Quality]-Decay in Qlty from PD\
[Quality]-Decrease in Qlty from DIP Discard[Quality],
Initial Qlty[Quality,DIP])
~ Dmnl
~ It is accumulated cost of the designs in production.
|

Qlty from DRProd[Quality]= INTEG (
+Rise in Qlty from ProdStart[Quality]+Rise in Qlty from DRProd[Quality]-Rise in Qlty from MRStart\
[Quality]-Decrease in Qlty from DRProd Discard[Quality]-Rise Qlty from Reworked DRProd\
[Quality],

```
		Initial Qlty[Quality,DRP])
	~	Dmnl
	~	It is accumulated cost of the designs ready to be produced.
	|

Qlty from DUD[Quality]= INTEG (
	+Rise in Qlty from DW[Quality]+Rise in Qlty from Develop[Quality]+Rise in Qlty from Reworked Prot\
		[Quality]+Rise Qlty from Reworked DRProd[Quality]-Rise in Qlty from ProtStart[Quality\
		]-Decrease in Qlty from DUD Discard[Quality],
		Initial Qlty[Quality,DUD])
	~	Dmnl
	~	It is accumulated quality of the designs being developed.
	|

Qlty from NPP[Quality]= INTEG (
	+New Qlty from NPP[Quality]-Discard Qlty from NPP[Quality]-Rise in Qlty from DW[Quality\
		],
		Initial Qlty[Quality,PPI])
	~	Dmnl
	~	It is accumulated quality of the potential innovations.
	|

Qlty from Prototyping[Quality]= INTEG (
	+Rise in Qlty from ProtStart[Quality]+Rise in Qlty from Prot[Quality]-Rise in Qlty from ProdStart\
		[Quality]-Decrease in Qlty from DUProt Discard[Quality]-Rise in Qlty from Reworked Prot\
		[Quality],
		Initial Qlty[Quality,DUP])
	~	Dmnl
	~	It is accumulated cost of the designs being tested.
	|

Research Capability= INTEG (
	+RC Increase Rate-RC Decay Rate,
		Initial RC)
	~	Dmnl
	~	It represents the level of capability already accumulated by HEIs.
	|

"S&T Policy-Design Capability"= INTEG (
	"S&TPC Increase Rate"-"S&TPC Decay Rate",
		"Initial S&TPC")
	~	Dmnl
	~	It represents the level of capability already accumulated by the GIs.
	|

Technology Level[Technology,Capital Types]= INTEG (
	+Increase in Tech[Technology,Capital Types]+Capital Upgrade[Technology,Capital Types\
		]-Decrease in Tech[Technology,Capital Types],
		Initial Capital[Capital Types]*Initial Average Tech Level[Technology,Capital Types]\
		)
	~	Dmnl
	~	Technology is a trait (or feature) of capital. It is modeled as a coflow \
		of the capital stock.
	|

WIP= INTEG (
	+Production Start Rate-Production Rate,
		Initial WIP)
	~	Unit
	~	Work in process inventory.
	|

********************************************************
	.Rates
********************************************************~
	|

AC Increase Rate=
	Potential Absorptive Capacity*(Absorptive Capacity/Target AC)/Time to Adj AC
	~	Dmnl/Year
	~		|

Acquisition[Capital Types]=
	DELAY3(Expansion[Capital Types],Capacity Adjustment Time)+DELAY3(Replacement[Capital Types\
		],Capacity Adjustment Time)
	~	CapUnit/Year
	~	It represents new capital units to be used in either production or R&D.
	|

Amortization=
	Debt*Amortization Fraction*Effect of Liq on Debt Amortization
	~	$/Year
	~	It is the actual debt amortization. It is determined by the firm's \
		liquidity.
	|

Borrowing=
	Indicated Financing
	~	$/Year
	~	Money borrowed per year to finance assets.
	|

Capital Upgrade[Labour,Production]=
	Capital Upgrade Investment[Labour,Production]*CapUpgradeInvest Productivity[Labour,Production\
		] ~~|
Capital Upgrade[Labour,Research]=
	Capital Upgrade Investment[Labour,Research]*CapUpgradeInvest Productivity[Labour,Research\
		] ~~|
Capital Upgrade[Other Resources,Production]=
```

Capital Upgrade Investment[Other Resources,Production]*CapUpgradeInvest Productivity\
[Other Resources,Production] ~~|
Capital Upgrade[Other Resources,Research]=
Capital Upgrade Investment[Other Resources,Research]*CapUpgradeInvest Productivity[Other Resources\
,Research]
~ Dmnl/Year
~ It accounts for improvement in the technological level of the actual \
capital.
|

Cash Inflow=
Borrowing+Revenue
~ $/Year
~ |

Cash Outflow=
Amortization+Payments
~ $/Year
~ |

Change Gov W=
(Indicated Gov W-"Government Willingness to Invest in R&D")/Time Adj Gov W
~ Dmnl/Year
~ |

Change in Attractiveness=
(Indicated Attractiveness-Attractiveness)/Time to Adj Attractiveness
~ Dmnl/Year
~ |

Change in DRPC=
(Desired DRP Capacity-Design Ready for Production Capacity)/Time to Adj Capacity
~ Design/(Year*Year)
~ |

Change in EPC=
(Unit Production Cost-Expected Production Cost)/Time to Adj EPC
~ $/(Unit*Year)
~ It represents the rate of change in the Expected Production Cost per Unit. \
This rate depends on the gap between the Unit Production Cost and the \
Expected Production Cost, and on the time needed to adjust the expectation.
|

Change in Firm W=
(Indicated Firm W-"Firm Willingness to Invest in R&D")/Time Adj Firm W
~ Dmnl/Year
~ |

Change in Government Budget=
("Ind Gov R&D Budget"-"Government R&D Budget")/Time to Adj GovBudget
~ Dmnl/Year/Year
~ |

Change in HEI Budget=
("Ind HEI R&D Budget"-"HEI R&D Budget")/Time to Adj HEI Budget
~ Dmnl/Year/Year
~ |

Change in HEIs W=
(Indicated HEIs W-"HEIs Willingness to Invest in R&D")/Time to Adj HEIs W
~ Dmnl/Year
~ |

Change in Labour Productivity=
(Indicated Labour Productivity-Labour Productivity)/Time to Adj LP
~ Unit/(Year*Design*Person*Week)
~ |

Change in PC=
(Desired Prototyping Capacity-Prototyping Capacity)/Time to Adj Capacity
~ Design/(Year*Year)
~ |

Change in Price=
(Indicated Price-Price)/Time to Adj Price
~ $/Unit/Year
~ It represents the rate of change in the Product Price. This rate depends \
on the gap between the Indicated Price and the Price, and on the time \
needed to adjust the Price to the Indicated Price. Sterman (2000).
|

Decay in Cost from PD=
Product Discard*Average Cost of DIProd
~ $/(Year*Year)
~ It accounts for the cost lost due to the designs scrapped.
|

Decay in Qlty from PD[Quality]=
Average Qlty of DIProd[Quality]*Product Discard
~ Dmnl/Year
~ It accounts for the quality lost due to the designs scrapped.
|

Decrease in Cost from DIProd Discard=
DIProd Discard*Average Cost of DIProd
~ $/(Year*Year)
~ It accounts for the cost eliminated due to the designs discarded at this \
stage.
|

Decrease in Cost from DRProd Discard=
DRProd Discard*Average Cost of DRProd
~ $/(Year*Year)
~ It accounts for the cost eliminated due to the designs discarded at this \
stage.
|

Decrease in Cost from DUD Discard=
DUD Discard*Average Cost of DUD
~ $/(Year*Year)
~ It accounts for the cost eliminated due to the designs discarded at this \
stage.
|

Decrease in Cost from DUProt Discard=
DUProt Discard*Average Cost of DIProt
~ $/(Year*Year)
~ It accounts for the cost eliminated due to the designs discarded at this \
stage.
|

Decrease in Qlty from DIP Discard[Quality]=
DIProd Discard*Average Qlty of DIProd[Quality]
~ Dmnl/Year
~ It accounts for the quality lost due to the designs discarded at this \
stage.
|

Decrease in Qlty from DRProd Discard[Quality]=
DRProd Discard*Average Qlty of DRProd[Quality]
~ Dmnl/Year
~ It accounts for the quality lost due to the designs discarded at this \
stage.
|

Decrease in Qlty from DUD Discard[Quality]=
DUD Discard*Average Qlty of DUD[Quality]
~ Dmnl/Year
~ It accounts for the quality lost due to the designs discarded at this \
stage.
|

Decrease in Qlty from DUProt Discard[Quality]=
DUProt Discard*Average Qlty of DIProt[Quality]
~ Dmnl/Year
~ It accounts for the quality lost due to the designs discarded at this \
stage.
|

Decrease in Tech[Labour,Capital Types]=
Average Tech Level[Labour,Capital Types]*Discard[Capital Types] ~~|
Decrease in Tech[Other Resources,Capital Types]=
Discard[Capital Types]*Average Tech Level[Other Resources,Capital Types]
~ Dmnl/Year
~ It is the decrease in the technological level due to capital discard.
|

Depreciation[Capital Types]=
Assets[Capital Types]/Average Economic Life[Capital Types]
~ $/Year
~ It is the decrease in value of the assets. It is caused by deterioration \
or obsolescence. It is calculated using the straight-line method and the \
savage value is assumed zero.
|

Design Win=
Potential Product Innovations*Probability Project is Viable/Perception Time
~ Design/Year
~ It represents the designs flowing to the next stage. These designs are \
feasible in both commercial and technical grounds.
|

Discard[Capital Types]= DELAY FIXED (
Acquisition[Capital Types], Average Technical Life[Capital Types], Initial Capital[Capital Types\
]/Average Technical Life[Capital Types])
~ CapUnit/Year
~ It represents the capital units scrapped when they reach the end of their \
life cycle.
|

Discard Qlty from NPP[Quality]=
PPI Discard*Perceived Qlty per NPP[Quality]
~ Dmnl/Year
~ It accounts for the quality lost due to the designs discarded at this \
stage.
|

Exp Decay Rate[Production]=
Labour Force[Production]*Average Experience[Production]*Fractional Exp Decay Rate ~~|
Exp Decay Rate[Research]=
Labour Force[Research]*Average Experience[Research]*Fractional Exp Decay Rate
~ Week*Person/Year
~ |

Firing[Production]=
Discard[Production]*Average Labor Requirements[Production] ~~|
Firing[Research]=
Discard[Research]*Average Labor Requirements[Research]

~ Person/Year
~ |

Hiring[Production]=
Acquisition[Production]*Labour Req of New Capital[Production] ~~|
Hiring[Research]=
Acquisition[Research]*Labour Req of New Capital[Research]
~ Person/Year
~ |

Increase in AI=
EBIT
~ $/Year
~ |

Increase in Cost from Develop=
Designs Under Development*Av Cost per DUD*Fractional Change in Cost due to Learning
~ $/(Year*Year)
~ It is the cost added to the design at this stage.
|

Increase in Cost from DRProd=
Designs Ready for Production*Av Cost per DRProd*Fractional Change in Cost due to Learning
~ $/(Year*Year)
~ It is the cost added to the design at this stage.
|

Increase in Cost from Prot=
Prototyping*Av Cost per DIProt*Fractional Change in Cost due to Learning
~ $/(Year*Year)
~ It is the cost added to the design at this stage.
|

Increase in Exp from Hiring[Production]=
Hiring[Production]*Average Exp of New Hires[Production] ~~|
Increase in Exp from Hiring[Research]=
Hiring[Research]*Average Exp of New Hires[Research]
~ Week*Person/Year
~ |

Increase in Exp from OJT[Production]=
Labour Force[Production]*Fractional Exp from Production Routine ~~|
Increase in Exp from OJT[Research]=
Labour Force[Research]*"Fractional Exp from R&D Routine"
~ Week*Person/Year
~ It indicates the labour experience gained from learning-by-doing.
|

Increase in Exp from Training[Capital Types]=
Training Expense[Capital Types]*Training Productivity[Capital Types]
~ Week*Person/Year
~ |

Increase in Tech[Labour,Capital Types]=
Acquisition[Capital Types]*Desired Tech[Labour,Capital Types] ~~|
Increase in Tech[Other Resources,Capital Types]=
Acquisition[Capital Types]*Desired Tech[Other Resources,Capital Types]
~ Dmnl/Year
~ It is the increase in the technological level due to capital acquisition.
|

Innovation Capability Decay Rate=
Innovation Capability/IC Span Life
~ Dmnl/Year
~ It indicates that there is a loss of innovation capability as technology \
and knowledge evolve overtime and render the capability of the firm \
obsolete.
|

Innovation Capability Increase Rate=
(Potential IC*(Innovation Capability/Target IC))/Time to Adj New Knowledge
~ Dmnl/Year
~ |

Investment[Capital Types]=
MAX(0,(Expansion[Capital Types]+Replacement[Capital Types]))*Purchase Value of NC
~ $/Year
~ It comprises the new capital, measured in monetary terms, that is acquired \
either by expansion or replacement.
|

Loss of Exp from Firing[Production]=
Firing[Production]*Average Experience[Production] ~~|
Loss of Exp from Firing[Research]=
Firing[Research]*Average Experience[Research]
~ Week*Person/Year
~ |

Market Release Start=
Aux 3/Average Lauching Time
~ Design/Year
~ It represents the designs flowing to the next stage. These designs are \
feasible in both commercial and technical grounds.
|

Marketing Capability Decay Rate=
Marketing Capability/MC Span Life
~ Dmnl/Year
~ It indicates that there is a loss of marketing capability as customer \

needs change overtime and render the capability of the firm obsolete.
|

Marketing Capability Increase Rate=
((Marketing Capability/Target MC)*Potential MC)/Time to Adj MC
~ Dmnl/Year
~ |

New Potential Products=
10
~ Design/Year
~ It represents design ideas that may potentially develop into innovations. \
It is assumed to be a constant rate of 10 designs per year.
|

New Qlty from NPP[Quality]=
New Potential Products*Qlty per NPP[Quality]
~ Dmnl/Year
~ It represents the quality added by the new potencial products.
|

Potential IC Increase Rate=
Innovation Capability Decay Rate
~ Dmnl/Year
~ |

Potential MC Increase Rate=
Marketing Capability Decay Rate
~ Dmnl/Year
~ |

Potential RC Increase Rate=
RC Decay Rate
~ Dmnl/Year
~ |

"Potential S&TPC Increase Rate"=
"S&TPC Decay Rate"
~ Dmnl/Year
~ |

PPI Discard=
Potential Product Innovations*(1-Probability Project is Viable)/Perception Time
~ Design/Year
~ It indicates the number of designs discarded because they are not feasible \
either in commercial or technical grounds.
|

Product Discard= DELAY FIXED (
Market Release Start, Average Design Life, 0)
~ Design/Year
~ It indicates that products are scrapped when they reach the end of their \
life cycle.
|

Production Rate=
DELAY3(Production Start Rate, Manufacture Cycle Time)
~ Unit/Year
~ |

Production Start=
min(Design Ready for Production Capacity*Eff PD, Aux 2/TIME STEP)
~ Design/Year
~ It represents the designs flowing to the next stage. These designs are \
feasible in both commercial and technical grounds.
|

Production Start Rate=
min(Expected Demand,Production Capacity)
~ Unit/Year
~ |

Prototype Start=
min(Prototyping Capacity*Eff DD,Aux 1/TIME STEP)
~ Design/Year
~ It represents the designs flowing to the next stage. These designs are \
feasible in both commercial and technical grounds.
|

RC Decay Rate=
Research Capability/Avg RC Span Life
~ Dmnl/Year
~ |

RC Increase Rate=
(Potential RC*Research Capability/Target RC)/Time to Adj RC
~ Dmnl/Year
~ |

Rise in Cost from DW=
Design Win*Average Cost per Design Win
~ $/(Year*Year)
~ It represents the product cost flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Cost from MRStart=
Market Release Start*Average Cost of DRProd
~ $/(Year*Year)

~ It represents the product cost flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Cost from ProdS=
Production Start*Average Cost of DIProt
~ $/(Year*Year)
~ It represents the product cost flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Cost from ProtStart=
Prototype Start*Average Cost of DUD
~ $/(Year*Year)
~ It represents the product cost flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Cost from Reworked DRProd=
Reworked Designs from DRP*Average Cost of DRProd
~ $/(Year*Year)
~ It represents the product cost flowing back to previous stage. This flow \
is simultaneous to the flow of reworked designs ready for production.
|

Rise in Cost from Reworked Prototypes=
Reworked Prototypes*Average Cost of DIProt
~ $/(Year*Year)
~ It represents the product cost flowing back to previous stage. This flow \
is simultaneous to the flow of reworked prototypes.
|

Rise in Qlty from Develop[Quality]=
Designs Under Development*Average Qlty per DUD[Quality]*Effect of Tech on Qlty
~ Dmnl/Year
~ It is the quality added to the design at this stage.
|

Rise in Qlty from DIProd[Quality]=
Average Qlty per DL[Quality]*Designs in Production
~ Dmnl/Year
~ It is the quality added to the design at this stage.
|

Rise in Qlty from DRProd[Quality]=
Designs Ready for Production*Average Qlty per DRProd[Quality]*Effect of Tech on Qlty
~ Dmnl/Year
~ It is the quality added to the design at this stage.
|

Rise in Qlty from DW[Quality]=
Design Win*Average Qlty of NPP[Quality]
~ Dmnl/Year
~ It represents the product quality flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Qlty from MRStart[Quality]=
Average Qlty of DRProd[Quality]*Market Release Start
~ Dmnl/Year
~ It represents the product quality flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Qlty from ProdStart[Quality]=
Average Qlty of DIProt[Quality]*Production Start
~ Dmnl/Year
~ It represents the product quality flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Qlty from Prot[Quality]=
Prototyping*Average Qlty per DIProt[Quality]*Effect of Tech on Qlty
~ Dmnl/Year
~ It is the quality added to the design at this stage.
|

Rise in Qlty from ProtStart[Quality]=
Average Qlty of DUD[Quality]*Prototype Start
~ Dmnl/Year
~ It represents the product quality flowing to next stage. This flow is \
simultaneous to the flow of designs.
|

Rise in Qlty from Reworked Prot[Quality]=
Reworked Prototypes*Average Qlty of DIProt[Quality]
~ Dmnl/Year
~ It represents the product quality flowing back to previous stage. This \
flow is simultaneous to the flow of reworked prototypes.
|

Rise Qlty from Reworked DRProd[Quality]=
Reworked Designs from DRP*Average Qlty of DRProd[Quality]
~ Dmnl/Year
~ It represents the product quality flowing back to previous stage. This \
flow is simultaneous to the flow of reworked designs ready for production.
|

"S&TPC Decay Rate"=

```
		"S&T Policy-Design Capability"/"Avg S&TPC Span Life"
	~	Dmnl/Year
	~		|

"S&TPC Increase Rate"=
	("Potential S&T Policy-Design Capability"*("S&T Policy-Design Capability"/"Target S&T Policy-Design Capability"\
		))/"Time to Adj S&TPC"
	~	Dmnl/Year
	~		|

Shipment Rate=
	Desired Shipment Rate*Order Fulfillment Ratio
	~	Unit/Year
	~		|

********************************************************
	.RealityCheck
********************************************************~
	|

No Absorptive Capacity Lower Innovation Capability:THE CONDITION:
	Absorptive Capacity=RC STEP( Absorptive Capacity, 0):IMPLIES:Innovation Capability<=\
		RC COMPARE CHECK( 'current' , Innovation Capability
		, 1, 1)
	~
	~		|

"No Firm's Innovation Capability Lower GIs S&T Policy-Design Capability":THE CONDITION:
	Innovation Capability=RC STEP(Innovation Capability, 0):IMPLIES:"S&T Policy-Design Capability"\
		<=RC COMPARE CHECK('current', "S&T Policy-Design Capability", 1, 1)
	~
	~		|

No Firm's Innovation Capability Lower HEIs Research Capability:THE CONDITION:
	Innovation Capability=RC STEP(Innovation Capability, 0):IMPLIES:Research Capability<=\
		RC COMPARE CHECK('current', Research Capability, 1, 1)
	~
	~		|

"No Firm's R&D Investments Lower Absorptive Capacity":THE CONDITION:
	"R&D Effort"=RC STEP( "R&D Effort",0):IMPLIES:Absorptive Capacity<=RC COMPARE CHECK(\
		 'current' , Absorptive Capacity, 1, 1)
	~
	~		|

"No HEIs R&D Investments Lower Research Capability":THE CONDITION:
	"HEI R&D Budget"=RC STEP("HEI R&D Budget", 0):IMPLIES:Research Capability<=RC COMPARE CHECK\
		( 'current' , Research Capability, 1, 1)
	~
	~		|

No HEIs Willingness Lower Firm's EBIT:THE CONDITION:
	"HEI R&D Budget"=RC STEP( "HEI R&D Budget", 0):IMPLIES:EBIT<RC COMPARE CHECK
		( 'current', EBIT, 1, 1)
	~
	~		|

"No HEIs Willingness No HEIs R&D Investments":THE CONDITION:
	"HEIs Willingness to Invest in R&D"=RC STEP( "HEIs Willingness to Invest in R&D", 0)\
		:IMPLIES:"HEI R&D Budget"<=RC COMPARE CHECK( 'current', "HEI R&D Budget", 1, 1)
	~
	~		|

No Innovation Capability Lower Designs:THE CONDITION:
	Innovation Capability=RC STEP( Innovation Capability, 0):IMPLIES:Designs Ready for Production\
		<=RC COMPARE CHECK( 'current' , Designs Ready for Production, 1, 1)
	~
	~		|

"No R&D Effort Lower EBIT":THE CONDITION:
	"R&D Effort"=RC STEP("R&D Effort", 0):IMPLIES:EBIT<=RC COMPARE CHECK( 'current' , EBIT\
		, 1, 1)
	~
	~		|

"No S&T Policy Capability Lower Firm's EBIT":THE CONDITION:
	"S&T Policy-Design Capability"=RC STEP("S&T Policy-Design Capability", 0):IMPLIES:EBIT\
		<=RC COMPARE CHECK( 'current' , EBIT, 1, 1)
	~
```