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**UNIVERSITAT POLITÈCNICA DE CATALUNYA ·
BARCELONATECH (UPC)**

DEPARTAMENT D'ORGANITZACIÓ D'EMPRESSES

P.h D. THESIS

**LONG TERM CAPACITY PLANNING WITH
PRODUCTS' RENEWAL**

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Abstract

Long Term (or Strategic) Capacity Planning (LTCP) consists of deciding the capacity state of the production system for a long term. It consists of decisions that are related to strategic planning such as buying or selling of production technologies, and making tactical decisions regarding capacity level and configuration. Long term decisions are usually solved by means of non-formalized procedures, such as generating and comparing solutions, which do not guarantee the optimal solution. The thesis formalizes and solves a long term capacity planning problem with the following main characteristics: (1) short-life cycle products and their renewal, with demand interactions (complementary and competitive products) considered; (2) different capacity options (acquisition, renewal, updating and reducing); (3) some tactical decisions (aggregate production planning and financial planning). The problem is solved by means of a Mixed Integer Linear Program (MILP) model which, according to the results of a wide computational experiment, can be considered as an appropriate tool to deal with this kind of problem.

Keywords: Long term capacity planning, product renewal, mixed integer linear programming

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LIST OF ABBREVIATIONS AND SYMBOLS

| Symbol | Meaning |
|---------------|---------------------------------------|
| LTCP | : Long Term Capacity Planning |
| LTCPP | : Long Term Capacity Planning Problem |

Summary

Long Term Capacity Planning (LTCP) consists of deciding the type and amount of capacity of production systems for multiple periods in a long term planning horizon. It involves decisions related to strategic planning, such as buying or selling of production technology, outsourcing, and making tactical decisions regarding capacity level and configuration. Making these kinds of decisions correctly is highly important for three reasons. Firstly, they usually involve a high investment; secondly, once a decision like this is taken, it cannot be changed easily (i.e. they are highly irreversible); thirdly, they affect the performance of the entire system and the decisions that will be possible at a tactical level. If capacity is suboptimal, there will be lost demand (in the present and possibly in the future); if the system is oversized, there will be unused resources, which may represent an economical loss. Long term decisions are typically solved with non-formalized procedures, such as generating and comparing solutions, which do not guarantee an optimal solution. In addition, the characteristics of the long term capacity planning problem make the problem very difficult to solve, especially in cases in which products have a short life cycle. One of the most relevant characteristics is the uncertainty inherent to strategic problems. In this case, uncertainty affects parameters such as demand, product life cycle, available production technology and the economic parameters involved (e.g. prices, costs, bank interests, etc.). Selection of production technology depends on the products being offered by the company, along with factors such as costs and productivity. When a product is renewed, the production technology may not be capable of producing it; or, if it can, the productivity and/or the quality may be poor. Furthermore, renewing a product will affect its demand (cannibalization), as well as the demand and value of the old products. Hence, it is very important to accurately decide the correct time for product renewal. This thesis aims to design a model for solving a long term capacity planning problem with the following main characteristics: (1) short-life cycle products and their renewal, with demand interactions (complementary and competitive products) considered; (2) different capacity options (such as acquisition, renewal, updating, outsourcing and reducing); and (3) tactical decisions (including integration strategic and tactical decisions).

1. INTRODUCTION

Long Term Capacity Planning (LTCP), also called strategic capacity planning (SCP), in manufacturing is essentially related to determining what kind and type of capacity should be used. It also involves when and by how much capacity levels should change, including decisions about capacity augmentations or capacity reductions (Olhager et al., 2001; Karabuk and Wu, 2003) within a long term horizon. LTCP is concerned with the capacities that take a long time to change, such as acquiring new capacity or reducing capacity levels (Olhager et al., 2001). MirHassani et al. (2000) explain that capacity decisions in the long term are associated with acquiring the resources that are needed to survive and to succeed in the long term. These capacity decisions include increasing, decreasing, updating, renewing and outsourcing. Increasing refers to adding production technology, which includes production lines, production processes, equipment, tools, and machines, etc.; whereas decreasing is just the opposite. Renewing is changing the old resources for the new ones when the properties of the machines are the same, whereas updating is changing an old machine for a new one when the properties of the machines are not the same. Updating may be necessary to produce new products, because old production technology may not be capable of producing new products and even if it can, the yield and quality of the resulting products may be poor. New technology may be better in terms of both productivity and quality. Outsourcing is using external resources instead of internal resources for production (White and James, 2000); for instance, firms use third parties to provide the intended products or services rather than investing in new production technology. The most important objectives of outsourcing are to reduce unit costs, decrease the expenditure of capital, increase access to modern technology, and achieve the benefits of new technology (White and James, 2000). The outsourcing agreements can be different and include very different components.

LTCP includes deciding the amount of investment and selecting resources such as equipment, facilities, systems, people, etc. to use in a manufacturing site (Uribe et al, 2003). MirHassani et al. (2000) explain that capacity planning (capacity level) and capacity utilization (efficient usage) are two of the most important decisions for manufacturing firms. The sequencing and scheduling of production technology purchases and the removal of old or out of date production technology are investment decisions made just a few times at most. These decisions involve trade-offs among finance, throughput, cycle times and risk, and are difficult to change with regards to investment and labor costs (Geng and Jiang, 2009). These decisions seek a balance between financial objectives, production objectives (e.g. productivity, cycle time, timing) and risks and must be made in the face of uncertainty with regards to future realizations of demand, price and technology data (MirHassani et al., 2000). Due to the high capital investment cost for short life cycle products, overestimation or underestimation of capacity will either lead to low utilization of production technology or to a lack of sufficient capacity (Geng and Jiang, 2009). To supply according to current demand, firms may make a decision to invest in more production technology, but if future demand is low, firms will be left with excess capacity, meaning it would be a suboptimal investment

decision. Selecting accurate production technology within the right acquisition time frame is very important and related to high capital expenditure.

Another important issue that LTCP has to deal with is shortening product life cycles and the introduction of new products. Products with short life cycles (1-2 years) are becoming increasingly common in several industries (Kurawarwala and Matsuo, 1996). Due to the continuous evolution of science and technology, personalized products, and combinations of functional products with innovative products, products upgrade with increasing frequency. New production technology is introduced often and more products have the characteristics of short life cycles, especially high tech goods, consumer electronics, and personal computers (Kurawarwala and Matsuo, 1996; Xu and Zhang, 2008; Aytac and Wu, 2011). Both capacity and investment in capacity are costly, and firms must avoid over-investing in capacity, particularly for innovative products (Pangburn and Sundaresan, 2009). Hence, deciding the right time for a product renewal is a vital decision for firms. In addition, product renewal affects both the value and the demand of the old product/s. An appropriate function of the demand for both the new and the old product should be considered (Pangburn and Sundaresan, 2009).

Lead times for installing new production technology should also be taken into account because installing the system may take anywhere from months up to several years. Installing and implementing new systems is a lengthy process from the time firms make an investment decision to the time the new system produces the first product on the product line. Thus, capacity decisions generally have to be made before demand is fully realized. Moreover, adopting new technology usually comes with high costs, which may prevent investment decisions in new production technology from being made at the best time (Wu and Chuang, 2010). Huh et al. (2006) explain that the early purchase of production technology often results in unnecessary capital spending, whereas tardy purchases lead to lost revenue, especially in the early stages of the product life cycle when profit margins are the highest. This is especially the case in high tech industries such as the semiconductor, consumer electronics, telecommunications and pharmaceutical industries. In such industries, products quickly become more complex and the range of products is very wide; therefore, management of production technology is a critical factor for long term success.

Increasing competitive pressure from the globalization of manufacturing activities and markets means that manufacturing organizations must reorient their strategies, operations, processes and procedures to remain competitive. Today's capacity planning decisions significantly affect future revenue (Huh et al., 2006). To achieve competitive standing, manufacturing organizations must be able to adapt their long term plans for a changing world (Gomes et al., 2004). The competitive position of manufacturing firms is based on their ability to create strategic cooperation between market opportunities and their own manufacturing capabilities. Yaman (2008) states that well-established, well-managed manufacturing companies have gained many competitive advantages as a result of proper usage of manufacturing capacity. These advantages include cost reductions (effective use of resources), and quality improvements on products and services.

Sustainable long-term success for a firm depends on accurate, rational, and optimum LTCP taking into the account of uncertainties in demand fluctuation, product life cycles, new products and technology (production technology and acquisition time). Although the importance of the problem is clear, there is a lack of formalized solving procedures as until a few years ago, there was no technology available to cope with this kind of problem. In most cases, the solution is chosen by generating and evaluating different options, which requires a lot of knowledge and may not lead to the optimal solution. Since production capacity is the most important part of capital investment, a slight change in managers' decisions might lead to a significant financial loss. Once a decision is made, it affects the whole system, and is typically irreversible; once the production technology is installed, it cannot be changed easily. Consequently, making suboptimal decisions may lead to huge financial losses in the future.

Most of the recent studies on LTCP have been done on the semiconductor manufacturing industry (e.g., Karabuk and Wu, 2003; Huh and Roundy, 2005; Barahona et al., 2005; Geng et al., 2009). A literature review of the existing strategic capacity planning studies was done by Geng and Jiang (2009), who identified emerging methods for long term capacity planning in the semiconductor industry. In their review, they investigate current research and fundamental methods to overcome the problems in LTCP. This is a high tech industry with rapidly changing products that requires intensive capital investment. Rapidly changing products and production technology require high degrees of flexibility and innovation. The total capital investment for a plant is typically several billion dollars (Barahona et al., 2005), and the development time for high tech products is uncertain, as the products have a very short life cycle with unpredictable demand.

Models, tools and procedures must be designed and developed to help with the LTCP decision process. Most of the solutions proposed in the existing literature on capacity planning do not take into account a dynamic design of the system (that is, one in which the capacity can be changed from one period to another). In addition, the decisions about renewing products are not included, and the effects on the demand of new and old products are not fully considered. Financial implications are often considered in a very rudimentary way, as many of the possibilities for financing and surplus disposal are not included. The aim of this proposal is to design tools for Long Term Capacity Planning for companies offering short-life cycle products, taking into consideration product and production technology renewals and economic feasibility.

The remainder of the document is organized as follows: in Section 2, the long term capacity planning problem is explained; in Section 3, the objectives and thesis definition are defined; in Section 4, a literature review and conclusions of literature review are given; in Section 5, the problem definitions are defined; in Section 6, the mathematical model is given; in Section 7, the computational experiment and analysis are done; in Section 8, the conclusions and further research are explained; Section 9 contains the publication; and Section 10 concludes with the references.

2. THE LONG TERM CAPACITY PLANNING PROBLEM

The questions of what the capacity type and levels should be and when investment in production technology should occur Long Term Capacity Planning (LTCP) defines the Long Term Capacity Planning Problem (LT CPP). It is concerned with major changes that affect the overall level of output in the long term by using capacity optimally under given uncertainties in products and production technology (Kumar and Suresh, 2009). Long-term capacity requirements are difficult to determine because future demand and technology are not certain. Attempting to forecast the future in the long term is both risky and difficult. Sometimes a company's current products may not even exist in the future, rendering current production technology useless in the future. (Kumar and Suresh, 2009). Moreover, LT CPP has to deal with the very complex decision process. The decisions primarily address two major topics: (i) how much capacity to build and (ii) whether to invest in dedicated or flexible systems, or a combined portfolio consisting of both systems (Ceryan and Koren, 2009). It must decide the optimal timing and the optimal levels of capacity acquisition and allocation, which hold major importance in strategic capacity planning for a wide array of applications (Huang and Ahmed, 2009).

LTCP or SCP deals with the capacity changes that usually come in large, discrete steps rather than in small increments (Olhager et al., 2001). The strategic capacity decisions of a company are concerned with acquiring the production technology needed to survive and prosper over the long term (MirHassani et al., 2000). This type of capacity planning has a time horizon longer than a year, depending on the kind of activity. Karabuk and Wu (2003) explain that LTCP is considered at the beginning of each fiscal year, with a time horizon of three to five years. They divide LT CPP into two main groups: capacity expansion, which involves identifying the required manufacturing technology, and the capacity levels to be physically expanded or outsourced in the planning timeframe; and capacity configuration, which involves determining how to configure the facility and the mixture of technology. Their goal is to determine both existing and future capacity as well as production technology while dealing with uncertainties. The system should be flexible so it can be adapted to changes in product characteristics and even to new products.

Rapid changes in technology and products, complex fabrication process, long lead times, the high cost of capacity increments, high uncertain demand, and capacity are the factors that make LTCP difficult to overcome (Geng and Jiang, 2009). It is difficult to find an optimal solution for capacity planning related to the long term. There are a few complex factors of the LT CPP that means it is tough to find optimal and accurate results. Uribe et al. (2003) make a list of common pitfalls that firms come across while tackling these problems, including ignoring the impact of uncertainties, focusing solely on internal operations, inadequately understanding operational constraints, and a lack of awareness of the needs of immediate and ultimate customers.

2.1. Difficulties in LTCP

The difficulties related to LTCP should be well defined in order to provide better understanding of the problem and to enable firms to design appropriate solutions. These main factors that make manufacturing capacity planning difficult are explained below.

- High uncertainty in product life cycle and demand causes floating capacity usage: One of the important factors that make the problem difficult is uncertainty. Karabuk and Wu (2003) state that capacity planning in manufacturing often suffers from high variability in demand. Also, the life cycle of products is becoming shorter, making forecasted future demand more uncertain (Swaminathan, 2000). According to Geng and Jiang (2009), without having deterministic demand (that is, without knowing the exact number of units to be produced), estimations in demand can easily be underestimated or overestimated, which will either lead to under-utilization of production technology or a lack of capacity.
- Production technology and products change rapidly: Customers' desires change quickly due to globalization, fast moving information and the contribution of developments in information science. In order to survive, firms should adapt to market demand. This may require product development in order to keep or gain market shares. High technology products in particular are developed quickly. New versions of existing products or new products entirely are introduced to the market in a short time frame, affecting both the demand and value of old versions. New products are being introduced constantly (Swaminathan, 2000) and incorporating them into the existing production technology may be costly and inefficient. The same factors that lead to the development of new products also lead to development in production technology. New production technology may be expensive and seen as unnecessary, but the old technology may not be able to process the new products easily. Even if it can produce similar products, the productivity might be low, the cycle time may increase, and quality may be poor. In contrast, the new technology may be able to process old products in a short time frame of higher quality at a lower cost. LTCP should consider the breakeven point with regards to new/old products and new/old production technology.
- Improving products may require a different manufacturing process: When improving products, especially in high tech industries, the production processes often become more complex. They may even need different processes beyond what existing production technology can offer. According to Geng et al., (2009), using the example of semiconductor industries, producing a wafer involves 300-400 operational steps, and each improvement on products means redesigning the existing processes. A small change in the product design may mean a vast change in the processes and require new product technology. Wu and Chuang (2010) state that production technology is rapidly evolving in high tech industries and that the introduction of new production technology is usually accompanied with new product lines and increased production efficiency. Moreover, in the high-tech industry,

manufactures must continually invest in new products and state-of-the-art technology, which may be costly.

- Capacity increments may have long lead times: Capacity planners have to decide on tool procurement based on forecasts for demands. In a rapidly evolving technology environment, these forecasts may be highly inaccurate (Swaminathan, 2000). The necessity of capacity augmentation should be analyzed in advance and, in cases of high lead times, new production technology should be ordered several months ahead of time. Installing a new production technology can take several months and initializing production can take even more time. As a result, the manufacturer must use inaccurate demand forecasts for products (Swaminathan, 2000). When these kinds of decisions are made, the knowledge of real future demand may be very poor. Furthermore, Karabuk and Wu (2003) point out that the semiconductor wafer fabrication process requires state-of-the-art production technology, which costs millions of dollars and must be ordered up to 12 months in advance. During that time, some products may become outdated or be replaced by another version or a new product within a few months. LTCP should consider of the timing of changing processes and production technology.

2.2. The important features of the LTCP problem in manufacturing

LTCP is a complex process involving many difficulties, as detailed above. The important features of the problem include capacity, acquisition and reduction of production technology, characteristics of products and product renewal, financial issues, tactical decisions and uncertainties. These features affect the results with different levels of importance. The features and the evaluation criteria of the solutions are explained below.

2.2.1. Capacity

Long term capacity planning is directly related to the state of capacity in a long term planning horizon. The main goal is using capacity in the most efficient way. Efficiency helps firms and businesses meet customer requirements such as low prices, high product variety, high quality and shorter lead times. Capacity options in a strategic level can be increased or decreased in terms of production technology. Increasing capacity is obtained by acquisition and decreasing capacity is obtained by reduction.

2.2.2. Acquisition of Production Technology

LTCP should provide an answer for decisions involving capacity expansion. Generally, long term capacity planning is done in order to increase capacity levels by purchasing production technology. Options for firms include buying additional technology, renewing or updating existing production technology, and outsourcing.

2.2.2.1. *Additional Production Technology*

This refers to the acquisition of new production technology in order to support increasing demand. Excessive demand, new versions of existing products, and entirely new products are three of the important reasons that force firms to increase existing capacity by adding new production technology.

2.2.2.2. *Renewing*

Renewing is changing existing production technology for the same or similar technology, which may be because of breakdowns in the existing technology or simply that the existing technology has reached the end of its life. Renewing is primarily done by protecting existing capacity levels; however, in many cases, it can lead to improvements in capacity levels.

2.2.2.3. *Updating*

Updating is changing an existing production technology with a state-of-the-art new one. Modifications to existing products or new products may require new processing. Updated or new versions of the production technology mainly have an impact on yield by shortening the process time and improving quality. Instead of renewing existing production technology, updating production technology by acquisition may be a more economically viable option.

2.2.2.4. *Outsourcing*

Outsourcing helps production gain temporary capacity without any investment. Uncertainty induces a higher level of outsourcing, and outsourcing decisions can be delayed until uncertainty is reduced during the planning period (Karabuk and Wu, 2003). Implementation of outsourcing typically requires a shorter lead time than for acquisition decisions.

2.2.3. Reduction of Production Technology

Capacity reduction is decreasing capacity levels. Capacity can be decreased when there is a low demand for products, which causes low plant utilization and blocked up capital (Kamath and Roy, 2007). When a decision is made to decrease capacity levels to add a value to the system.

The acquisition, second hand and salvage values of production technology are important data for LTCPP, and their costs and values must also be taken into account. When more production technology is necessary, it can be bought; when it is unnecessary, it can be sold. The physical boundaries of the firm may have a limit and new production technology may not be able to be installed, or there may be constraints in inventory storage area.

2.2.4. Characteristic of products (short life cycle products) and product renewal

Long term capacity requirements are dependent on marketing plans, product development and the life cycle of the product (Kumar and Suresh, 2009). According to product life cycles, products can be divided

into two groups: short life cycle products and long life cycle products. (Georgiadis et al., 2006). Long life cycle products have more predictable demand and fewer profit margins than short life cycle products. Kamath and Roy (2007) define short life cycle products as the products sold for a short period of time. Having products with a short life cycle makes LTCP even more difficult. Shortening life cycles mean products can become outdated shortly after their launch, which directly affects management of the product portfolio and the optimal timing of capacity investment (Wu and Chuang, 2010). Particularly in high-tech industries such as consumer electronics, telecommunications equipment, and semiconductors, technology has been rapidly improving and new products with shortening life cycles are frequently introduced to the market (Wu et al., 2006).

Short product life cycles lead to a rapid production technology obsolescence rate. In many industries, new production technology can also be used to produce existing products, but short life cycle products often require newer production technology and long lead times, which prevent firms from responding quickly to demand in the market (Wu et al., 2006).

Shortening product life cycle leads to high obsolescence in products and production technology. Such technology may no longer be able to perform required functions such as being available for purchase or being able to be repaired affordably (Wu and Chuang, 2010). Products may also become obsolete when they are replaced by a newer version of the same product. New products are most attractive when they are initially released, and price declines over time due to obsolescence (Pangburn and Sundaresan, 2009). With high-tech products there are significant obsolescence effects, so firms must consider the tradeoff between its capacity costs and subsequent product life cycle revenues (Pangburn and Sundaresan, 2009).

When renewing products, the demand functions of the new product (or version) and the changes in the demand of the old product (or version) must be considered. Of course, the demand may depend on the prices of the new and old product, so prices should also be taken into consideration.

Demand for short life cycle products is always volatile and thus challenging to manage. Rapid innovation in technology causes greater product diversification in products with shortening life cycles. Traditional forecasting methods are often inappropriate for estimating demand for a product with a short life cycle because they do not take into account the characteristics of the product's life cycle and usually require a significant demand history, which is available only after the product has been sold for some time (Zhu and Thonemann, 2004). For short life cycle products, little or no historical data is available for forecasting demand, which makes it very difficult to predict demand (Kamath and Roy, 2007; Xu and Zhang, 2008). A useful demand prediction system must accommodate the unique characteristics of the short life cycle product. Extensive market research allows firms to assess the market and predict the total life cycle for sales (Kurawarwala and Matsuo, 1996). Kahn (2006) classifies the challenges in new product forecasting into four categories: (1) *draw*: the percent of a new product's volume coming from products within a product category; (2) *cannibalization*: the percent of a new product's volume coming from other company products; (3) *category growth*: the percent of a new product's volume coming from

new category buyers who enter the category to purchase the new product; (4) *category expansion*: the percent of a new product's volume coming from increased category consumption among current category buyers, where the purchase of the new product is incremental in volume for the buyer.

In LTCP, firms should take into account these elements and carefully determine when to launch new products, how much of them to produce, and the price point at which they will sell these products. The capacity investment decisions and the trading structure of the company (which products at how much and when to produce) are directly linked (Levis and Papageorgiou, 2004).

Finally, renewing short life cycle products involves another problem - lead times for production technology procurement are a very high in proportion to the products' life cycles. Production and procurement decisions need to be made well in advance of the product's introduction stage (Kurawarwala and Matsuo, 1996). Shortening life cycles for products mean that firms must have flexible product lines and tools for multiple tasks. LTCP has to determine levels of production technology that satisfy the requirements of both current and future products (Kurawarwala and Matsuo, 1996). Short life cycles require short end-to-end pipelines to enable demand to be continuously replenished during the life cycle (Aitken et al., 2003). Replenishment lead times must align with the stage the product is in in its life cycle, so firms are able to reduce lost sales and obsolescence risks (Aitken et al., 2003). Inventory is difficult to project for short life cycle products, which involve volatile factors such as sales, product mix, product cost, manufacturing yield, cycle-time variation, and supply volatility (Wu et al., 2006). With short life cycle products, many manufacturers prefer to maintain a negligible amount of finished goods in their inventory because these products face rapidly declining prices and a high risk of obsolescence, especially in the case of highly profitable products (Huh et al., 2006). The cost of key components declines over time (Kurawarwala and Matsuo, 1996).

2.2.4.1. Time frame of new product launch

To stay competitive, it is critical that firms release each new product into the right market(s), at the right time in the right volume, and that they pace the release over the product's entire life cycle (Wu et al., 2010). It is absolutely vital to compensate for any investment in developing new products as soon as possible (Levis and Papageorgiou, 2004). Druehl et al. (2009) investigate the optimal pace of product introduction and highlight two important issues: firstly, if the product introduction happens too early, it may incur high costs in product development or distribution channels that may prematurely cannibalize sales of the previous generation of products. Secondly, if the firm delays product introduction, competitors will profit from the market when the margins are high and the market will become saturated.

2.2.5. Financial issues

In order to have an effective LTCP, financial decisions must be made simultaneously in capacity planning. Financing in investments (e.g. cash movements or credits) is an important factor that should be taken into account in LTCP.

2.2.5.1. *Budget*

The budget is one of the key resources that causes financial limitations. Long-term decisions involve the selection of manufacturing technology and the allocation of the budget to acquiring specific production technology (Uribe et al., 2003). Allocation of money is one of the most important constraints to be considered before making significant decisions.

2.2.5.2. *Detailed financial planning*

One of the important issues in LTCP is to ensure that firms buy and install tools with the correct timing with appropriate allocation of budgetary resources. Karabuk and Wu (2003) explain that a premature transition leads to costly underutilization and a late transition leads to missed market opportunities. Olhager et al. (2001) state that the main focus of capacity management is the timing of capacity changes, such as decisions to buy or sell. These decisions will affect firms for at least 5 to 10 years, depending on the firm. In addition, these decisions must be made before future demand is fully realized. Moreover, most production technology is highly customized and made to order, so the lead time for procuring a new piece of production technology may range anywhere from three months to a year (Swaminathan, 2000). Planners have to make decisions related to production technology procurement based on forecasts for demand by taking into account the firm's cash flow. In a rapidly evolving technological environment these forecasts can be highly inaccurate. The earlier a firm takes the decision, the more risk there is. The risk should be reduced or disposed.

2.2.6. **Tactical decisions (aggregate planning)**

It is desirable to include some tactical decisions in the LTCP. The investment decisions that are made at a strategic level are directly related to installed capacity, which is a decisive factor for tactical capacity planning. It is difficult to separate decision classes in successive levels, and in some cases one factor can have a strong impact on the next level. Tactical decisions for LTCP include decisions related to production levels, overtime, hiring and dismissal of workers, production quantities, packing quantities, ordering, transportation, stock levels and outsourcing. LTCP should not disregard tactical decisions.

2.2.7. **Uncertainties**

One of the important issues that makes the LTCP problem hard is uncertainty. Uncertainties can affect almost all of the parameters involved. The most important uncertainties are in demand, and technology the economy.

2.2.7.1. *Demands*

Demand is one of the important and complex factors that make long term capacity planning difficult. Catay et al. (2003) explain that for capacity planning, demand is one of the most important pieces of data for making appropriate decisions on both new products and possible modification of existing products within the limits of the given technology. Kamath and Roy (2007) express that organizations are forced

to cope with uncertain changes in the product mix, production volume, and also product life cycles. Demands should be determined in advance or forecast with appropriate techniques. Therefore, to overcome these uncertainties, the researchers use stochastic techniques in capacity planning. With the developments in computation techniques, stochastic models have been applied in the last two decades (Geng and Jiang, 2009). Stochastic models yield much more realistic results than the deterministic models. Firms may falsely conclude that the system is over or under-sized, both of which will lead to negative consequences in the future.

2.2.7.2. Production technology

Firm should plan and install manufacturing infrastructure taking into account both current and future products. A capital and equipment intensive industry with high tech, short life cycle products involves a high level of uncertainty in terms of technological development (Chou et al., 2007). While producing current products, firms should consider future products and technology. Production technology investments are thus a requirement for firms to survive, rather than an option. LTCP has to consider both current and future production technological to determine which production technology the company should invest in. New production technology may be able to handle both old and new products easily, but older production technology may not necessarily be able to process newer products.

2.2.7.3. Economic parameters

Prices, costs and other economic parameters such as bank interests also present an important degree of uncertainty.

2.2.8. Evaluation criteria

In LTCP firms must take into account a number of criteria. Some of the most important criteria are economical ones such as minimizing expenses, maximizing incomes or profits, and maximizing revenue. Non-economic criteria such as minimizing risks and maximizing demand satisfaction are also key.

3. OBJECTIVE, THESIS DEFINITION, METHODOLOGY AND SCOPE

LTCP must consider all major aspects of the decision-making process involved in acquiring new production technology, decreasing of capacity or renewing existing production technology, and the possibility of updating existing production technology. The results must provide an economically viable option for suitable investments, considering the characteristics of available financial resources and providing possibilities for the placement of excessive funds. Financing needs and consequences for the system performance must also be considered.

Capacity planning in the long-term is usually carried out by algorithms that generate and evaluate alternatives. These procedures do not guarantee the best solution for firms. The quality of the results often depends heavily on the know-how of the person responsible for making the decision.

A better system would take into account how such a plan will work; that is, if tactical decisions are considered. There is a need for research on coordinated optimization model formulation with multiple objective criteria, and solution methodology (Kekre et al.,2004). One aim of this thesis is to consider the integration between strategic and tactical capacity decisions that should be included in the LTCPP.

Former quantitative methods for solving the LTCPP fail to consider some of the most relevant features of the problem, such as taking into account products with a short life cycle, decisions regarding product renewal, detailing specific capacity options, detailed finance management options, and tactical decisions.

LTCP should be suited to the current needs of businesses and take advantage of the scientific and technological capabilities available today. The calculation methods that are available today can solve mathematical models of problems involving strategic capacity decisions and tactical capacity decisions.

A large number of versions of the LTCP problem exist, depending on the specific characteristics of the case. Even though a general framework or approach can be proposed, the model and the corresponding solving procedure need to be designed ad hoc for every situation.

The **objective** of the thesis is to design and formalize tools to efficiently solve a variant of the LTCPP, production technology and economic parameters; short life cycle products; product renewal; changes in production technology; and financial management. It is necessary to clearly define LTCP and the relationships between the various variables. The thesis will focus on manufacturing companies (human resources, which are highly important in service companies, will not be considered in detail) and the following characteristics will be included:

- Introduction of new products with a short life cycle,
- Replacement of old products with demand interactions,
- Acquiring, renewing, updating, outsourcing and reducing capacity options,
- Financial planning in detail (bank loans, amortization, interest and inflation),
- Tactical capacity decisions (aggregate planning in LTCP).

The following points justify the elaboration of this thesis:

1. Generally, the procedures for solving LTCP found in the existing literature do not guarantee a solution that optimizes a given utility function in a reasonable amount of time. Nowadays with the available calculation methods, it is possible to optimize and solve many mathematical models in a reasonable time frame.
2. Most procedures consider a static situation; that is, the capacity of the system for the long term is determined without considering the possibility of change from one period to another.
3. Short life cycle products renewal, along with all its implications (for production technology selection, demand of new and old products, etc.), is usually not considered.
4. Financial implications are considered in a rudimentary manner (that is, they do not consider all the possibilities for financing and surplus disposal).
5. Tactical implications are not detailed in models, and the LTCP is not viewed as an instrument of integration between strategic and tactical objectives.

3.1. Methodology

The methodology are detailed and justified below. An overall description of the solution approach is defined in this section, along with what methods and materials will be used. Any particular challenges that may arise will also be discussed in this section.

The company may have existing products with short life cycles and new products to introduce to market. In both cases, the decisions of acquiring, renewing, updating, outsourcing, and reducing production technology are crucial. Tactical capacity decisions should be made using detailed financial planning. Using the findings from the literature review and the best of our knowledge, a deterministic *mixed integer linear programming model* will be developed. In order to determine uncertainties in real life cases, *scenario-based optimization* can be added to deal with uncertainty. A comprehensive computing experiment will be performed to validate the developed models.

Some models may not be solvable in a reasonable time period and with accurate results when using mixed integer linear programming in standard commercial software (such as that has been used in recent projects, OPL Studio, CPLEX libraries). There will be a heavy workload of programming models and data preparation in order for the testing computer to reliably solve a large number of experiments and process the results of them for later analysis.

4. LITERATURE REVIEW AND ANALYSIS

In this section, the literature review focuses on long term capacity planning, strategic capacity planning and product life cycles. The most relevant findings are summarized with a brief explanation in *Table 1* and *Table 2*. The conclusion will take into account unique LTCP features.

4.1. Long Term Capacity Planning

MirHassani et al. (2000) develop a two-stage stochastic program (SP) with a mixed-integer model in a multi-period to determine an optimal solution for capacity planning for long term. This includes acquiring resources and utilizing production under uncertainty. Their aim is to minimize the costs given limitations such as physical capacity, material balances, and shortage of demand. The first stage decisions are related to the opening and closing of plants and distribution centers, along with setting capacity levels using the 0-1 integer decision variables. In the second stage, the decisions are focused on optimizing production and distribution costs - such as production quantities, packing quantities and transportation amounts - that are represented with stochastic continuous variables. Their finds show that when firms choose a “good” scenario, the solution time is greatly reduced.

Swaminathan (2000) formulated a scenario based two-stage stochastic mixed integer program under demand uncertainty, due to the challenges providing an analytical model for tool procurement planning. Tool procurement planning is based on deterministic forecasts, and uncertainty in demand often leads to shortages or under-utilization of tools. The objective is to minimize the expected stock out cost (the gap between capacity and actual demand). He uses a basic budget constraint in order to not exceed the procurement of tools for the period and limits the total number of products produced in each tool. First, they model the problem for a single quarter (a discrete single period) that makes plans for procurement of tool in the next period. Later, they expand their models into a multi-period model which consists of four quarters. The first stage variables represent the number of tools to be procured before demand is known. The second stage continuous variables represent the production of wafers in each scenario to minimize stock-out costs. As this is a the real life case involving a large industry-wide problem, it is impossible to find the optimal solution within a reasonable time frame. In order to solve this two stage stochastic mixed integer program, they develop two heuristics. These heuristics generate quick and reasonable solutions for real large-scale problems. They compared the results of the two heuristics to the solution of the deterministic plan, and noted that the heuristics are more efficient and provide workable solutions even for large problems.

Papageorgiou et al. (2001), who analyze the planning process involved selecting which products to develop in LTCP, believe the key problem is to bridge the information gap that currently exists for decision makers in traditionally isolated areas, such as product development, manufacturing, accounting, and commercialization in pharmaceutical industries. Their aim is to aggregate the decision makers. Their objective is to select the optimal product development and introduction strategies together with long-term

capacity planning and investment strategies at multiple sites. They include the decision of whether to develop a new product or not, but the demand of the product is supposed to be known and independent from the demand of other products. They use a deterministic mixed-integer linear programming model. The model includes product, production, inventory, sales and product lifetime balance constraints. They solve MILP with CPLEX 6.0 with a tolerance of 5 percent to obtain the solution in an appropriate timeframe. The results of the model show which products to select, which locations to operate at and which products to invest in. The results are good illustrative examples, but when applied to real life large cases they propose investigating alternative solutions.

Wang and Lin (2002) study resource expansion and allocation problems under budget constraints in a semiconductor testing facility. The main issue in their work is appropriate selection of tests (in terms of both type and kind) to invest in for future orders for wafers and chips, as well as how to allocate tester capacity for the orders. They ignore lead times for machine procurement and the time value of capital, as well as use capacity, demand, budget and cost constraints. They do not allow demand be less than it was in the previous period. The researchers developed both a mathematical model and a genetic algorithm to compare the results with the objective function of maximizing the profit. The mathematical model is written and solved using Lingo software. The outcomes show that the genetic algorithm is not sensitive to changes in the budget, except when the number of chromosomes is too few. The genetic algorithm outcomes are very close to the ones from the solution, and the computation time is less than when using the mathematical model, especially when the budget constraints are tight. They suggest the time value of money can be included in the model.

Uribe et al. (2003) describe the capacity problem as deciding the amount of the investment, selecting flexible hardware (machines, tools, and equipment) and allocating the budget to these acquisitions. They develop a practical and agile method to be used in uncertain demand conditions in a manufacturing system. This allows them to consider multiple products, tools, flows, and operations. In the case that demand is highly variable and there is reasonably low process flexibility, they suggest using a simulation approach. They employ capacity and demand constraints, and set the total assignment tools to operations equal to the number of tools per tool type. Total investment should be less than the budget limits. They use a two-stage stochastic integer program with simulation and develop two models: 1) *wait and see*, in which the decisions is assumed to be able to be put off to later period when the random coefficients are realized; 2) and *here and now*, in which the decisions must be made before or at least without knowing the realization. They generate scenarios and simulate them, but the results are not in a solution time when taking into account computational efficiency. They suggest expanding this work by including set-up times, batching policies, dispatching policies, and analyzing demand variability at different levels.

Karabuk and Wu (2003) view strategic capacity planning as a coordination of distinct viewpoints of marketing and manufacturing. They formulate a two-stage scenario-based stochastic program with demand and capacity uncertainties set to meet estimated demand, and with the objective function of

minimizing total expansion and capacity configuration costs in the semiconductor industry. The model considers limited capacity expansion, balanced capacity, inventory, outsourcing, demand, and a technology-specific capacity constraint. They consider outsourcing as a capacity option and use demand constraints that are balanced by inventory from previous periods and outsourcing at that period. Capacity changes are considered at the beginning of the planning year. Capacity expansion is described as identifying the required manufacturing technology and their capacity levels to be physically expanded or outsourced through the planning horizon. Capacity configuration is defined as determining which facility is to be configured with which technology mix. The decisions at the first stage are related to expansion of capacity at the present time including 0-1 binary variables. The second stage is setting the capacity to allocate resources to products. While their aim is to integrate two different types of decisions (marketing and production, which perform different recovery actions under each particular scenario of capacity and demand), they simulate different decentralization strategies. They suggest a strategy that would decentralize decisions to the manufacturing and marketing managers. Their model provides a strategic vision combining capacity and outsourcing decisions, and aspects of different cost implications.

Catay et al. (2003) define LTCPP as defining the right time for purchases and retirements of tools, including tactical capacity planning. They study the problem of planning wafer production over multiple time periods within a single facility, assuming that a demand forecast is known for each wafer type for each period. A mixed-integer programming model is developed to minimize the costs for machine tool operating, new tool acquisition, and inventory holding. The model has demand constraint, capacity limits for tool groups and no backorder constraints. They do not solve the mixed-integer programming model (an attempt is done with CPLEX) because it is not practically possible to obtain a solution within a reasonable computing time. They develop heuristics and report the gap between bounds and the solutions. They realize that as the problem gets larger Linear Programming (LP) provides a better approximation. The tool procurement decisions become less crucial and LP does not affect the solution value. They suggest that their model could be used for an extended replacement of production technology as well as expansion and disposal of production technology to adjust to changing demand.

Hua and Liang (2004) study capacity expansion under demand uncertainty. They also deal with capacity expansion problems to determine if additional capacity should be installed at the beginning of each time period for each machine line. They developed a large-scale two-stage stochastic mixed integer program and solved it with a genetic algorithm with an objective function of minimizing the costs of purchasing and installing machines, expected production cost, and expected subcontracting cost. They forecast demand at the family level as it is easy to operate. Their model includes production assignment constraint that does not exceed a machine's capacity, a machine line constraint that requires all insertions for a product family be completed on one machine line, a demand balance constraint with inventory, production and subcontracting, and a capital investment constraint with a budget limitation in order not to exceed the procurement of tools for the period. Instead of solving the model, they develop genetic algorithms that have advantages on calculation time. Their model also includes decisions on

subcontracting as a capacity option and integrates strategic capacity planning, aggregate production planning and master production planning.

Kekre et al.'s (2004) study focuses on how strategic and tactical capacity decisions interact when demand is uncertain. The main questions they attempt to answer are how long-term (strategic) capacity levels affect short-term (tactical) capacity costs, what long-term capacity level will maximize total expected profits, and how long-term capacity levels affects profit variance. They formulate stochastic mathematical formulations for a single-product and multi-period production by integrating long-term and tactical capacity decisions. In their model they do not consider overtime production. Instead of applying an overtime production option they use the option of subcontracting. They use CPLEX to solve the problem, but it takes so much time that they designed a new, optimal solution approach. Through computational experiments, they observe the impact of cost coefficients, demand variability, seasonality, and correlation on profit means and risk, which provides insight into the annual capacity planning problem.

Levis and Papageorgiou (2004) study multi-site capacity planning in the pharmaceutical industry and develop a two-stage, multi-scenario, mixed integer linear programming (MILP) mathematical model by extending the work of Papageorgiou et al. (2001). Their aim is to integrate traditionally isolated areas, such as product development manufacturing, accounting and marketing for optimizing. They select both the product portfolio and multi-site capacity planning simultaneously. The objective function is the expected net present value after taxes. They explain that pharmaceutical companies are constantly faced with making decisions about the best use of limited resources available in order to obtain the highest profit. The proposed algorithm is used in five illustrative examples to validate the applicability of the proposed mathematical model and its corresponding solution strategy. Illustrative instances have significant savings in computational effort.

Huh and Roundy (2005) deal with the strategic capacity planning problem by determining the sequence and timing of acquiring tools in the semiconductor industry by using multiple resource types and multiple product families under demand uncertainty. A stochastic programming model is developed for multiple resource types and product families for a continuous time period. All the capacity acquisition plans are made at the beginning, while production decisions are made at each time instant after demands come into existence. Constraints on production mean that it cannot exceed demand, and capacity is sufficient when it meets demands, allocation and production capacity limits. Lost sales are the difference between demand and production, and they allow decreasing demand. They assume no backorders and allow a small amount of inventory due to the characteristics of semiconductor products' life cycles. They find the optimal solution in a good time frame for the given data set. The authors add that these models and theoretical results may serve as a prototype in constructing more complex and robust strategic capacity planning systems by modifying algorithms.

Barahona et al. (2005)'s study focuses on identifying a set of tools that satisfy the scenarios, as well as buying them at the right time. They formulated a two-stage stochastic mixed-integer programming model in the semiconductor manufacturing industry to minimize total expected unmet demand and penalty terms that come from purchasing decisions for tools. They have constraints for demand for each product with production variables and unmet demand. Total production load cannot exceed the available capacity or the upper bounds for the unmet demand for each product and budget. They try to optimize it in CPLEX 8.1 with a small example (half constraints and variables) but solving the process is a lengthy process. Therefore, they present a heuristic based on a branch and bound procedure that uses cutting planes to produce good solutions. Their method produces good solutions in a reasonable computational time.

Huh et al. (2006) present a strategic capacity-planning problem with the goal as determining the timing of potential tool purchase or retiring multiple products in equipment-intensive industries. They use a continuous-time by using a cluster-based heuristic algorithm. The objective is to minimize the sum of the lost sales cost and the tool purchase cost minus the tool sale price. They implement their algorithm using the Matlab 6.5 language. Instead of solving it with Matlab's own function, they use CPLEX 6.6, as they believe that CPLEX runs significantly faster than Matlab. Their algorithm, with a proper initialization method, delivers good solutions in reasonable computation times. Previously, most of the models did not allow for the possibility of decreasing demand, but this model does enable it and also takes into account tool retirement, which gives an opportunity for firms to renew products or product technology.

Li et al. (2008) develop a two-stage stochastic integer programming model for long term capacity-expansion planning that deals with uncertainties presented in terms of fuzzy sets and probability distributions for solid waste management systems. The objective is to minimize the sum of the first-stage cost and the second-stage random penalty for the expenses of all processes and expansion of waste-management facilities, minus the revenues from the waste-treatment facilities. They allow facility capacity to be expanded once in each period. In this model, excess incapacity and penalties are represented as rising transportation and operating costs, so it gives insight into the trade-offs between environmental and economic objectives. They state that in order to use the deterministic model; the variability of random variables should help enhance the robustness of the developed methodology. The solutions can provide desired waste-flow-allocation and capacity-expansion plans with minimized system costs and maximized system feasibility.

Bihlmaier et al. (2009) present a deterministic and a stochastic model that considers the strategic flexibility and capacity planning to integrate tactical workforce planning, strategic investment and cost parameters under uncertain demand conditions in production networks for automobile manufacturers. The objective is to determine the production and transportation capacities by minimizing strategic decisions. They know the demand and provide supply quantities and unfulfilled demand constraints. They also use a material balance constraint that includes incoming and outgoing resources, and a product

allocation decision constraint. They provide corporate strategies and policies by designing a two-stage stochastic, mixed-integer program under conditions of uncertain demand. They solve a deterministic equivalent formulation by using CPLEX 10.0. The solution approach developed by authors greatly decreases the solution time in comparison to both standard decomposition models and deterministic equivalent models. When they compare their results with deterministic models, the results are almost optimal. Their methods can handle large-scale, real-world problems and lead to better decisions than many widely accepted methods for actual planning problems in the automotive industry.

Geng et al. (2009), studied the importance of decentralized or centralized decision making in tool procurement, production, stock out and inventory decision-making processes. They developed scenario-based two-stage stochastic programming models that consider demand and capacity uncertainties in scenarios for multiple periods in the semiconductor manufacturing industry. The objective is maximizing revenue. The model has bounds on the number of new tools in each period and constraints of each tool group. In addition, its production time should be less than or equal to its available time, a constraint that ensures that each tool group is used effectively. They also include balance in demand, production, inventory, and stock out numbers, and place the constraint of no inventory at the beginning and ending periods. They do not take the budget into account. They implement the models in OPL and use the CPLEX 10 solver. They found out the resulting capacity planning decisions are more robust to the variation of capacity. They observe that demand variation leads to the expansion of capacity, while capacity variation is balanced by out by sales. They have good solutions in reasonable time using the stochastic model by development in computational operations.

Huang and Ahmed (2009) define the problem as deciding the optimal timing and level of capacity acquisition and allocation. By using a scenario tree to model the evolution of uncertainties, they develop a multistage stochastic integer programming formulation to investigate the value of multistage stochastic programming and the performance of the proposed approximation scheme. They first describe a specific deterministic model, and then they extend the model into a two stage and multistage stochastic one to compare the optimal values. The objective function is to minimize the sum of tool acquisition costs, production costs, and costs for unmet demand. The model has constraints on capacity production, the actual number of production and required processing steps, production, shortage quantities and demand. They ignore the budget constraints because they claim that their approach is not designed to handle such a constraint. Their models give decisions of how many of each tool type to acquire and how to allocate production to the tools in each period. They use CPLEX 9.0 to solve the models. They design and solve generic multi-period capacity planning problems under uncertainty involving multiple resources, tasks, and products. They realize that the value of the multistage stochastic for their problem is quite high and the performance of the approximation scheme is efficient and of good quality.

Wu and Chuang (2010) model the capacity planning problem on Markov Decision Processes and develop an algorithm to solve the problem of providing a strategic capacity expansion plan under price

uncertainties, demand fluctuation and uncertain product life cycles regarding obsolescence of equipment and product life cycles. The objective is to find a capacity expansion policy that maximizes expected total profit in each period. The model has upper bounds for purchasing the number of tools due to constraints on budget, facility size constraints and a capacity expansion. They assume one time period for the lead time of machine procurement and installation in the model. They take into account the salvage value of equipment. They use both stochastic and deterministic demand forecasts in order to compare results. They solve the capacity planning problem with and without considering throughput, price and demand uncertainties, and they compare the results of the deterministic and stochastic models. They express that to decrease risks on the capacity portfolio over time, manufacturers usually use two types of production technology; dedicated ones to produce only one product family, and advanced ones that can be made available for multiple product families. Advanced machines are relatively expensive and have the flexibility to produce different products, while existing or old generation machines are less expensive but can only produce limited product types. Their model is an example of capacity expansion decision including replacement of equipment and introducing new products regarding life cycles. They model the price as dynamic, which makes the model more realistic. The stochastic model results are more robust and improve the mean profit. Including price, demand, and yield uncertainties also significantly reduces the risk of the capacity expansion decision.

Chung and Hsieh (2010) present effective solutions for the appropriate type and quantity of equipment shutdown planning due to low equipment utilization during periods of economic recession. The aim is to assist effective mapping out of the optimum portfolio for equipment shutdown. They relate equipment shutdown directly to cycle time and use this as a decision variable in the model. The objective is to minimize the effect of shutdowns on cycle time (cost savings) to maintain the time-to-market competitiveness. They use an integer-programming model solved by the branch and bound method using Lingo software to find the optimal solution of this problem. The model is solved in a short time and the solution is optimal.

Lin et al. (2011) study a capacity allocation and expansion model for strategic capacity planning that is robust to demand uncertainties. They develop a scenario-based two-stage stochastic programming model regarding high investment cost, long construction and machine procurement lead-time, and space limitations of the existing site. They claim demand forecasts are usually inaccurate and vary rapidly over time, so a strategic capacity planning model must include demand forecast uncertainty considerations to enhance the robustness of solutions. In their model, prices of each product are given and vary over time, and yield rates are given. Capacity expansion decisions focus on the procurement of auxiliary tools and the phase-out time of a production group can be estimated. The overall objective is to maximize the expected total revenue minus expected total costs (production variable costs, inventory holding costs and high capacity expansion costs). The model has constraints of capacity expansion lead times, capacity expansion upper bounds, production balance, inventory balance, demand satisfaction, batch size and production capability, bottleneck machines and auxiliary tool capacity of a product group. They also

solve the model by using expected forecast demands (deterministic) and Monte Carlo simulation to verify the quality and effectiveness of stochastic solutions. They note that the performance of the stochastic model is not improved when the number of scenarios is increased. When they compare the results to the deterministic approach, their stochastic model significantly improves system robustness via demand uncertainties.

Chien et al. (2012) see the problem as capacity expansion and migration planning under uncertainties in demand and product mix. They define capacity migration as taking into account the possibility of employing excess advanced equipment capacity to produce mature products. Advanced equipment is usually more productive than outdated equipment for mature products. Producing mature products will sacrifice cost efficiency. The stochastic demand treatments of different products are modeled on the Markov chain and a dynamic optimization method is developed. They solve the model with and without capacity immigration and look for improvements in capacity shortage, capacity surplus and total capacity loss. For instance, when capacity migration is considered, the total capacity loss can be reduced by more than 20%. The authors reveal that the results of capacity migration considerations actually change the capacity expansion decision.

4.2. Product Life Cycle

Meixell and Wu (2001) develop a methodological approach for generating demand scenarios using leading indicators to be used in a stochastic program. They analyze demand data for some 3500 products in high-tech industries, such as semiconductor and electronics, and find that these products follow approximately six life cycle patterns. They group the products according to these patterns using statistical cluster analysis. In each cluster a leading indicator product exists, which provides advanced indication of changes in demand trends. They consider positive correlation of demand among the product families, which can be caused by the industrial life cycle of the leading indicator product, e.g. a chip set, affecting the demand for the other products. Leading indicators that contain timely, useful information that reduces the size of the scenario tree are used to provide early-warning information about changes in trends in cluster demand in upcoming periods.

Druehl et al. (2009) study defining optimal pace for product introduction to the market. They explain that faster margin decay, faster diffusion, and higher market growth rate all trigger a faster pace in new product introduction. They developed a model for the timing of new product introduction that depends on these factors:

- *Product development cost* (development cost curve): Introducing products too early may incur excess product development costs due to more frequent introductions and possibly crashing costs, whereas introducing products too late may decrease overall product development costs, but may increase the product development costs per introduction.

- *The new product diffusion rate*: This is a coefficient of innovation and imitation. When diffusion occurs quickly enough, it is profitable for the firm to introduce another product to seize the high initial margin of each new generation.
- *The rate of margin decline*: Introducing products too early reduces potential profit margin from the previous generation. Introducing products too late results in sales of the previous generation at small margins, by which time the margins for the existing product may have declined significantly.
- *The growth in potential market*: The overall market size grows incrementally over time (or remains constant).

Druehl et al.'s results show that there is a significant link between the optimal pace of generations of products and the rate of product diffusion. At the end of various numerical examples, they show that the speed of diffusion is one of the key factors in product introduction.

Chien et al., (2010) propose a multiple generation product diffusion model for demand forecast based on technology diffusion and product life cycle, which incorporates seasonal factors, market growth rates, price, repeat purchases and technology substitutions. These are defined as follows:

- *Seasonal factors*: some products' sales can be affected by seasons.
- *Market growth rate*: describes the market structure and economic environment. The growth rate affects customer behavior, and demand is positively correlated with the market growth rate.
- *Price*: a key influence on customers' purchase decisions. Reduction in prices can increase product demand.
- *Repeat purchases*: in which the sales equal the number of first purchases plus the number of repeat purchases.
- *Technology substitution*: newer technologies are continually being introduced to the market.

In the model, an empirical study was done using real data to validate the proposed model in order to forecast the demands of semiconductor products. The results validate the viability of their approach to accurately forecast the demand for semiconductor products. Their model supports a systematic approach for capacity planning decisions and manufacturing strategies.

Rastogi et al. (2011) develop a two-stage stochastic integer-programming model that proposes strategic capacity decisions. They develop a model to analyze how variability in demand affects the make/buy decisions and also to investigate how correlation between demands of different products affects strategic decision making processes. They consider 3 types of demand patterns: (1) positive correlation of demand between the product families, which can be caused by the industrial life cycle of the leading indicator product (e.g. a chip set), affecting the demand for the other products; (2) negative correlation on the demand of product families, which can occur in high tech industries where an increase or decrease in demand for the newer technology may lead to an increase or decrease in the demand for the older

technology; (3) no correlation between the demand of product families. In a case study they divide the products (chips) into two groups regarding their speed, and the demands for chips are clustered together by product family. They use the Meixell and Wu (2001) article to parameterize the uncertain demand by its deviation from the mean and the correlation between the demands of the two product families. Once a new product is introduced into the market, demand for the current product typically declines. The new product launched has a life cycle trend similar to the first one. They find out that positive correlation between the products (e.g. increasing market size) involves higher risk compared to negative (e.g. introduction of new products) or no correlation. They assume constant pricing throughout the product life cycle, but a dynamic pricing policy would be enriched by taking into account obsolescence.

Qin and Nembhard (2012) developed a dynamic demand model of stochastic product diffusion over the life cycle based on a geometric brownian motion. They explain that demand depends on several factors:

- Initial demand: at $t = 0$ the system has actual demand. Real demand can be used to predict product life cycles of existing demand;
- The growth in the potential market: the expected growth rate of demand with regards to the growth rate of similar or previous products;
- Cannibalization from the previous generation: introduction of new products to the market decreases the demand for previous products;
- Cannibalization expected from the next generation: introduction of next generation products reduces the demand for existing products;
- Product price: an important factor that directly affects product sales.

Their model is parameterized by these important characteristics of demand:

- Volatility of demand that measures the uncertainty in the growth rate of demand;
- Peak demand point, which is closely related to the diffusion speed;
- Initial demand, which represents the early adoption level of the product and expected cumulative demand over a product's life cycle. It also measures the expected market size.

They examine the degree to which perturbations of model parameters change the demand forecasts. Their model provides both qualitative and quantitative information for enterprises to design strategies for stochastic product life cycle conditions in order to plan production during each product life cycle.

4.3. Conclusions of the Literature Review

All the above approaches show models and methods for special variants of Long Term Capacity Planning Problems. All models used in the articles in the literature review are summarized in *Table 4-1* to their release date in terms of how they investigate and overcome the LTCP.

Table 4-1 Relationships between articles and Long Term Capacity Planning Issues

| LONG TERM CAPACITY PLANNING ISSUES 1 / 2 | | | | | | | | | | | | | | | | | | |
|--|---|-----------------------------|---------------------------|---------------------------|--------------|----------------------|----------------------------|--------------------|----|--------------------|-------------------|-----------------|---------|--------------------|-------------|-------------------|--|--|
| Authors | Problem Definitions | Capacity Options | | | New Products | Financial Management | | Objective Function | | Tactical Decisions | | Demand Forecast | Results | Objective Function | Constraints | Solving Procedure | | |
| | | Additional Production Tech. | Renewing Production Tech. | Updating Production Tech. | | Outsourcing | Reduction Production Tech. | Yes | No | Not Considered | Budget Constraint | | | | | | Detailed Financial Plan | Max Profit |
| MirHassam et al., (2000) | Capacity Planning Including with Acquiring the Resources and Utilization of Production under Uncertainty | | | | | | | | | | | | | | | | Physical capacity limitations Material Balances Shortage of demand | Two-Stage Integer Stochastic Programming |
| Swaminathan, (2000) | To design an Analytical Model for Estimating Future Tool Requirements based on Demand Forecasts with the Best Time | | | | | | | | | | | | | | | | Number, Products & Tool Constraints Tools Procurement & Budget Balance | Scenario Based Two-Stage Stochastic Mixed Integer Programming |
| Papageorgiou et al., (2001) | To Aggregate the Decision Makers on Product Development & Introduction Strategy and a Capacity Planning & Investment Strategy | | | | | | | | | | | | | | | | Product, Production, Inventory, Sales And Product Lifetime Balance Constraints Timing Constraints Scale-up Constraints Qualification Constraints | Mixed-Integer Linear Programming |
| Wang and Lin, (2002) | Capacity Expansion under Budget Constraint and Adequate Capacity Allocation Plan to High Profit. | | | | | | | | | | | | | | | | Total Equipment Cost & Budget Constraint Capacity & Demand Constraint | Genetic Algorithms |
| Urbe et al., (2003) | The Selection of Manufacturing Technologies under an Uncertain Demand Stream, within Budget Constraints | | | | | | | | | | | | | | | | Capacity & demand constraint Total Assignment Tools & Total Tools Operations Balance Total Investment & Budget Constraint | Scenario Based Two-Stage Stochastic Integer Programming |
| Karabak and Wu, (2003) | Integration of Distinct Viewpoints of Marketing and Manufacturing Perspectives under Uncertainties in Demand and Capacity | | | | | | | | | | | | | | | | Capacity Expansion Limits, demand & inventory, Outsourcing Balance Capacity Utilization & Demands Balance Technology-Specific Capacity Constraint | Scenario Based Multi-Stage Stochastic Programming |
| Catay et al., (2003) | Investment Decisions on Procuring New Equipment and Aggregate Capacity Planning under Uncertainties | | | | | | | | | | | | | | | | Satisfied Demand Constraint, Capacity Limits for Tool Groups No Backorders Constraints | Mixed-Integer Programming |
| Hua and Liang, (2004) | Capacity Expansion Problem under Demand Uncertainty | | | | | | | | | | | | | | | | Production Assignment & Machine's Capacity Constraints, Machine Line is dedicated to One Product Family Constraints, Demand Balance Production and Subcontracting, Capital Investment with a Budget Limitation Constraint | Two-Stage Stochastic Mixed Integer Programming Genetic Algorithms |
| Levis and Papageorgiou, (2004) | Optimizing both Selecting both the Product Portfolio and Multi-Site Capacity Planning, Simultaneously | | | | | | | | | | | | | | | | Product, Production, Inventory, Sales Constraints Lifetime Constraints of Inventory Timing Constraints Scale-up Constraints Qualification Constraints | Two-Stage, Multi-Scenario, Mixed-Integer Linear Programming |
| Huh et Rounky, (2005) | To Determine the Sequence and Timing of Acquiring Tools for Multiple Resource | | | | | | | | | | | | | | | | Production & Demand Constraint Capacity & Demand Constraints Allocation and Production Capacity Limit Lost Sales balance with Demand minus Production | Stochastic Programming |
| Barahona et al., (2005) | To identify and to Purchase a Set of Tools Under Demand Uncertainty | | | | | | | | | | | | | | | | Demand balance with Production and Unmet Demand, Total Production Available Capacity Limitation Upper Bounds for Unmet Demand Limitation Budget Constraint | Scenario Based Two-Stage Integer Stochastic Programming |

Table 4-1 (continued)

| LONG TERM CAPACITY PLANNING ISSUES 2 / 2 | | | | | | | | | | | | | | | | | | | |
|--|--|-----------------------------|---------------------------|---------------------------|--------------|----------------------------|----------------------|----|----------------|--------------------|-------------------------|--------------------|----------|-----------------|----------|---------|--------------------|--|--|
| Authors | Problem Definitions | Capacity Options | | | New Products | | Financial Management | | | Objective Function | | Tactical Decisions | | Demand Forecast | | Results | Objective Function | Constraints | Solving Procedure |
| | | Additional Production Tech. | Renewing Production Tech. | Updating Production Tech. | Outsourcing | Reduction Production Tech. | Yes | No | Not Considered | Budget Constraint | Detailed Financial Plan | Max Profit | Min Cost | Other | Included | | | | |
| Huh, et al., (2006) | Determining the Sequence and Timing of Tool Purchases and Possibly Retirements | + | + | | | | | | | | | | | | | | | Unmet Demand balance with Realized Demand and Satisfied Demand Tool Capacity & Product Constraint Allocation of a Tool's Capacity Constraint Capacity of a Tool Group Constraint Purchases within a Tool Group Constraint Retirements within a Tool Group Constraint | Scenario Based Stochastic Mixed Integer Programming |
| Li et al., (2008) | Capacity Expansion Planning for Facilities under Uncertainties | + | | | | | | | | | | | | | | | | Production & Demands are limited by Existing and Expanded Capacity Capacity Expansion Constraints | Two-Stage Fuzzy Robust Integer Programming |
| Bhimaier et al., (2009) | Integrating Tactical Workforce Planning and Strategic Investment and Cost Parameters | + | | | | | | | | | | | | | | | | Demand and Provided Supply Quantities & Unfulfilled Demand Constraint, Incoming and Outgoing Material Balance Constraint Product Allocation Decisions Constraint | Two-Stage Stochastic Mixed-Integer Programming |
| Geng et al., (2009) | Capacity Planning Problem under High Uncertainties both in Market and Manufacturing Systems, Short Product Life Cycle and Expensive Capital Investment | + | | | | | | | | | | | | | | | | The number of new tools Tools available time The relationship between the demand, production, inventory, and stockout number | Scenario Based Two-Stage Integer Stochastic Programming |
| Huang and Ahmed, (2009) | Deciding the Optimal Timing and Level of Capacity Acquisition and Allocation | + | | | | | | | | | | | | | | | | Capacity Production Constraint Actual Number of Production and Required Processing Steps Constraint Production, Shortage Quantities and the Demand Constraint | Scenario Based Multistage Stochastic Integer Programming |
| Wu and Chuang, (2010) | Capacity and Expansion Planning under Price Uncertainties, Demand Fluctuation and Uncertain Product Life Cycle | + | | | | | | | | | | | | | | | | Purchasing the Number Tools & Budget Constraint Capacity Expansion Constraint | Stochastic Dynamic Programming |
| Chung and Hsieh, (2010) | Enhancing Operating Performance during a Period of Economic Downturn | | | | | | | | | | | | | | | | | The upper-limit for the quantity to be shut down Network flow constraints Capacity constraints Tool counting constraints Facility counting constraints Number of tools limiting constraints Contract cancellation constraint Demand constraint | Integer Programming |
| Rastogi et al., (2011) | Incorporating Optimization Methodology to Increase Factory Capacity | + | | | | | | | | | | | | | | | | Capacity Expansion Capability Capacity Expansion Lead Times Capacity Expansion Capability Constraint Capacity Expansion Upper Bound Constraint Production Balance Constraint Inventory Balance Constraint Demand Satisfaction Constraint Batch Size and Production Capacity Constraint Bottleneck Machine Capacity Constraint of Each Site Auxiliary Tool Capacity Constraint of a Product Group at a Production Site | Two Stage Stochastic Integer Programming |
| Lin et al., (2011) | A Capacity Allocation and Expansion Model for Strategic Capacity Planning that is Robust to Demand Uncertainties | + | | | | | | | | | | | | | | | | To Maximize the Expected Total Revenue minus Expected Total Costs (Production Variable Costs, Inventory Holding Costs and High Capacity Expansion Costs) | Scenario-Based Two-Stage Stochastic Programming |
| Chien et al., (2012) | Capacity Expansion and Migration Planning under Demand and Product-Mix Uncertainties | + | | | | | | | | | | | | | | | | Minimize Capacity Shortage Cost, Capacity Idling Cost, and Capacity Migration Cost | Markov Chain Dynamic Optimization Method |

Table 4-1 summarizes key studies by assessing how capacity issues are handled in the long term, whether the papers involve new products, how financial issues are taken into account, what kind of objective functions are chosen, what kind of constraints the models include, whether tactical decisions are included or not, whether demand is considered stochastic or not, what kind of solving procedures are proposed and whether the results are optimal and in good time.

In Figure 4-1, the articles that include new products, financial issues and tactical decisions in long term capacity planning are classified. There is just one paper (Wu and Chuang 2010) that dealt with both new product introduction and financial planning, and two papers that dealt with both financial issues and tactical decision. None of the papers take into the account new product introduction, financial issues and tactical decisions.

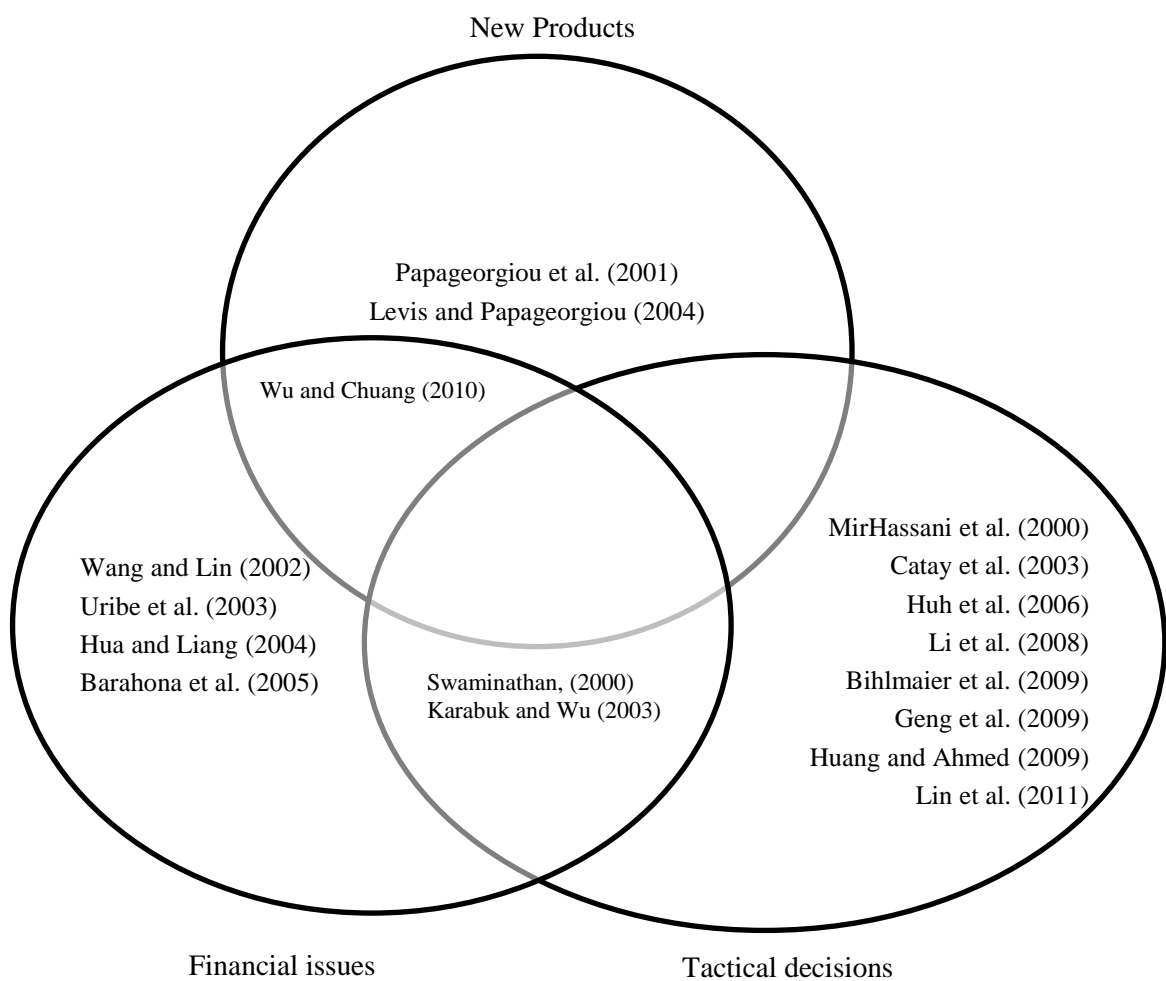


Figure 4-1 Classification of papers regarding the consideration of new products, financial issues and tactical decisions.

The details of each topic shown in Table 4-1 are explained below.

4.3.1. Capacity options

All the articles listed above about LTCP take into account capacity level change decisions that affect the system in the long-term horizon. Before making decisions about capacity, the advantages and disadvantages of all capacity options should be considered carefully. These capacity options are explained below.

4.3.1.1. *Additional production technology*

All the papers, with the exception of Chung and Hsieh (2010), take into account acquisition capacity by purchasing production technology, as this is a simple way to increase capacity.

4.3.1.2. *Renewing*

None of the papers, with the exceptions of Huh and Roundy (2005) and Wu and Chuang (2010), take into account changing existing equipment for newer equipment. It is clear that the life of production technology can be outdated, and thus there could be a need to renew production technology. Huh and Roundy (2005) mention production technology retirements in addition to purchases, and Wu and Chuang (2010) take into account the salvage value of each production technology.

4.3.1.3. *Updating*

None of the papers take into account the option of updating existing production technology.

4.3.1.4. *Outsourcing*

None of the papers except Hua and Liang (2004), Karabuk and Wu (2003) and Rastogi et al. (2011) take into account outsourcing. Outsourcing provides a quick response when demand fluctuation is high and does not require changing existing production technology capacity. Karabuk and Wu (2003) claim that planning outsourcing requires a short lead time and that the decisions of outsourcing can be delayed until uncertainty is somewhat reduced. Hua and Liang (2004) define subcontracting costs and use them in an objective function and use a demand constraint that is balanced by production or subcontracting variables.

4.3.1.5. *Reduction*

Generally, the papers take into account the option of reducing existing capacity levels in their models. Wang and Lin (2002) allow demand to be less than in the previous period, but in the model they do not take into account capacity reduction in long term. Chung and Hsieh (2010) define the problem as equipment shutdown planning, and searching for economical and optimal shutdowns for long term capacity planning.

4.3.2. Characteristics of products (short life cycle products) and product renewal with demand interaction

Recently, in many industries the products have been developed so rapidly that new versions of existing products and new products enter the market faster than ever. In a planning horizon for the long term, product life cycles should be taken into account in order to deal with the uncertainty regarding product development. The decreasing life cycles of products in the long-term planning horizon means that firms may consider existing products, new versions of products and new products entirely. In LTCP introducing and producing new products considering the short life cycles of products with demand cannibalization should be taken into account.

Papageorgiou et al. (2001) study the introduction of new products in the pharmaceutical industry. They use binary decision variables to select a product to develop and produce and in their model the demand of all products is known and independent.

Levis and Papageorgiou (2004) develop the previous deterministic model of Papageorgiou et al. (2001). They use a set of potential products and their forecasted nominal demands. They also know the probability of success in clinical trials for each product. Product selection is achieved by binary decision variables to define the product portfolio (i.e. which products from the candidate portfolio to manufacture).

Wu and Chuang, (2010) divide products into two groups: a mature product whose demand will decrease until the end of the planning horizon, and a new product whose demand will keep increasing in the near future. They assume that the probability distribution of the demand is known. They also define market states as low, medium and high levels and this is known in the beginning of each period. The market state transition probability is given by a Markov chain for each product.

Qin and Nembhard (2012) take into the account cannibalization from the previous generation and cannibalization expected from the next generation.

4.3.3. Financial issues

Financial limits should be considered when designing a realistic LTCP. Financial issues are, for the most part, not taken into account or are considered at a very elementary level. Detailed financial plans should be considered when making buying and selling decisions. Detailed investment plans, bank loan time value of the money, interest and inflation rates, and depreciation and amortization should all be taken into account when creating detailed financial management plans. The lead times for technology procurement are also important for budget planning.

Budget constraint:

Most of the papers do not take into account finance in their models, although some of them include basic budget constraints and equations in order not to exceed the existing budget limitations.

4.3.3.1. *Detailed financial management*

Bihlmaier et al. (2009) include interest rates in a detailed financial plan, while the rest of the papers do not.

4.3.4. **Objective functions**

Objective functions of the models are typically minimization of costs or maximization of profits for the system. Barahona et al. (2005) set the objective function as minimizing total expected unmet demand and Huh et al. (2006) have an objective function to minimize the sum of the lost sales cost. Chung and Hsieh (2010) choose an objective function to minimize the effect of shutdowns on cycle times.

4.3.5. **Tactical decisions**

Most authors consider tactical decisions in LT CPP. Some models use only basic inventory and stock out balance constraints. Some of the decisions made at the tactical level need to be considered in strategic planning, ensuring the integration of decisions made at both levels. LT CP should not dismiss tactical decisions given that strategic decisions have a direct effect on tactical ones.

4.3.6. **Demand forecasts**

In LT CPP, one important sub-problem is demand forecasting. Demand and available money are two important things that directly affect LT CP. Demand forecast methods are divided into two main groups: deterministic and stochastic. Deterministic methods are much easier to model, but under conditions of increasing uncertainties the stochastic methods have gained importance in terms of reliability.

4.3.7. **Solution procedure and results**

As shown in Table 1, the majority of the articles have been modeled in MILP and solved by heuristic or the suitable algorithms that have been developed by authors to have a computational advantage with a near-optimal solution. In the model, all the authors develop Mixed Integer Linear Programming (MILP) or Integer Programming (IP). Results of the models without heuristics are generally optimal with tardy results. Results of models that are solved using heuristics are obtained in a short timeframe. Scenario based procedures give an alternative method to overcome the uncertainties of real life situations, rather than relying on forecasting.

4.3.8. **Conclusions**

The papers detailed above do not consider all the aspects of the LT CP problem in detail. LT CP includes capacity level decisions, the purchase or sale of production technology in order to decrease or reduce capacity, or renewing and updating production technology, all of which affect the state of production technology in the long term. Solutions must additionally provide a quick response to changing demand, and outsourcing decisions should be taken into the account. While making investment decisions, a detailed

financial management should be implemented, which should include information about the economic feasibility of investments, the availability of funding sources, and the time value of money. The problem cannot be sufficiently tackled without these tactical decisions that allow us to understand the system in detail. Shortening product life cycles and introduction of new products in the planning horizon are two more crucial factors in LTCP.

5. PROBLEM DEFINITION

As it discussed in Chapter 3, the major problem in LTCP is that it is difficult to make an optimal decision about production technology. The problem consists of determining the type and amount of production capacity at each period of a long planning horizon, taking into account product renewal by the best time to introduce a product. A model is needed to increase all the features of the problem to lead to a rational and optimal solution. When necessary, new products can be introduced, production technology can be sold, new or next generation production technology can be purchased, and warehouse capacity can be increased. When dealing with product introduction, the effects of products interactions on demand should be taken into account.

The specific characteristics of the problem are detailed below.

5.1. Characteristics of the Problem

LTCPP may be characterized as follows:

5.1.1. Time

Firms must define appropriate time periods and planning horizons based on the time frame in which these decisions will affect them.

- *Planning Horizon:* Time is taken into account in a long term plan (usually five to ten years). The time horizon is typically divided into periods.
- *Time periods:* The planning horizon is divided into time intervals called time periods (e.g. months). Production technology can be installed, renewed, upgraded or sold at the beginning of each time interval. During these periods, capacity level, capacity decisions, rate of production and stock levels are assumed to be constant.

5.1.2. Products

In a long term planning horizon, the products may change entirely. Initial versions of products may become outdated, newer versions of products may be produced, and new products may be introduced. New products come with some difficulties; for example, the existing production technology may not be able to process new products, and the design of the existing processes may not be suitable for new products. Both introduction of new products and development of existing products may require renewing and/or upgrading the existing technology.

The characteristics that we will take into account in this problem are listed below:

- *Multi-Products:* There may be more than one product in the problem.
- *Inventory:* Products can be stored for maximum amount of time. Inventory holding costs depend on product size, volume, and the time that they remain in storage.

- *Obsolete products:* Short life cycle products are treated as perishable; that is, their commercial value can expire, so storing them for a long time is not desirable.
- *Eliminating obsolete product:* Any products in the inventory can be eliminated when the life of products ends. This is associated with an eliminating cost.
- *Next/future generation and new products:* In a long term product horizon, new versions of existing products can be developed and introduced into the market. New products can sometimes be produced with existing production technology, although they may require renewing existing production technology.
- *Timing of product introduction to the market:* The time at which a product is introduced to the market must be decided. This affects the required production technology, the demand of the product, the development cost and the possibility of introducing other products. Hence, appropriate functions for demand and cost must be considered.

5.1.3. Demand and product life cycle

Demand curves of products have the shape of a normal product life cycle. Some products may be at the end of life cycles while others may be at the introduction stage with a demand curve showing different tendencies. Demand initially increases before stabilizing, and finally falls. Newer versions of existing products and entirely new products may have a negative effect (competitive products) or a positive effect (complementary products) on existing products' demand.

Short life cycle products can be defined as the innovative products that have life cycles of less than 2 years. Generally, short life cycle products experience a drop off in demand before the corresponding production technology has become obsolete. For example, a product may have 2 year life cycle but its production technology's life cycle may be 10 years; in this case, there is a question of what firms can do with existing production technology.

Short and long life cycle products are shown graphically in terms of life cycle demand and cumulative demand below.

Lifecycle demand and cumulative demand.

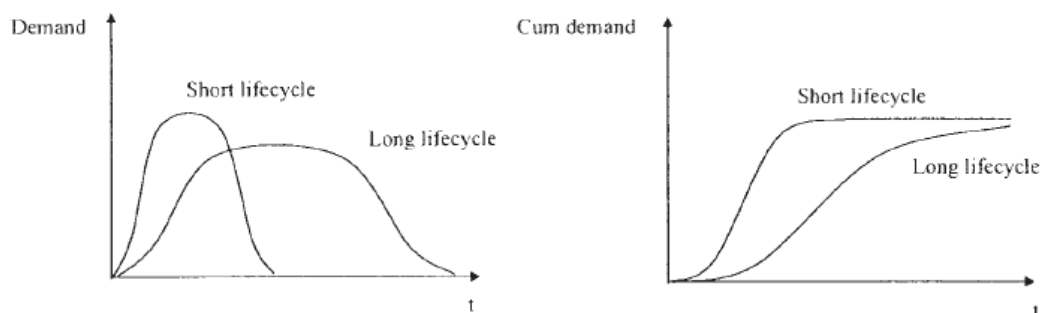


Figure 5-1 Typical demand patterns for products with short and long life cycles and their cumulative demand curve over time (Georgiadis et al., 2006).

The list of characteristics that this problem takes into account are listed below.

- *Demand Curve:* Demand has rapid introduction with growth, a long maturity period, and a rapid decline. Typically, demand increases, then saturates and decreases when the end of the life cycle is approaching. The shape of the demand curve is considered the same as product life cycle curve, and it depends of life cycle of products. In this problem, new product introduction time and demand of product are decision variables.
- *Price:* The price of the products is initially is high and then experiences a decrease. Price may be a decision to consider, but it can also be assessed in terms of how price may affect the demand at each stage of a product's life cycle. The price can either be considered as a data point or as a decision firms must make.
- *Products' life cycle stages:* Generally, products' life cycle are divided into 4 stages - introduction, growth, maturity and decline (Che, 2009; Georgiadis et al., 2006; Chou et al., 2007). These stages have different costs, demand levels, and sales price parameters.
 - *Introduction stage:* Demand is initially small and subsequently increases. At this stage, costs are very high. Although sales prices are high, the firm makes very little or no money due to high product development costs.
 - *Growth Stage:* In this stage, demand increases significantly. Costs are reduced due to economies of scale, and increased competition leads to price decreases.
 - *Maturity Stage:* Demand peaks and market saturation is reached. Costs are lowered as a result of production volumes increasing and experience curve effects. Prices tend to drop due to an increase of competing products in the market. A mature product will be phased out in a near future.
 - *Decline Stage:* Demand declines. Costs become counter-optimal; that is, the costs added to increase the product sales do nothing to improve sales. Prices and profitability decline.
- *Product Development Costs:* The cost of improving products must be taken into account. These costs can depend on the decision of which product is to be introduced to the market and when. Druehl et al. 2009 claim that they are the first to introduce a U shape functional form for modeling product development costs.
- *Lost demand:* Demand cannot be transferred from one period to another. Demand that cannot be satisfied is lost (no delays are allowed). There is no penalty for lost demand.
- *Number of product introduction in a period:* While there is a product in the market, continue to develop the next generation of products. In each period only one product can be introduced to the market.

5.1.4. Demand Interaction

Demand of one product can be affected by introduction of another product to the market. When there are at least two products that simultaneously exist in the market, each of them can affect the others' demand. Generally, products can be divided into two types depending on their effect on demand interaction: competitive products and complementary products.

- *Competitive products:* The usage and function of these products are similar, so these products cannibalize sales of individual demands. Introduction of next generation product can cannibalize and demand of existing product and lead to a large decrease in demand, while demand for the next generation products may decline slightly.
- *Complementary products:* The usage and function of those products complete each other, so a customer may choose to purchase both of them. The individual demand for these products rises when both of them are in the market.

In this problem, both competitive products and complementary products are taken into account.

5.1.5. Manufacturing Capacity Options

Generally, capacity level changes are achieved by acquiring additional production technology. Firms raise capacity for products experiencing demand increases, while reducing the capacity for the products experiencing demand decreases. They may also renew and upgrade existing production technology depending on economically viability, timing, and lead times for the acquisition and installation of such technology. The purchasing cost, second hand values and salvage values of the technology all play a role.

- *Additional Production Technology:* In case of excess demand, new production technology can be acquired. However, the possibility of acquisition may depend on physical and financial limitations. The new production technology can be selected from a finite number of options with different capacities and associated costs, which may depend on the product firms choose to produce.
- *Renewing:* Renewing is taken into account in case of production technology breakdowns or when a machine simply reaches the end of its life. Salvage value of the existing production technology is considered in the problem.
- *Updating:* Existing production technology can be replaced with newer versions with different characteristics.
- *Capacity Reduction:* Capacity reduction is an option when demand is at a lower level than current capacity, so a firm may sell the existing production technology. Total maintenance and overhead costs will decline, and firms will consider the second hand value of the technology.
- *Tactical Decisions:* For long-term decisions, tactical decisions must be taken into account to improve performance of the system.

- *Overtime*: There will be an upper bound of overtime for any given period.
- *Outsourcing*: If there is excessive demand that cannot be supported by overtime in the short term, firms may choose to outsource production.
- *Inventory management*: Production, demand and sales levels balance the inventory.

5.1.6. Production Technology

There are essentially two choices in terms of production technology: updating and renewing. Generally, new production technology (i.e. advanced production technology) allows the flexibility to produce single or multiple products with yield, quality and cost advantages with a higher acquisition cost. In contrast, existing production technology has no acquisition cost and may have a high maintenance cost. Each production technology has production capacity limits. The number of the maximum number each machine can produce has a fixed upper boundary.

The following characteristics of production technology are taken into account in the problem:

- *Acquisition and installation of production technology*: Each production technology has a unique acquisition and installation cost depending on the time frame.
- *Fixed Costs*: Each production technology has a unique operating cost (including workforce costs and general costs). The costs depend on general expenses of the plant (salaries, electricity, water, gas, rent of the building, etc.)
- *Maintenance cost*: This depends on the type, quantity, and age of the production technology. Each unit has a unique maintenance cost depending on the age of the technology. Initially the maintenance cost is typically low, increasing over time.
- *Production cost*: Each production technology has a unit production cost based on its specifications. Production costs depend on products and the current production technology.
- *Production per hour*: Each production technology has a different production capacity based on its specifications. This may depend on the product.
- *Lead time*: The time between purchasing the production technology, installation and initialization of producing the product is taken into account.
- *Ramp up period*: There may be a delay between the time production technology is installed and the time it attains maximum production capacity.
- *Availability*: Firms may not have the option of acquiring production technology in every period. Not all kinds of product technology may be available at all time periods. Furthermore, production technology renews itself; that is, a production technology may exist at the beginning of the planning horizon, but due to the technological development, it may not be in the market until the next period. At each period, a set of available production technology will be considered.

- *Production Plant:* A single site production plant is considered in this problem.
- *Total Production Area:* The plant production area is limited. Purchasing decisions will take into account total production area.

5.1.7. Evaluation Criteria

The objective is to *maximize the cash balance* at the end of the horizon, having made and received all payments, and having valued all assets for their second hand value.

- *Interest:* The cash balance at the end of each period can be positive or negative. In the case of negative balance the firm owes interest; in the case of positive balance the firm collects interest.
- *Revenue:* These include sales income, sales of second hand technology, and salvage values of production technology.
- *Cost:* Firms may incur costs related to production, production technology acquisition, renewing and upgrading, capacity level changes, outsourcing, inventory, and finances.

5.1.8. Additional Characteristics

- *Financial Planning:* Financial planning should be included in detail, covering bank loans, interest levels, and inflation so as to include the time value of money.
 - *Bank loans:* In order to acquire additional technology, the company will likely apply for external funding.
 - *Budget Constraints:* In order to stay within cash limits, there will be limitations on investment in order not to exceed the maximum available financial resources.
 - *Income from sales of products.* The firm may acquire this at the time of sales or as a check that may be cashed in the future.
 - *Income from sales of second hand and salvage values:* Production technology can be sold during its life cycle or at the end of its life. The income of sold production technology can be gained at the time of sale or in installments over a period of time.

5.1.9. Characteristics that are not included

The problem can be more complicated when uncertainties in demand, production technology and detailed financial plans are taken into account. There are the other papers that show how to model these issues, so in this problem, these related issues are not taken in account for the sake of clarity.

6. MATHEMATICAL MODELING

6.1. Data

| | |
|------------------|--|
| T | Number of periods in the planning horizon |
| N | Set of products (all existing and next and future products) |
| PT | Set of production technologies (all existing and future production technology) |
| W | Number of potential warehouses (all existing and future warehouse capacities) |
| R_i | Set of products that interact with product i ($\forall i \in N$). |
| N_m | Set of products that production technology m is able to produce product ($\forall m \in PT$). |
| $d\phi_{its}$ | Potential demand of product i in period t , being introduced in period s ($\forall i \in N$; $s = ltMin_i, \dots, ltMax_i$; $t = s, \dots, \min(s + LN_i - 1, T)$). |
| p_{its} | Price of product i in period t , being introduced in period s ($\forall i \in N$; $s = ltMin_i, \dots, ltMax_i$; $t = s, \dots, \min(s + LN_i - 1, T)$). |
| α_{ijslt} | Quantity that must be added to the demand of product i in period t , when i has been introduced in period s and product j has been introduced in period l . It can be positive or negative ($\forall i \in N R_i \neq \{\phi\}$; $\forall j \in R_i l \leq t \leq l + LN_j - 1$; $s = \max(ltMin_i, t - LN_i + 1), \dots, \min(ltMax_i, t)$; $l = \max(ltMin_j, t - LN_j + 1), \dots, \min(ltMax_j, t)$; $t = ltMin_i, \dots, \min(ltMax_i + LN_i - 1, T)$). |
| LN_i | Maximum life of product i ($\forall i \in N$). |
| v_{imt}^P | Variable unit production costs of product i which is produced in production technology m , in period t ($\forall i \in N$; $\forall m \in PT$; $t = \max(tMin_m, ltMin_i), \dots, \min(ltMax_i + LN_i - 1, T)$). |
| v_{iwt}^W | Variable warehouse costs of product i , in warehouse w , in period t ($\forall i \in N$; $w = 1, \dots, W$; $t = ltMin_i - 1, \dots, \min(ltMax_i + LN_i - 1, T)$). |
| τ^s | Number of periods between a sale and the moment in which payment is received (an invoice issued at t is cashed at $t + \tau^s$). |
| τ^P | Number of periods between the acquisition of variable-cost resources and the payment of the acquisition (the resources used at t are paid at $t + \tau^P$). |

| | |
|----------------|---|
| i_t^b, i_t^d | Respectively; interest rates that apply to the borrowed amount (the absolute value of the balance of the account when it is negative) and the interest rates that apply to the deposited amount (the balance of the account when it is positive). It is assumed that interest is accrued and paid in the same period in which it is calculated. |
| β_{im}^P | Manufacturing capacity required to manufacture one unit of product i with production technology m ($\forall i \in N_m; \forall m \in PT$). |
| β_i^W | Units of warehouse capacity that are required to store a unit of product i ($\forall i \in N$). |
| s_{iw0} | Initial inventory level of product i in warehouse w in period 0 ($\forall i \in N; w = 0..W$). |
| $ltMin_i$ | Minimum launching time of product i ($\forall i \in N$). |
| $ltMax_i$ | Maximum launching time of product i ($\forall i \in N$). |
| $tMin_m$ | Minimum period in which product technology m can be acquired ($\forall m \in PT$). |
| $tMax_m$ | Maximum period in which product technology m can be acquired ($\forall m \in PT$). |
| IPT_{ms} | Investment required to acquire production technology m in period s ($\forall m \in PT; s = tMin_m, \dots, tMax_m$). This cost also includes the installation cost of production technology. |
| SPT_{mts} | Sale price of production technology m acquired in period s and sold in period t ($\forall m \in PT; s = tMin_m, \dots, tMax_m; t = s, \dots, T$). |
| MPT_{mts} | Maintenance cost of production technology m for period t , paid in period t , acquired in period s ($\forall m \in PT; s = tMin_m, \dots, tMax_m; t = s, \dots, T$). |
| RPT_{mTs} | Residual value of production technology m acquired in period s and sold in final period T ($\forall m \in PT; s = tMin_m, \dots, tMax_m; t = T$). |
| IW_{jwT} | Investment required to increase warehouse capacity from C_j^W to C_w^W ($j = 0, \dots, w-1; w = 1, \dots, W; t = 1, \dots, T$). This cost also includes the installation cost of warehouse. |
| MW_{wTs} | Maintenance cost of warehouse w for period t , paid in period t , acquired in period s ($w = 1, \dots, W; t = 1, \dots, T; s = 1, \dots, t$). |

| | |
|------------|---|
| RW_{wts} | Residual value of warehouse w for period t , paid in period t , acquired in period s ($w = 1, \dots, W; t = 1, \dots, T; s = 1, \dots, t$). |
| C_m^P | Capacity of one unit of production technology m in period t ($\forall m \in PT; C_0^P = 0$). |
| C_w^W | Capacity of warehouse w ($w = 0..W; C_0^W = 0$). |
| CF_t | Fixed costs (costs that are independent of capacity and level of activity) for period t ($t = 1, \dots, T$). |
| CI_{it} | Cost of introduction of product i in period t ($\forall i \in N; t = ltMin_i, \dots, ltMax_i$). |
| h_0 | Initial cash balance. |
| B | Maximum amount of the absolute value of a negative cash balance (expressed as an absolute value). |
| σ_i | Factor used to value inventories ($0 < \sigma_i < 1$). The inventory value of product i at t is $\sigma_i p_{it}$ ($\forall i \in N$). |
| PG_{ij} | 1 if product i is introduced before product j ($\forall i, j \in N$). |

6.2. Variables

6.2.1. Real variables (all non-negative)

| | |
|----------------|--|
| q_{imt} | Number of units of product i produced with production technology m in period t ($\forall i \in N_m; \forall m \in PT; t = \max(tMin_m, ltMin_i), \dots, \min(ltMax_i + LN_i - 1, T)$). |
| d_{it} | Demand for product i in period t ($\forall i \in N; t = ltMin_i, \dots, \min(ltMax_i + LN_i - 1, T)$). |
| IN_{it} | Income of product i in period t ($\forall i \in N; t = ltMin_i, \dots, \min(ltMax_i + LN_i - 1, T)$). |
| s_{iwt} | Inventory level of product i in warehouse w in period t ($\forall i \in N; w = 0, \dots, W; t = ltMin_i - 1, \dots, \min(ltMax_i + LN_i - 1, T)$). |
| h_t^+, h_t^- | Respectively, positive and negative bank account balances (in absolute figures) at the end of period t ($t = 1, \dots, T$). |

6.2.2. Integer and binary variables

| | |
|-----------|--|
| z_{mts} | Number of units of production technology m used in period t , acquired in period s ($\forall m \in PT; s = tMin_m, \dots, tMax_m; t = s, \dots, T$). |
|-----------|--|

y_{jw} 1 if warehouse capacities in periods $t-1$ and t are, respectively C_j^W and C_w^W ($j=0,\dots,W$;
 $w=j,\dots,W$; $t=1,\dots,T$).

δ_{is} 1 if product i is introduced in period s ($\forall i \in N$; $s = ltMin_i, \dots, ltMax_i$).

γ_{ijsl} 1 if product i is introduced in period s and product j is introduced in period l (
 $\forall i \in N | R_i \neq \{\phi\}$; $\forall j \in R_i$; $s = ltMin_i, \dots, ltMax_i$; $l = ltMin_j, \dots, ltMax_j$)

6.3. MILP Model

$$\begin{aligned}
 [\text{MAX}] \ Z = & \left[h_t^+ - h_t^- \right] + \left[\sum_{t=T-\tau^s+1}^T \sum_{S_1} IN_{it} \right] + \left[\sum_{w=1}^W \sum_{s=ltMin_i}^{ltMax_i} \sum_{S_2} \sigma_i \cdot p_{its} \cdot S_{iwt} \right] + \left[\sum_{s=ltMin_m}^{tMax_m} \sum_{m \in PT} RPT_{mTs} \cdot z_{mTs} \right] + \\
 & \left[\sum_{w=1}^W \sum_{s=1}^T \sum_{j=0}^{w-1} RW_{wTs} \cdot y_{jws} \right] - \left[\sum_{t=T-\tau^p+1}^T \sum_{m \in PT} \sum_{S_3} v_{imt}^p \cdot q_{imt} \right] - \left[\sum_{t=T-\tau^p+1}^T \sum_{w=1}^W \sum_{S_4} v_{iwt}^w \cdot S_{iwt} \right] \quad (1)
 \end{aligned}$$

$$S_1 = \{ \forall i \in N | ltMin_i \leq t \leq ltMin_i + LN_i - 1 \}$$

$$S_2 = \{ \forall i \in N | s \leq T \leq s + LN_i - 1 \}$$

$$S_3 = \{ \forall i \in N | \max(ltMin_i, tMin_m) \leq t \leq ltMax_i + LN_i - 1 \}$$

$$S_4 = \{ \forall i \in N | ltMin_i \leq t \leq ltMin_i + LN_i - 1 \}$$

$$d_{it} = \sum_{s=\max(ltMin_i, t-LN_i+1)}^{\min(ltMax_i, t)} d\phi_{its} \cdot \delta_{is} + \sum_{S_5} \sum_{s=\max(ltMin_i, t-LN_i+1)}^{\min(ltMax_i, t)} \sum_{l=\max(ltMin_j, t-LN_j+1)}^{\min(ltMax_j, t)} \alpha_{ijslt} \cdot \gamma_{ijsl}$$

$$S_5 = \{ j \in R_i | l \leq t \leq l + LN_j - 1 \} \quad \forall i \in N \quad t = ltMin_i, \dots, \min(ltMax_i + LN_i - 1, T) \quad (2)$$

$$IN_{it} = \sum_{s=\max(ltMin_i, t-LN_i+1)}^{\min(ltMax_i, t)} d\phi_{its} \cdot \delta_{is} \cdot p_{its} + \sum_{S_6} \sum_{s=\max(ltMin_i, t-LN_i+1)}^{\min(ltMax_i, t)} \sum_{l=\max(ltMin_j, t-LN_j+1)}^{\min(ltMax_j, t)} \alpha_{ijslt} \cdot \gamma_{ijsl} \cdot p_{its}$$

$$S_6 = \{ j \in R_i | l \leq t \leq l + LN_j - 1 \} \quad \forall i \in N \quad t = ltMin_i, \dots, \min(ltMax_i + LN_i - 1, T) \quad (3)$$

$$\gamma_{ijsl} \geq \delta_{is} + \delta_{jl} - 1 \quad (4)$$

$$\gamma_{ijsl} \leq \delta_{is} \quad (5)$$

$$\gamma_{ijsl} \leq \delta_{jl} \quad (6)$$

$$\forall i \in N | R_i \neq \{\phi\} \quad \forall j \in R_i \quad s = ltMin_i, \dots, ltMax_i \quad l = ltMin_j, \dots, ltMax_j$$

$$\delta_{jt} \leq \sum_{s=ltMin_i}^{\min(ltMax_i, t-1)} \delta_{is} \quad \forall i, j \in N \mid PG_{ij} = 1 \quad t = ltMin_j, \dots, ltMax_j \quad (7)$$

$$\sum_{s=ltMin_i}^{ltMax_i} \delta_{is} \leq 1 \quad \forall i \in N \quad (8)$$

$$s_{iw, ltMin_i-1} = 0 \quad w=1, \dots, W \quad \forall i \in N \quad (9)$$

$$\sum_{w=1}^W s_{iw, t-1} + \sum_{S_7} q_{imt} = d_{it} + \sum_{w=1}^W s_{iwt}$$

$$S_7 = \{m \in PT \mid i \in N_m \cup \max(ltMin_i, tMin_m) \leq t \leq ltMax_i + LN_i - 1\}$$

$$\forall i \in N \quad t = ltMin_i, \dots, \min(ltMax_i + LN_i - 1, T) \quad (9)$$

$$\sum_{S_8} \beta_{im}^P \cdot q_{imt} \leq \sum_{s=tMin_m}^{\min(t, tMax_m)} C_m^P \cdot z_{mts}$$

$$S_8 = \{i \in N_m \mid \max(ltMin_i, tMin_m) \leq t \leq ltMax_i + LN_i - 1\} \quad \forall m \in PT \quad t = 1, \dots, T \quad (10)$$

$$z_{mts} \leq z_{m, t-1, s} \quad \forall m \in PT \quad t = tMin_m, \dots, T \quad s = tMin_m, \dots, \min(tMax_m, t-1) \quad (11)$$

$$\sum_{S_9} \beta_i^W \cdot s_{iwt} \leq \sum_{j=0}^w C_w^W \cdot y_{jw}$$

$$S_9 = \{i \in N_m \mid ltMin_i \leq t \leq ltMax_i + LN_i - 1\} \quad w=1, \dots, W \quad t = 1, \dots, T \quad (12)$$

$$\sum_{w=0}^W \sum_{j=0}^w y_{jw} = 1 \quad t = 1, \dots, T \quad (13)$$

$$\sum_{w=0}^W y_{0w} = 1 \quad (14)$$

$$\sum_{k=j}^W y_{jkt} = \sum_{i=0}^j y_{ij, t-1} \quad j = 0 \dots W \quad t = 2, \dots, T \quad (15)$$

$$h_0^+ - h_0^- = h_0 \quad t = 0 \quad (16)$$

$$\begin{aligned}
[h_t^+ - h_t^-] &= [h_{t-1}^+ - h_{t-1}^-] + \left[\frac{1}{2}(h_t^+ + h_{t-1}^+) \cdot i_t^d - \frac{1}{2}(h_t^- + h_{t-1}^-) \cdot i_t^b \right] + \left[\sum_{S_{10}} IN_{i,t-\tau^s} \right] + \\
&\left[\sum_{m \in PT} \sum_{s=tMin_m}^{\min(t-1, tMax_m-1)} SPT_{mts} \cdot (z_{m,t-1,s} - z_{mts}) \right] - [CF_t] - \left[\sum_{m \in PT | tMin_m \leq t \leq tMax_m} IPT_{mt} \cdot z_{mt} \right] - \left[\sum_{w=1}^W \sum_{j=0}^{w-1} IW_{jw} \cdot y_{jw} \right] - \\
&\left[\sum_{m \in PT} \sum_{s=tMin_m}^{\min(t, tMax_m)} MPT_{mts} \cdot z_{mts} \right] - \left[\sum_{w=1}^W \sum_{s=1}^t \sum_{j=0}^{w-1} MW_{w,t-s,t} \cdot y_{jws} \right] - \left[\sum_{i \in N} CI_{it} \cdot \delta_{it} \right] - \\
&\left[\sum_{m \in PT} \sum_{S_{11}} v_{im,t-\tau^p}^p \cdot q_{im,t-\tau^p} \right] - \left[\sum_{w=1}^W \sum_{S_{12}} v_{iw,t-\tau^p}^w \cdot s_{iw,t-\tau^p} \right]
\end{aligned}$$

$$S_{10} = \{i \in N | tMin_i \leq t - \tau^s \leq tMax_i + LN_i - 1\}$$

$$S_{11} = \{i \in N_m | \max(tMin_i, tMin_m) \leq t - \tau^p \leq tMax_i + LN_i - 1\}$$

$$S_{12} = \{i \in N | tMin_i \leq t - \tau^p \leq tMax_i + LN_i - 1\} \quad t = 1, \dots, T \quad (17)$$

$$h_t^- \leq B \quad t = 1, \dots, T \quad (18)$$

The objective function (1) is to maximize the cash balance at the end of the horizon, taking into account: the final cash balance, the sales income from the last τ^s periods (account receivable), the value of the inventory of products that are in the stock at final period T , the residual of production technology at final period T , the residual of warehouse assets at final period T , variable production costs for the last τ^p periods, variable inventory holding costs for the last τ^p periods. (2) expresses the demand equation for product i (current product) that takes into account cannibalization of sales of product k (previous generation product), as well as product j 's (future next generation product) cannibalization of product i . Equation (3) corresponds to the incomes for each product and period. (4) (5) and (6) links variables γ and δ . (7) ensures that product introduction sequence (product i is introduced after product j). (8) ensures that only one product can be introduced in a single period. Equation (9) expresses the inventory and production balance. (10) ensures that production technology capacity is not exceeded. (11) avoids using units of production that have been sold in previous periods and ensures that used production technology is acquired in a previous period. (12) ensures that warehouse capacity is not exceeded. Equations (13), (14) and (15) ensure that changes in warehouse capacity are for expansion purposes. (16) expresses that initial bank account balance equals initial cash balance and (17) expresses the bank account balance in period t ; balance from previous periods, credit and debit interest, sales income from τ^s previous periods, sales of production technology, fixed production costs, costs for acquiring production technology, expense for changing warehouse capacity, expense for maintaining production technology,

costs for maintaining warehouses, new product introduction costs, variable costs of production and variable costs of warehouses. (18) ensures that the negative bank account balance does not exceed the limit established.

7. COMPUTATIONAL EXPERIMENTS AND ANALYSIS

In the previous chapter, a mixed integer linear programming (MILP) is suggested as technique used to solve cases that can be obtained from LTCPP of short life cycle products with demand interaction; this is dealt with in previous sections. The results of the MILP model are shown in this section.

The computational demonstration is done for two reasons: first, to check the validity and robustness of the models that have been developed, including the influence of certain parameters on solving times; and second, to observe the influence of a number of parameters on the solution.

For the first objective, developed models were used for cases that have at the greatest number of variables. The instances tested are solved in a short time (considering the kind of problem being solved) that is short enough to perform an extensive computational experiment. Solving a large number of instances allow us to observe the effect of the number of products, production technology and life cycles on solving times.

For the second objective, developed models were used to determine the effect of select relevant parameters on the outcome.

This chapter is organized as follows: in the first section, software and hardware are introduced; in the second section data are defined; in the third section, the performance of the model is tested; in the fourth section, solutions are analyzed and computational experiments are carried out; in the fifth section, computational experiments are concluded.

7.1. Software and Hardware

The MILP model is implemented in and solved with ILOG OPL CPLEX 12.5 to yield an exact solution. Eclipse Java is used to create correlated data.

The experiments were run in a Pc Intel Core i7 CPU with @2.93 GHz and 4.00 GB RAM.

7.2. Definition of Data

The data used to solve the model are detailed in this section. Some data are constant and some are parameters during the entire computing experience. The solutions are dependent on the values of certain parameters.

The data set is given below.

Time Periods (T):

60 periods (months), which corresponds to 5 years, is taken into account in the experience.

Number of products (N):

Number of products is 5 and 11, following two different product family's patterns below.

- a) 5 products are designed by generations in *Figure 7-1*. Product 1 is the first generation, Product 2 is the second, and Product 3 is the third generation, and so on. These products have competitive product patterns. Demand cannibalization occurs between competitive (consecutive) products. An example of this pattern would be different version of the same products (e.g. iPad, iPad2, iPad3 ...)

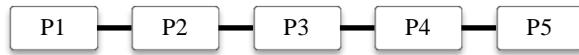


Figure 7-1 Structure of 5 products by generations

Relationships and interactions between 5 products are shown in *Table 7-1* below.

Table 7-1 Interaction between 5 products case

| Related Products | Products | | | | |
|------------------|----------|-----|-----|-----|---|
| | 1 | 2 | 3 | 4 | 5 |
| Interaction with | 2 | 1,3 | 2,4 | 3,5 | 4 |

- b) 11 products are designed by generation and product families in *Figure 7-2* and *Figure 7-3*. *Figure 7-2* shows the interaction between competitive products, while *Figure 7-3* shows the interaction between complementary products. For instance, Product 6 and Product 10 are competitive products, while Product 6 and Product 7 or Product 7 and 10 are complementary products. In the example of Figures 7-2 and 7-3 there are four different products, each one with different versions (there is a competitive interaction between versions) and there are two pairs of complementary products (Products 4 and 8 with Products 5 and 9; and Products 6 and 10 with Products 7 and 11).

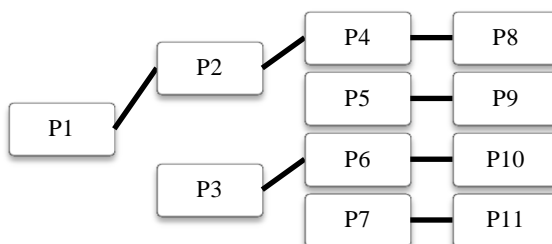


Figure 7-2 Interactions and structure of generations of competitive products for the 11 products case.

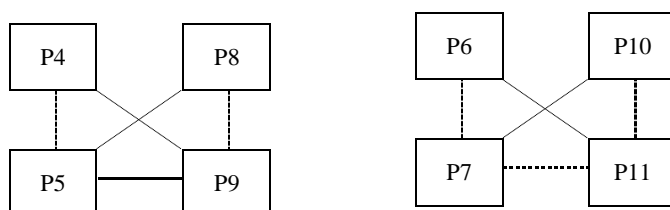


Figure 7-3 Interaction and structure of generations of complementary products for the 11 products case.

Interactions between 11 products are shown in *Table 7-2*, Competitive relations between 11 products are given in *Table 7-3* and complementary relations between 11 products are given in *Table 7-4*, below.

Table 7-2 Interaction between 11 products case

| Related Products | Products | | | | | | | | | | |
|------------------|----------|-----|---|---------|-------|-----------|---------|-------|-------|--------|--------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Interaction with | 2 | 1,4 | 6 | 2,5,8,9 | 4,8,9 | 3,7,10,11 | 6,10,11 | 4,5,9 | 4,5,8 | 6,7,11 | 6,7,10 |

Table 7-3 Competitive relations between 11 products case

| Related Products | Products | | | | | | | | | | |
|------------------|----------|---|---|-----|---|------|----|---|---|----|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Competitive with | 2 | 1 | 6 | 2,8 | 9 | 3,10 | 11 | 4 | 5 | 6 | 7 |

Table 7-4 Complementary relations between 11 products case

| Related Products | Products | | | | | | | | | | |
|--------------------|----------|---|---|-----|-----|------|------|-----|-----|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Complementary with | | | | 5,9 | 4,8 | 7,11 | 6,10 | 5,9 | 4,8 | 7,11 | 6,10 |

Minimum and Maximum Launching Times of Products ($ltMin_i, ltMax_i$):

For each consecutive product, there is at least one common period in which both of the products can be produced. Minimum and maximum launching times are given for 5 products in *Table 7-5* and for 11 products in *Table 7-6*, below.

Table 7-5 Minimum and maximum launching times when there are 5 products

| Product | $ltMin_i$ | $ltMax_i$ |
|---------|-----------|-----------|
| 1 | 1 | 16 |
| 2 | 11 | 27 |
| 3 | 21 | 38 |
| 4 | 31 | 49 |
| 5 | 41 | 60 |

Table 7-6 Minimum and maximum launching times when there are 11 products

| Product | $ltMin_i$ | $ltMax_i$ |
|---------|-----------|-----------|
| 1 | 1 | 10 |
| 2 | 5 | 15 |
| 3 | 9 | 20 |
| 4 | 13 | 25 |
| 5 | 17 | 30 |
| 6 | 21 | 35 |
| 7 | 25 | 40 |
| 8 | 29 | 45 |
| 9 | 33 | 50 |
| 10 | 37 | 55 |
| 11 | 41 | 60 |

Life Cycle of Products (LN_i):

In our experiments, we use 2 ranges of life cycle: (1) Products with life cycles of 12 to 15 periods and (2) Products with life cycles of 15 to 18 periods. These 2 ranges are based on the case of Apple’s iPhones in *Figure 7-4* and *Table 7-7*, which has been taken as an example because the characteristics are similar to the ones considered in this thesis and because the information of release time to the market, product life’s in the market and demand can easily be obtained (Apple, 2013).

Apple’s iPhones are high-end products with short life cycles. Their life cycles are at least 12 months long and at most 27 months long. The average product life cycle for an iPhone is around 15 months. In *Table 7-7* there is a list of iPhone models, their release dates to the market and their life cycles in the market.

The model of Apple’s iPhones and their life cycle are shown in *Figure 7-4*. In 2008, when a new model is introduced, the old version loses its foothold on the market. In late 2012, when a new model is introduced, the old version can exist in the market at the same time.

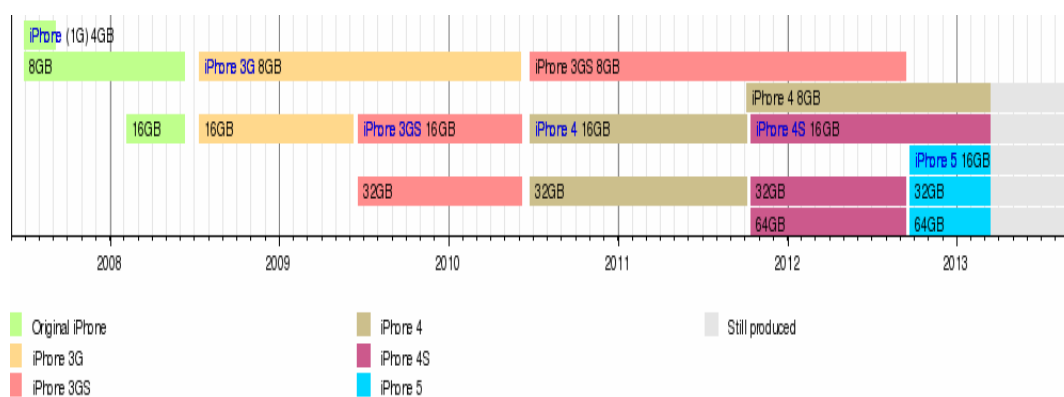


Figure 7-4 Timeline of Apple’s iPhones (data from March 2013)

Table 7-7 Release date and production life of models of Apple's iPhones

| Model | Release date | Life of Product |
|-----------------|----------------|--------------------------------|
| iPhone 1G 4GB | June 2007 | 2 Months |
| iPhone 1G 8GB | June 2007 | 12 Months |
| iPhone 1G 16GB | February 2008 | 5 Months |
| iPhone 3G 8GB | June 2008 | 24 Months |
| iPhone 3G 16GB | June 2008 | 12 Months |
| iPhone 3GS 16GB | June 2009 | 12 Months |
| iPhone 3GS 32GB | June 2009 | 12 Months |
| iPhone 3GS 8 GB | June 2010 | 27 Months |
| iPhone 4G 16GB | June 2010 | 15 Months |
| iPhone 4G 32GB | June 2010 | 15 Months |
| iPhone 4G 8GB | October 2011 | 22 Months (cont.) ¹ |
| iPhone 4GS 16GB | October 2011 | 22 Months (cont.) |
| iPhone 4GS 32GB | October 2011 | 12 Months |
| iPhone 4GS 64GB | October 2011 | 12 Months |
| iPhone 5G 16GB | September 2012 | 11 Months(cont.) |
| iPhone 5G 32GB | September 2012 | 11 Months(cont.) |
| iPhone 5G 64GB | September 2012 | 11 Months(cont.) |

Potential Demand of Products ($d\phi_{its}$):

The potential demand of a product (e.g. demand that the product would have if no other product made by the same company exists in the market) can exist between minimum introduction time ($ltMin_i$) and maximum introduction time plus its life cycle ($ltMax_i + LN_i - 1$). In the experiments, it is assumed that the earlier a product is introduced into the market, the shorter its potential demand. This happens with technological products whose market is still experiencing growth, although with other kind of products could be the opposite. It is assumed that potential demand is higher for new products. This can be seen in *Figure 7-5*, where there are 2 products (product i and product j); product i has minimum introduction time $ltMin_i = 1$ and maximum introduction time $ltMax_i = 10$ with a life cycle $LN_i = 9$ and product j has minimum introduction time $ltMin_j = 5$ and maximum introduction time $ltMax_j = 12$ with a life cycle $LN_j = 9$.

¹ Data from July 2013

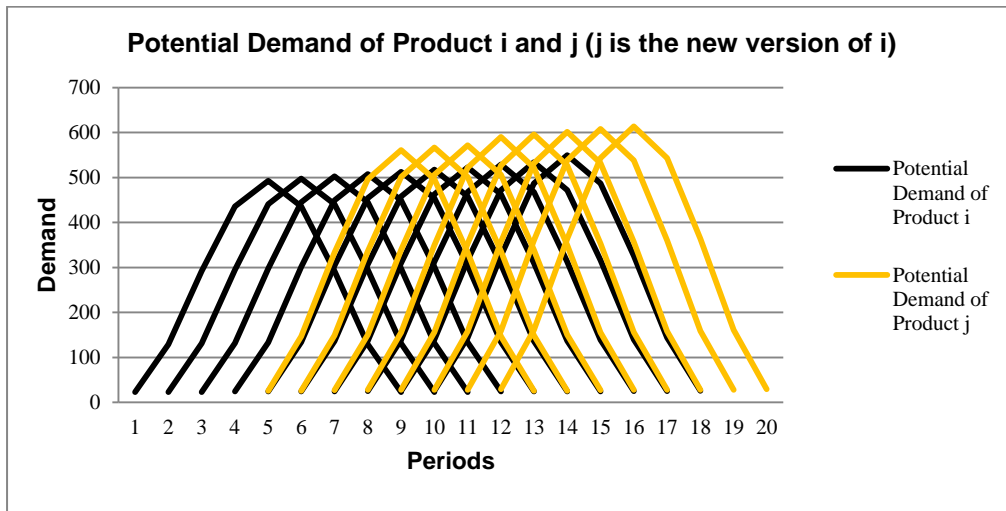


Figure 7-5 Potential demand of products i and j in time horizon.

In the experiments, the demand curves are assumed to have the shape of a product's life cycle. Chen et al. (2007), use a beta distribution function where $\alpha = 6$ and, $\beta = 3$ resulting in an upward demand function curve with a product life cycle shape.

Beta distribution with shape parameters $\alpha > 0$ and $\beta > 0$, over the interval (a, b) , where $a < b$ is given.

Density Function:

$$f(x) = (x - a)^{\alpha-1} (b - x)^{\beta-1} / [B(\alpha, \beta)(b - a)^{\alpha+\beta-1}] \quad \text{for } a < x < b, \text{ and } 0 \text{ elsewhere (19)}$$

Distribution function:

$$F(x) = I_{\alpha, \beta}(x) = \int_a^x (\zeta - a)^{\alpha-1} (b - \zeta)^{\beta-1} / [B(\alpha, \beta)(b - a)^{\alpha+\beta-1}] d\zeta, \quad \text{for } a < x < b \text{ (20)}$$

with parameters $\alpha = \text{alpha}$ and $\beta = \text{beta}$, and time interval (a, b) .

A demand function which is used in experiment is given as below.

$$d\phi_{its} = \text{Initial demand} * \text{Beta Function} * (1.01)^s \quad (21)$$

Initial demands of products are listed in *Table 7-8* and *Table 7-9*. The effect of introduction of product varies demand by $(1.01)^s$.

Table 7-8 Initial demand of products when there are 5 products

| Product | Initial Demand |
|---------|----------------|
| 1 | 6000 |
| 2 | 6500 |
| 3 | 7000 |
| 4 | 7500 |
| 5 | 8000 |

Table 7-9 Initial demand of products when there are 11 products

| Product | Initial Demand |
|---------|----------------|
| 1 | 6000 |
| 2 | 6500 |
| 3 | 7000 |
| 4 | 7500 |
| 5 | 8000 |
| 6 | 8500 |
| 7 | 9000 |
| 8 | 9500 |
| 9 | 10000 |
| 10 | 10500 |
| 11 | 11000 |

In *Figure 7-6*, by using different α and β values, different demand curves can be obtained with a different slope of the demand in different stages. In the experiments, the beta distribution function has been modified to include other characteristics (essentially, to include a number of periods with a constant demand, which corresponds to the maturity stage of the product), and the α and β values are set to 3 (the black curve in *Figure 7-6*).

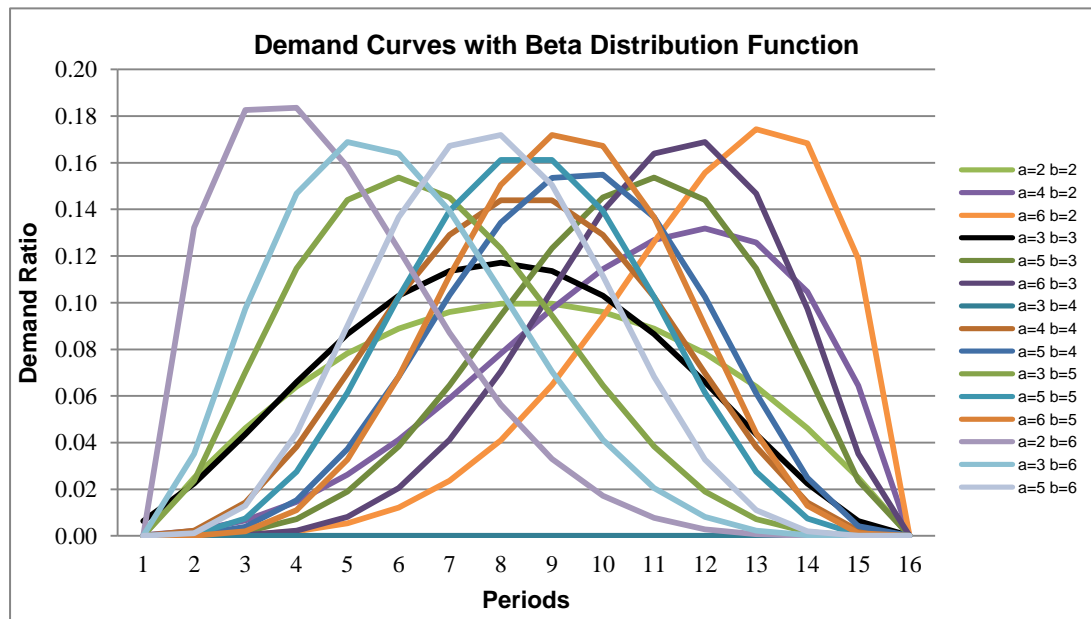


Figure 7-6 Beta distribution functions with different α and β values (a and b in the figure).

Product life cycle is divided into 3 stages - growth, maturity and decline. In the experiment, it is assumed that growth stage is 20% of a product life cycle, maturity stage is 60% and decline stage is 20% (in *Figure 7-7*).

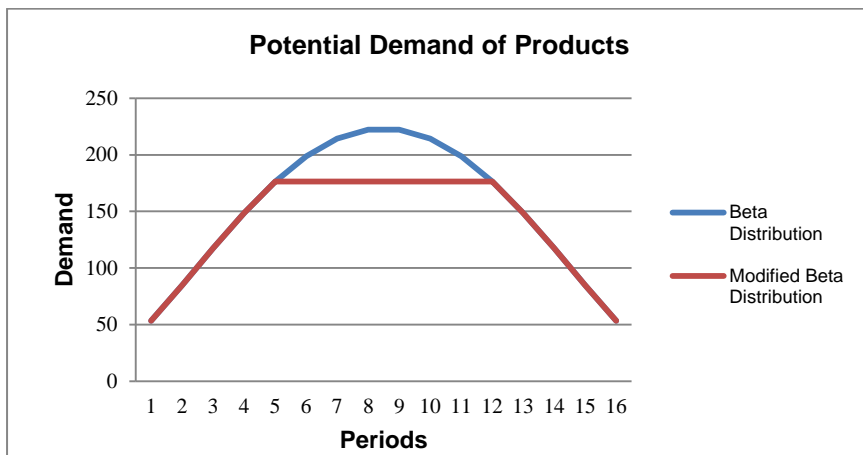


Figure 7-7 Potential demand of product ($d\phi_{its}$) with and without constant between periods $0.2 * LN_i < t < 0.8 * LN_i$ with $\alpha = 3$ and $\beta = 3$.

Interaction between products (R_i):

The interaction between competitive and complementary products is taken into account. An example of this interaction is depicted in Figure 7-8. In the case of product i (which has a life cycle of $LN_i = 9$ periods and is introduced in period $s = 1$) and product j (which has a life cycle of $LN_j = 9$ periods and is introduced in period $l = 7$) cannibalization can occur between periods 7 and 9 (red colored lines in Figure 7-8).

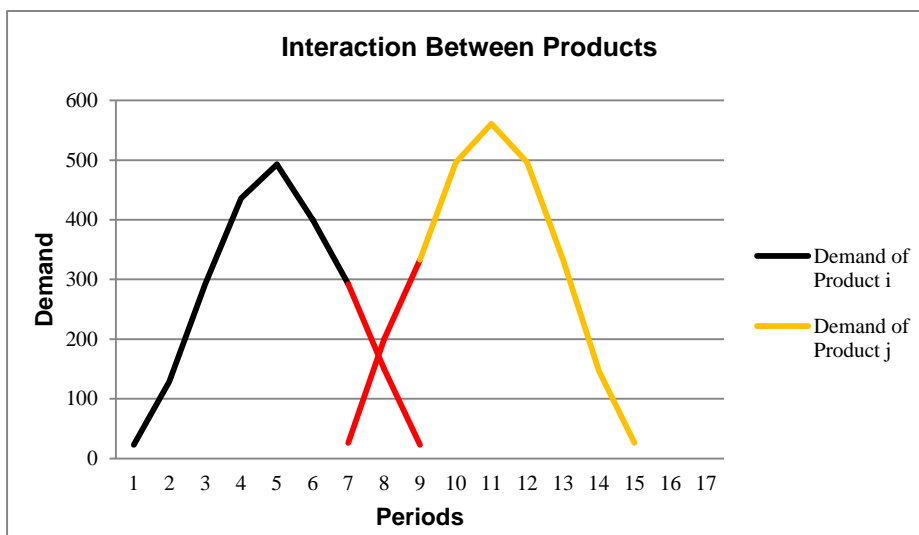


Figure 7-8 The interaction between products and cannibalization periods.

Demand(d_{it}) after interaction of products:

When there is interaction between products and there is at least one common period in which those products are simultaneously in the market, demand cannibalization can occur. Demand interaction is different between competitive products and complementary products:

- Competitive products: In the example of *Figure 7-9*, in period 8, potential individual demand of product i ($d\phi_{i81}$) is equal to 150 and the potential individual demand of product j ($d\phi_{j87}$) is equal to 200. If they are competitive products, when they are in the market simultaneously, the total demand is supposed to be shorter than the biggest individual demand $\max(d\phi_{i81}, d\phi_{j87})$, and each product is supposed to keep a certain percentage of the total potential demand. In this thesis, it is assumed that existing product will have 5% of $\max(d\phi_{i81}, d\phi_{j87})$ and next product will have 95% of $\max(d\phi_{i81}, d\phi_{j87})$ as their demands after cannibalization (interaction). In this example, for period 8, $\max(d\phi_{i81}, d\phi_{j87})=200$ and demand after interaction (d_{it}) for product i (d_{i8}) is $200*0,05=10$ and for product j (d_{j8}) is $200*0,95=190$ (in *Figure 7-9*, below).

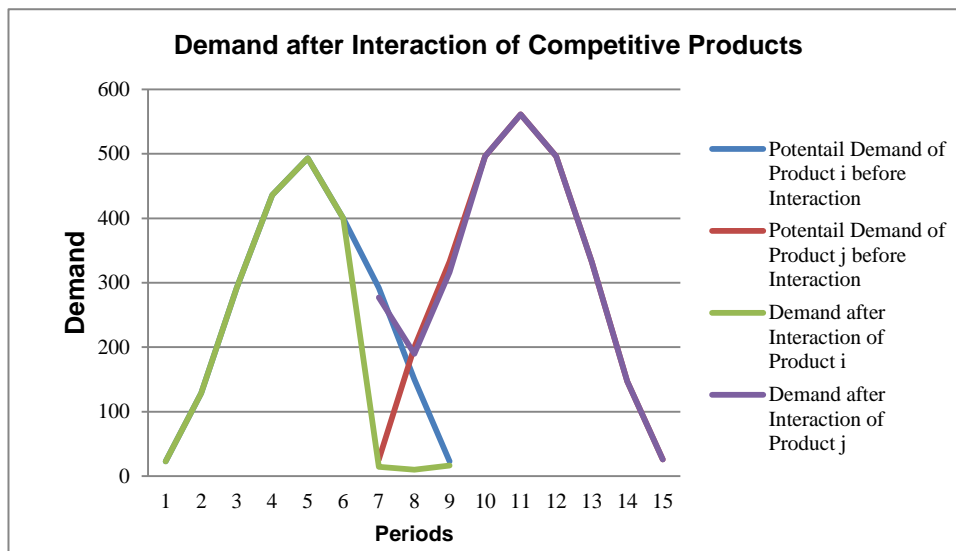


Figure 7-9 Demand after interaction of competitive products

- Complementary products: In the case of complementary products (e.g. Product 6 and Product 7 in *Figure 7-3*), the total demand is supposed to increase when those products are in the market at the same time. In the experiments, the demand interaction (d_{it}) is assumed to be 20% more than its potential individual demand ($d\phi_{its}$). In this example, for period 6, demand after interaction (d_{it}) for product i (d_{i6}) is $150*1.2=180$ and for product j (d_{j6}) is $200*1.2=240$ (in *Figure 7-10*, below).

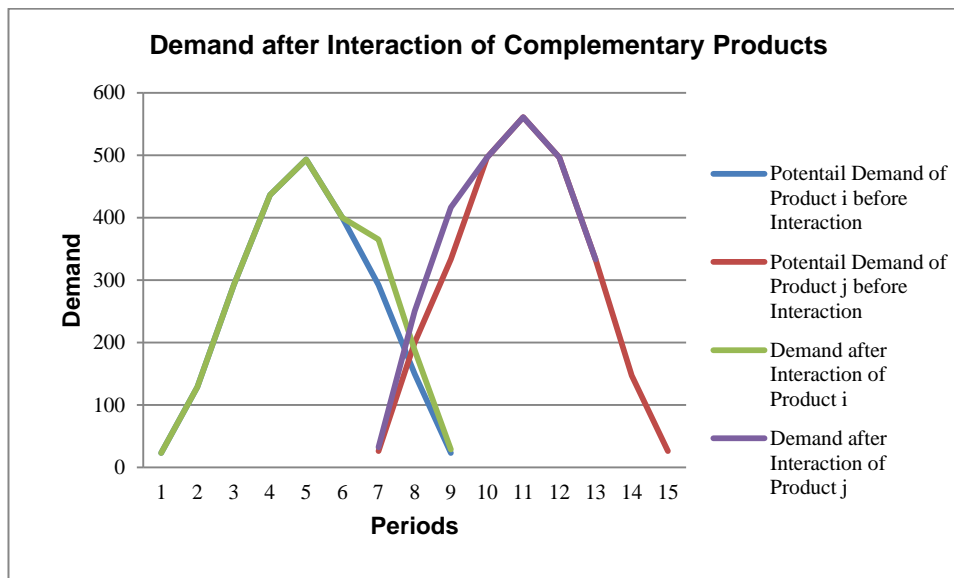


Figure 7-10 Demand after interaction of complementary products

Product Introduction Cost (CI_{is}):

According to Druehl et al. (2009), product introduction costs can be modeled as a U-shaped cost curve defined by 2 parameters: the shape of the curve and the time between generations of products. Based on Druehl et al. (2009), a reverse form of beta function (1-Beta) is developed where $\alpha = 3$ and $\beta = 5$. The distribution over time depends on the lifetime of products and time periods, which can be seen in Table 7-10 and in graph form in Figure 7-11. It is assumed that in the initial stages, the introduction costs will be high due to high development costs. After this stage, costs go down to a minimum point, after which they increase. Companies introduce products to the market early when there are fewer rivals, which then brings about higher introduction costs. Late introduction of product leads to higher introduction cost due to the costs of modification and promotion when there are rivals present in the market.

Table 7-10 The graph of 1-Beta distribution function over [0-1] by different life times of products and periods.

| Life Time of Products | Time Periods | | | | | | | | | | | | | | | | | |
|-----------------------|--------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 12 | 1.00 | 0.95 | 0.86 | 0.80 | 0.79 | 0.83 | 0.88 | 0.93 | 0.97 | 0.99 | 1.00 | 1.00 | | | | | | |
| 14 | 1.00 | 0.97 | 0.90 | 0.85 | 0.82 | 0.83 | 0.86 | 0.89 | 0.93 | 0.97 | 0.99 | 1.00 | 1.00 | 1.00 | | | | |
| 16 | 1.00 | 0.98 | 0.93 | 0.89 | 0.86 | 0.85 | 0.85 | 0.88 | 0.91 | 0.94 | 0.96 | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 | | |
| 18 | 1.00 | 0.98 | 0.95 | 0.91 | 0.88 | 0.87 | 0.87 | 0.87 | 0.89 | 0.92 | 0.94 | 0.96 | 0.98 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 |

An example of 1-Beta distribution function for 3000 of initial introduction cost over minimum and maximum introduction periods ($ltMin_i, ltMax_i$) is given in the Table 7-11 below. For instance, at period 3, when the life cycle of product is 14, the product introduction cost is 2700, and when the life cycle of product is 18, the product introduction cost is 2850.

Table 7-11 Product introduction costs with different product life time over time

| Product Introduction Costs (CI_{is}) | | | | | | | | | | | | | | | | | | |
|--|--------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Life Time of Products | Time Periods | | | | | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| 12 | 3000 | 2850 | 2580 | 2400 | 2370 | 2490 | 2640 | 2790 | 2910 | 2970 | 3000 | 3000 | | | | | | |
| 14 | 3000 | 2910 | 2700 | 2550 | 2460 | 2490 | 2580 | 2670 | 2790 | 2910 | 2970 | 3000 | 3000 | 3000 | | | | |
| 16 | 3000 | 2940 | 2790 | 2670 | 2580 | 2550 | 2550 | 2640 | 2730 | 2820 | 2880 | 2940 | 2970 | 3000 | 3000 | 3000 | | |
| 18 | 3000 | 2940 | 2850 | 2730 | 2640 | 2610 | 2610 | 2610 | 2670 | 2760 | 2820 | 2880 | 2940 | 2970 | 3000 | 3000 | 3000 | 3000 |

The shape of data in Table 7-9 is given in Figure 7-11 below.

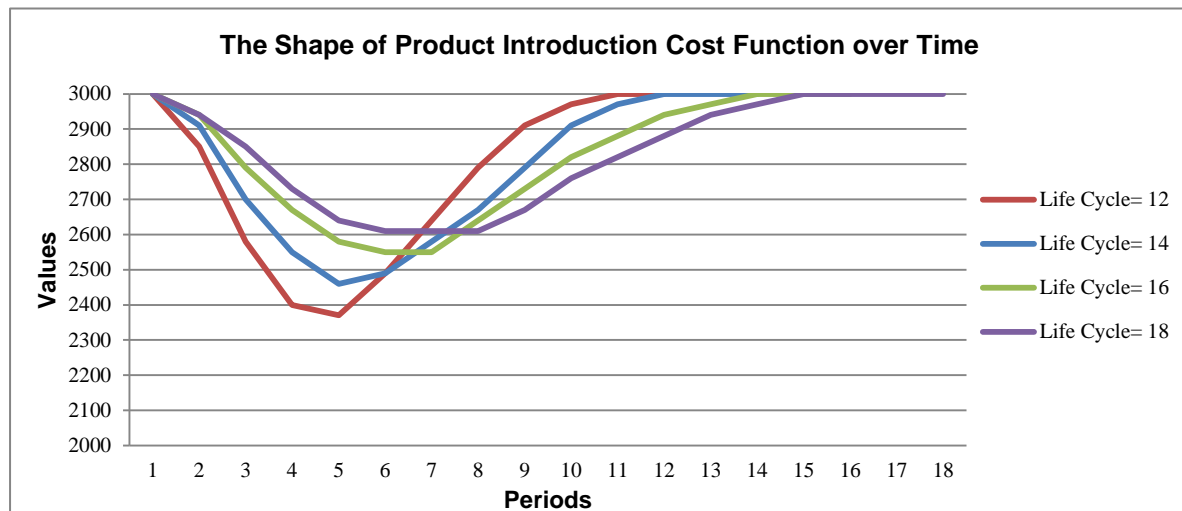


Figure 7-11 The Shape of Product introduction cost function over time during the life cycle (LN_i)

$$CI_{is} = \text{Initial Introduction Cost} * (1 - \text{Beta Function}) \tag{22}$$

Initial introduction costs of products are in Table 7-12 and Table 7-13 below.

Table 7-12 Initial introduction costs of products when there are 5 products

| Product | Initial Price |
|---------|---------------|
| 1 | 3000 |
| 2 | 3500 |
| 3 | 4000 |
| 4 | 4500 |
| 5 | 5000 |

Table 7-13 Initial introduction costs of products when there are 11 products

| Product | Initial Price |
|---------|---------------|
| 1 | 3000 |
| 2 | 3500 |
| 3 | 4000 |
| 4 | 4500 |
| 5 | 5000 |
| 6 | 5500 |
| 7 | 6000 |
| 8 | 7000 |
| 9 | 7500 |
| 10 | 8000 |
| 11 | 9500 |

Price of product (P_{its}):

The price of the product may depend on the product introduction time. Products introduced early generally have a higher price point, which then decreases. A price function, similar to Druehl et al. (2009)'s model is used to model price. Based on Druehl et al. (2009)'s model, unit profit margins decrease exponentially from period to period per the relationship $r_i(t) = r_0 \exp(-b(t - t_i))$ where b denotes the rate of profit margin decrease per periods. In our model, we use their model where r_0 is the initial cost and b is the decreasing ratio of price.

In the experiments, the price of the product from an existing product to a new product increases exponentially from period to period.

Different b values differentiate function. In *Table 7-14*, the distributions of exponential function with different b values over time when the initial cost is $r_0 = 30$ can be seen, and in *Figure 7-12* its graph is depicted.

Table 7-14 The distributions of exponential function with different b over time when the initial cost is $r_0 = 30$.

| b values | Time Periods | | | | | | | | | | | | | | | |
|----------|--------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 0.03 | 30.0 | 29.1 | 28.3 | 27.4 | 26.6 | 25.8 | 25.1 | 24.3 | 23.6 | 22.9 | 22.2 | 21.6 | 20.9 | 20.3 | 19.7 | 19.1 |
| 0.02 | 30.0 | 29.4 | 28.8 | 28.3 | 27.7 | 27.1 | 26.6 | 26.1 | 25.6 | 25.1 | 24.6 | 24.1 | 23.6 | 23.1 | 22.7 | 22.2 |
| 0.01 | 30.0 | 29.7 | 29.4 | 29.1 | 28.8 | 28.5 | 28.3 | 28.0 | 27.7 | 27.4 | 27.1 | 26.9 | 26.6 | 26.3 | 26.1 | 25.8 |

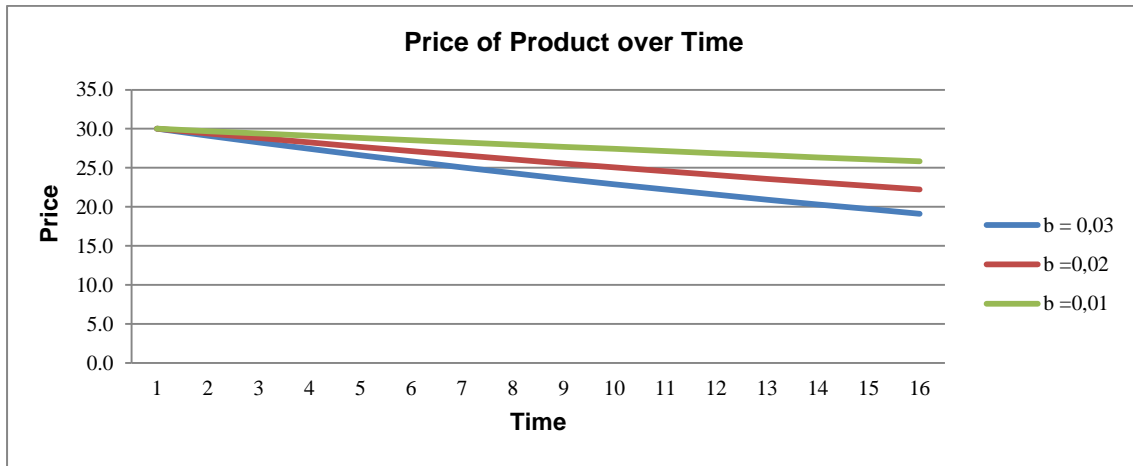


Figure 7-12 Slope of price of the product over time with different b values.

In *Table 7-15*, an example of price function of product i which has a minimum and maximum introduction time ($ltMin_i = 1, ltMax_i = 10$) which has a life cycle time ($LN_i = 10$) when $b = 0.01$, can be seen. In computational experiments, b value is taken 0.01. Initial prices of 5 products are listed in *Table 7-16* and of 11 products are listed in *Table 7-17*, below.

Table 7-15 Price of product over time with different introduction time

| Introduction Time (s) | Time Periods (t) | | | | | | | | | | | | | | | | | | | | |
|-----------------------|------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| 1 | 20 | 20 | 19 | 19 | 19 | 19 | 19 | 18 | 18 | 18 | | | | | | | | | | | |
| 2 | | 20 | 19 | 19 | 19 | 19 | 19 | 18 | 18 | 18 | 18 | | | | | | | | | | |
| 3 | | | 19 | 19 | 19 | 19 | 19 | 18 | 18 | 18 | 18 | 18 | | | | | | | | | |
| 4 | | | | 19 | 19 | 19 | 19 | 18 | 18 | 18 | 18 | 18 | 18 | | | | | | | | |
| 9 | | | | | | | | | 18 | 18 | 18 | 18 | 18 | 17 | 17 | 17 | 17 | 17 | | | |
| 10 | | | | | | | | | | 18 | 18 | 18 | 18 | 17 | 17 | 17 | 17 | 17 | 17 | | |

Table 7-16 Initial prices of products when there are 5 products

| Product | Initial Price |
|---------|---------------|
| 1 | 20 |
| 2 | 21 |
| 3 | 23 |
| 4 | 24 |
| 5 | 25 |

Table 7-17 Initial prices of products when there are 11 products

| Product | Initial Price |
|---------|---------------|
| 1 | 20 |
| 2 | 21 |
| 3 | 23 |
| 4 | 24 |
| 5 | 25 |
| 6 | 26 |
| 7 | 27 |
| 8 | 28 |
| 9 | 26 |
| 10 | 29 |
| 11 | 30 |

Production Technology (PT):

In the experiment when the number of products is 5, the number of different production technology is set at 3. When the number of products is 11, the number of different production technology is set at 5.

It is assumed that there is no ramp-up time; production technology, which is bought at period t , is available to produce at period t .

Set of products that production technology m is able to produce product (N_m):

Production technology cannot produce all the products. Available production technology and its ability to produce products is detailed in Table 7-18. In all cases, the available production technology is able to produce at least 3 products, in order to allow opportunities to renew and update production technology. Production technologies 1, 2 and 3 are able to produce 3 products each. Production technology 4 and 5 are able to produce 4 products each with different production variable costs and capacity.

Table 7-18 Production technology and products that can be produced

| Product Number | Production Technology | | | | |
|----------------|-----------------------|-------|-------|---------|-----------|
| | 1 | 2 | 3 | 4 | 5 |
| 5 | 1,2,3 | 2,3,4 | 3,4,5 | | |
| 11 | 1,2,3 | 2,4,5 | 3,6,7 | 4,5,8,9 | 6,7,10,11 |

Variable unit production costs (v_{imt}^P):

Variable production costs depend on production technology and product generations. Variable costs for the case of 5 products are given in Table 7-19 and variable costs for the case of 11 products are given in Table 7-20.

The variable cost of product i declines by production technology generations, and the variable cost of production technology j increases by product generations. It is assumed that the newest production technology has lower production costs, and that the newest products generally have higher costs because they may require more operations to be produced.

Table 7-19 Variable production costs when there are 3 production technology and 5 products

| Production Technology | Product | | | | |
|-----------------------|---------|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 6 | 12 | 18 | | |
| 2 | | 6 | 9 | 12 | |
| 3 | | | 6 | 8 | 10 |

Table 7-20 Variable production costs when there are 5 production technology and 11 products

| Production Technology | Product | | | | | | | | | | |
|-----------------------|---------|----|----|----|----|----|----|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 6 | 12 | 18 | | | | | | | | |
| 2 | | 6 | | 12 | 15 | | | | | | |
| 3 | | | 6 | | | 12 | 14 | | | | |
| 4 | | | | 6 | 7 | | | 12 | 13 | | |
| 5 | | | | | | 7 | 8 | | | 12 | 13 |

Manufacturing capacity required to manufacture one unit of product (β_{im}^P):

The required production capacity of a product depends on both the product's generation and the production technology's generation. Required manufacturing capacity for the case of 5 products is given in *Table 7-21* and required manufacturing capacity for the case of 11 products are given in *Table 7-22*.

The required manufacturing capacity of product i declines by production technology generations, and the required manufacturing capacity of production technology j increases by product generations. Just as variable unit production costs, it is assumed that the newest production technology requires lower capacity, and that the newest products require higher capacity because they may need more operations in order to be produced.

Table 7-21 Manufacturing capacity required to manufacture one unit of product with 5 products and 3 production technology

| Production Technology | Product | | | | |
|-----------------------|---------|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | 6 | 12 | 18 | | |
| 2 | | 6 | 9 | 12 | |
| 3 | | | 6 | 8 | 10 |

Table 7-22 Manufacturing capacity required to manufacture one unit of product with 11 products and 5 production technology

| Production Technology | Product | | | | | | | | | | |
|-----------------------|---------|----|----|----|----|----|----|----|----|----|----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 6 | 12 | 18 | | | | | | | | |
| 2 | | 6 | | 12 | 15 | | | | | | |
| 3 | | | 6 | | | 12 | 14 | | | | |
| 4 | | | | 6 | 7 | | | 12 | 13 | | |
| 5 | | | | | | 7 | 8 | | | 12 | 13 |

Interest Rate of Borrowed Amount of Money (i_t^b):

This interest rate is assumed to be 8% per year and around 0.0066 per period (month).

Interest Rate of Deposit Amount of Money (i_t^d):

This interest rate is assumed to be 2% per year and around 0.0016 per period (month).

Minimum and Maximum time to acquire a production technology ($tMin_m, tMax_m$):

The time needed to acquire production technology depends on the type of production technology. Taking into account the uncertainty of technology and planning for 60 periods, the available periods of production technology acquisitions for future generations ($tMax_m - tMin_m$) are higher than previous ones. Minimum and maximum times to acquire production technology are listed in Table 7-23 and Table 7-24, below.

Table 7-23 Minimum and maximum times to acquire for 3 production technology when there are 5 products

| Production Technology | $tMin_m$ | $tMax_m$ |
|-----------------------|----------|----------|
| 1 | 1 | 50 |
| 2 | 11 | 55 |
| 3 | 21 | 60 |

Table 7-24 Minimum and maximum times to acquire for 5 production technology when there are 11 products

| Production Technology | $tMin_m$ | $tMax_m$ |
|-----------------------|----------|----------|
| 1 | 1 | 40 |
| 2 | 5 | 45 |
| 3 | 9 | 50 |
| 4 | 13 | 55 |
| 5 | 17 | 60 |

Investment cost of production technology (IPT_{ms}):

It increases linearly over time and with each production technology generation.

$$IPT_{ms} = 3000 + 500 * m + 10 (s - tMin_m) \tag{23}$$

Where m is the number of production technology, s is the acquisition period and $tMin_m$ is the minimum available time to purchase.

The list of acquisition cost of production technology for 22 periods for 3 production technology is in Table 7-25 and for 5 production technology is in Table 7-26, below.

Table 7-25 Acquisition cost of production technology over time for 5 products and 3 production technology case

| Prod. Tech. | Time Periods (t) | | | | | | | | | | | | | | | | | | | | | |
|-------------|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 1 | 3000 | 3010 | 3020 | 3030 | 3040 | 3050 | 3060 | 3070 | 3080 | 3090 | 3100 | 3110 | 3120 | 3130 | 3140 | 3150 | 3160 | 3170 | 3180 | 3190 | 3200 | 3210 |
| 2 | | | | | | | | | | | 3500 | 3510 | 3530 | 3560 | 3600 | 3650 | 3710 | 3780 | 3860 | 3950 | 4050 | 4160 |
| 3 | | | | | | | | | | | | | | | | | | | | | 4000 | 4010 |

Table 7-26 Acquisition cost of production technology over time for 11 products and 3 production technology case

| Prod. Tech. | Time Periods (t) | | | | | | | | | | | | | | | | | | | | | |
|-------------|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 1 | 3000 | 3010 | 3020 | 3030 | 3040 | 3050 | 3060 | 3070 | 3080 | 3090 | 3100 | 3110 | 3120 | 3130 | 3140 | 3150 | 3160 | 3170 | 3180 | 3190 | 3200 | 3210 |
| 2 | | | | | 3500 | 3510 | 3520 | 3530 | 3540 | 3550 | 3560 | 3570 | 3580 | 3590 | 3600 | 3610 | 3620 | 3630 | 3640 | 3650 | 3660 | 3670 |
| 3 | | | | | | | | | 4000 | 4010 | 4020 | 4030 | 4040 | 4050 | 4060 | 4070 | 4080 | 4090 | 4100 | 4110 | 4120 | 4130 |
| 4 | | | | | | | | | | | | | 4500 | 4510 | 4520 | 4530 | 4540 | 4550 | 4560 | 4570 | 4580 | 4590 |
| 5 | | | | | | | | | | | | | | | | | 5000 | 5010 | 5020 | 5030 | 5040 | 5050 |

Second hand value of production technology (SPT_{mts}):

It decreases linearly over time for each production technology generation.

$$SPT_{mts} = 1500 + 50*m - 10 (t - s) \tag{24}$$

Where m is the number of production technology, s is the acquisition period and t is the period.

The list of acquisition cost of production technology for 3 production technology is in *Table 7-27* and for 5 production technology is in *Table 7-28*, below.

Table 7-27 Acquisition cost of production technology over time for 5 products and 3 production technology case

| Prod. Tech. | Time Periods (t) | | | | | | | | | | | | | | | | | | | | | |
|-------------|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 1 | 1500 | 1480 | 1460 | 1440 | 1420 | 1400 | 1380 | 1360 | 1340 | 1320 | 1300 | 1280 | 1260 | 1240 | 1220 | 1200 | 1180 | 1160 | 1140 | 1120 | 1100 | 1080 |
| 2 | | | | | | | | | | | 1550 | 1530 | 1490 | 1430 | 1350 | 1250 | 1130 | 990 | 830 | 650 | 450 | 230 |
| 3 | | | | | | | | | | | | | | | | | | | | | 1600 | 1580 |

Table 7-28 Acquisition cost of production technology over time for 11 products and 3 production technology case

| Prod. Tech. | Time Periods (t) | | | | | | | | | | | | | | | | | | | | | |
|-------------|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 1 | 1500 | 1480 | 1460 | 1440 | 1420 | 1400 | 1380 | 1360 | 1340 | 1320 | 1300 | 1280 | 1260 | 1240 | 1220 | 1200 | 1180 | 1160 | 1140 | 1120 | 1100 | 1080 |
| 2 | | | | | 1550 | 1530 | 1510 | 1490 | 1470 | 1450 | 1430 | 1410 | 1390 | 1370 | 1350 | 1330 | 1310 | 1290 | 1270 | 1250 | 1230 | 1210 |
| 3 | | | | | | | | | 1600 | 1580 | 1560 | 1540 | 1520 | 1500 | 1480 | 1460 | 1440 | 1420 | 1400 | 1380 | 1360 | 1340 |
| 4 | | | | | | | | | | | | | 1650 | 1630 | 1610 | 1590 | 1570 | 1550 | 1530 | 1510 | 1490 | 1470 |
| 5 | | | | | | | | | | | | | | | | | 1700 | 1680 | 1660 | 1640 | 1620 | 1600 |

Salvage value of production technology (RPT_{mTs}):

It exists in the last period and increases with each production technology generation.

$$RPT_{mTs} = 200 + 50*m \tag{25}$$

Where m is the number of production technology. The list of salvage of production technology for 3 production technology is in *Table 7-29* and for 5 production technology is in *Table 7-30*, below.

Table 7-29 Salvage value of production technology when there are 5 products and 3 production technology case

| Production Technology | T=60 |
|-----------------------|------|
| 1 | 200 |
| 2 | 250 |
| 3 | 300 |

Table 7-30 Salvage value of production technology when there are 11 products and 5 production technology case

| Production Technology | T=60 |
|-----------------------|------|
| 1 | 200 |
| 2 | 250 |
| 3 | 300 |
| 4 | 350 |
| 5 | 400 |

Maintenance cost of production technology (MPT_{mts}):

It is assume that maintenance cost of production technology increases linearly with respect to the age of production technology over time for each production technology generation.

$$MPT_{mts} = 100 + 10*m + 2 (s - tMin_m) \tag{26}$$

Where m is the number of production technology, s is the acquisition period and $tMin_m$ is the minimum available time to purchase.

The list of maintenance cost of production technology for 3 production technology is in the *Table 7-31* and for 5 production technology is in *Table 7-32*, below.

Table 7-31 Maintenance costs of production technology when there are 5 products and 3 production technology case

| Prod. Tech. | Time Periods (t) | | | | | | | | | | | | | | | | | | | | | |
|-------------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 1 | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 | 136 | 138 | 140 | 142 |
| 2 | | | | | | | | | | | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 |
| 3 | | | | | | | | | | | | | | | | | | | | | 120 | 122 |

Table 7-32 Maintenance costs of production technology when there are 11 products and 5 production technology case

| Prod. Tech. | Time Periods (t) | | | | | | | | | | | | | | | | | | | | | |
|-------------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 1 | 100 | 102 | 104 | 106 | 108 | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 | 136 | 138 | 140 | 142 |
| 2 | | | | | 110 | 112 | 114 | 116 | 118 | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 | 136 | 138 | 140 | 142 | 144 |
| 3 | | | | | | | | | 120 | 122 | 124 | 126 | 128 | 130 | 132 | 134 | 136 | 138 | 140 | 142 | 144 | 146 |
| 4 | | | | | | | | | | | | | 130 | 132 | 134 | 136 | 138 | 140 | 142 | 144 | 146 | 148 |
| 5 | | | | | | | | | | | | | | | | | 140 | 142 | 144 | 146 | 148 | 150 |

Capacity of Production Technology (C_m^P):

Capacity of production technology increases by generation of production technology. The lists of capacity of production technology are in *Table 7-33* and *Table 7-34* below.

Table 7-33 Capacity of production technology when there are 5 products and 3 production technology case

| Production Technology | C_m^P |
|-----------------------|---------|
| 1 | 3000 |
| 2 | 3500 |
| 3 | 4000 |

Table 7-34 Capacity of production technology when there are 11 products and 5 production technology case

| Production Technology | C_m^P |
|-----------------------|---------|
| 1 | 3000 |
| 2 | 3500 |
| 3 | 4000 |
| 4 | 4500 |
| 5 | 5000 |

Capacity of Investment cost of Warehouses ($IW_{jw,t}$):

There are 2 different types of warehouses with increasing storage capacity consecutively. The investment cost of warehouses increase linearly over time and for each warehouse.

$$IW_{jw,t} = 1000 * w + 10 * t \quad (27)$$

Where w is the number of warehouse and t is period. The list of investment cost of warehouses is in *Table 7-35*, below.

Table 7-35 Investment costs of warehouses over periods

| Warehouse | Time Periods (t) | | | | | | | | | | | | | | | | | | | |
|-----------|------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 1 | 1000 | 1010 | 1020 | 1030 | 1040 | 1050 | 1060 | 1070 | 1080 | 1090 | 1100 | 1110 | 1120 | 1130 | 1140 | 1150 | 1160 | 1170 | 1180 | 1190 |
| 2 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 | 2080 | 2090 | 2100 | 2110 | 2120 | 2130 | 2140 | 2150 | 2160 | 2170 | 2180 | 2190 |

Residual value of warehouse (RW_{wts}):

In the final period, there is a residual value for all the production technology, which increases by warehouse capacity. The list of residual value of warehouses is in *Table 7-36* below.

Table 7-36 Residual value of warehouses at period T=60

| RW_{wts} | T=60 |
|------------|------|
| 1 | 100 |
| 2 | 200 |

Maintenance cost of warehouse (MW_{wts}):

Maintenance costs of warehouses are constant for period increases with warehouse capacity. The list of maintenance costs of warehouses is in Table 7-37 below.

Table 7-37 Maintenance cost of warehouses over time

| Warehouse | Time Periods (t) | | | | | | | | | | | | | | | | | | | |
|-----------|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 1 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 2 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |

Variable warehouse costs (v_{iwt}^W):

Warehousing costs are assumed to be the same for all products.

Capacity of Warehouses (C_w^W):

Capacity of warehouse increases by warehouse type. The lists of capacity of warehouses are in Table 7-38 below.

Table 7-38 Capacity of Warehouses

| Warehouse | C_w^W |
|-----------|---------|
| 1 | 100 |
| 2 | 200 |

Units of warehouse capacity required to store a unit of product (β_i^W):

The unit of warehouse capacity is supposed to be same for all products.

Stocks:

Stocks are permitted between a period before minimum launching time ($ltMin_i - 1$) and maximum launching time plus its life cycle ($ltMax_i + LN_i - 1$) for each product.

Fix Cost (CF_t):

Fix costs are supposed to increase linearly for each period.

$$CF_t = 1500 + 10*t \quad (28)$$

Where t is time periods

7.3. Performance of the Model

The set of data used for the computational study are designed to cover a number of representative real cases specific to the problem to determine whether the model can be solved in a reasonable computing time.

The performance of the model and the results of a computational experiment are given below.

The data and their values used for this experiment are detailed in *Table 7-39* below.

Table 7-39 List of the data used in the first computational experiment.

| Data | Values |
|---|---|
| Periods (T) | 60 periods |
| Products (N) | (1) 5 products (2) 11 products |
| Number of Warehouses (W) | 2 |
| Production Technology (PT) | (1) 3 (2) 5 |
| Life Cycle of Products (LN) | (1) 12-15 periods (2) 15 -18 periods |
| Potential Demand Pattern ($d\phi_{its}$) | Equation (21) <i>Table 7-8 and Table 7-9</i> |
| Price of product (p) | <i>Table 7-15, Table 7-16 and Table 7-17</i> |
| Product Introduction Cost (CI_{is}) | Equation (22) <i>Table 7-12, Table 7-12 and Table 7-13</i> |
| Set of products that production technology m is able to produce product (N_m) | <i>Table 7-18</i> |
| Interest Rate of Borrowed Amount of Money (i_t^b) | 0.006 |
| Interest Rate of Deposit Amount of Money (i_t^d) | 0.0016 |
| Periods between a sale and it's payment (τ^s) | 2 |
| Periods between an acquisition and it's payment (τ^p) | 2 |
| Factor to value inventory at final period (σ_i) | 0.001 |
| Initial cash balance (h_0) | 250000 |
| Maximum negative cash balance (B) | 100000 |

Table 7-39 (Continued)

| Factor | Factor Levels |
|--|--|
| Capacity of Production Technology (C_m^P) | Table 7-33 and Table 7-34 |
| Capacity of Warehouses (C_w^W) | Table 7-38 |
| Manufacturing capacity required to manufacture one unit of product in a production technology (β_{im}^P) | Table 7-21 and Table 7-22 |
| Units of warehouse capacity that are required to store a unit of product (β_i^W) | 5 |
| Minimum and Maximum time of Product Introduction ($ltMin_i$) ($ltMax_i$) | Table 7-6 |
| Minimum and Maximum Time of acquisition of Production Tech. ($tMin_m$) ($tMax_m$) | Table 7-23 and Table 7-24 |
| Cost of acquisition of Production Tech. (IPT_{ms}) | Equation (23) Table 7-25 and Table 7-26 |
| Second hand value of production technology(SPT_{mts}) | Equation (24) Table 7-27 and Table 7-28 |
| Salvage value of production technology (RPT_{mTs}) | Equation (25) Table 7-29 and Table 7-30 |
| Maintenance cost of production technology (MPT_{mts}) | Equation (26) Table 7-31 and Table 7-32 |
| Cost of acquisition of Warehouse (IW_{jwT}) | Equation (27) Table 7-35 |
| Residual value of warehouse (RW_{wTs}) | Table 7-36 |
| Maintenance cost of warehouse (MW_{wTs}) | Table 7-37 |
| Variable warehouse costs (v_{iwt}^W) | 5 |
| Variable unit production costs (v_{imt}^P) | Table 7-19 and Table 7-20 |
| Fix Cost (CF_t) | Equation (28) |

The computing time depends on the number of variables, the number of constraints (size of the model) and the values of the parameters. One of the limitations of a large-scale MILP model is that the solution may require an excessively long time, and in some cases, the optimizer stops due to the capacity limit of the equipment being used.

The maximum computing time is limited to 7200 seconds (two hours), which is a short time considering the type of problem (strategic) being solved and that the designed model has a large number of integer variables and constraints (both in number and type of constraints).

Relative and absolute tolerances are set to; 1E-04 and 1E-06, respectively.

4 cases are tested to analyze the solving times, depending on the number of product and production technology and the life cycle of products. For each case 100 instances were generated by setting the life cycle of each product (LN_i) at random. Cases are given in *Table 7-40*.

Table 7-40 Cases that are tested

| | N | LN |
|--------|----|-------|
| Case 1 | 5 | 12-15 |
| Case 2 | 5 | 15-18 |
| Case 3 | 11 | 12-15 |
| Case 4 | 11 | 15-18 |

The results of these examples are shown below. The number of variables, constraints and integer variables used in the cases is summarized in *Table 7-41*.

Table 7-41 Number of variables, constraints and integer variables

| | N | LN | Minimum Number of Variables | Average Number of Variables | Maximum Number of Variables | Number of Integer Variable | Minimum Number of Constraints | Average Number of Constraints | Maximum Number of Constraints |
|--------|----|-------|-----------------------------|-----------------------------|-----------------------------|----------------------------|-------------------------------|-------------------------------|-------------------------------|
| Case 1 | 5 | 12-15 | 7944 | 7971.03 | 7998 | 3855 | 12790 | 12803.62 | 12817 |
| Case 2 | 5 | 15-18 | 7998 | 8025.39 | 8052 | 3855 | 12817 | 12830.68 | 12817 |
| Case 3 | 11 | 12-15 | 16253 | 16309.79 | 16354 | 6570 | 30504 | 30532.95 | 30555 |
| Case 4 | 11 | 15-18 | 16399 | 16443.08 | 16485 | 6570 | 30579 | 30602.19 | 30624 |

In Case 1 and Case 2 all the instances are solved in less than 7200 seconds. 9 samples of Case 3 can be solved in 7200 seconds. None of the samples of Case 4 can be solved in 7200 seconds. The details are listed in *Table 7-42*.

Table 7-42 Number of proved optimum solutions

| | N | LN | Solution | |
|--------|----|-------|-------------|---------|
| | | | Time Limits | Optimum |
| Case 1 | 5 | 12-15 | | 100% |
| Case 2 | 5 | 15-18 | | 100% |
| Case 3 | 11 | 12-15 | 91% | 9% |
| Case 4 | 11 | 15-18 | 100% | |

Table 7.43 summarizes the minimum, maximum and average times of each case. There is a summary of the minimum, maximum and average gaps ($100 * (\text{best bound} - \text{objective function}) / \text{objective function}$). The average gap for Case 3, which cannot be solved in 7200 seconds, is 0.48% and the average gap for Case 4, which cannot be solved in 7200 seconds, is 1.13%. Overall the results are very satisfactory.

Table 7-43 Solving percentage, solution times and gaps.

| | N | LN | Solving percentage | Minimum Time | Maximum Time | Average Time | Average Gap | Minimum Gap | Maximum Gap |
|--------|----|-------|--------------------|--------------|--------------|--------------|-------------|-------------|-------------|
| Case 1 | 5 | 12-15 | 100% | 9.56 | 360.38 | 37.09 | - | - | - |
| Case 2 | 5 | 15-18 | 100% | 25.82 | 1959.40 | 217.63 | - | - | - |
| Case 3 | 11 | 12-15 | 9% | 113.84 | 7200 | 6712.71 | 0.48% | 0.06% | 1.04% |
| Case 4 | 11 | 15-18 | | 7200 | 7200 | 7200 | 1.13% | 0.31% | 4.79% |

Obtained solution times are very satisfactory even for large samples; 50% of the samples are solved in less than 1000 seconds, an insignificant amount of time considering the type and size of the problems solved.

With the data used for the experiments, solving Case 4 needs more computational time than the other cases. Allowing more computing time can lead to solutions with lower gaps; for example, for the instance number 164, the gap after 7200 seconds is 0.32%, after 72 hours is reduced to 0.11% and after 90 hours to 0.1%.

The results of product introduction time, acquisition and selling of production technology, warehouse decisions and cannibalization of products of 4 chosen samples of each case are included in the Annex.

7.4. Solution Analysis

The basic data set of the experiment is the same as the one used in the numerical example described in the previous section.

The effect of production introduction costs (CI_{is}), cannibalization quantity (α_{ijst}) and the price of the product (p_{its}) are studied. The influence of the values chosen for the parameters is analyzed by comparing the solutions of the problems.

In instance number 79 (among the 400 solved) Case 3 is selected. The solution time of the sample is 420.04 seconds with an objective value of 861641. The number of variables is 16276, number of integer variables is 6570 and the number of constraints is 30516. The details of this solution are included in Annex Case 3.

The problem solved does not occur very often in companies; probably, at best, once every six months to 12 months. Therefore, the solution times are not included where they are extremely small (relative to a planning horizon of 5 years).

2 kinds of experiments are done.

- 1) The effect of a certain parameter when its value changes. The effects of parameters on product introduction are searched individually. The values of the parameters are given in *Table 7-44* below.
- 2) The search of the combination of parameters. The values of parameters are given in *Table 7-48*.

Details and results of the experiments are given below.

7.4.1. Analysis of Parameters Individually

The values of production introduction costs (CI_{is}), cannibalization quantity (α_{ijst}) and the price of the product (p_{its}) are changed individually and their effect on objective function and product introductions is observed. Parameters and their values are summarized in *Table 7-44*.

Table 7-44 Summaries of parameters used in computational experiment

| Factor | Symbol | Values |
|----------------------------------|-----------------|---|
| Products & Production Technology | N PT | N:11 PT:5 |
| Life Cycle of Products | LN | 12-15 |
| Production Introduction Cost | CI_{is} | 0.5*CI, 0.75*CI, 1.25*CI, 1.5*CI, 1.75*CI, 2*CI, 2.25*CI, 2.5*CI, 2.75*CI, 3*CI |
| Price of the product | p_{its} | 0.5*p, 0.6*p, 0.7*p, 0.8*p, 0.9*p, 1.1*p, 1.2*p, 1.3*p, 1.4*p, 1.5*p, 2*p, 2.5*p, 3*p |
| Cannibalization quantity | α_{ijst} | see <i>Table 7-47</i> |

The values of product introduction costs and price of products have been multiplied by a coefficient to increase or reduce them.

Product Introduction Cost (CI_{is}): Product introduction cost is an important element of the model that affects the introduction time of products. As it is expected, when product introduction cost (CI_{is}) declines, the objective value (Z) decreases.

In this experiment, when the values of CI's are doubled or more, for some products, the model waits until the period where CI costs are lower (U-shaped CI is used in the experiments) in order to introduce the products at the first available time.

In *Table 7-45*, the model tends to produce the products at the first available time. When the introduction costs are 2 times or greater, the introduction of some products is delayed: Product 2 at 8th period, Product 4 at 14th period and Product 6 at 22nd period.

Table 7-45 Result of changes in product introduction cost

| Sample Number | CI | Objective | Introduction Time of Products | | | | | | | | | | |
|---------------|--------------|-----------|-------------------------------|---|---|----|----|----|----|----|----|----|----|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 0.5 * CI | 1.04 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 2 | 0.75 * CI | 1.02 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 3 | Original One | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 4 | 1.25 * CI | 0.98 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 5 | 1.50 * CI | 0.96 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 6 | 1.75 * CI | 0.94 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 7 | 2 * CI | 0.93 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 8 | 2.25 * CI | 0.91 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 9 | 2.5 * CI | 0.89 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 10 | 2.75 * CI | 0.87 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 11 | 3 * CI | 0.85 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |

Figure 7-13 shows that when introduction costs increases, the objective value decreases slightly.

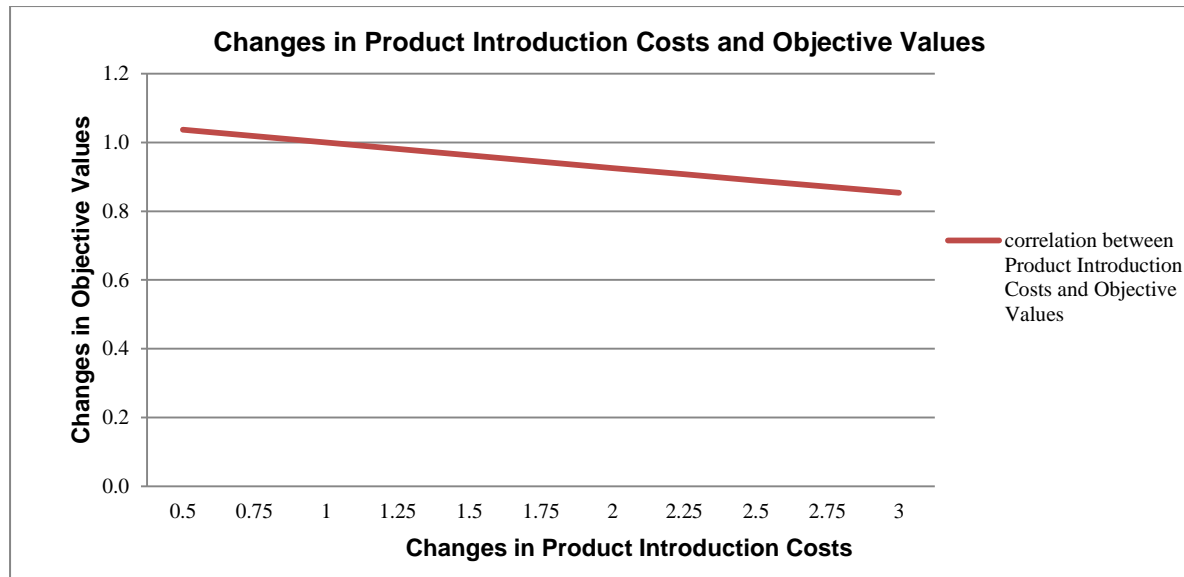


Figure 7-13 Changes in product introduction costs and objective values

Price of the product (p_{its}): There is a strong correlation between price and objective function since the price affects the incomes. From the performance point of view, when the prices are close to the costs, the model requires more time to obtain optimum results.

Price is one of the most important incomes in the model. In the experiment, it is observed that when the prices are low, products are not introduced into the market because their costs are higher than the potential incomes. On the opposite, when prices rise, more products are introduced into the market. As it is seen in Table 7-46, when the prices are $0.7 * p$ and less, model introduce less products to the market. And also, depending on changes in price, introduction times of some products can delay a period.

There is a competitive relationship between products 1, 2 and 4. When those products exist simultaneously in the market, existing product loses most of its demand and in some cases a new product gains demand. Introduction times change with price regarding relationship with demand cannibalizations.

In *Table 7-46* when prices are 50% of the original prices, Product 1 is introduced at 1st period and Product 3 at 9th period due to a break-even decision between producing and not producing.

When the prices are 60% and 70% of the original prices, the first 7 products are produced.

When the prices are 80% of original prices, more products are produced: Product 8 at 29th period, Product 10 at 37th and Product 11 at 41st periods.

When the prices are 90% and greater than the original prices, all the products are produced.

When the prices are 110%, the introduction times of products start changing: Product 2 at 8th period, Product 4 at 14th period, Product 6 at 22nd period.

When the prices are 130%, the introduction time of Product 8 is at 30th period.

When the prices are 150%, the introduction time of Product 2 is at 5th period.

Table 7-46 Results of changes in price of the product

| Sample Number | Price | Objective | Introduction Time of Products | | | | | | | | | | |
|---------------|--------------|-----------|-------------------------------|----------|---|-----------|----|-----------|----|----|----|----|----|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 0.5 * p | 0.21 * Z | 1 | | 9 | | | | | | | | |
| 2 | 0.6 * p | 0.27 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | | |
| 3 | 0.7 * p | 0.39 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | | |
| 4 | 0.8 * p | 0.54 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | | 37 | 41 |
| 5 | 0.9 * p | 0.77 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 6 | Original One | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 7 | 1.1 * p | 1.25 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 8 | 1.2 * p | 1.47 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 9 | 1.3 * p | 1.72 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 37 | 41 |
| 10 | 1.4 * p | 1.95 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 37 | 41 |
| 11 | 1.5 * p | 2.22 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 12 | 2 * p | 3.39 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 13 | 2.5 * p | 4.61 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 14 | 3 * p | 5.78 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |

The correlation between prices and objective function can be observed in *Figure 7-14*. There is a positive and strong correlation between price and objective function.

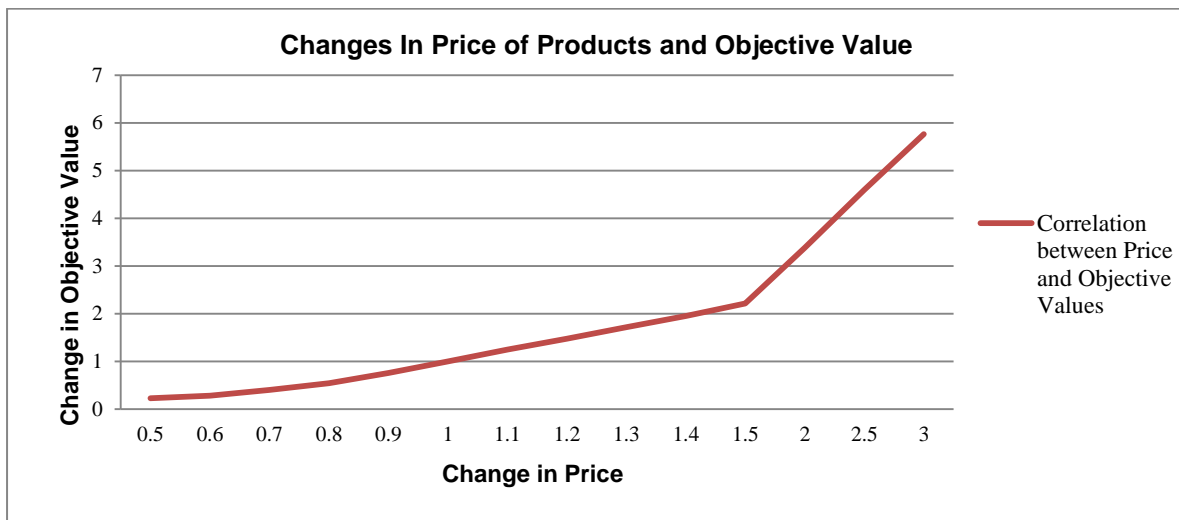


Figure 7-14 Changes in prices of product and objective value

Cannibalization quantity (α_{ijst}): In Table 7-47, cannibalization amounts have been changed. Increasing cannibalization quantities of competitive products slightly decreases objective function but does not affect (in this case) the introduction time of products.

Cannibalization directly affects demand. When there is cannibalization between products, existing product always loses its demand, and new product gains demand in some cases (when the potential demand of the existing product is higher than new product's potential demand at the period).

The introduction time of products highly depends on the relations between products. When there is a complementary relation between two products, each product is introduced at the first available time, because both of them gains demand (potential demand of product multiplies with a multiplier when there are both in the market). On the other hand, when competitive products are both in the market, potential demands of the product decline (the total demand cannot be more than the maximum demand of each and then they share that demand together), so the introduction time of the newest product is delayed. This, of course, may also depend on the prices and the costs (if selling price of the new product was very high probably the product would be introduced earlier).

In this set of experiment changes in cannibalization ratio affect product introduction times. When complementary effect is 10% and competitive effects are less than 10%, the introduction time of product 2, 4 and 9 changes (bold in Table 7-47). The model tends to introduce product 2nd lately and delay a period the introduction of product 4th and 6th.

Table 7-47 Result of changes in cannibalization quantity

| Sample Number | Competitive | | Complementary | Objective | Introduction Time of Products | | | | | | | | | | |
|---------------|------------------|--------------|---------------|-----------|-------------------------------|---|---|----|----|----|----|----|----|----|----|
| | Existing Product | Next Product | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | 5% | 95% | 10% | 0.96 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| Original One | 5% | 95% | 20% | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 3 | 10% | 90% | 10% | 0.95 * Z | 1 | 7 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 4 | 10% | 90% | 20% | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 5 | 20% | 80% | 10% | 0.95 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 6 (Low) | 20% | 80% | 20% | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 7 | 30% | 70% | 10% | 0.95 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 8 | 30% | 70% | 20% | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 9 | 40% | 60% | 10% | 0.95 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 10 | 40% | 60% | 20% | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |

7.4.2. Analysis of Combination of Parameters

In this section, 18 scenarios are analyzed by combining product introduction costs, cannibalization quantities and the prices of products. The details of the parameters are given in *Table 7-48*.

In order to compare the solutions of the problems each case has been solved with the 3 parameters.

Table 7-48 List of combination of parameters

| Factor | Symbol | Rank | Values |
|----------------------------------|-----------------|-------------------|---|
| Products & Production Technology | N PT | | N:11 PT:5 |
| Life Cycle of Products | LN | | 15-18 |
| Product Introduction Cost | CI_{is} | Low, Normal, High | 0.5*CI, CI, 2*CI (see <i>Table 7-45</i>) |
| Price of product | p_{its} | Low, Normal, High | 0.7*p, p, 2*p (see <i>Table 7-46</i>) |
| Cannibalization quantity | α_{ijst} | Normal, Low | Original One and Sample 6 (see <i>Table 7-47</i>) |

The following paragraphs summarize the main results obtained in each of the 18 instances tested. The results of the experiments are listed in *Table 7-49*.

Price is the one most important parameter that changes product introduction and product introduction time and changes objective value. In *Table 7-49*, the objective values are affected excessively by changes in the price of the product (p_{its}). Small changes in price result in a large change in objective value. The

best objective value is obtained when price of product (p_{its}) is high (H), production introduction costs (CI_{is}) is low (L), and cannibalization quantity (α_{ijst}) is normal (N).

It is not easily justified why these changes occur in the introduction period of products. It is a large scale optimization and some data are not linear (life cycle curve, exponential and U shaped etc...).

Table 7-49 Result of Combination of Parameters

| Sample Number | IC | Alpha | Price | Objective Value | Introduction Time of Products | | | | | | | | | | |
|---------------|----|-------|-------|-----------------|-------------------------------|---|---|----|----|----|----|----|----|----|----|
| | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 1 | L | N | L | 0.41 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | 37 | |
| 2 | L | N | N | 1.04 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 3 | L | N | H | 3.43 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 4 | N | N | L | 0.39 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | | |
| 5 | N | N | N | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 6 | N | N | H | 3.39 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 7 | H | N | L | 0.35 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | | |
| 8 | H | N | N | 0.93 * Z | 1 | 8 | 9 | 14 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |
| 9 | H | N | H | 3.32 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 10 | L | M | L | 0.41 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | 37 | |
| 11 | L | M | N | 1.04 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 12 | L | M | H | 3.43 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 13 | N | M | L | 0.39 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | | |
| 14 | N | M | N | Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 15 | N | M | H | 3.39 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |
| 16 | H | M | L | 0.35 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | | | | |
| 17 | H | M | N | 0.93 * Z | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |
| 18 | H | M | H | 3.32 * Z | 1 | 5 | 9 | 14 | 17 | 22 | 25 | 30 | 33 | 38 | 41 |

Product 1: In all the samples Product 1 is always introduced at 1st period.

Product 2: In all the samples Product 2 is always introduced at 5th period except sample 8 is introduced at 8th period.

Product 3: In all the samples Product 3 is always introduced at 9th period.

Product 4: In all the samples Product 4 is always introduced at 13th or 14th periods. Generally, when the price of the product is high (H), it is introduced at 14th period.

Product 5: In all the samples Product 5 is always introduced at 17th period.

Product 6: In all the samples Product 4 is always introduced at 21st or 22nd periods. Generally, when the price of product is high (H), it is introduced at 22nd period.

Product 7: In all the samples Product 7 is always introduced at 25th period.

Product 8: When the price of the product is low (L), product 8 is not introduced. When the price of product is normal (N), it is introduced at 29th period and when the price of the product is high (H), it is introduced at 30th period.

Product 9: When the price of the product is low (L), product 9 is not introduced. When the prices of products are normal (N) and high (H), they are introduced at 33rd period.

Product 10: When the price of the product is low (L), product 10 is not introduced except first sample. In the first sample, it is introduced at 37th period. When the price of the product is normal (N), it is introduced at 37th period and when the price of the product is high (H), it is introduced at 38th period.

Product 11: When the price of the product is low (L), product 11 is not introduced. When the prices of products are normal (N) and high (H), they are introduced at 41rd period.

In *Figure 7-15*, the parameters and objective values are shown. Changes in price affect the objective function more than any other chosen parameter. The best objective value is obtained in Sample 3. The objective value is 3.43 * Z and all the products are introduced.

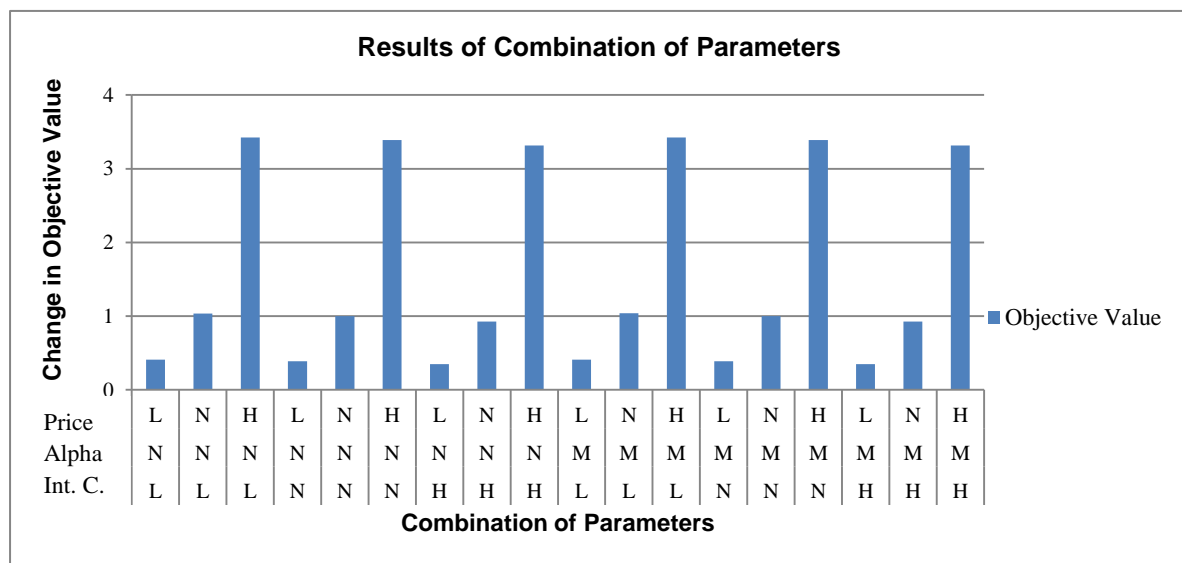


Figure 7-15 Objective values obtained from combination of parameters

7.5. Conclusions of the Computational Experiments

The main conclusions drawn from computational experiments carried out are the following:

- Most of the tested models can be solved in a very satisfactory manner; therefore the model can be considered to be an efficient decision and analysis tool.
- In all cases, optimum or near optimum solutions are obtained in an acceptable time frame.
- Small changes in the chosen parameters can easily change introduction time of products, thus the set of data has to be obtained and analyzed carefully.
- The procedures for the solution of the models developed for the industrial case may be a strategic tool, e.g., each firm can use the model appropriate to their case, with their key parameters and for different possible decisions. Thus, companies can decide when to possibly introduce products to the market and make decisions in regard to production technology based on quantitative information.

8. CONCLUSIONS AND FURTHER RESEARCH

This chapter contains the main conclusions and contributions of this doctoral thesis and suggests several ideas for future research.

This PhD thesis provides companies with the ability to obtain long-term capacity, economically viable tools through efficient and formalized plans. It gives managerial branches insight into the strategic decision-making involved in product renewing and dealing with production technology.

As not all companies have the same characteristics and needs, optimization models are suitable for cases or situations that occur more frequently in reality, and solution procedures may be used for representative cases.

One of the most critical points that may appear when applying the model to a real case is data collection and data modeling, especially those data affecting the cycle life (the demand of a product and the demand when there are interaction of products).

8.1. Conclusions

The most relevant conclusions and contributions are the following:

- This thesis formalizes the problem of LTCP with product renewal, including short life cycles of products with demand interaction. It should be noted again that despite its growing importance, LTCP is a relatively new problem in the literature, including LTCP with product renewal for short life cycle products with demand cannibalization.
- The problem is examined and discussed in relation to the existing literature (Chapter 4), including LTCP and renewing short life cycle products with demand cannibalization.
- Definition of the LTCPP is detailed (Chapter 5).
- A detailed mixed-integer linear programming model for LTCPP is proposed (Chapter 6). This is a deterministic model with a discrete time and a finite horizon. Optimum introduction time of a product takes into account variation in acquisition and demand (demand cannibalization), and renewing and updating of production technology by taking in into account detailed financial management.
- A set of problem instances has been designed and a way of designing data sets has been proposed.
- A solution procedure based on mixed integer linear programming and mixed (MILP) is proposed (Chapter 6) and a computational experience is performed (Chapter 7). The model is solved with CPLEX using instances of several dimensions. For most cases, proposed models are fully operational solution procedures. Solution times are acceptable, taking into consideration the type of problem being solved. In all cases, optimal or near optimal solutions are obtained.

With respect to the stated objectives, a solution to a relatively new and increasingly important problem in production systems has been designed.

The MILP technique proves to be an appropriate solution, and formulated models provide a tool for decision support for companies that are considering introducing new products and updating their production technology.

Finally, following the results of the computational experience, it should be noted that it has been demonstrated that a company has the opportunity to make optimal decisions with regard to introducing products to the market, renewing products, and making decisions related to production technology (including renewing, updating, acquiring and selling).

8.2. Further Research

Besides of considering extensions such as including uncertainty or expanding the type of tactical decisions included (e.g., financial flows and workforce planning), there are two clear research objectives that can be derived from this thesis:

- The price of a product could depend not only on its introduction time but also on the introduction of products that interact with this product. Modelling of this non-linear issue would be much more complex and the models would probably require much more time to be solved.
- Interactions of products have been considered by pairs. Further research could consider the interaction between a larger set of products (for example, between three products).

In order to handle the uncertainty of real life, stochastic versions of the model can be developed. A scenario-based optimization model can be designed in which, for example, the scenarios represent various possible capacity demands, each one with a given probability.

9. PUBLICATIONS

The list of books and books chapters, abstracts and paper presentations is listed in this section.

9.1. Books and Book Chapters

1. Yilmaz, G., Lusa, A., and Benedito, E., 2013. “Long term capacity planning with products’ renewal”, 7th International Conference on Industrial Engineering and Industrial Management y del XVII Congreso de Ingeniería de Organización (CIO), July 10-12, Valladolid, Spain. pp 620 – 628. (ISBN: 978-84-616-5410-9).

9.2. Abstract & Paper Presented

1. Yilmaz, G., Lusa, A., and Benedito, E., 2013. “Long term capacity planning with products’ renewal”, The 26th EURO-INFORMS European Conference on Operational Research, July 1-4, Rome, Italy, p 47.
2. Yilmaz, G., Lusa, A., and Benedito, E., 2013. “Products Renewal and Long Term Capacity Planning”, The International IIE (Institute of Industrial Engineers) Conference (YAEM, 2013), June 26-28, Istanbul, Turkey, p108.

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Annex

Case 1: N=5, LN=12-15

Data number 65 is selected. The solution time is 24.47 seconds. The objective is 355677. The details of results are below.

Table A-0-1 Introduction time of product

| N | PT | LN | Introduction Time of Products | | | | |
|---|----|-------|-------------------------------|----|----|----|----|
| | | | 1 | 2 | 3 | 4 | 5 |
| 5 | 3 | 12-15 | 1 | 11 | 21 | 21 | 41 |

Table A-0-2 Acquisition and selling time of production technology

| Production Technology | Unit | Periods | |
|-----------------------|------|---------|------|
| | | Bought | Sold |
| 1 | 1 | 1 | 12 |
| 2 | 1 | 11 | 24 |
| 3 | 1 | 21 | 52 |
| 3 | 1 | 33 | 51 |
| 3 | 1 | 43 | 50 |

Table A-0-3 Periods in which warehouse capacity increases

| Warehouse | Periods |
|-----------|---------|
| 0 | 0 |
| 1 | - |
| 2 | - |

Table A-0-4 Periods in which cannibalization starts and finishes between products i and j

| Product i | Product j | Periods | |
|-----------|-----------|---------|--------|
| | | Start | Finish |
| 2 | 11 | 11 | 12 |
| 3 | 21 | 21 | 24 |
| 4 | 31 | 31 | 32 |
| 5 | 41 | 41 | 43 |

Case 2: N=5 LN=15-18

Data number 22 is selected. The solution time is 269.17 seconds. The objective is 325286. The details of results are below.

Table A-0-5 Introduction time of product

| N | PT | LN | Introduction Time of Products | | | | |
|---|----|-------|-------------------------------|----|----|----|----|
| | | | 1 | 2 | 3 | 4 | 5 |
| 5 | 3 | 15-18 | 1 | 11 | 21 | 21 | 41 |

Table A-0-6 Acquisition and selling time of production technology

| Production Technology | Unit | Periods | |
|-----------------------|------|---------|------|
| | | Bought | Sold |
| 1 | 1 | 1 | 16 |
| 2 | 1 | 11 | 27 |
| 3 | 1 | 21 | 56 |
| 3 | 1 | 34 | 54 |

Table A-0-7 Periods in which warehouse capacity increases

| Warehouse | Periods |
|-----------|---------|
| 0 | 0 |
| 1 | - |
| 2 | - |

Table A-0-8 Periods in which cannibalization starts and finishes between products i and j

| Product i | Product j | Periods | |
|-----------|-----------|---------|--------|
| | | Start | Finish |
| 1 | 2 | 11 | 16 |
| 2 | 3 | 21 | 27 |
| 3 | 4 | 31 | 37 |
| 4 | 5 | 41 | 46 |

Case 3: N=11 LN=12-15

Data number 79 is selected. The solution time is 420.04 seconds. The objective is 861641. The details of results are below.

Table A-0-9 Introduction time of product

| N | PT | LN | Introduction Time of Products | | | | | | | | | | |
|----|----|-------|-------------------------------|---|---|----|----|----|----|----|----|----|----|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 11 | 5 | 12-15 | 1 | 5 | 9 | 13 | 17 | 21 | 25 | 29 | 33 | 37 | 41 |

Table A-0-10 Acquisition and selling time of production technology

| Production Technology | Unit | Periods | |
|-----------------------|------|---------|------|
| | | Bought | Sold |
| 1 | 1 | 1 | 12 |
| 2 | 1 | 5 | 18 |
| 3 | 1 | 9 | 21 |
| 4 | 1 | 13 | 47 |
| 4 | 1 | 18 | 45 |
| 4 | 1 | 19 | 43 |
| 4 | 1 | 35 | 42 |
| 5 | 1 | 21 | 55 |
| 5 | 1 | 23 | 53 |
| 5 | 1 | 27 | 49 |
| 5 | 1 | 42 | 48 |
| 5 | 1 | 43 | 47 |

Table A-0-11 Periods in which warehouse capacity increases

| Warehouse | Periods |
|-----------|---------|
| 0 | 0 |
| 1 | - |
| 2 | - |

Table A-0-12 Periods in which cannibalization starts and finishes between products i and j

| Product i | Product j | Periods | |
|-----------|-----------|---------|--------|
| | | Start | Finish |
| 1 | 2 | 5 | 12 |
| 2 | 4 | 13 | 18 |
| 2 | 5 | 17 | 18 |
| 3 | 6 | 21 | 21 |
| 4 | 5 | 17 | 24 |
| 4 | 8 | - | - |
| 4 | 9 | - | - |
| 5 | 8 | - | - |
| 5 | 9 | - | - |
| 6 | 7 | 25 | 32 |
| 6 | 10 | - | - |
| 6 | 11 | - | - |
| 7 | 10 | 37 | 37 |
| 7 | 11 | - | - |
| 8 | 9 | 33 | 43 |
| 10 | 11 | 41 | 49 |

Case 4: N=11 LN=15-18

Data number 164 is selected. The objective is 773201 at the end of 7200 seconds. The details of results are below.

Table A-0-13 Introduction time of product

| N | PT | LN | Introduction Time of Products | | | | | | | | | | |
|----|----|-------|-------------------------------|---|---|----|----|----|----|----|----|----|----|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 11 | 5 | 15-18 | 1 | 5 | 9 | 15 | 17 | 22 | 25 | 29 | 33 | 37 | 41 |

Table A-0-14 Acquisition and selling time of production technology

| Production Technology | Unit | Periods | |
|-----------------------|------|---------|------|
| | | Bought | Sold |
| 1 | 1 | 1 | 15 |
| 2 | 1 | 5 | 20 |
| 3 | 1 | 9 | 23 |
| 4 | 1 | 15 | 50 |
| 4 | 1 | 19 | 48 |
| 4 | 1 | 34 | 46 |
| 4 | 1 | 36 | 44 |
| 5 | 1 | 22 | 57 |
| 5 | 1 | 27 | 55 |
| 5 | 1 | 39 | 54 |
| 5 | 1 | 43 | 52 |
| 5 | 1 | 44 | 51 |

Table A-0-15 Periods in which warehouse capacity increases

| Warehouse | Periods |
|-----------|---------|
| 0 | 0 |
| 1 | 30 |
| 2 | - |

Table A-0-16 Periods in which cannibalization starts and finishes between products i and j

| Product i | Product j | Periods | |
|-----------|-----------|---------|--------|
| | | Start | Finish |
| 1 | 2 | 5 | 15 |
| 2 | 4 | 15 | 20 |
| 2 | 5 | 17 | 19 |
| 3 | 6 | 22 | 23 |
| 4 | 5 | 17 | 28 |
| 4 | 8 | 29 | 32 |
| 4 | 9 | - | - |
| 5 | 8 | 29 | 31 |
| 5 | 9 | - | - |
| 6 | 7 | 25 | 36 |
| 6 | 10 | - | - |
| 6 | 11 | - | - |
| 7 | 10 | 37 | 42 |
| 7 | 11 | 41 | 42 |
| 8 | 9 | 33 | 46 |
| 10 | 11 | 41 | 53 |