November 22, 2005

Applying System Dynamics to Confront Complex Decision Making in R&D Systems

Arash Golnam
Nader Ale Ebrahim

APPLYING SYSTEM DYNAMICS TO CONFRONT COMPLEX DECISION MAKING IN R&D SYSTEMS

Arash Golnam*
a.golnam@ikd-co.com
Nader Ale_Ebrahim*
al_e_ebrahim@ikd-co.com
Iran Khodro Diesel Co.*, Azadegan Highway, Tehran, Iran

Abstsract

Research and development has always played a strategically important role in the survival and the growth of technology-based firms. R&D is positively linked to company performance measures such as sales, productivity and shareholder returns and in addition to this, facing increased competition, as a result of globalization the viability of many established firms is based on the efficiency of their R&D activities.

Similar to other business models, R&D systems are characterized by complex structure and dynamic behavior. It's often difficult to predict or trace the consequences of certain decisions due to the existence of delays, non-linearities and causal feedback inherent to such systems, in other words, the effect of making a decision in one part of the R&D function can manifest itself in another part of the business system at an unexpected time.

There's a widely held belief that System Dynamics is the only knowledge based way for challenging the increasing complexity of decision making in general and the best solution to avoid unintended consequences.

This paper investigates the links between complex decision making in R&D management by describing how a dynamic simulation model, which broadly characterizes the causal feedback structure and the dynamic behavior of a typical R&D system, can be built to increase R&D systems efficiency.

In this paper, first we start with defining R&D and highlighting the importance of R&D. Then systems are defined and we explore complexity and its different types within the systems. As the next step we provide an answer to the question, how decision making complexities are originated in R&D. Then we take a brief look at the history of system dynamics and we become familiar with system dynamics tools (i.e. Causal Loop Diagrams and Stock and Flow Diagrams). Finally we get into modeling complexities faced in R&D decision making by system dynamics approach, starting from basic models and ending with more complex ones.

Keywords: System Dynamics; Decision Making; Research and Development (R&D); Dynamic Behavior; Causal Feedback; Dynamic Simulation Model; Causal Loop Diagrams (CLDs); *Stock and Flow Diagrams (SFDs).*

Arash Golnam: Bachelors of Industrial Engineering, Head of Iran Khodro Diesel Engineering Dep. Project Control Center .
Nader Ale_Ebrahim: Masters of Mechanical Engineering, Iran Khodro Diesel Engineering Deputy.
Iran Khodro Diesel: The Biggest Commercial Vehicle Manufacturer in the Middle East

1.INTRODUCTION

In this paper, we have tried to provide the reader with definitions of the new concepts put forward in this paper so that we all come to one common understanding and language throughout the paper that will no doubt serve to a better grasp of the approach we have devised and presented in this paper.

In this paper the approach we introduced as System Dynamics is a perfect illustration for a knowledge based method and a systematic approach in managing R&D. I preferred no to focus on the Knowledge aspect of this approach instead we put more emphasis on the practical application of this approach in R&D. As a result the knowledge side of this approach is not mentioned but it's implied, and will surely be grasped.

We will begin with defining R&D and its purposes then we explore some R&D statistics clarifying R&D importance, next the importance of R&D will be highlighted once more by describing the link between a company's R&D system and the company's success, when we finally come to the conclusion that R&D is vital for a company's growth and survival.

As the next step in order to understand and explore the complexities we encounter in R&D, we define the concept of systems, introduce classes of systems and sources of complexities in systems, then we tried to simulate the R&D system with a business model, by exploring the complexity sources within R&D systems.

In the next section as mentioned earlier we will go through some complexities in the nature of R&D systems that make the policy setting and the decision making within an R&D system difficult most of the time leading to serious problems.

As a solution for making more accurate and precise decisions in R&D we will introduce System Dynamics, a knowledge based approach for challenging complexities in all systems, we discuss its origins, its tools and its application.

Finally we begin modeling R&D systems with system dynamics tools (i.e. CLDs and SFDs). The first model we present is a reinforcing feed back loop, in which an exponential growth could be witnessed leading to either company's success or its bankruptcy and the leverage points by which managerial decisions could be implemented.

The second model is a Complex Growth Limit archetype demonstrated in a balancing loop in which well intended actions could originate negative feed backs.

The last model which is in fact the most complex ones is about R&D strategic policy making when facing market dynamics, in which four scenarios will analyzed by means of system dynamics simulation technique.

In the following page there's a summary of the issues either discussed, defined, explored, illustrated or analyzed in this paper, I think taking a look at it will give you a good overall idea about what you are going to read in this paper.

2.PAPER ORGANIZATION

R&D & its Importance

- Defining R&D
- R&D Purposes
- Investment in R&D Verses Company's Success
- The importance of R&D
- How Can Success in R&D be Guaranteed?

Systems and System Dynamics

- What are systems?
- Systems Characteristics
- Classes of Systems
- Why are some systems complex?
- Dynamic Behavior of systems
- System Dynamics
- Origins and Fundamental Notions of System Dynamics
- What Is System Dynamics?
- Why Is System Dynamics Important?
- Systems Thinking as a Perspective:
- System Dynamics as a Special Language
- System Dynamics as a Set of Tools
- Causal Loop Diagrams
- Stocks and Flows
- Linking System Dynamics with R&D
- What are the origins of decision making complexity in R&D?
- How can system dynamics help decision makers to overcome strategic R&D Complexities?

Modeling R&D with System Dynamics

- Model 1
  Modeling R&D Management Work Cycle with CLD

- Model 2
  Modeling the effect of R&D on a firm's Cash Flow by means of Stock and Flow Diagrams

- Model 3
  The Research and Development Policy Designs and their Ability to Accommodate Radical Market Change

3.RESEARCH AND DEVELOPMENT

3.1.What is R&D?

R&D can be defined as *any project to resolve scientific or technological uncertainty aimed at achieving an advance in science or technology*. Advances include new or improved products, processes and services or in other words it can simply be defined as *technical pursuit of a new technology or decision to support a strategic goal*.

Business R&D has increased in real terms in recent years, An increase in the levels of business R&D will stimulate business innovation and help raise productivity, particularly in the manufacturing sector, which undertakes the majority of R&D in the UK.

3.2.The Purposes of R&D

Research and development (R&D) is concerned with three strategic purposes (Roussel *et al*, 1991);

- To defend, support, and expand existing business
- To drive new business
- To broaden and deepen a company's technological capabilities

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

3.3.Investment in R&D Verses Company's Success

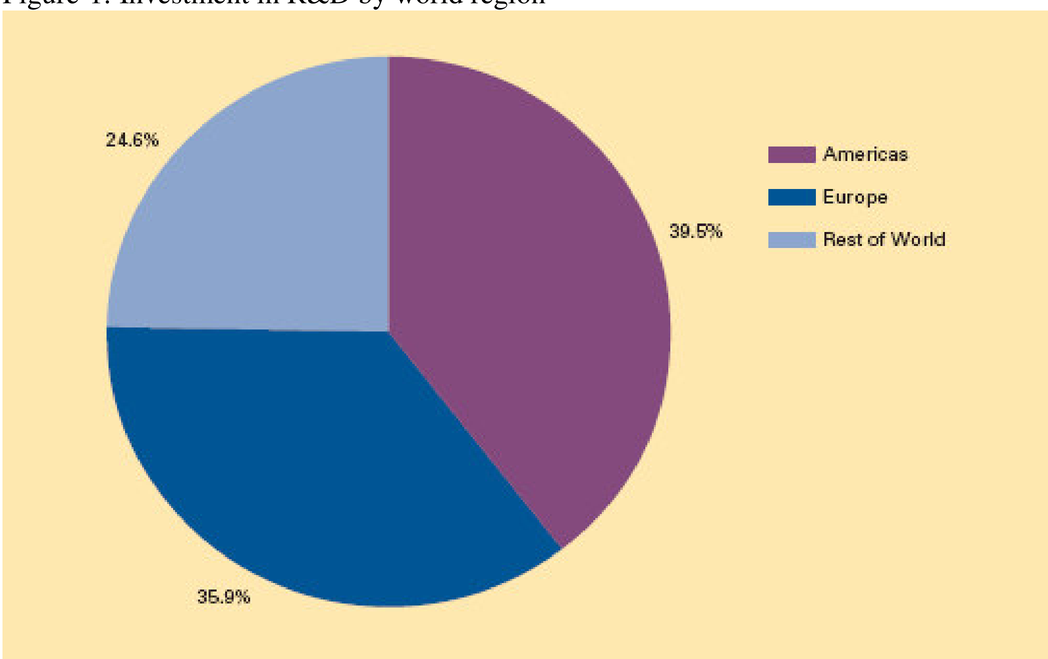
In this section we want to have a deeper look at the role of R&D in the success of a company by going through some up to date statistics, *from R&D scoreboard released in 2004*, these statistics generally involve R&D investment proportion in the world, ranking of the countries and the sectors which allocate a high R&D investment through out the world.

- R&D is important for many sectors of the economy since it generates the new products, processes and services that give a company a competitive edge in the market and help it to increase value added. The ten largest sectors by R&D internationally account for nearly 90% of all international R&D and the five sectors with the highest R&D intensity (R&D as % sales) contribute 57% of all R&D.

- *The overall business environment for R&D-active companies was much more favorable in 2003/04 than in the previous two years*. Overall *operating profit doubled* to reach 8.2% of sales and both sales and R&D increased over the previous year. These increases were particularly marked for companies in the Americas and also Asia Pacific but European companies showed a small reduction of 1% in both sales and R&D.

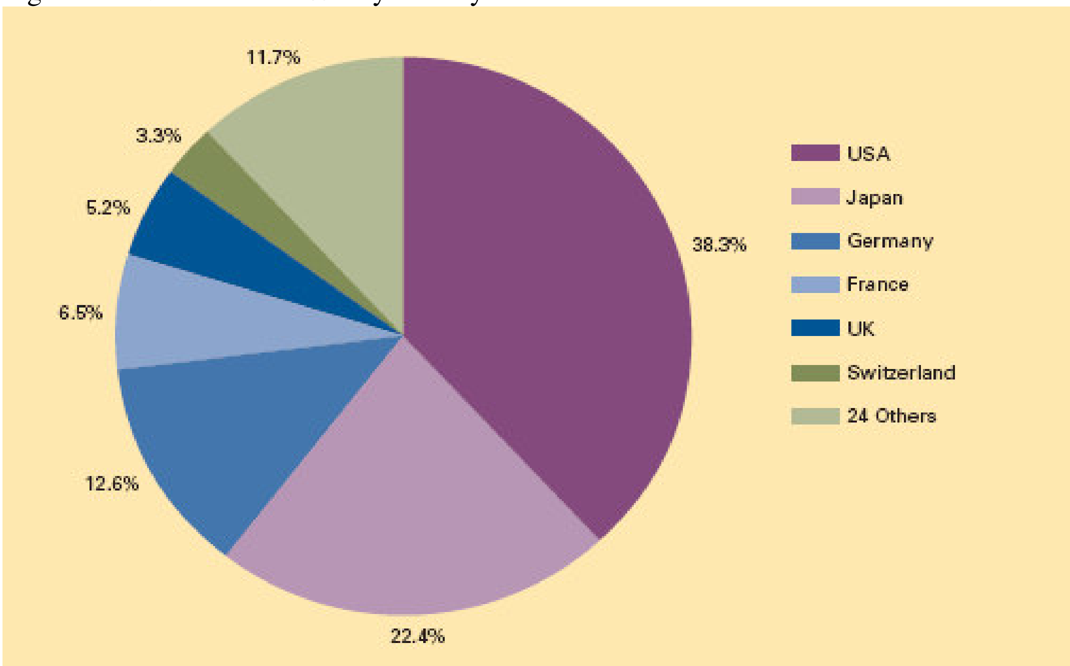
- The Americas (primarily the USA) have the largest proportion of international 700 R&D (39.5%) and the highest R&D intensity (4.9% of sales). Europe has almost as large a proportion (36%) but a smaller R&D intensity (3.7% of sales) while Asia-Pacific has the lowest proportion (24.6%) but an intensity of 4%. These R&D intensity differences mainly reflect differences in sector mix between the regions although there are regional variations of intensity within sectors.

Figure-1: Investment in R&D by world region



Source: The 2004 R&D Scoreboard

Figure-2: Investment in R&D by country

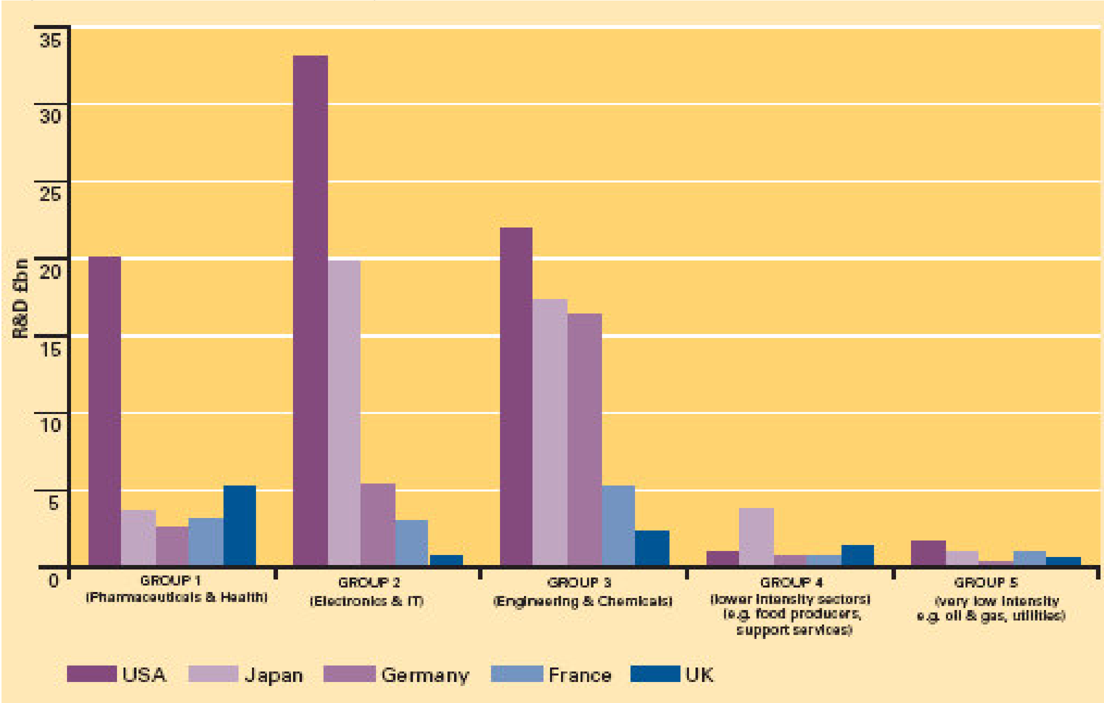


Source: The 2004 R&D Scoreboard

3.4.The sector mix of R&D and R&D for the major countries

- The three international sectors that account for the largest share of R&D internationally are IT hardware (20% of the total), automotive (19%) and pharmaceuticals & biotechnology (18%). In the UK, pharmaceuticals & biotechnology (39%) and aerospace & defense (12%) are by far the largest sectors. The top two companies account for some 20% of R&D in each of the largest international sectors but over 70% in the UK's two largest sectors.

Figure-4: Investment in R&D by sectors and countries



Source :The 2004 R&D Scoreboard

3.5.The importance of R&D

As you could see in the previous section nowadays it's generally accepted that a company's success is undoubtedly linked to the investment in R&D and the term R&D costs is replaced by R&D investment throughout the world.

Why is R&D important ?

- R&D generates the new products, processes and services that give such companies a competitive edge in the market.
- R&D is a substantial financial item for R&D-active companies.
- For sectors where R&D is a significant investment, R&D is positively linked to company performance measures such as sales growth, productivity and shareholder returns. This means that companies with above average R&D intensity are more likely to have above average performance on these measures.

- R&D is particularly important for developed economies which have higher labor costs (and also environmental costs) and rely for their competitive edge on value added derived from R&D (for new products, processes and services) together with investments in brands, skills, market development.

Table-1: Links between R&D and company performance

Links established between R&D and company performance	**For which sectors**
4. Sales growth rises with R&D intensity	Wide range of R&D performing sectors
2. Higher R&D intensity associated with higher share price growth	For higher R&D intensity companies
3. 74% of companies with above average wealth creation efficiency have investment intensity (R&D or capital) above average	For 12 sectors characterized by significant R&D
4. Labor productivity rises with investment	(R&D) per employee For sectors where R&D investment is significant

Source :The 2004 R&D Scoreboard

3.6.How Can Success in R&D be Guaranteed?

As you may also come to conclusion after taking a look at the previous sections of this paper the survival of companies throughout the world and in different business field highly depends on their R&D efficiency, so we may say that *R&D investment in itself can not be taken into account as the major source of a company's success, the efficiency of the R&D is what that matters.*

It's actually the survival of the fittest.

The higher the efficiency of a company's R&D systems the higher the chance of it's survival in the highly competitive market nowadays.

However, due to some unexpected problems R&D strategies in a company, although well considered, fail, in other words a well intended action turns out to be a complete disaster after passing of time.

Besides, usually decision makers have to consider so many different and unpredictable factors that, the chance of arriving at an accurate and precise strategic decision reduces dramatically.

Similar to other business models, R&D systems are characterized by complex structure and dynamic behavior. It's often difficult to predict or trace the consequences of certain decisions due to the existence of delays, non-linearities and causal feedback inherent to such systems, in other words, the effect of making a decision in one part of the R&D function can manifest itself in another part of the business system at an unexpected time.

In order to find a way of dealing with these complexities we should first become familiar with systems, classes of systems, characteristics of a system and finally complexity in systems .

4.SYSTEMS

4.1.What are systems?

What exactly is a system? A system is a group of interacting, interrelated, and interdependent components that form a complex and unified whole. Systems are everywhere—for example, *the R&D department in your organization*, the circulatory system in your body, the predator/prey relationships in nature, the ignition system in your car, and so on.

The word system probably has more varied meanings than any other word in use today. Another definition for this word is as follows:

A system is an entity which maintains its existence through the mutual interaction of its parts.

The key emphasis here is "**mutual interaction**," in that something is occurring between the parts, over time, which maintains the system. A system is different than a heap or a collection, mostly.

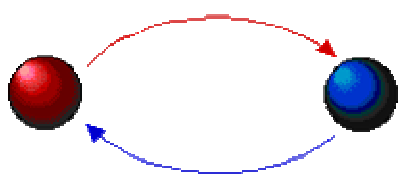


Figure-4:mutual interaction in systems

This definition of a system implies something beyond cause and effect. Rather than simply A affects B, there is an implication that B also affects A. Examples of systems are particle, atom, molecule, cell, organ, person, community, state, nation, world, solar system, galaxy, and universe, in increasing levels of complexity. In truth there is only one system, "the Universe," and all other systems are really just sub-systems of this larger system. The relevant question has to do with where one chooses to draw the boundaries.

4.2.Systems have several defining characteristics:

• **Every system has a purpose within a larger system.** Example: *The purpose of the R&D department in your organization is to generate new product ideas and features for the organization.*

• **All of a system's parts must be present for the system to carry out its purpose optimally.** Example: *The R&D system in your organization consists of people, equipment, and processes. If you removed any one of these components, this system could no longer function.*

• **A system's parts must be arranged in a specific way for the system to carry out its purpose.** *Example: If you rearranged the reporting relationships in your R&D department so that the head of new-product development reported to the entry-level lab technician, the department would likely have trouble carrying out its purpose.*

• **Systems change in response to feedback.** The word feedback plays a central role in systems thinking. Feedback is information that returns to its original transmitter such that it influences that transmitter's subsequent actions. Example: Suppose you turn too sharply while driving your car around a curve. Visual cues (you see a mailbox rushing toward you) would tell you that you were turning too sharply. These cues constitute feedback that prompts you to change what you're doing (jerk the steering wheel in the other direction somewhat) so you can put your car back on course.

• **Systems maintain their stability by making adjustments based on feedback.** Example: Your body temperature generally hovers around 98.6 degrees Fahrenheit. If you get too hot, your body produces sweat, which cools you back down.

4.3.Classes of Systems

There are multiple ways of characterizing systems. Of those I have come to understand to date, several of the most useful are as follows.

Isolated, Open and Closed Systems

Systems may be characterized as either closed or open. A closed system is one that does not need to interact with its environment to maintain its existence. Examples are atoms and molecules. Mechanical systems are closed systems. Open systems are organic and must interact with their environment in order to maintain their existence. People are open systems in that they must interact with their environment in order to take in food, water, and obtain shelter. People provide waste products to the environment in return.

The examples of the furnace, filling the water glass, adjusting the shower tap are all open systems as there are elements outside the system which are considered to have an effect yet are not elaborated.

An open system may interact with its environment in a growth or balancing fashion. Often the time of influence of the open system on the environment or the environment on the system may be of such lengthy duration or of such minimal nature as to limit its need to be considered. In 1927 Ludwig von Bertalanffy first proposed that the human organism should be treated as an open system.

Any system taken in a large enough context can be considered a closed system. It is often more appropriate to consider a system as a subsystem of some larger system with which it must interact in some way. Taking the larger system into account is unnecessary for understanding the operation of the subsystem. All systems are both subsystems of larger systems and composed of subsystems at the same time.

4.4.Why are some systems complex?

For a better understanding of complexities in systems we should first become familiar with some the factors accounting for these complexities.

4.4.1Feedback

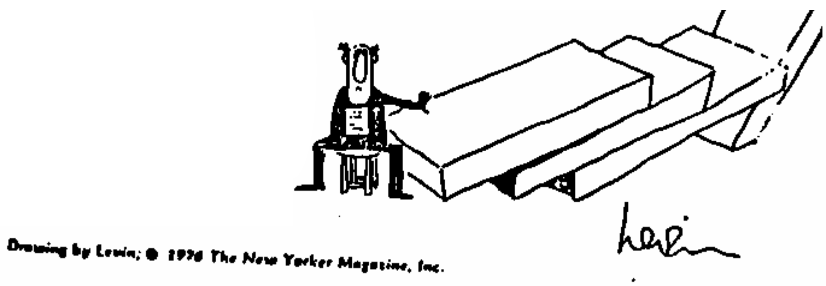
Actions taken on an element in a system result in changes in the state of the element. These, in turn, bring about changes in other linked elements, and the effects may trail back to the "first" element. This is called feedback. Feedbacks are of two types: 1) Positive or self-reinforcing, which amplify the current change in the system; and 2) Negative or self-correcting, which seek balance and provide equilibrium by opposing the change taking place in the system.

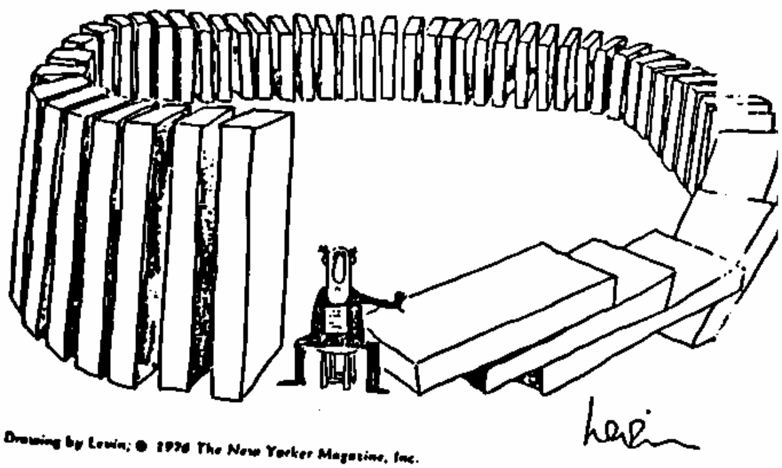
Systems can some times be described as **Tightly Coupled** because

"Everything influences everything else"
"You can't just do one thing"

Complex systems are "complex" because of the multiple feedbacks/interactions among the various components of the system.

Figure-5: Feedback in Systems





4.4.2.Dynamic Behaviors

Exponential Growth arises from positive or **self-reinforcing feedback**. The greater a quantity is, the greater is its net change (increase/decrease), and this is the feedback to the process that further augments the net change. Thus this is a self-reinforcing feedback and there is an exponential growth/decline.

Figure-6:Self-reinforcing feedback in systems

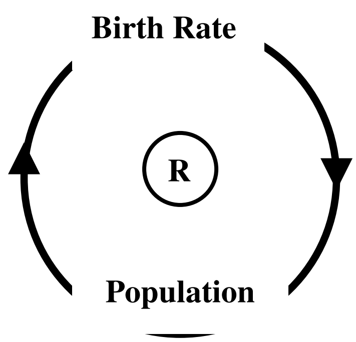
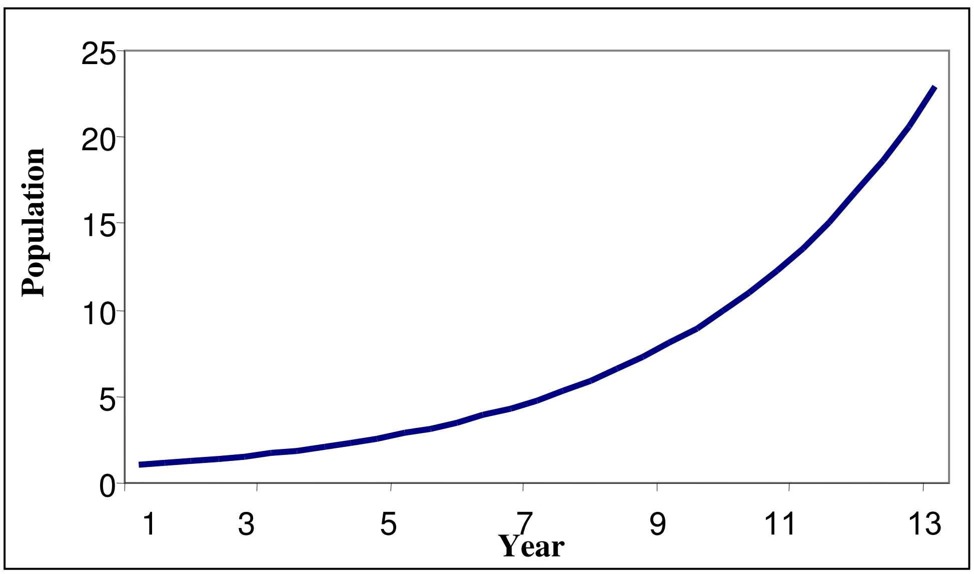


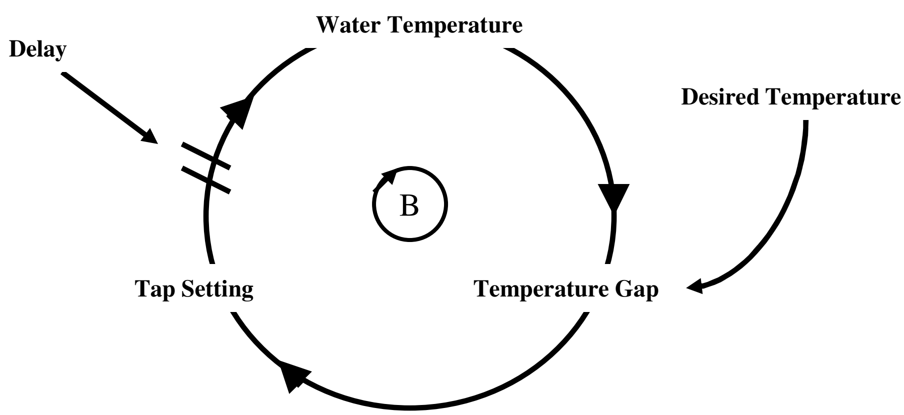
Figure-7:The effects of Self-reinforcing feedback in systems



4.4.3.Delays

When results take time to occur in balancing loops. As a good illustration for this matter we can refer to Managing Water Temperature in a Shower.
When taking a shower, most of us have faced this situation, what I mean is for example if we want to decrease the temperature of the water this decrease in temperature will be implemented with some delay, in the delay time , because we have not reached the desired temperature, we take some other action like trying to decrease the temperature again, but after some time the result of our first effort to decrease the temperature occur but the extra action we have taken in the delay time won't let it last long and these series of events keep occurring on and on till we finally grasp the idea of delays.

Figure-8: A simple example of delays in systems



What do you think would happen in a more complicated setting, Where you have to share the supply of hot water (critical resource) with someone/something else?

Delays are one of the most troublesome dynamic behaviors of a system that lead to extra and unnecessary actions that most of the time account for serious tragedies resulting a companies bankruptcy.

For more reading in this regard you can refer to The Beer Game in the Book The Fifth Discipline by Peter Senge.

5.SYSTEM DYNAMICS

5.1.System Dynamics

The only way to challenge complexities and dynamic behavior

There's a widely held belief that System Dynamics is the only way for challenging the increasing complexity of decision making caused by non linearities and dynamic behavior in general and the best solution to avoid unintended consequences.

In the next section we first give you some ideas about system dynamics origins, its definition its importance and the tools used in it.

5.2.Origins and Fundamental Notions of System Dynamics

System Dynamics (SD) is a policy modeling methodology based on the foundations of (1) decision making, (2) feedback mechanism analysis, and (3) simulation. Decision making focuses on how actions are to be taken by decision-makers. Feedback deals with the way information generated provides insights into decision-making and effects decision-making in similar cases in the future. Simulation provides decision-makers with a tool to work in a virtual environment where they can view and analyze the effects of their decisions in the future, unlike in a real social system.

Forrester first used the concept of System Dynamics in an article entitled “Industrial Dynamics: A Major Breakthrough for Decision Makers” which appeared in *Harvard Business Review* in 1958. His initial work focused on analyzing and simulating microlevel industrial systems such as production, distribution, order handling, inventory control, and advertising. Forrester expanded his system dynamics techniques in *Principles of Systems* in 1968, where he detailed the basic concepts of system dynamics in a more technical form, outlining the mathematical theory of feedback system dynamics (Forrester, 1968).

System Dynamics is an approach whose main purpose is to understand and model complex and dynamic systems.

5.3.What Is System Dynamics?

Systems Dynamics offers you a powerful new perspective, a specialized language, and a set of tools that you can use to address the most stubborn problems in your everyday life and work. System Dynamics is a way of understanding reality that emphasizes the relationships among a system's parts, rather than the parts themselves..

5.4.Why Is System Dynamics Important?

Why is system Dynamics valuable? Because it can help you design smart, enduring solutions to problems. In its simplest sense, system Dynamics gives you a more accurate picture of reality, so that you can work with a system's natural forces in order to achieve the results you desire. It also encourages you to think about problems and solutions with an eye toward the long view—for example, how might a particular solution you're considering play out over the long run? And what unintended consequences might it have? Finally, system dynamics is founded on some basic, universal principles that you will begin to detect in all arenas of life once you learn to recognize them.

5.5.Systems Thinking as a Perspective: Events, Patterns, or System?

Systems thinking is a perspective because it helps us see the events and patterns in our lives in a new light—and respond to them in higher leverage ways. For example, suppose a fire breaks out in your town. This is an **event**. If you respond to it simply by putting the fire out, you're reacting. (That is, you have done nothing to prevent new fires.) If you respond by putting out the fire and studying where fires tend to break out in your town, you'd be paying attention to **patterns**. For example, you might notice that certain neighborhoods seem to suffer more fires than others. If you locate more fire stations in those areas, you're adapting. (You still haven't done anything to prevent new fires.) Now suppose you look for the **systems**—such as smoke-detector distribution and building materials used—that influence the patterns of neighborhood-fire outbreaks. If you build new fire-alarm systems and establish fire and safety codes, you're creating change. Finally, you're doing something to prevent new fires!

This is why looking at the world through a systems thinking "lens" is so powerful: It lets you actually make the world a better place.

5.6.System Dynamics as a Special Language

As a language, system dynamics has unique qualities that help you communicate with others about the many systems around and within us:

• It emphasizes wholes rather than parts, and stresses the role of interconnections—including the role we each play in the systems at work in our lives.
• It emphasizes circular feedback (for example, A leads to B, which leads to C, which leads back to A) rather than linear cause and effect (A leads to B, which leads to C, which

leads to D, . . . and so on).
• It contains special terminology that describes system behavior, such as reinforcing process (a feedback flow that generates exponential growth or collapse) and balancing process (a feedback flow that controls change and helps a system maintain stability).

5.7. System Dynamics as a Set of Tools

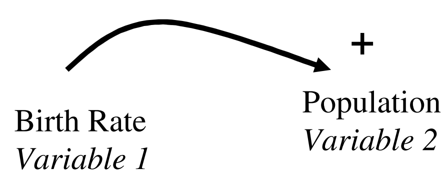
The field of system dynamics has generated a broad array of tools that let you (1) graphically depict your understanding of a particular system's structure and behavior, (2) communicate with others about your understandings, and (3) design high-leverage interventions for problematic system behavior.

These tools include causal loop diagrams, behavior over time graphs and stock and flow diagrams,—all of which let you depict your understanding of a system—to computer simulation models and management "flight simulators," which help you to test the potential impact of your interventions.

5.8.Causal Loop Diagrams

The feedback structure of complex systems is qualitatively mapped using causal diagrams. A Causal Loop Diagram (CLD) consists of variables connected by causal links, shown by arrows. Each link has a polarity. A positive (denoted by "+" on the arrow) link implies that if the cause increases (decreases), the effect increases (decreases) above (below) what it would otherwise have been. A negative (denoted by "-" on the arrow) link implies that if the cause increases (decreases), the effect decreases (increases) *below (above) what it would otherwise have been* (Sterman, 2000).

Figure-9: A simple example of Causal Loop Diagrams



Causal loops are immensely helpful in eliciting and capturing the mental models of the decision-makers in a qualitative fashion. Interviews and conversations with people who are a part of the system are important sources of quantitative as well as qualitative data required in modeling. Views and information from people involved at different levels of the system are elicited, and from these, the modeler is able to form a causal structure of the system.

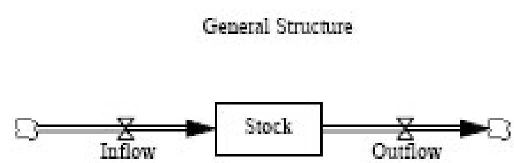
5.9.Stocks and Flows

Causal loops are used effectively at the start of a modeling project to capture mental models. However, one of the most important limitations of the causal diagrams is their inability to capture the stock and flow structure of systems. Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory. Stocks are accumulations as a result of a difference in input and output flow rates to a process/component in a system. Stocks give the systems inertia and memory, based on which decisions and actions are taken. Stocks also create delays in a system and generate disequilibria (Sterman, 2000).

Notation:

All stock and flow structures are composed of stocks (represented by rectangles), inflows (represented by arrows pointing into the stock), outflows (represented by arrows pointing out from the stock), valves, and sources and sinks for flows (represented by clouds).

Figure-10: General Structure of a Stock and Flow



Figu

Mathematical Representation of Stocks and Flows

$$\text{Stock}(t) = \text{Stock}(t0) + \int[\text{Inflow}(t) - \text{Outflow}(t)]\,dt$$

Stocks are the state variables or integrals in the system. They accumulate (integrate) their inflows less their outflows. Flows are all those which are rates or derivatives. If a snapshot of a system was taken at any instant of time, what would be seen is the state of different processes or components of the system. These are the stocks in the systems. The inflows and outflows are what have been frozen and so cannot be identified. Stock and flow networks undoubtedly follow the laws of conservation of material. The contents of the stock and flow networks are conserved in the sense that items entering a stock remain there until they flow out. When an item flows from one stock to another, the first stock loses exactly as much as the second one gains.

6.SYSTEM DYNAMICS AND R&D

6.1.Linking System Dynamics with R&D

Now that we have become familiar with systems and system dynamics and its tools it's the time for linking it with the common problems faced in R&D decision making, in order for this to happen we have chosen the following approach:
First we try to identify the sources of complexity in R&D systems and then we get into modeling complexities faced in R&D decision making by system dynamics approach, starting from basic models and ending with more complex ones.

6.2.What are the origins of decision making complexity in R&D?

A number of structural and policy making characteristics contribute to the challenge of managing the R&D activity;

- Organizational complexity-intra and inter complexity has implications for how R&D policies are developed and aligned with broader organizational objectives and market dynamics(i.e. how decision rules guide the stream of R&D decisions within and across R&D projects).

- Resource complexity-volume or scale of human, capital and technological resources required to move projects along an R&D pipeline through to commercialization.

- Technological complexity- level of innovation involved in the product or process.

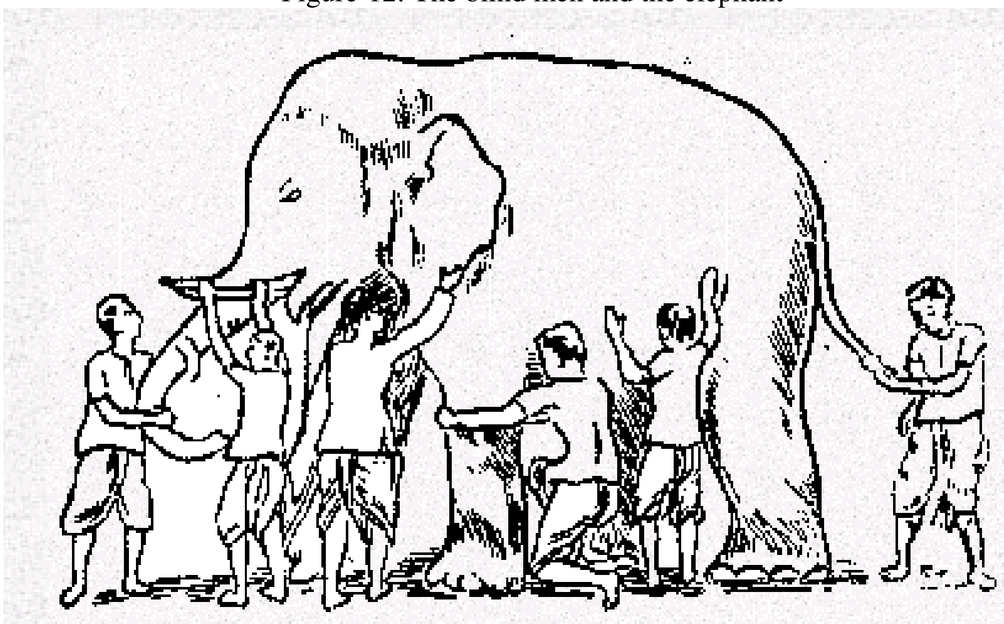
Together these may lead to the common problem- a combination of seemingly random processes generates uncertainty, whilst delays and complex feedback loops deleteriously affect managers' application of their flexibility.

6.3.How can system dynamics help decision makers to overcome strategic R&D Complexities ?

Business can be regarded as systems, bound by interrelated actions which often take years to fully play out their effects (Senge, 1990).Since we are often immersed in our own part of business function it is hard to see the whole pattern of change, in other words we all

lack some certain overall vision of the situation we are involved in, as a good illustration of this case we can refer to the well known story of Elephant in the Dark.
Each person thought he had a good understanding of the part he was exploring but these individual and partly understanding never led to a correct overall vision.

Figure-12: The blind men and the elephant



As a result we can come to the conclusion that breaking a system apart into small components can not always be considered as a systematic approach to understand the system functions.

In most of R&D systems instead of trying to grasp an overall vision of the system, we tend to focus on isolated parts of the system and wonder why deeper problems remain unsolved or unexpected side-effects keep occurring. In a way we might be fighting symptoms, without addressing the underlying patterns of cause and effect.

System dynamics is a framework and tool that can make these patterns clearer in R&D systems and can help us see how to change them effectively with the aim of overcoming the complexities of decision making.

“System dynamics is a method to enhance learning in complex systems” (Sterman, 2000).Just as an airline uses flight simulators to help pilots learn about dynamic complexity, understand the sources of policy resistance and to design more effective policies, system dynamics (Particularly the use of CLDs, causal loop diagrams) or system dynamics modeling (with SFDs , Stock flow diagrams) is definitely appropriate for exploring, explaining and evaluating the complexity of strategic R&D problems by articulating and quantifying the links between policy and dynamic behaviors in R&D systems.

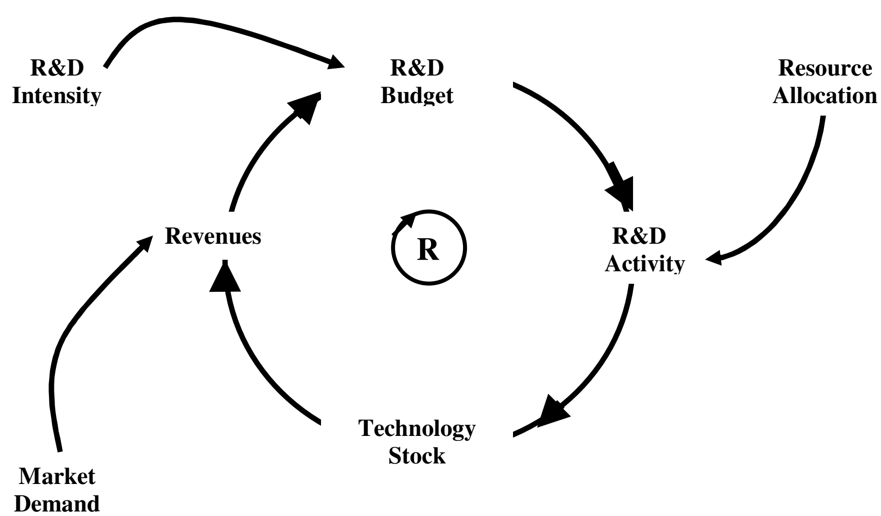
7.MODELS

7.1.Model 1
Modeling R&D Management Work Cycle with CLD

In this model a feedback structure of R&D that may approximate to several industries is illustrated in Fig 5.The diagram contains a feedback loop, capturing a work cycle that links a number of R&D management activities together.

R&D budged is governed by both revenues generated and the fraction of revenue spent on R&D (the R&D Intensity). If R&D budged were lowered over time, for example, the R&D staffing would also be lowered (either through retirement, or redundancies and redeployment of staff); less research would be carried out; as a result there would be a depleted flow of development; and consequently less technologies to commercialize; leading to diminished revenues available for R&D investment. Reinforcing behavior is evident in this feedback loop.

Figure-12: Modeling R&D Management Work Cycle with CLD



There are three points of leverage indicated in this diagram where management decisions can be employed: extent of market demand, R&D intensity, and proportion of staff time (resource) allocated between R&D activities. Market demand in this simple structure is assumed to be exogenous to a firm's operations, whereas R&D intensity and the amount of staff time allocated between separate R&D activities are policies which are endogenous to the firm's business model.

In this model each of the above mentioned drivers can be considered as the decision making tools available for the managers to bring the chance of company's survival higher.

In other words a higher R&D intensity, involving more resources in R&D activities and projects and/or capturing a larger proportion of the market that leads to more budget allocated to R&D activities will all serve to more and more commercialized technologies that in itself will be again a source for more revenue, more R&D budget, more resources and consequently more R&D activities and this reinforcing loop goes on and on.

We should bear in mind that this loop can also act negatively, leading to the company's bankruptcy.

This may originate from a wrong managerial decision to decrease the number of the R&D department (due to lack of an overall vision) in order to reduce the costs or in other words increase the profitability of the firm. Although this decision may lead to some temporary profit but over a period of time the feedbacks and the exponentially growing self reinforcing loops(as discussed and explained earlier) will lead to serious repercussions in the market resulting in firm's loosing the market share and finally a permanent bankruptcy.

As another wrong managerial decision we can mention a decrease implemented in the R&D personnel salary, or lack of motivating or recognition policies for the purpose of cost reduction, this decision will definitely lower the spirit of the personnel causing a loss in intangible assets of the company resulting in a lower work efficiency and less commercialized technology ending with less revenue and profit.

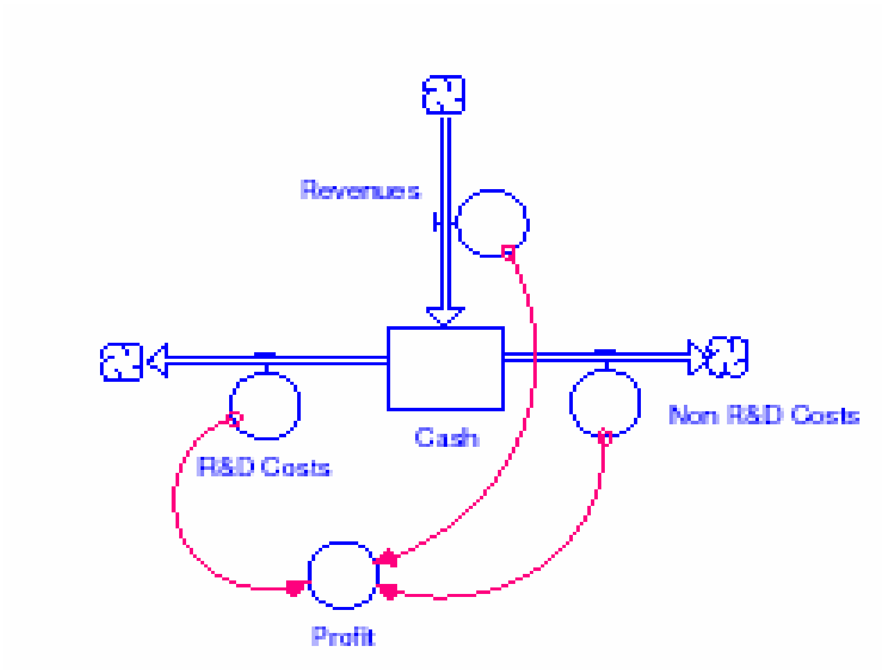
7.2.Model 2

Modeling the effect of R&D on a firm's Flow by means of Stock and Flow Diagrams

A CLD often allows a mental simulation of a process to take place, in cases where there is an inherent complexity, captured in multi loop forms CLDs may be difficult to develop or to be comprehended. In such cases it's highly recommended that a Stock and Flow Diagram (as introduced earlier) be used. Applying of SFDs will also enable us to develop simulations and what-if analyses by means of System Dynamic Softwares such as Vensim .

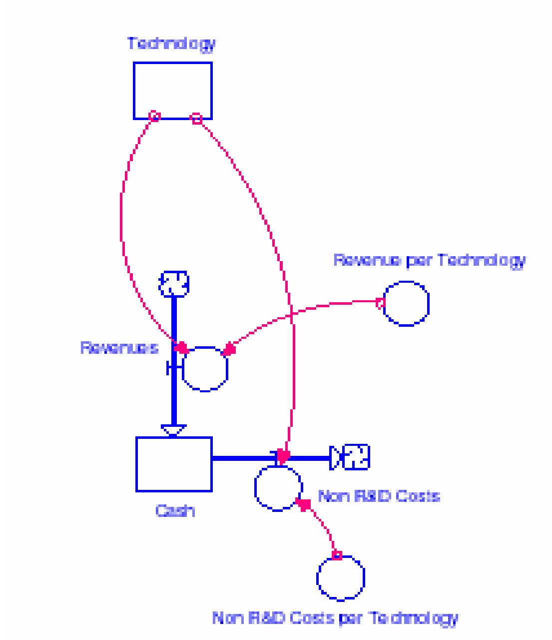
Representing an R&D problem in terms of stocks and flows allows an understanding of the underlying causal structure to be grasped. Figure 6 is a stock and flow representation of R&D cash flow. As illustrated the firm's stock of cash is increased by incoming revenues from sales, and is depleted by R&D and other operating expenses incurred. The algebraic difference between revenues and expenses gives (instantaneous) profit.

Figure-13: How cash Flow is Presented



But where do the revenues originate? In a technologically focused firm, its stock of commercialized technologies forms the basis fro the market offering (see Fig. 14)

Figure-14: From where do revenues originate?



This stock may be measured in end products and can be characterized as a unit of technology in terms of average revenue earned per year per unit of technology stock .

These technologies and products offered for consumption generate revenues. The revenues (filling the cash stock) are in balance with the costs incurred through the production, marketing and distributing of the technologies (depleting the cash flow).

But from where do the technologies originate ?

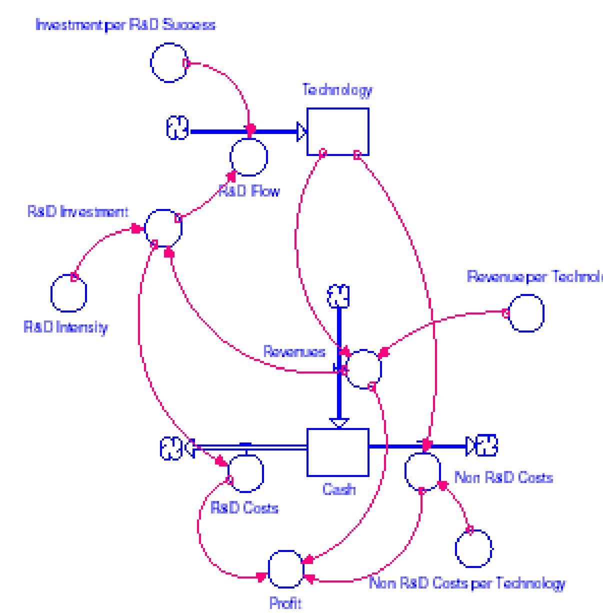
R&D projects (R&D flow) in the firm progress along a pipe line (Fig.15).

This flow of projects is governed by two constraints:

1) The R&D intensity (i.e. the proportion of revenue reinvested in R&D activity)
2) The investment required to take an R&D project through a commercialized technology.

A positive feedback (reinforcing behavior) is now evident in this model. Technologies provide revenue for fresh R&D activities and R&D activities render a flow of fresh technologies for commercialization.

Figure-15: From where does technology originate?



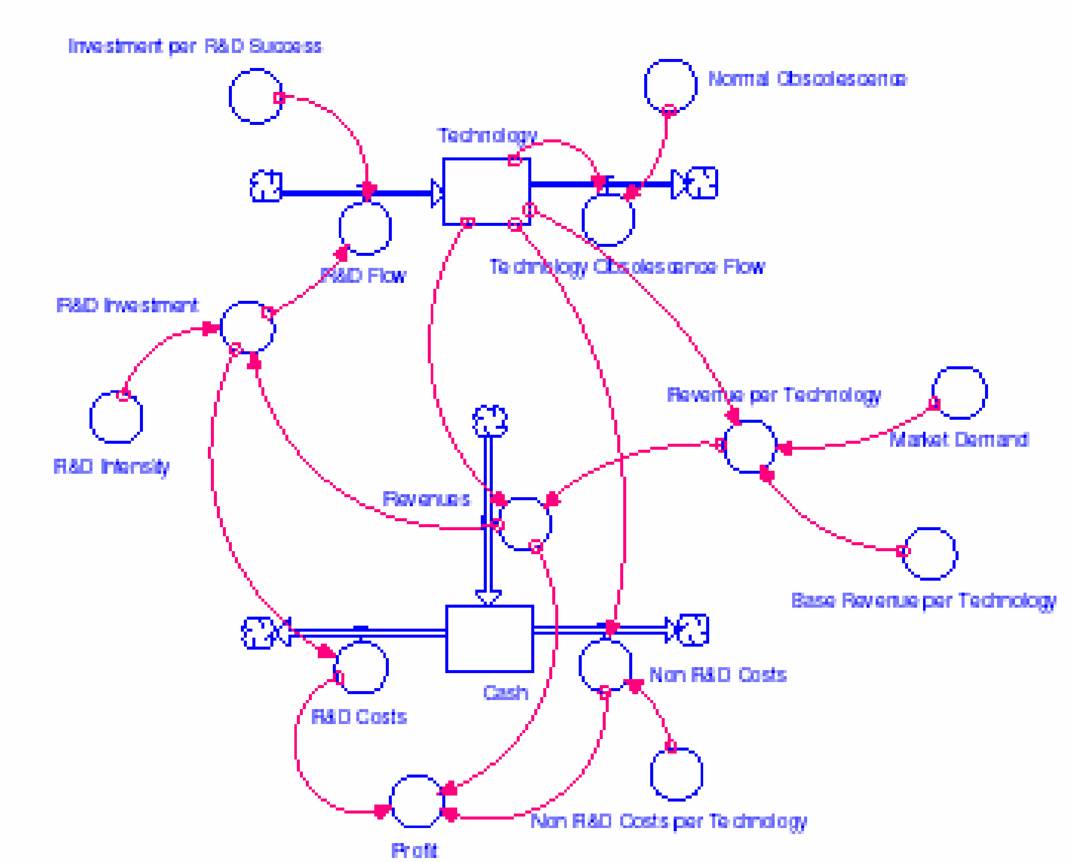
But what are the simple constraints to this model company's growth?

The growth of the company might be governed by two constraints:

1) Technologies become obsolescent over a number of years, such a constraint is often the characteristic of the industry.

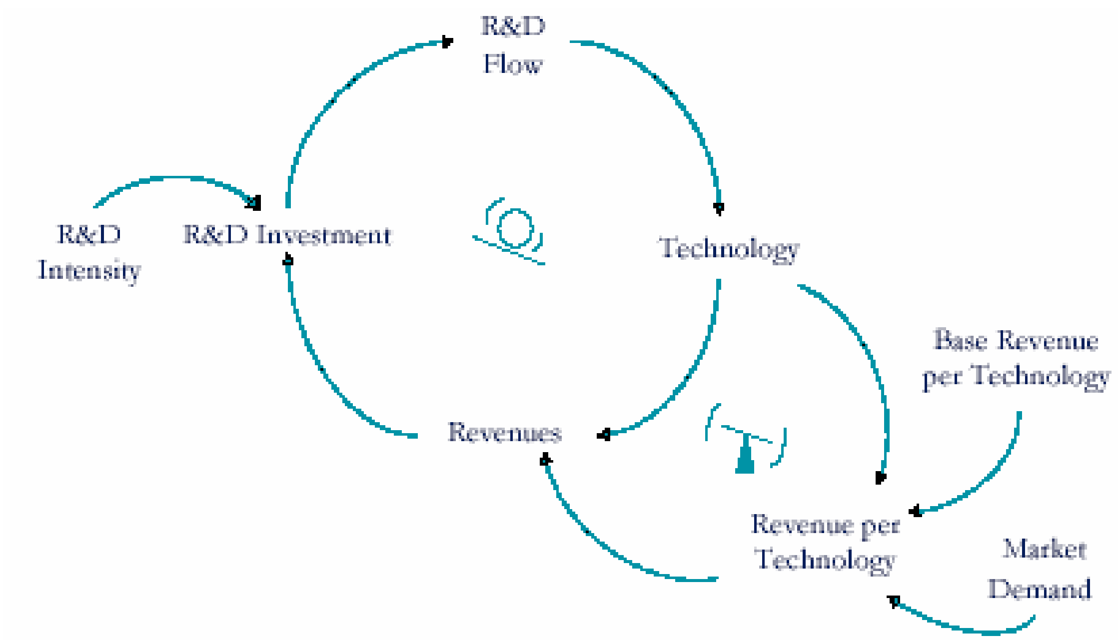
2) Market Demand can only absorb a certain number of technologies from the industry (Fig.16)

Figure-16: How is the company growth constrained?



In this model we witnessed that there is a limit for the growth of such a company, or in other words contrary to the first model in which no constraint existed, here we do confront serious constraints of technological obsolescence that lead to a decrease in the base revenue per technology and also market demand that definitely influences the revenue of the company. This model can also be illustrated as a simplified CLD.

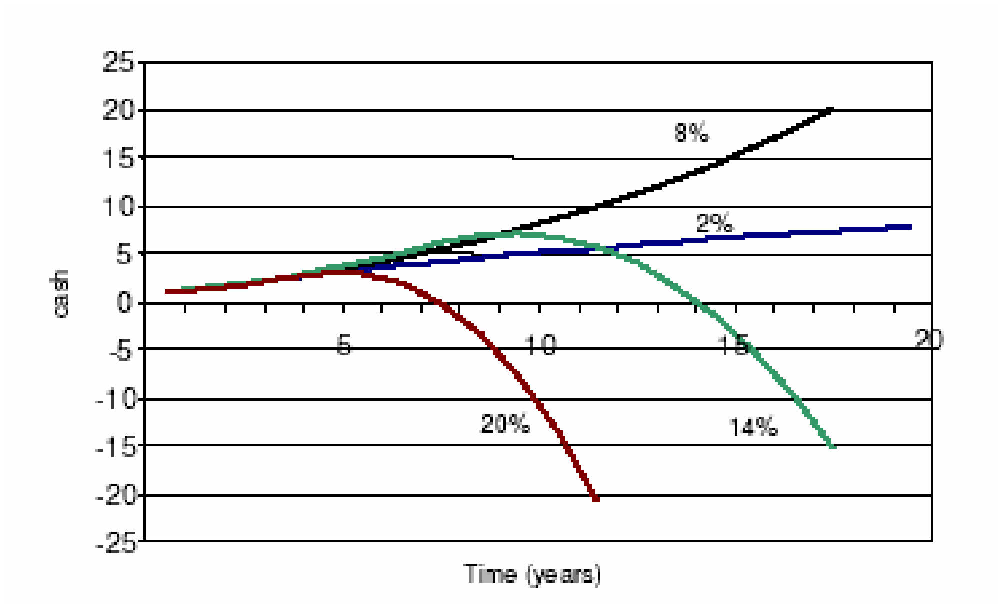
Figure-17: Simplified CLD Showing how is the company growth constrained?



Unlike the first model, increase in R&D will not positively influence the company's revenue, here the out side factors (Exogenous Factors) form a blanching loop shown by a Seesaw, that limits the growth of the Reinforcing loop.
In such situations Not only increasing R&D investment will not lead the company to success! But also it may even result in some unexpected reactions (emanating from the balancing loop).

This model is simulated by a system dynamics software and different scenarios have been examined by a what if analysis, the result of this simulation is shown in Fig.11.

Figure-18: The effect of 4 different R&D intensity policies on Cash-Flow for a fixed market growth condition



In this diagram R&D investment (as percentage of sales) is demonstrated for a time period of 20 years.

Surprisingly we see that policies in which the decision makers chose to increase R&D intensity failed, or in other words the more managers invested in R&D , the sooner the company went bankrupt, on the contrary we can come to the conclusion that moderate R&D investment increased company's profit as a result of more revenue.

<u>7.3.Model 3</u>

The Research and Development Policy Designs and their Ability to Accommodate Radical Market Change

Imagine a situation where up to year three a stable relationship exists between market and firm in the simulation. The market demand is static and predictable. This allows the firm to maintain a steady flow of R&D projects through to commercialization. The simulation model runs in a steady-state or equilibrium. At year three, the market experiences an episodic shift. There is a simultaneous step increase in "Market Demand" (100%) and a step decrease in "Base Revenue per Commercial Project" (25%) causing a state of disequilibrium. The market now requires .more for less.

The firm has to decide how to respond to these new market conditions. There are a number of policy alternatives that they could employ as a means of stabilizing or even growing profit in response to this market discontinuity. Given the complexity associated with aligning R&D, commercialized products and market demand, the firm would benefit from looking at this problem in its totality. Using a system dynamics simulation allows an exploration of longitudinal change in performance and capabilities under different sets of policy combinations.

A range of alternative policy confluences are explored in the five scenarios outlined below. The efficacy of these strategic decisions is mapped out over 20 years of simulated time. A range of indicators of the firm's performance and capabilities are monitored during each simulation run.

The policy analysis is designed to identify R&D policies which result in improved performance within the firm as measured across a range of indicators. A number of key metrics are selected to allow behavioral and numerical analysis of simulation performance. The final values and trajectories of these are noted for each simulated scenario and used for comparison. The selected indices are defined as follows:

Profit . The positive financial gain from the business operation after subtracting the R&D and operating expenses.

R&D Team . Personnel responsible for the R&D activities.

Normalized Revenue per Commercialized Project (NRPCP) . Inverse S-shaped relationship between the firm's supply of commercial technology stock, and the market demand for those technologies. If the ratio between these is high, then the NRPCP is low. The higher the NRPCP, the higher the revenue accrued per commercial technology stock.

Work Effectiveness. The efficiency (or productivity) with which the average R&D member of staff works., the relationship between work effectiveness and the R&D Backlog per R&D Team is bi-polar. The optimum work effectiveness is evident where neither work stretch (staff having extra time) nor work compression (staff under intense stress) is manifest.

In reaction to the market changes, the R&D policy maker could act in a number of ways. A range of policy modifications can be explored and their ability to deal successfully with a discrete market change measured and evaluated. Four broad policy scenarios are explored using the simulator:

• Scenario 1 . no change;
• Scenario 2 . greater R&D intensity;

• Scenarios 3. balancing resources and work loads between the respective R&D activities;
• Scenario 4 . lower R&D intensity.

These policy experiments have been set up as a means of capturing insights into the range of behaviors that the R&D system is capable of, with the desire to design policies which may render improved performance to technology firms operating under such business conditions.

Scenario 1: Business as Usual (Base Run)

The first scenario to be explored is titled .business as usual. This consists of keeping all policy decisions as fixed throughout the course of the simulation run, i.e. the firm does not modify its policy decisions in the face of this discrete shift in market demand. This scenario is set as the base run for the subsequent policy tests, and alternative scenarios are played out with a view to discovering if more desirable behavior can be exhibited by the simulation model.
The feed back structure of this scenario is illustrated in by a simplified CLD (Fig.19).

Figure 20 shows that if no alternative action is taken in response to the new conditions, then profit declines. This decline results from a diminished flow of R&D projects through to commercialization.

Declining revenues have resulted in lower absolute investment in the R&D team. As this capability reduces, then the flow of R&D projects is arrested. The NRPCP or ability of a given commercial technology to provide a return increases as the gap between market demand and the commercialized technologies extends. Unfortunately, as the output of the firm is diminishing so is its means of covering its operational overheads. The work effectiveness of team members remains constant as the volume of R&D work and size of the team declines together. Although the firm has not entered a free-fall, it is moving towards a slow death.

Figure-19: The CLD for the Business as usual Scenario

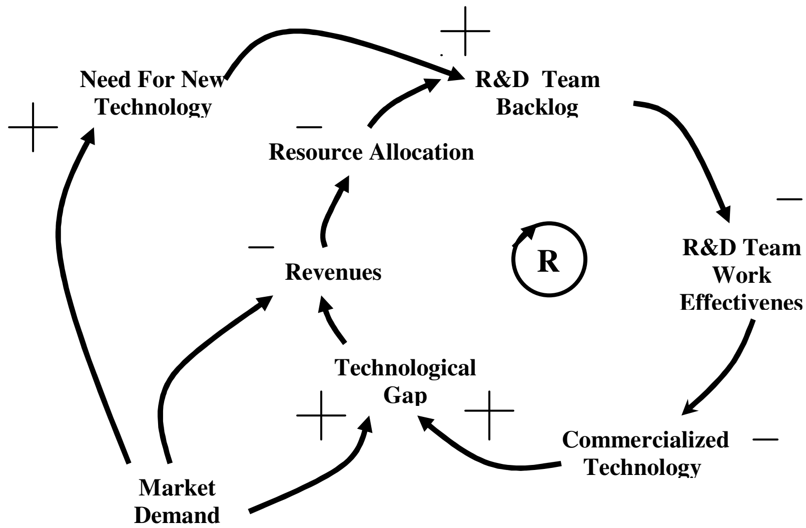
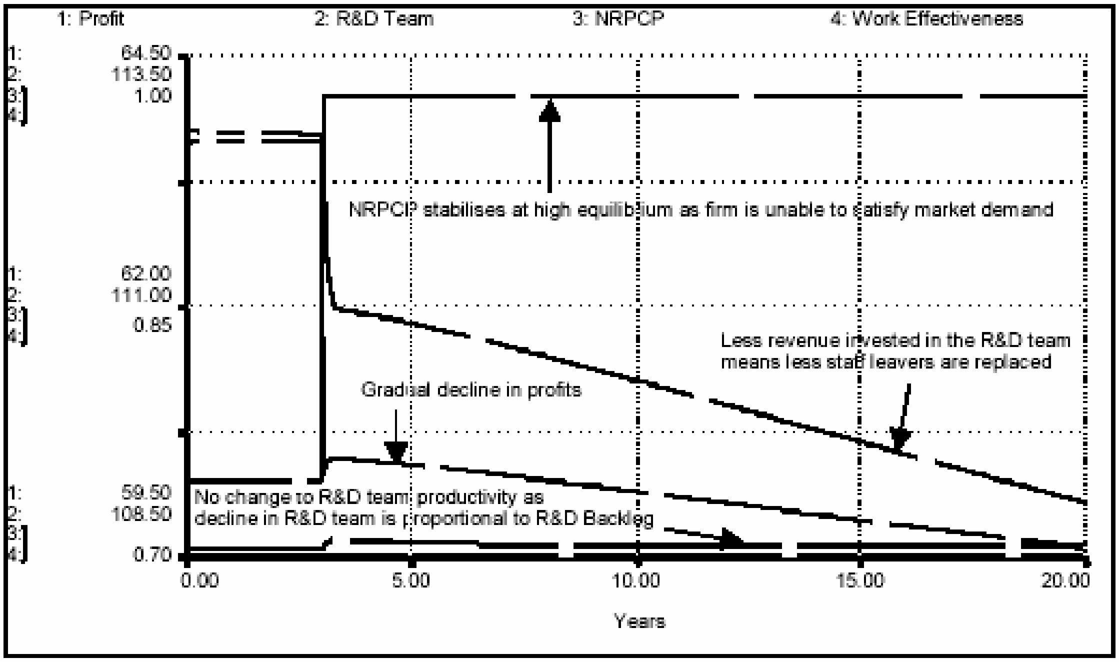


Figure-20: The Simulated Result of the Business as usual Scenario



Scenario 2: Higher R&D Intensity

In the "business as usual" scenario where no policy modifications are instituted, the performance of the simulated firm slowly deteriorates, with nearly all outputs exhibiting undesirable behavior. The policy makers may see fit to improve the R&D system through boosting the amount of R&D activity.

The "higher R&D intensity" scenario shows the effect of doubling the proportion of resources committed to the R&D function in comparison with the base run, whilst keeping all other policies invariant.

Figure 14 shows a greater deterioration in system performance than seen in the base run. Profit stabilizes then collapses into losses. This decline results from too rapid a growth in the flow of R&D projects through to commercialization. Over time, an over-supply of commercial technologies to the market emerges and revenues consequently decline. Lower absolute investment in the R&D team occurs, and as this capability reduces, the flow of R&D projects slowly diminishes. The NRPCP collapses due to the market over supply. The work effectiveness of team members recovers as the volume of R&D backlog per team member grows to a more optimal level. If the firm cannot turn around the financial loss making then it may not survive over the 20 simulated years. The simplified CLD is shown in Fig.22.

Figure-.21: The Simulated Result of the "higher R&D intensity" Scenario

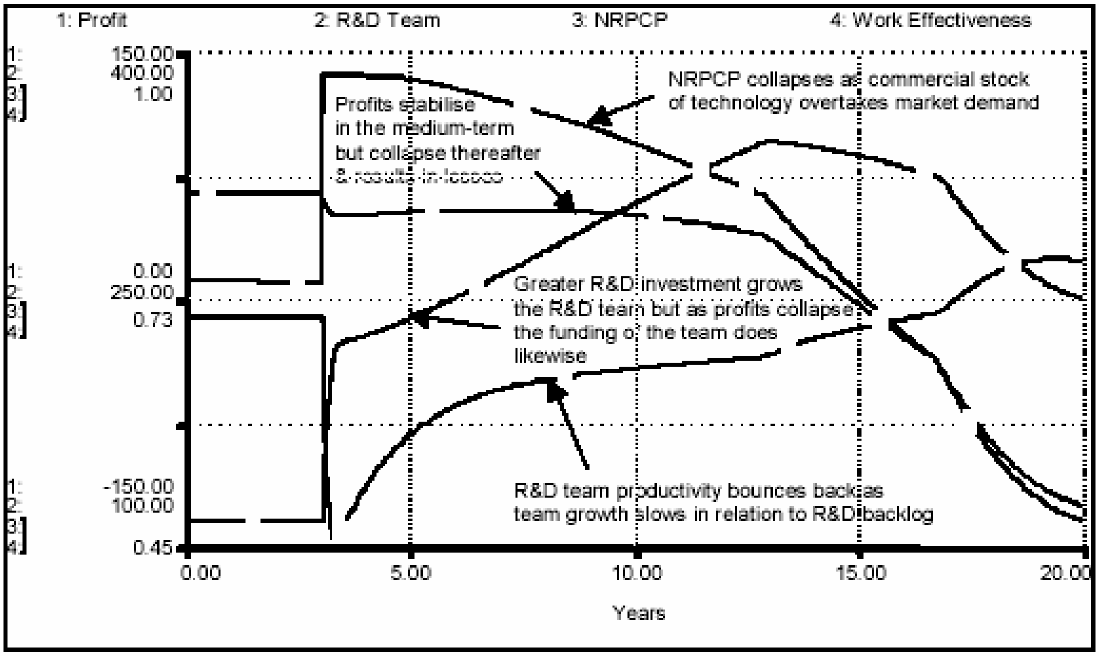
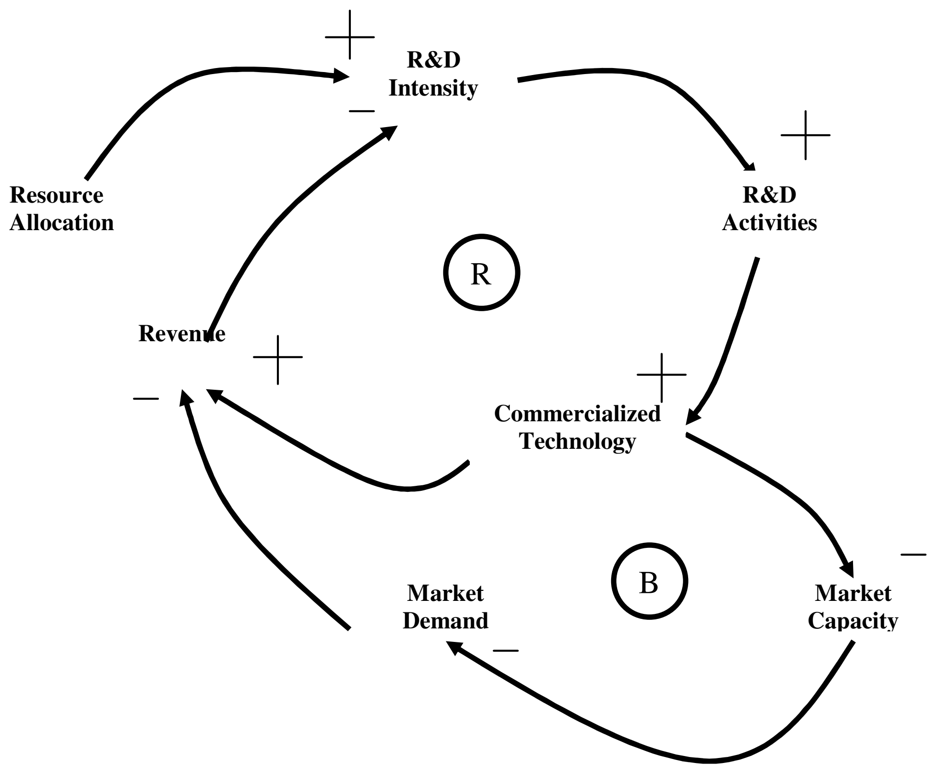


Figure-22: The CLD for the “higher R&D intensity” Scenario

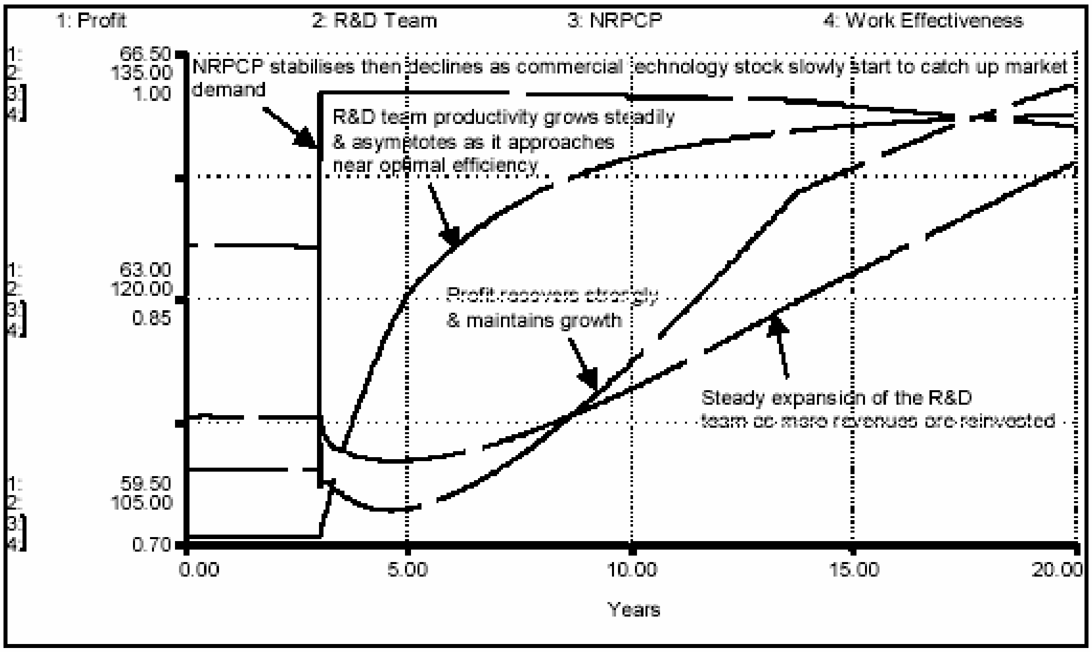


Scenario 3: More Research and Less Development

In the “higher R&D intensity” scenario the performance of the firm greatly deteriorates across most measures from the medium and into the long-term. An alternative scenario to heavily financing the growth of the R&D function may be to make better use of existing resources through better allocation of staff time between respective R&D activities. The “more research and less development” scenario shows the effect of modestly increasing the proportion of resources committed research at the expense of development in an effort to boost the backlog of R&D ready for commercialization. All other policies remain fixed.

Figure 16 shows a general improvement in the system as compared to the base run. Profit grows consistently and, after a period of time, exceeds the initial profit. This improvement results from a steady growth in the flow of R&D projects through to commercialization. Over time, the stock of commercial technologies gradually approaches market demand and revenues remain strong but grow at a lessening rate. As expected, the NRPCP declines slowly as the market is better satisfied. The work effectiveness of team members approaches an optimal level (i.e. a good balance for the team between trying to compress their work or stretching it out). The health of the firm looks to be secure under these market conditions into the long-term.

Figure-23: The Simulated Result of the “More Research and Less Development” Scenario

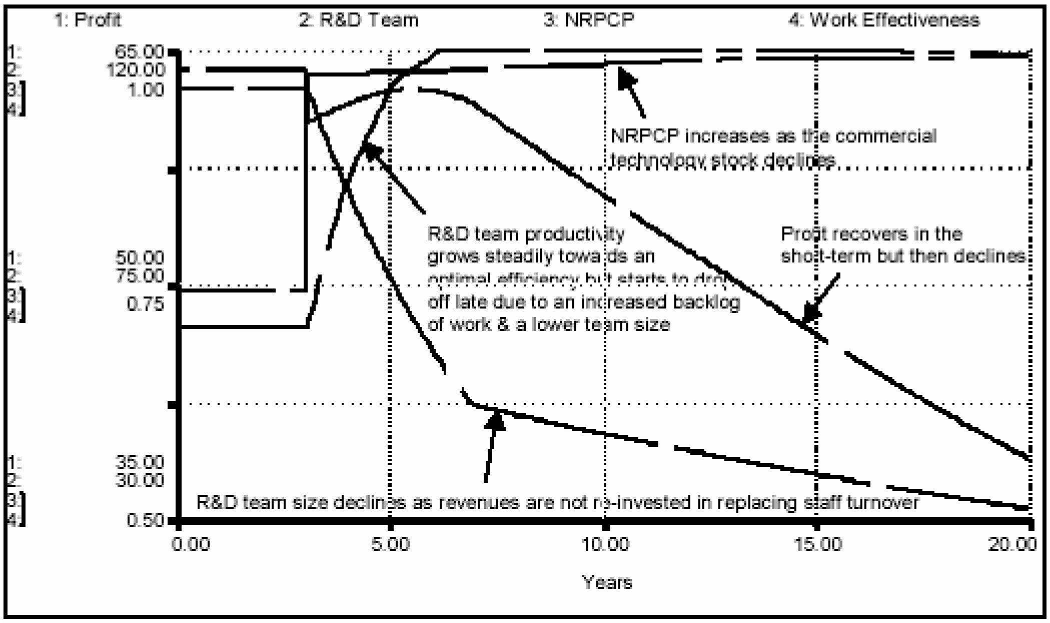


Scenario 4: Lower R&D Intensity with Modest Development

Can the policy makers offset the fall in base revenues by reducing the R&D intensity to a lower level whilst maintaining a moderate amount of development over research allocation? This policy confluence is tested in the .lower R&D intensity with modest development scenario.

Figure 17 shows a greater deterioration in system performance than seen in the base run. Profit recovers temporarily but then declines into the long-term. A diminishing R&D team reduces the flow of R&D projects through to commercialization. Over time, an under-supply of commercial technologies to the market emerges and revenues consequently decline. This results from a lower relative and absolute investment in the R&D capability. The NRPCP improves due to the market under-supply. Although work effectiveness improves over the medium into the longer term, by year 18, even this starts to decline as the R&D team depletes at a greater rate than the R&D stock is being worked down. If the firm can not turn around the ever reducing profits, then its operations are not sustainable in the long-term. The CLD of this scenario is similar to that of the first scenario.

Figure-24:The Simulated Result of the "Lower R&D Intensity with Modest Development" Scenario



In the end the summary of the effect of the scenarios on the company's performance can be summarized in the following Table Fig.25.

Figure-25: Summary of business performance for selected scenarios (final values)

	Profit (£M's)	Profit per R&D Team Member (£M/Employ.)	NRPCP	Work Effectiveness
Scenario 1	59.54	0.55	0.98	0.70
Scenario 2	-127.43	-0.51	0.47	0.77
Scenario 3a	128.14	1.94	0.95	0.96
Scenario 3b	44.35	0.56	0.99	0.50
Scenario 4	38.70	1.23	0.99	1.00

As you could also witness different strategies in decision making lead to unpredictable and holistic results, that can only be examined and analyzed through System Dynamics Approach.

8.SUMMARY & RESULTS

The ability to think and manage strategically, especially against a backdrop of short-termism and operational imperatives, is the toughest of senior management tasks. This paper touched on the use of dynamic simulation to explore R&D management systems. The approach aims to highlight the dimensions of complexity in R&D management and to provide some tools and techniques that can help in envisioning longer-term futures and taking a more 'holistic' or inclusive view of enterprise.

This article described how a dynamic simulation model can be built which broadly characterizes and captures the causal feedback structure and performance behavior inherent to a generic R&D system within a firm.

The models we explored and the approach we presented can sometimes mean the difference between life and death for a company. As we discussed in the first model the feed back structure of causal diagrams in reinforcing loops if not understood or envisioned lead to company's bankruptcy, this holistic structure and the leverage points that resembled managerial decisions that could bail a company out of trouble or sink the whole firm under the water forever.

The second model was also another common phenomenon that illustrated a growth limit archetype, in some companies the R&D policy makers decide to increase the overall revenue of the company by investing more and more in the R&D resulting in high intensity R&D system , but what they do not consider due to lack of an overall vision are the growth limit factors such as market demand that is soon lowered by the flood of more and more commercialized emanating from R&D system, this factor will soon originate a negative feedback loop that in no time will leave the company in bankruptcy.

The last model was R&D strategy setting in confronting sudden market changes, in this model we discussed, illustrated and analyzed through different scenarios.

Overall system dynamics provides great assistance for decision making in complex environments applying system dynamics is sort of a preventative measure that avoids getting into really great disasters. Since decision making is of a high importance in R&D, we can come to the conclusion that practicing this approach is necessary and vital for R&D decision making.

BIBLIOGRAPHY

- Jonathan D. Moizer and Mike J. Towler (2005). How to Tackle the Complexity of R&D management .
- Jonathan D. Moizer and Mike J. Towler (2004). Research and Development Resourcing When Faced with Fundamental Market Dynamics.
- The 2004 R&D Scoreboard, available: www.innovation.gov.uk/projects/rd_scoreboard/analysis/analysis.htm.[19th March 2004].
- Gene Bellinger (2004) Systems, A Journey Along the Way.
- Gene Bellinger (2004) Systems Thinking, An Operational Perspective of the Universe.
- Pavinder Monga (2002)A System Dynamics Model of the Development of New Technologies for Ship Systems.
- Erik R Larsen (2002) Introduction to System Dynamics Presentation.
- Stermann, JD (2000).Business Dynamics: Systems Thinking and Modeling for a Complex World: Irwin McGraw-Hill .
- Senge (1990). The Fifth Discipline: The Art and Practice of The Learning Organization.
- Jay W. Forrester (1989) The Beginning of System Dynamics.
- System Dynamics Home Page, http://www. SystemDynamics.org.
- Kim Warren, Competitive Strategy Dynamics