A strategic decision making model on global capacity management for the manufacturing industry under market uncertainty

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A thesis submitted in partial fulfilment of the requirements of
Nottingham Trent University for the degree of Doctor of Philosophy

Nottingham Business School
Nottingham Trent University

March 2012

Abstract

Multi-national, large-scale and complex manufacturing systems, such as those for automotive manufacturers, often require a significant investment in production capacity, as well as great management efforts in strategic planning. Capacity-related investment decisions are often irreversible or prohibitively expensive and time-consuming to change once they are in place. Furthermore, such companies operate in uncertain business environments, which can significantly influence the optimal decisions and the systems' performance. Therefore, a strategic question is how to globally and interactively set production resources for such systems so their optimal performance can be achieved under business uncertainty. Conventional optimisation models in this field often suffer from one or more drawbacks, such as deterministic styles, non-inclusive and non-comprehensive decision terms, non-integrated frameworks, non-empirical approaches, small size practices, local/non-global approaches or difficult-to-use methods/presentations.

This research develops a new scenario-based multi-stage stochastic optimisation model, which is capable of designing and planning the production capacity for a multi-national complex manufacturing system over a long-term horizon, under demand and sales price uncertainty. Unlike many other stochastic models, this model can simultaneously optimise many strategic capacity-related decisions in an integrated framework, which helps to avoid sub-optimality. These decisions comprise capacity volume, location, relocation, merge, decomposition, product management, product-to-market decisions, product-to-plant planning, flexibility choices, etc. Furthermore, an enumerated scenario approach, which rightly fits real strategic decision making practices, has been employed in the model development. This model is also empirically designed for non-OR specialist users (managers), exploiting a programming technique and a more user-friendly input & output interface, which potentially makes the model more practical in real-scaled industrial applications.

The model's ability and its contribution to practice in real systems are demonstrated in two case studies from the automotive reference system, after a set of validations and verifications with fourteen hypothetical cases.

Finally, in a systematic analysis the models' features and abilities are compared with other newly developed analytical models and state-of-the-art researches in this field and the contribution to knowledge of this research is established.

Acknowledgements

First, I wish to express my most sincere appreciation to my first supervisor, Professor Baback Yazdani, whose endless and kind support made this research possible. Being Baback's student was an absolute privilege.
I am also grateful to my second supervisor, Dr Kostas Galanakis, who patiently and continuously provided me with his comments and assistance.

Great appreciation goes to Nottingham Business School (NBS) and the graduate office, for providing a fully-funded scholarship, all facilities and academic support. I am particularly grateful to Professor Paul Whysall, Professor Stephanie Walker and Professor Matt Henn, who were always available to help. I am also thankful to Ms Rachael Cincinski and Ms Kim Keirnan for their very kind administrative support. My gratitude should also be expressed to my dear colleagues in the 'Management Division' at NBS, who assisted me in my research, gave me teaching opportunities and finally helped me getting my academic job.

Furthermore, I would like to thank Dr Sophie Strecker for editing and proofreading this thesis, Dr Nima Rouhpour for all his moral support to start my PhD and all of my other friends who made my student life easier in Nottingham.

This journey would be impossible without the unwavering love and support of my parents, Morteza Sabet Ghadam and Shahla Nazari. Their pride and inspiration has given me the courage to pursue my dreams and to undertake my studies.
Finally, I would like to dedicate this work with all my heart to my lovely beautiful wife, Nahid, who has always been by my side for better for worse, for richer for poorer, in sickness and in health, to love and to cherish…

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Nomenclatures

AM: Agile Manufacturer

AMS: Advance Manufacturing System

BAU: Business As Usual

CKD: Complete Knock Down

CNC: Computer Numerical Control

DM: Decision making

DML: Dedicated Manufacturing Line

DMSS: Decision making Support System

DSS: Decision Support System

FMS: Flexible Manufacturing System

ICOM: Input, Output, Control, Mechanism approach

JLR: Jaguar Land Rover Company

MILP: Mixed Integer Linear Programming

MPC: Manufacturing Planning and Control

MSP: Multi-Stage Stochastic Programming

NBS: Nottingham Business School

NBS-DMM-CI: Nottingham Business School - Decision making Model – Capacity Investment

NPD: New Product Development

OM: Operation Management

OR: Operation Research

PESTEL: Political, Economic, Social, Technological, Environmental, Legal.

ROA: Real Option Analysis

ROI: Return on Investment

SB-SP: Scenario Based Stochastic Programming

SCN: Supply Chain Network

SP: Stochastic Programming

TMUK: Toyota Motors UK

TSP: Two-Stage Stochastic Programming

VAT: Value Added Tax

VMS: Value of Multi-stage Stochastic Programming over two-stage one

VSS: Value of Stochastic Solution over Deterministic one

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Chapter 1 : Introduction

The word 'strategy' comes from the Greek words 'stratos' (army) and 'agein' (leading), which, together, means 'army-leading'. It was originally used for military-related purposes. The meaning of strategy, as a war-related concept, was employed by Sun Tsu, the Chinese general who wrote “The Art of War” in around 500 BC. The ancient Roman philosopher, Seneca (4 BC to 65 AD), on the other hand, introduced strategy in non-military activities (Ambrosi 2010).

Nowadays, from a corporate perspective, strategy is “the direction and scope of an organization over a long term which achieves advantage in a changing environment through its configuration of resources and competences with the aim of fulfilling stakeholder expectations” (Johnson et al. 2008). In a different definition of the corporate strategy, Andrews (1980, pp. 18-19) believes it is “the pattern of decisions in a company that determines and reveals its objectives, purposes, or goals, produces the principal policies and plans for achieving those goals, and defines the range of business the company is to pursue, the kind of economic and human organization it is or intends to be, and the nature of the economic and non-economic contribution it intends to make to its shareholders, employees, customers, and communities" (Andrews 1997).

Johnson et al. (2008) believes strategies are likely to:

- Be complex in nature
- Be made in an uncertain environment
- Be faced with considerable changes by time, because of complexity and uncertainty
- Have impact on operational and tactical decisions
- Be considered in an integrated framework

All abovementioned characteristics of strategy will be considered in the frame development for this research as will be addressed later.

Strategic planning determines a long-term road-map of a company, while taking any market change into account (Verderame et al. 2010). Strategic planning, in other words, is employed by companies to increase their chance of being sustainable and profitable, and to make them adjustable to continuous change as well as self-organized. Strategic resource planning, as a part of the broader concept of strategic planning, aims to manage and plan the resources of the company in a way to maximise the stakeholders’ expectations. Many studies have addressed resource planning as the most important set of decisions in the manufacturing industries during the last 5 decades (Chen et al. 2002, Mohamed et al. 2001, Santoso et al. 2005, Hammami et al. 2009, Hammami et al. 2008, Nagar et al. 2008, Nagar et al. 2008, Nagar et al. 2008, Gimenez 2006, Fleischmann et al. 2006, Huang et al. 2009, Julka et al. 2007, Klibi et al. 2010).

Among the available resources for a large manufacturing organisation, many researchers believe production capacity is the most important one (Chen et al. 2002, Mohamed et al. 2001, Santoso et al. 2005, Hammami et al. 2009, Hammami et al. 2008, Nagar et al. 2008, Nagar et al. 2008, Nagar et al. 2008, Gimenez 2006, Fleischmann et al. 2006, Huang et al. 2009, Julka et al. 2007, Klibi et al.

2010). This is why this research will focus on a long-term production capacity management and planning model.

Both qualitative and quantitative methods have been employed to analyse strategic capacity planning (Julka 2008). But, due to the parametric nature of strategic capacity decisions, the quantitative approach has received more fortune in this field (Julka 2008, Pidd 2003).

Previous efforts on analytical capacity planning models have made significant contributions to decision making methods and have helped companies to better design and plan their resources (Meixell et al. 2005). Thanks to the significant progress in this field, firms have succeeded in improving their competitiveness by reducing the costs and/or production cycle time (Li et al. 2009).

1-1- Capacity Design and Planning

Capacity planning, by making a strong connection between the company's long-term goals and its mid-term actions, aims to ensure that the company has the right capacity to act within a complex structure (Ambrosi 2010). In general, a capacity plan should clarify how a company manages its capacity, comprising how much, where and when to invest or disinvest in capacity, and how to schedule it (Naraharisetti et al. 2010), as well as its type and technology (Hayes et al. 1984).

Production planning in the manufacturing industries is often categorised in 3 different stages, including 'short-term', 'mid-term' and 'long-term' planning (Olhager et al. 2001). These stages are also called 'scheduling problem', 'planning problem' and 'design problem' (Chopra et al. 2001), or operational, tactical and strategic planning (Ballou 1999). Direct users of these models are production coordinators for the operational models, sales or procurement managers for the tactical models (Sodhi et al. 2009), and finally senior managers and investors for the strategic models (Walsh 2005).

Syam (2000) categorised capacity planning in a purely strategic group. Many other researchers (Naraharisetti et al. 2010, Escudero et al. 1995), however, maintain that although capacity management is a strategic decision, it also has some overlaps with tactical considerations. The facility-related aspects such as type, size, volume and location are defined as strategic decisions (Escudero et al. 1995) and capacity allocation, distribution of the products, capacity replacement, and work force level are named as tactical aspects (Naraharisetti et al. 2010, Escudero et al. 1995).

Therefore, in a more comprehensive definition, capacity management can be defined as "how to best utilise the 'slow moving' resources for manufacturing operations" (Olhager et al. 2001) and "deciding the optimal timing and level of capacity acquisition and allocation" (Ahmed et al. 2003).

The important role of capacity planning for large multinational manufacturing firms, in which capital equipment costs are high and investment/disinvestment on capacity is a long-time practice, is highlighted by Wu et al. (2005). The electronic and semiconductor industry, the biotech industry or the automotive sector are good examples of such large manufacturing industries, with the abovementioned characteristics. Strategic decisions about the capacity in such industries are often quite expensive to change once they have been put into practice (Frausto-Hernandez et al. 2010).

Moreover, strategic capacity planning mostly behaves as an aggregated level, which deals with the forecasted demand of product families and key plants, rather than the forecasted demand of each individual product and production line, in order to provide a general managerial and strategic prospect for the company (Olhager et al. 2001).

Berry et al. (1982) described the relationship of capacity planning and other decisions of manufacturing planning and control (MPC) in general, which is depicted in figure 1-1. This figure shows how production planning, resource planning and capacity planning are connected and lead to the shop-floor operational activities (Berry et al. 1982).

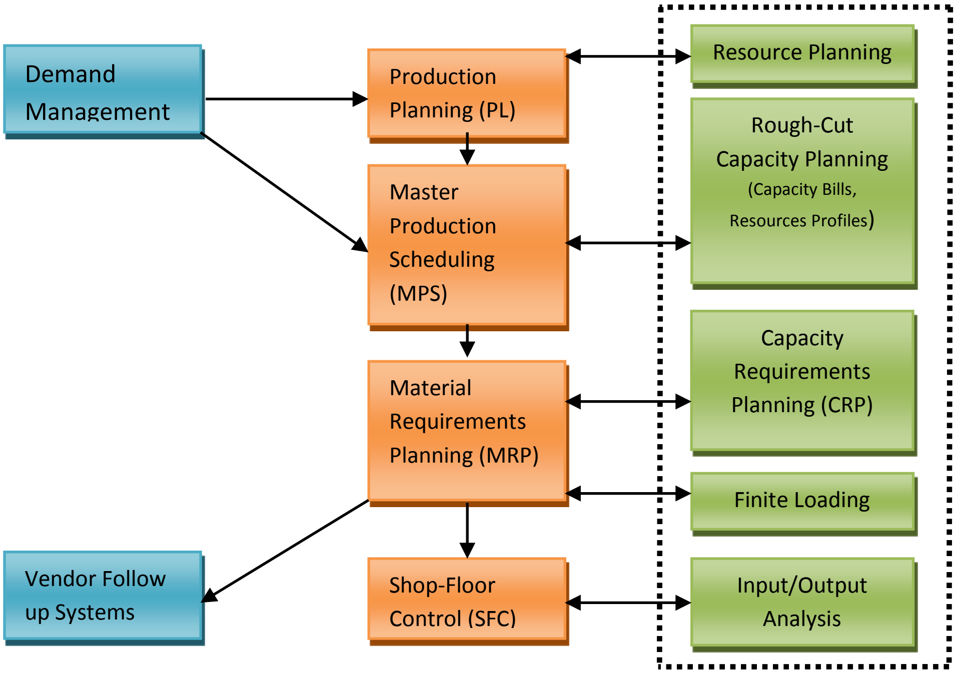
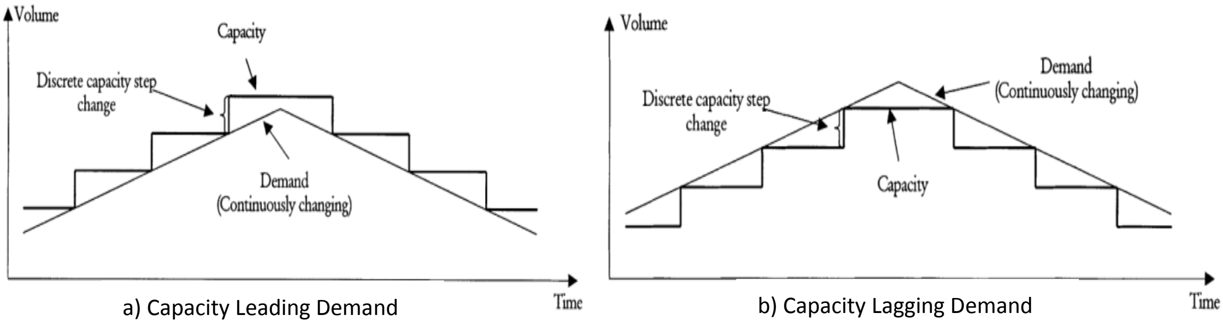


Figure 1-1: Relationship between strategic, tactical and operational levels in manufacturing planning
Source: (Berry et al. 1982)

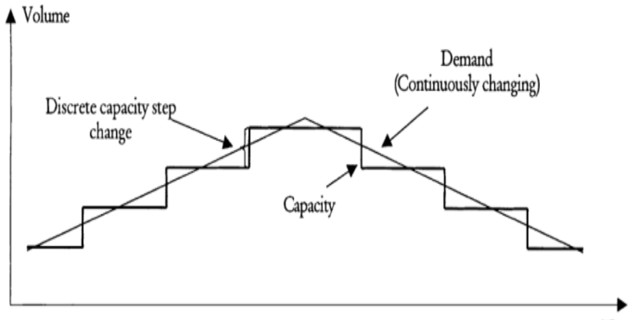
Demand forecast is the main input for any capacity planning model (Olhager et al. 2001). However, demand is an uncertain parameter, which is the most challenging issue in capacity planning problems (Peidro et al. 2009). Three different approaches have been highlighted for capacity planning in an uncertain business environment, which are lead, lag or track approaches (Olhager et al. 2001). These three approaches are illustrated in figure 1-2.

In the lead approach capacity comes first, before demand realisation, as opposed to the lag approach in which capacity adjustment happens after demand realisation. These decisions are also called here-and-now vs. wait-and-see, respectively (Nagar et al. 2008, Nagurney et al. 2005, Shapiro 2004). In practice, manufacturing companies mostly have to make capacity decisions fairly ahead of knowing the actual demand (Eppen et al. 1989) and afterwards, when the demand occurs, they adjust the level of capacity utilisation. Therefore, the track capacity planning approach, which is known as the switching approach to keep the minimum gap between capacity and demand (Olhager et al. 2001), has received more appreciation. In other words, the track strategy is applied on a rolling time horizon, and, consequently, is a more dynamic and effective strategy. This strategy is employed in this study to develop a multi-stage model, as will be discussed later in chapter 3 and 4.



a) Capacity Leading Demand

b) Capacity Lagging Demand



c) Capacity Tracking Demand

Figure 1-2: Demand / Capacity Strategies, Leading, Lagging and Tracking Strategies
Source: (Olhager et al. 2001).

Due to the lumpy nature of capacity and the fact that changing capacity is often quite expensive and time-consuming, the level of capacity and demand cannot always be matched. In other words, the demand-capacity gap reduction strategy is not always an efficient solution (Karnik et al. 2009). According to Eppen et al. (1989), a manufacturing company might have 3 different strategies against the demand-capacity gap. The company might plan its capacity and resources in a way to: 1- Satisfy all possible demand; 2- Satisfy most of the possible demand; or 3- Keep a high level of capacity utilisation and satisfy as much demand as it can (Eppen et al. 1989). Generally, selecting one of these strategies is based on a trade-off between profit from revenue and investment on capacity, considering market uncertainty as well as threats and opportunities. Therefore, depending on the current internal and external situation and the future prospect, one of these strategies should be chosen in a period of time. This decision is dynamic and may change for a different period of time or a different situation. A well-organised model can assist managers to better understand these trade-offs, which helps them in their capacity management decisions (Eppen et al. 1989). This, basically, highlights a need for an optimisation model to find the most feasible decision under uncertainty. The outline of such a model and its objectives and terms will be discussed in the next chapter. But before that, in the next section, the background of the study and the gaps in this field of research will be highlighted.

1-2- Background of the Study

This section will identify the gaps in this area of study, which then will be aimed to be closed by this research. A chronological overview of the previous work will be given in order to assess what the general approach as well as the development trend has been in this field. Furthermore it will be discussed how the gaps have been highlighted, addressed and closed. Lastly the questions left open will be identified.

Our study shows that after 2005 at least one review paper has been published each year in the field of resource management modelling, which shows this field is still a hot topic. Due to the fact that this section is aimed at finding current gaps which are yet to be filled, we do not go further back than 1995 in the discussion of review papers. From 2005 on, review papers are discussed on an annual basis, while earlier papers are categorised in one group, as explained below.

Before 2005: Geoffrion and Power (1995), in their extensive review paper, reviewed almost all of the first efforts starting from 1970 in the field of strategic distribution system design (Geoffrion et al. 1995). They observed that using optimisation methods to design strategic production-distribution systems has become feasible since the 1970's and developments have occurred at a rapid rate ever since. They categorised these developments in terms of six evolutionary processes among which they mentioned these four as the core: evolution of algorithms, data development tools, model features and, finally, software capabilities. They mentioned, however, that all of these terms should be improved for future works (Geoffrion et al. 1995).

Vidal and Goetschalckx (1997), in a critical and extensive review with emphasis on global resource planning and strategic production–distribution models, have pointed out that the main drawback in this field is the lack of employing a comprehensive range of uncertainties in current models. They also believed that the global Bill of Material (BOM), exchange rate, tax and duty were not fully applied in the current models, simultaneously. The lack of powerful solving algorithms, as well as comprehensive metrics to apply in the models is also highlighted by them as an important drawback. The lack of management awareness of substantial optimisation models is then counted as a main reason for insufficient utilisation of the models in the businesses (Vidal et al. 1997). Although international companies are increasingly exploiting decision making models, there is still a long way to go to persuade CEOs and top managers to pay more attention to numerical approaches. BMW, for example, used to employ Ms Excel ® for strategic load-planning just before 2005 (Fleischmann et al. 2006). The General Motors Company also used to employ spreadsheets and 'post-it' notes before 2001 (Inman et al. 2001).

Reviewing 28 leading journals, including those in the field of operations management, international businesses and general management over the years of 1986 to 1997, Prasad and Babbar (2000) made a wide-ranging extensive literature review on strategic international operations management.

One of the very important drawbacks they identified was the need for more practical models to help managers in real businesses (Prasad et al. 2000).

In their paper on plant location and flexible technology acquisition, Verter and Dasci (2002) had a quick review of new capacity investment and technology selection. They mentioned a need to develop models for selecting technology and the level of process and product flexibility (Verter et al. 2002). Several models on technology selection for new capacities, however, were developed later to address the gap (Chen et al. 2002, Gimenez 2006, Farooq 2007).

Strategic capacity management and its mutual connection with determining size, type, and timing of capacity investment under uncertainty has been reviewed in detail by Van Mieghem (2003). He also discussed risk aversion models as well as multi-objective decision making models, which had been developed in this area by his time. He highlighted major concerns of resource management comprising capacity location, capacity expansion, equipment replacement, technology management, new product development, operation strategies, aggregation planning, inventory and safety stock management, investment level and corporate finance. Van Mieghem (2003) maintained that capacity expansion studies focus on determining the size, timing, and location of new capacity, but are typically restricted to capacity expansion of one resource and cost minimisation, assuming that capacity is infinitely durable (no depreciation or replacement). Moreover, he also maintained that literature on equipment replacement puts the emphasis on replacing facilities, while it mainly fails to implement demand changes or scale economies. In other words, while technology management and new product development models deal with choice of technology, production planning is aimed at allocating products to limited resources in order to satisfy the demand. With this argument, he emphasised the need to develop more comprehensive models, which are able to apply all these terms in a unique framework (Van Mieghem 2003). He also explored how demand uncertainty in the models he reviewed was managed only by the chase demand technique (excess/safety capacity) or level production method (excess/safety inventory) after a sensitivity analysis. He argued, however, that these methods are not comprehensive enough for managing uncertainty in capacity planning. He suggested that the stochastic approach in capacity modelling rather enhances the brightness on the direct effect of uncertainty.

2005: A valuable critique on global resource management and supply chain design has been carried out by Meixell and Gargeya (2005). In their paper the decision-support models of global resource planning are criticised and the gap between the academic literature and pragmatic approaches are highlighted. Other gaps addressed by them are: (i) multi-objectivity, (ii) considering the supply chain network as a whole in the modelling practice, (iii) limited beneficiaries such as the automotive, computer and electronic industries and finally (iv) gaps in performance metrics (Meixell et al. 2005).

2006: Snyder (2006) reviewed papers on facility location under uncertainty. He went over stochastic and robust location models and illustrated a large variety of approaches for optimisation under uncertainty. On stochastic location problems he reviewed papers from the 1960's to 2004. He believed, by the time he wrote the paper, that the subject of multi-echelon facility location was quite new and very few studies had been published in the stochastic framework. Furthermore he found no publication in the robust frame (risk-avert). Finally he observed that relatively few academic models had found their way into real world applications. The cumbersome data requirements of stochastic models, which often require an estimation of many parameters over a range of hypothetical scenarios, is mentioned by him for this lack of empirical application. Robust optimisation, however, is emphasised by him as a data burden reduction procedure. Robust optimisation hedges against a set of scenarios the probabilities of which do not need to be known explicitly. In the end, Snyder (2006) revealed 4 gaps to be closed by future researchers: (i) Exact algorithm for 'minimax problems'; (ii) Multi-echelon models (iii) Stochastic programming: he maintained stochastic optimisation had just begun to be used in facility location modelling. Therefore, there was great potential for solving complex and realistic problems. (iv) Meta-heuristic approach for general problems: this approach had been successfully applied for deterministic location problems, but very few attempts had been carried out to adapt it to the stochastic and robust counterparts (Snyder 2006).

2007: In an extensive literature review, Julka et al. (2007) studied the current gaps in capacity management in the manufacturing industries. They highlighted a comprehensive set of factors which had been employed in several papers in this field. Then they highlighted the terms that should be addressed in a holistic model in the capacity management subject, and, in particular, for capacity expansion models. They chose 11 key papers in this field and analysed them very deeply. They subsequently revealed that the lack of a comprehensive multi-factor model is the major shortcoming of the current efforts in capacity management modelling. They also claimed that accounting policy, investment budgets, holding cost of current capacity, capacity replacement and depreciation costs were not considered by most authors (Julka et al. 2007). They finally pointed out the absence of industrial case studies, despite citing a few models existing in practice.

2008: The delocalization context of resource design has been reviewed by Hammami et al. (2008). They determined the terms and detailed characteristics of objectives, cost factors and constraints, which must be considered in a successful model of global supply chain design. Then they did a classification of precedent literature with regard to these features. They concluded that none of the previous models was comprehensive and strong enough to support resource-design delocalization decisions in the real manufacturing world (Hammami et al. 2008).

Baron et al. (2008), in their review paper on facility location under an uncertain environment, focused on methods and techniques, including stochastic programming, robust modelling and risk aversion optimisation. They concluded that more efforts should be made for the relaxation techniques and solution algorithms in the stochastic approach (Baron et al. 2008).

2009: Melo et al. (2009), in their review paper on resource management, focused on the more recent publications on location/allocation decision and reviewed around 120 of these, maintaining that this topic was becoming increasingly interesting for researchers. They believed that current facility location models were far away from approaching the realistic problems in strategic resource planning and should therefore be improved. They reported that more than 90% of the recent papers focused on the single-objective optimisation models and among them 75% were aimed at determining the network configuration to minimise the total cost. In contrast, profit maximisation, which they believed is the main aim of any business activity, had been aimed at for just 16% of the efforts. Other objectives, which had received more attention, after cost-related factors, were the time-related objectives to minimise the cycle time, delivery time, fill rate and service time (Melo et al. 2009).

Farahani et al. (2009), in the most comprehensive review papers in the field of capacity location, reviewed more than 140 papers. Similar to Melo Et al. (2009), they also believe that the topic of strategic decision making in resource planning and capacity location, although was not a new subject, was still a hot research area, especially in the recent years. In their conclusion, they came up with the following suggestions for further works in capacity location problems: 1- Reliability: considering objective functions that somehow guarantee reliability 2- Stochastic Methods and Robustness: similar to many other researchers, Faraharni et al. (2009) suggest employing stochastic and robust models to apply uncertainty and risk. 3- Sustainability: In the contemporary business atmosphere, a business should also focus on social, environmental and other sustainability-related features. 4- Game Theory: considering the game theory as a powerful method in capacity location investigation is also suggested by them. 5- Network Design: Supply chain network design, logistic network design and the capacity location decision are major strategic issues and should be employed in an integrated and unique model framework.

2010: Klibi et al. (2010), in their review paper on resource planning and strategic supply chain network (SCN) design, have highlighted: 1- Risk analysis: For resource planning purposes, the random variables and risk sources must be reduced to a manageable number. 2- Scenario Development and Sampling: An “importance” -based sampling approach must be developed to ensure that all important plausible future aspects are covered in the small sample of scenarios selected. 3- Value-based SCN design models: Most of the current studies focus on minimising costs; however, to increase the competitiveness of a company, the objective should be a sustainable value creation. In this way, not only can the competitive level of a company be compared, but also all the expenses over the project horizon can be estimated. 4- Modelling for robustness: They maintained that resource planning models should consider some representatives of the plausible future scenarios, and then implement them in the final decision by using a stochastic programming approach and/or robust optimisation. 5- Solution methods: Although nowadays almost all deterministic models can be easily solved with current commercial solvers, very few efficient heuristic methods have been developed to solve multi-stage stochastic problems (Klibi et al. 2010).

Kumar et al (2010), in a literature review on resource and SCN design management and planning, mentioned that simulation-based optimisation methodology, as well as optimisation under uncertainty, should be aimed at for future works in the resource planning area (Kumar et al. 2010).

Verderame et al. (2010), in their review on planning and scheduling under uncertainty, investigate several sectors, including the manufacturing and service industries, to find the current gaps in this field (Verderame et al. 2010). They revealed that the models' objectives and constraints vary from sector to sector; however, all of them share a common need for models with the ability to handle uncertainty and risk in an explicit manner. In terms of methodology, they also addressed some of the more common techniques to approach uncertainty, including stochastic programming, parametric programming, chance constraint programming, fuzzy programming and robust optimisation techniques (Verderame et al. 2010).

2011: In one of the most recent papers, Tenhiala (2011) maintains that there is still work to be done in the capacity planning research area, although it seems a mature topic (Tenhiälä 2011). He also emphasises the absence of a strong link between the academic models and practical applications. Like many other researchers (Wiers 1997, McKay et al. 2002, Jonsson et al. 2003, Kempf et al. 2011b), Tenhiala supports the idea that it is not always the most sophisticated models that are the most effective ones. By surveying data from the machinery manufacturers, he concludes that a model with a balanced practical approach and a modelling simplicity would stand a better chance to be employed by the decision makers in the manufacturing industries (Tenhiälä 2011).

Section Summary: A summary of the future work to be done in this field, as identified by the previous reviewers, can be captured by the following six general aspects:

1. *Uncertainty & Risk*: the majority of previous reviewers believed that market uncertainty should be applied in the future models to simulate the dynamic nature of the business environment. Many of these researchers referred to the stochastic programming technique as the most powerful approach for this application.
2. *Multi-factors*: Multi-Stage, multi-periods, multi-echelon, multi-layer, multi-products were also addressed by few previous researchers for future works. A need for a comprehensive set of factors to be applied in an inclusive model is also highlighted as an essential must for the future.

3. *Pragmatic approach*: A more practical approach to the modelling, including the consideration of the real manufacturing industries and their objectives as well as validation with real-scale data are emphasised by many reviewers.
4. *Integrated approach*: Developing an integrated decision making model which is able to design more resources in a unique framework is emphasised by some of the reviewers, in order to avoid sub-optimal solutions. The implication of the strategic decisions on tactical ones should be reflected in the modelling procedure.
5. *Objective*: Single objective modelling is also reported as one of the drawbacks of the previous models by some authors. Apart from the cost term, which has been the dominant objective for the optimisation models in the resource management field, other objectives which are cited are: total profit, NPV or other value based objectives, time-related objectives, responsibility, customer satisfaction, and reliability.
6. *Methodology and techniques*: New methods, such as the game theory as well as more effective solution algorithms for stochastic optimisation models, are highlighted to be developed to make the future complex models more solvable.

1-3- The Scope of This Study

This project seeks to develop a strategic decision making tool for long-term capacity design and planning for the manufacturing industries under business uncertainty, with a pragmatic approach. This PhD, however, is not aimed at contributing to solution algorithms and techniques. Therefore, all abovementioned future works to be done, except for the last one, are within the scope of this research.

The pragmatic strategic terms, which have to be employed in an integrated capacity design and planning model, are introduced in chapter 2 and will then be applied in the model development in chapter 4. These terms comprise: 1- Capacity level change: both capacity increase and decrease decisions for all scopes of long-, mid- and short -term, considering lead time and budget planning; 2- Capacity location/relocation and merge/decomposition: considering changes in transportation costs, supply costs, labour costs, maintenance costs, tax, custom duty, inflation, etc.; 3- Product and process flexibility: both costs and lead time of developing a new product or launching a production in a new line; 4- Load-planning: including product-to-market and product-to-plant decisions.

Although in this research the first series of validations will be done with hypothetical scenarios, two industrial case-studies with publicly released data from the automotive industry are also carried out, and reported in chapter 5. Since the scope of this research is capacity planning and management, other resources such as supply chain are beyond it. However, to avoid the unrealistic simplification of ignoring supply chain design, the effect of capacity location and inflation rates on the supply cost will be applied to the model.

1-4- Aims and Objectives

The aim of this project is to develop a strategic optimisation model for capacity design and planning in the manufacturing industry, under market uncertainty. This model is designed to cover the following objectives:

1- *Pragmatic and comprehensive approach:* A comprehensive collection of practical terms and features of capacity management and planning are *simultaneously* applied in the model.

2- *Global approach:* The model should be able to globally design and plan the facilities. The location, relocation, merge and decomposition considerations should be employed in the modelling procedure, as well as the financial terms of each region (custom duty, VAT, profit tax and inflation rates)

3- *Stochastic approach:* market uncertainty, with the two main uncertain sources of demand uncertainty and sale price uncertainty, is applied in the model.

1-5- Research Road-map and Thesis Outline

Figure 1-3, which is adopted and modified from the work by Giblert et al. (1999), depicts a road-map for this research. With reference to this figure, first a 'reference system' should be studied to draw a set of simplified, but most important, pragmatic, comprehensive and integrated terms for model development, as well as a set of criteria for results validation and verification. When the model is built on this basis, according to figure 1-3, the next step is to encode the logic and develop the 'model programming'. This 'model programming' step provides a foundation for the input of data into the model, the execution of the model and the generation of output results to analyse. These results, if verified, validated and genuine, are then publishable to generate knowledge.

This research is structured as follows: In chapter 2, the outline for a successful capacity management model will be discussed, followed by terms and factors which should be applied in a pragmatic and comprehensive strategic capacity design and planning model. Subsequently, in chapter 3, different methodologies and methods are explained and evaluated in order to assess which one is appropriate/desirable for the project. In chapter 4, based on the findings from chapters 1, 2 and 3, a new stochastic model as well as a programming approach will be established.

The concept of the open-box validation will be employed in developing the model in chapter 4. In chapter 5, a series of black-box validation with simplified cases (hypothetical data) will be organised to find the level of consistency for the model. Further in chapter 5 two real cases from the automotive 'reference system' will be analysed for the real-scale evaluation. Then in the discussion chapter, the validation criteria, which were suggested by Khazanchi (1996), will be recalled and discussed to establish the contribution of this study to the current state of knowledge in this field of research.

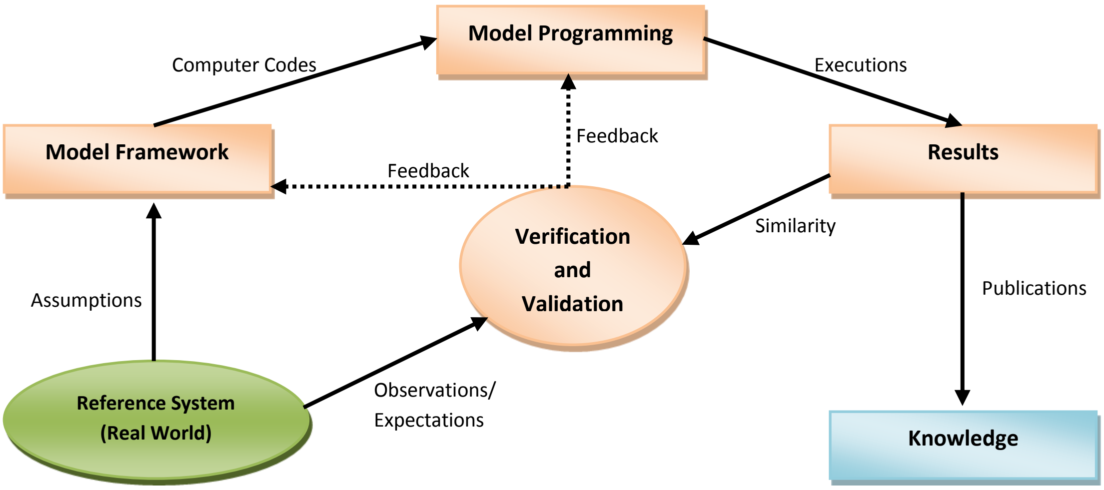


Figure 1-3: Methodology Proposition for quantitative modelling. This graph shows the methodology road-map for this research, including the concept, phases and mechanisms.

Source: adapted and revised from (Gilbert et al. 1999).

Chapter 2 : Capacity Management in the Large Manufacturing Industries

This chapter aims to identify: 1-an integrated outline for a successful capacity management model; and 2- the terms and factors that constitute such a model.

2-1- Capacity: Type and Measurement

The "maximum level of value-added activity over a period of time" is defined as *Capacity* (Julka et al. 2007). In other words, the number of product units which a resource (plant) is able to produce in a unit of time is named as the capacity of that resource (Buffa 1983). In a more comprehensive definition, capacity is a set of any possible kind of resources that can be used by a company to produce a product, or provide a service to its customer(s) in order to create value (Matta et al. 2005). Manufacturing capacity, in particular, is defined as a set of equipment and human resources that a company exploits to produce goods to sell. Three dimensions of type, amount and cost are mentioned for manufacturing capacity (Matta et al. 2005).

Manufacturing capacity can be measured in different ways, depending on the nature of the products which are being produced in the plant(s), including weight (e.g. tons of steel produced per year), length (e.g. kilometres of string produced per month), area (e.g. thousands of square meters of steel sheets produced per year) or volume (e.g. thousands of litres of acid produced per year). However, when production is more or less uniform, capacity may be measured in unit per time. Once the products are approximately the same, but with a slight difference in the characteristics (size, length, weight, volume, etc.), a measure in units typically refers to the average unit (Elmaghraby 2011).

For each plant, production line or a single machine in a production line, four different types of capacity can be measured (Elmaghraby 2011):

- *The Nominal Capacity*: This is the highest possible production capacity of the plant/production line/machine for a "standard" product/activity, under the best of circumstances. To estimate the nominal capacity, all supporting facilities such as work force, maintenance, required material, tools, utilities, logistics, storage, etc. are assumed to be ready with no limitation. Nominal capacity is also referred to as 'maximum' or 'theoretical' capacity.
- *The Operational Capacity*: This is the amount of capacity that comes from subtracting the *anticipated* and *unavoidable* losses in productivity from the *Nominal capacity.* These expected items include the productivity reduction due to depreciation, maintenance and overhauls, setting times resulting from product-mixes, the standard scrap rates, etc. However, supporting facilities which are mentioned for the nominal capacity, are still supposed to be prepared. This capacity is also referred to as '*realisable*' or '*disposable*' capacity. Although the nominal capacity is estimated for an average or a standard product, the operational capacity is measured for the product-mixes. Therefore, the nominal capacity is a single number but the operational capacity may change for different product-mixes.
- *The Planned Capacity Utilisation:* This is a proportion of the operational capacity, which is planned to be utilised over a period of time. It may be less than the operational capacity, mostly

due to lack of demand. It might also be more than the operational capacity, due to excess demand. These situations are called ‘under-planning’ and ‘over-planning’ or ‘underutilisation’ and ‘overutilisation’, respectively.

- *The Actual Utilised Capacity*: This is the actual utilisation which happens in practice and which is measurable after production realisation. Even in the best-case scenario with a very accurate forecasting, the planned capacity is not completely matched with the actual utilised capacity and a deviation is expected.

However, it is not always easy to measure these capacities. Six reasons are mentioned for why capacity measurement and planning is a complex task (Elmaghraby 2011):

- *The problem of product-mix*: The most prevalent reason mentioned for the inability to exact capacity measurement is the fact that the capacity rate depends on the product-mixes. The capacity amount of a production line or plant is defined by the capacity rate of the bottleneck operation of that production-line/plant for that particular product-mix. The bottleneck, however, often changes by changing the product-mix. Therefore the capacity of the whole plant changes from one product-mix to another.

- *The problem of the setup time*: changing a product-mix causes a *non-measurable* loss in productivity due to the setup time of the equipment for the new product(s). Training time for the staff to produce the new product(s) is also added to the setup time problem.

- *The problem of varying efficiency*: Production efficiency of each product-mix changes *non-measurably* (often improves) over time once production starts. It usually happens due to learning processes and continuous improvement. Therefore, it is not possible to accurately measure the capacity of a plant for different product-mixes in a rolling time horizon.

- *The problem of Scrap/Dropout*: In the most productions, scrap rates vary from one product to another and would change by a product-mix portfolio. The scrap rate, however, changes (often decreases) over time, due to learning and improvement procedures.

- *The problem of semi-finished items or subassemblies*: Sometimes having subassemblies, semi-finished products or subcontracting parts, ready in line, causes a high rate of output, which can be more than the nominal capacity of a plant or the nominal capacity of the plant’s bottleneck. It makes capacity estimation even more complex.

- *Some sociological, cultural, economic factors*: Although all abovementioned factors are technical, in many occasions the factors that make the capacity measurement more complex or impossible are not technical, but sociological and cultural, such as hiding the right data from the managers by employees to avoid problems, or to receive a bonus.

Apart from sociological factors which are beyond the scope of this research, factors such as product-mix complexity, variable setup time and varying efficiency for different products would be considered in the capacity planning procedure in this research. The scrap rate problem, which is an operational and short-term problem, is ignored in a strategic planning with a one-year time interval.

2-2- An Outlook on Capacity Management Models

2-2-1- Different Approaches to Capacity Management: Qualitative or Quantitative?

A comprehensive review of early papers on the capacity management problem has been presented by Luss (1982). He maintained that, although most of the studies before the 1950's were focused on the qualitative methods, due to the progress in modelling knowledge and computation abilities, more and more quantitative models have been proposed since then (Luss 1982). According to Bazeley (2004), who described both quantitative and qualitative techniques for capacity planning, qualitative methods are based on structured/unstructured textual information, with an exploratory type of investigation, and interpretive analysis. Quantitative methods, on the other hand, are based on numerical data with a confirmatory investigation and analytical/statistical analysis (Bazeley 2004). Although both qualitative (Ambrosi 2010) and quantitative (Klibi et al. 2010) methods are applied to carry out strategic resource planning for the manufacturing industries, quantitative approaches have received more appreciation in this area (Julka 2008, Pidd 2003). Van Miegham (2003), in his extensive review paper, "Capacity management, investment and hedging: Review and recent development", highlighted the quantitative approach (optimisation linear programming) as a strong answer and a dominant approach to capacity management problems. Julka (2008) believes that this prosperity is because of the parametric nature of the capacity management problem. In other words, all of the objectives and most of the constraints in capacity management and planning problems are quite straightforward and parametric, which make this sort of problems desirable for quantitative studies. Quantitative research on production planning goes back at least 50 years (Kempf et al. 2011a) and as Ahmed et al (2003) have observed; quantitative capacity planning models under uncertainty have been the subject of research since the 1960's. Still one of the major challenges in capacity planning problems is developing large-scale multi-period optimisation models (Frausto-Hernandez et al. 2010). As Inman et al. (2001) believe there is no other way for capacity design and planning than optimisation approaches. Avoiding optimisation modelling and computer programming makes the problem of finding an optimal or feasible allocation planning almost impossible (Inman et al. 2001).

Quantitative models for capacity design and planning have been studied in several industries, such as the automotive industry (Bihlmaier et al. 2010, Bihlmaier et al. 2010, Kauder et al. 2009, Kauder et al. 2009, Fleischmann et al. 2006, Fleischmann et al. 2006, Chandra et al. 2005, Mula et al. 2005), electronic goods and semiconductors (Geng et al. 2009b, Lin et al. 2010), food processing and pharmaceutical industries (Caro et al. 2009), chemical industries (You et al. 2009, Frausto-Hernandez et al. 2010), the petrochemical industry (LI et al. 2008), the agri-food industry (Ahumada et al. 2009) as well as other sectors, including communication networks, electric utilities and service industries (Ahmed et al. 2003). However, this field of research is still a hot topic and many researchers in the 2000's emphasised the need for developing quantitative decision making/support tools (Van Mieghem 2003, Naraharisetti et al. 2008, Verderame et al. 2010, Hammami et al. 2008, Julka et al. 2007, Klibi et al. 2010, Meixell et al. 2005, Prasad et al. 2000, Verter et al. 2002, Snyder 2006, Melo et al. 2009, Kumar et al. 2010, Tenhiälä 2011, Timpe et al. 2000, Lasschuit et al. 2004, Holland et al. 2005).

In chapter 3, applied quantitative methods in the capacity management subject will be discussed in detail to identify the right method for this research.

2-2-2- The Modelling Objective: Net Present Value under Uncertainty

Although some researchers believe that the final aim of the capacity planning process is to minimise the total costs (Karnik et al. 2009), the net present value (NPV) offers an adequate objective for the strategic network design problem, because it reflects both an 'efficiency principle' and 'temporary advantages' (Bihlmaier et al. 2010). In strategic capacity design and management, which involves investing a large amount of money in adjusting capacity and launching products in a long term planning horizon, the net present value (NPV) is the most appropriate objective (Fleischmann et al. 2006). Distribution of the net present value in each year provides a general feature of the risk involved in the project for the decision makers (Gatica et al. 2003).

To calculate the NPV, having an annual-based revenue and cost is not sufficient and a discount rate is also required (Bagajewicz 2008). Generally, the objective formulation of the models, which maximises the NPV of the company over a time horizon, is presented in the format below (Naraharisetti et al. 2010, Frausto-Hernandez et al. 2010, Lin et al. 2010):

$$Max\sum_{t=0}^{T}\left(1+\rho\right)^{-t}.[\mathrm{Re}v_t-(Oper_t+Inv_t)]$$

In this formulation *T* is the last year of the time horizon, ρ is the discount rate, which is the nominal rate of return for the company, Rev_t is the annual revenue of the company in year t, which comes from the total annual sales, Opr_t and Inv_t are the annual operation and investment costs of the company in year t, respectively.

The internal interest rate of the company and the inflation rates where the company is located should be known in order to calculate the discounted values of each cost and revenue to find the

NPV in a long-term horizon (Papageorgiou et al. 2001). In the more advanced capital budgeting models, to diminish the possible financial risks, the discount rate may be considered higher than the nominal rate of the company’s return (Eppen et al. 1989). For example, Dal-Mas et Al. (2011), in their strategic investment planning on capacity design for the chemical industry, have applied 15% as the minimum rate of return, which was considerably more than the standard risk free rate of 8%, which is a common rate in the investment decision models (Dal-Mas et al. 2011).

However, as uncertainty is an inevitable part of strategic management, the traditional approach to the investment feasibility study with a static NPV suffers from three main shortcomings: 1- uncertain nature of the strategic decisions (Dangl 1999); 2- NPV cannot implement flexibility inherent in the investment decision making process (Mittal 2004, Bowman et al. 2001); 3- The optimum time portfolio for an investment to cope with the demand changes (Dangl 1999). Therefore, the NPV of a company under uncertainty should be employed in an integrated capacity management model. This technique has been employed in many strategic capacity management models in the manufacturing industries (Bihlmaier et al. 2010, Bihlmaier et al. 2010, Dal-Mas et al. 2011, Kauder et al. 2009, Geng et al. 2009b, Chandra et al. 2005, Lin et al. 2010, Gatica et al. 2003, Papageorgiou et al. 2001, Colvin et al. 2009).

Therefore, the NPV under uncertainty will be aimed at as the modelling objective in chapter 4. In chapter 3 the implementation methods will be discussed.

2-2-3- The Framework of a Capacity Management Model: Input, Output, Control and Mechanism

In this section a modelling approach, which has been employed for capacity planning in different stages by Matta et al. (2005), will be introduced. This framework will be modified and employed in chapter 4 in order to develop the model's outline and in chapter 5 for the validation/verification plan. This framework employs a simple concept, which says that any capacity model can be explained by an input-output-control-mechanism (ICOM) procedure. In other words, whatever methodology and techniques have been used in the model development practice, the model's performance can be explained by ICOM terms.

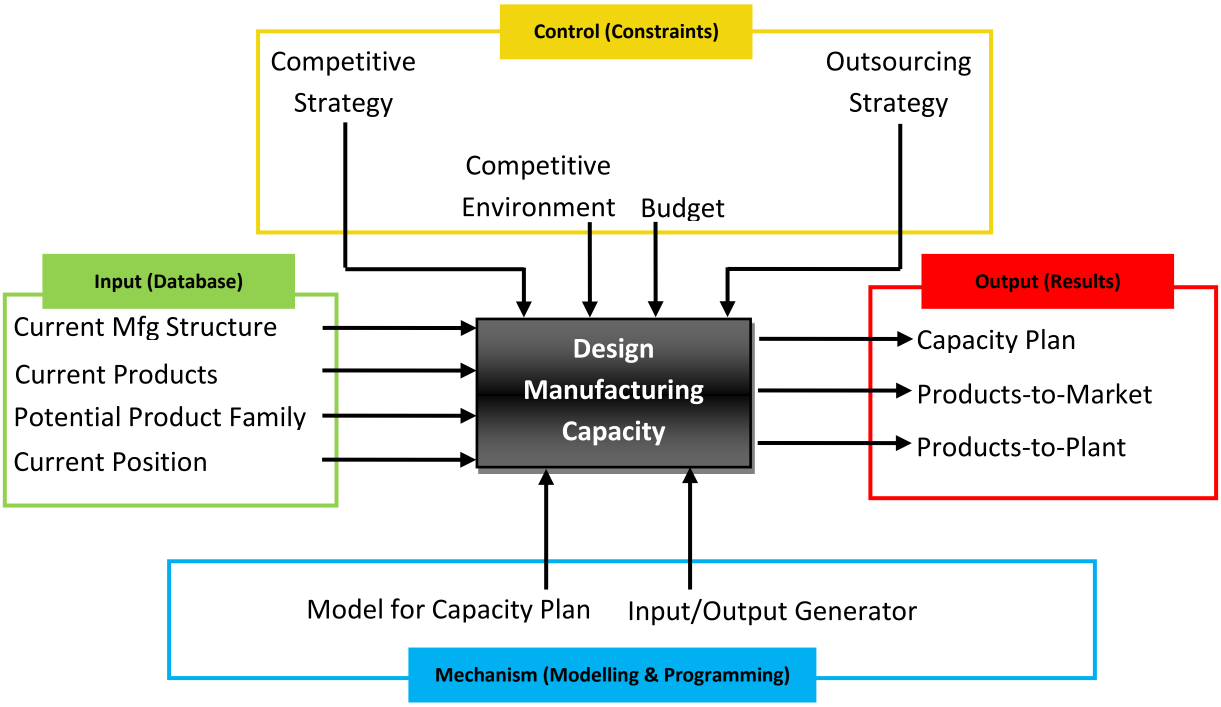


Figure 2-1: ***ICOM analysis of a strategic capacity planning model***

Source: Adapted from work by Matta et al. (2005)

This flow chart shows that the model inputs comprise the current position of the company in the market, the current and potential future products, and finally the current manufacturing structure (Matta et al. 2005).

The controlling factors (constraints) on the model are (Chakravarty 2005, Matta et al. 2005):

- Competitive strategy. It is, in fact, the corporate strategy of the company, including marketing strategy, operations strategy, human resource strategy, etc. This information is required in order to plan the capital investments.
- Competitive environment. The main exogenous factors that might affect the future market and activity of the company should be reflected as environmental/external constraints.

- Budget. Most often companies have a long-term maximum investment budget profile for investment. This constraint should be applied in the modelling practice, even as a rough estimate.

- Outsourcing Strategy, including supply policy, logistics and transportation strategy, etc.

Having these inputs and constraints for the model, the following outputs are expected to achieve from the model on a strategic level (Chakravarty 2005, Matta et al. 2005):

- A Capacity Design Plan. The decisional process leads to a long-term investment plan on the capacity, including how much, when and where to invest as well as volume, type and technology of each plant/production line.

- Product-to-Market plan: Selecting product-mixes for each market region on the planning horizon.

- Product-to-Plant plan: A strategic load-planning for current and future products in the current and future production lines. It also includes decisions about the new product development activities, which break down into R&D and new product launch phases.

In order to have these outputs from the abovementioned inputs and constraints, the following mechanisms should be developed (Matta et al. 2005):

- Decision models: A suitable quantitative method for decision making support system (DMSS)

- An input/output generator: A user-friendly and practical method of collecting data and generating results.

But how does this procedure work, how do the data transfer and how do the results generate in this flow chart? In other words, ‘what is the mechanism and logic behind this flow chart?’ The ‘black box’ in this chart is a programmed logic that simulates a simplified but realistic part of a ‘real world’ to solve and suggest the best solution to the managers, in order to facilitate the decision making procedure. Hence, this ‘black box’ formulates the logic, using the technique provided by the ‘blue box’, constraints from the ‘yellow box’ and inputs from the ‘green box’ to solve the problem and release the results in the ‘red box’.

In the next section of this chapter, the strategic and essential terms and the realistic constraints that should be considered in the ‘black box’ and ‘yellow box’ will be explained. Chapter 3, subsequently, identifies the general features of the ‘blue box’, including the right mechanism for modelling, programming and data processing.

2-3- Strategic Factors in Capacity Management

The majority of factors and parameters that have been applied in the capacity management models for the manufacturing industry are studied by Julka et al. (2007) in detail. They conducted research to find a holistic decision aid in this area of study (Julka et al. 2007).

Reviewing previous studies, some strategic terms, which should be applied in a comprehensive and integrated capacity design and planning model for the manufacturing industry, are identified. These main terms include volume, location and timing of investment/disinvestment in capacity (Chakravarty 2005, Matta et al. 2005), type, technology and flexibility of the capacity (Fleischmann et al. 2006), product management and NPD (Papageorgiou et al. 2001). These strategic terms and constraints will be discussed in detail in this section to identify the essential characteristics of a successful capacity management and planning model.

2-3-1- Managing Uncertainty

"The only certainty is that what we plan will not be what we manufacture" (Hood et al. 2003). Capacity planning should be done on a long-term (10-20 years) horizon (Eppen et al. 1989). For such a long-term scope, uncertainty is an inevitable part of the problem's nature (Johnson et al. 2008) and should be applied in any strategic capacity planning (Ahmed et al. 2003). Production planning under uncertainty is emphasised as one of the principal aspects of a plant-wide optimisation (LI et al. 2008, Mula et al. 2006, Sahinidis 2004). In strategic capacity planning, having a sustainable capacity management plan, which helps a company to survive in a volatile market, is more important than having good decision makers who can adapt their company to the new situations, and re-plan the capacity (Karnik et al. 2009). Re-planning the capacity in the strategic scope is quite expensive (Frausto-Hernandez et al. 2010) and time-consuming (Matta et al. 2005).

A clear distinction between risk and uncertainty is not universally accepted (Klibi et al. 2010) but one of the supported definitions is: in risk situations, there are uncertain parameters, the values of which are governed by probability distribution, which are known to the decision makers (Snyder 2006). Uncertainty, on the other hand, describes situations where the parameters are uncertain and it is not possible to attribute a distinct probability distribution to them (Rosenhead et al. 1972). In simple words, the difference between the required information for performing a task and the acquired information defines the level of uncertainty.

Considering the manufacturing industries, there are many sources of uncertainty that affect production processes (Mula et al. 2006). These sources of uncertainty are generally categorised into two groups: (i) environmental/external uncertainty and (ii) system/internal uncertainty (Ho 1989); or in other words: exogenous and endogenous uncertainty (Colvin et al. 2009). The environmental/external uncertainty includes types of uncertainty which are beyond the company's scope, such as demand uncertainty and supply uncertainty, freight rate changes, exchange rate fluctuations, tariff or tax changes, etc. The system/internal uncertainty, on the other hand, is about uncertainty within the production process, including production lead time uncertainty, operation yield uncertainty, quality uncertainty, failure of production line uncertainty, changes to product design, etc. (Mula et al. 2006). Three sources of uncertainty, which are uncertainty in demand, uncertainty in external supply and uncertainty in internal process, are generally accepted as the main sources of uncertainty in the capacity planning practice (Peidro et al. 2009, Graves 2011). The first two sources of uncertainty can be categorised as environmental/external uncertainty, and the third one comes from the internal system. Companies can often cope with internal or system uncertainty by internal decisions and actions (Colvin et al. 2009). Environmental/external uncertainty, however, is challenged as the most important source of uncertainty (Escudero et al. 1995, Farahani et al. 2010). All production plans are established and run on a demand forecast (Graves 2011), which can be quite unstable on a long-term horizon (Huang et al. 2009). Therefore demand uncertainty is highlighted as a source of uncertainty which has the highest impact on the firms' strategic decisions (Peidro et al. 2009, Karnik et al. 2009). As a consequence, it is vital to the firms to have a long-term capacity planning which considers demand uncertainty. Such a plan should be capable of moderate adjustment at the capacity level. Such adjustment should be applicable with the lowest possible cost and lead time (Karnik et al. 2009).

According to Peidro et al. (2009), who reviewed 103 bibliographic references from 1988 onward on resource planning under uncertainty, around 60% of the models in capacity planning which were designed to manage uncertainty, have applied only one source of uncertainty, followed by around 30% for 2 sources and 10% for three sources of uncertainty. Almost all of these models have considered demand uncertainty in their models (Peidro et al. 2009). For demand changes, historical and statistical data are seldom reliable data; and forecast-and-plan (scenario planning) should be employed (Karnik et al. 2009).

Not only external factors affect the level of demand, but also internal factors such as a firm's pricing policy and incentive decisions (Karnik et al. 2009). This is why demand and sale price uncertainty are highlighted as the most dominant sources of uncertainty in production planning problems by some researchers (LI et al. 2008, Ierapetritou et al. 1996, Li et al. 2004). Therefore, in the model development phase in chapter 4, both sources of demand and sales price uncertainty will be considered.

2-3-2- Capacity level Management (Increase/Decrease)

Once the detail of each current and future product on the time horizon of the planning is estimated for each scenario, the next step is identifying the capacity level of each plant in the planning time period, considering the company's policies and constraints (Papageorgiou et al. 2001).

Taking into account the lumpy nature of capacity in the manufacturing industries (Olhager et al. 2001), any change in the capacity volume can be carried out in 3 levels: slight, medium and significant (Lin et al. 2010).

- Slight increase in the capacity level can be done by a bottleneck analysis followed by an overutilisation solution, shift increase, etc.
- Medium increase, however, needs some expansion in the current capacity by adding new lines, tools, machineries, spaces etc.
- Establishing new plants or shops, on the other hand, leads to a significant increase in available capacity, for a long-term solution to a demand increase.

Likewise, in the case of a capacity reduction in a downturn situation, three empirical solutions are common, which all depend on the level of demand decrease and the downturn duration. If a significant demand slump is expected for several years, a company might decide to permanently shut down one or some of its production lines. If the demand decline is significant/moderate, but is expected to last for a short/mid-term (few years), capacity mothball is the empirical solution. However, if demand decrease is not considerable, or is expected to last for a very short term, underutilisation is the most practical approach. To see the abovementioned output(s) from a 'Capacity Level management' model, some input information is required. Major input data for the capacity level management models are:

- *Capital Costs:* Increasing or decreasing the level of capacity, according to demand prospect for the products, has different required investments (Chandra et al. 2005, Azaron et al. 2008, Zhang 2007). This cost includes all required investment in changing the level of capacity (Naraharisetti et al. 2010, You et al. 2009, Frausto-Hernandez et al. 2010, Wagner et al. 2009), as well as capacity depreciation costs (Naraharisetti et al. 2010, Zhang 2007, Chauhan et al. 2004, Bhutta et al. 2003).

- Significant capacity increase, which can be done by expansion of a current plant or establishing some new plants, may take several years. Gatica et al. (2003) highlighted the importance of applying 'Capacity Change Lead time' in an integrated capacity management model. A capacity expansion decision in the automotive industry, for example, should usually be made 3 years ahead (Kauder et al. 2009).

- *Fixed operations costs:* Annual-based costs of operation, including labour cost, utility cost, support cost etc. have been employed by modellers (Kauder et al. 2009, Verter et al. 2002, Gatica et al. 2003, Colvin et al. 2009, Claro et al. 2012, Stray et al. 2006). Fixed operations costs make the model sensitive to economies of scale (Claro et al. 2012). Some product-related unit costs, however, are inevitable (Papageorgiou et al. 2001), which will be discussed later in the product management section (2-4-4).

- Production efficiency: This is the production rate of each product in each possible plant (Papageorgiou et al. 2001, Melo et al. 2006). The matrix of allocation possibility identifies which product can be produced in each plant (Kauder et al. 2009, Karnik et al. 2009, Inman et al. 2001, Barahona et al. 2005). Then, production rates explain how the possible products fit into the plants (Bihlmaier et al. 2010, Lin et al. 2010, Gatica et al. 2003).

Capacity Increase Constraints:

Traditionally, capacity level management calls for capacity expansion modelling. Therefore, many of the current capacity expansion models do not only explain expansion of the current capacities, but also new capacity establishment, overutilisation and even capacity reduction (Julka et al. 2007). Modelling the capacity increase has been a hot research topic since the early 1960s (Julka et al. 2007). Demand uncertainty, products’ life cycle, depreciation rate, and the total required investment cost are the main constraints in capacity increase planning (Wu et al. 2005). Expansion of the current capacities, if it is possible, is limited to one or very few times with district range (Gatica et al. 2003). The automotive industry, for example, suffers from a limited expansion flexibility, due to very high cost, labour considerations and technological constraints (Chandra et al. 2005).

The capacity increase models have got overlaps with the capacity location models (Farahani et al. 2010). Moreover, in a multi-plant or multi-line capacity planning, the capacity of the system is equal to the capacity of the bottleneck of the system. According to the theory of constraints (Goldratt et al. 1992), if the capacity of a bottleneck is addressed to increase, it might cause a shift from one bottleneck to another, and the previous machine or line is not the bottleneck anymore (Slack et al. 2009). This is why modelling capacity level is not an easy task (Stray et al. 2006).

In the case of establishing a new plant / production line, the newly installed capacity should be enough for the whole life cycle of the product (Fleischmann et al. 2006) unless budget constraints on investment or capacity considerations restrict the decision, or the new capacity can be quickly and cost-freely expanded later. Slight increase with the least possible time and cost, on the other hand, is a very common approach by overutilisation of current capacity. Although managers are always concerned about the level of utilisation to reduce the final product price by benefiting from economies of scale (Johnson et al. 2008), avoiding capacity expansion and keeping capacity overutilised for a long period of time is not always the right solution (Luss 1982). It depends on the level of expected demand increase, the level of market uncertainty, the cost of expansion, and finally the duration of expected demand increase. Moreover it implies the necessity of an optimisation model with the ability of applying uncertainty to decide about the required capacity level (Van Mieghem 2003).

Capacity Decrease Constraints:

Capacity decrease becomes increasingly important in a downturn situation such as the recent recession (Zhang 2007) and therefore capacity reduction as well as capacity increase should be considered in a strategic long-term capacity planning model (Melo et al. 2006).

Taking one of three empirical decisions of underutilisation, capacity mothball or capacity shutdown in a downturn situation depends on the market prospect in terms of level of demand decline, and duration of the downturn and one needs to analyse different scenarios (Karnik et al. 2009, Lin et al. 2010) in an optimisation framework (Van Mieghem 2003).

In case of underutilisation, due to the fact that no actual change in capacity and hardware happens, there is usually no need for an extra factor or term in the model, except for possible work force redundancy, as far as the economies of scale are implemented in the modelling practice.

In a success story on capacity decrease modelling, the model that was developed by Eppen et al. (1989) suggested to shut down two to four of seven production plants of the General Motors Company in the US, to control the cost and profitability of the company. Although it did not happen, the model's outcome shed the light on the company's excess capacity and therefore some other strategic considerations, such as market share and customer loyalty, were highlighted (Eppen et al. 1989).

Bhutta et al. (2003) applied a simple term of capacity change for both capacity expansion and decrease. The main drawback in their model was the fact that the cost of changing the capacity level was assumed the same for both capacity increase and decrease, which is not realistic. The level of capacity change was also assumed to be a continuous term, with no effect on other parameters such as labour cost (Bhutta et al. 2003). Another model which successfully managed the underutilisation level was proposed by Geng et al. (2009). Moreover, some other studies have focused on the capacity shutdown problem (Naraharisetti et al. 2010, Bhutta et al. 2003, Stray et al. 2006, Melo et al. 2006).

2-3-3- Capacity Location, Relocation, Merge and Decomposition

In the last twenty years, global resource design and capacity relocating in/to low cost countries (LCCs) have considerably increased, especially for highly competitive businesses such as those in the automotive and electronic industries (Fleischmann et al. 2006, Lee et al. 2009). A capacity location decision results from a trade-off between two opposing factors (Syam 2000): 1- Attractiveness of producing overseas to benefit from lower cost and an emerging market. 2- The risk of overseas investment, including losing goodwill in the home country, losing the technology advantage, the possibly lower service quality, risk of uncertain exchange rates etc. (Syam 2000). It therefore highlights a need for the development of an optimisation-based multi-period capacity location decision making tool (Klibi et al. 2010).

Although capacity location modelling goes back to the 1960's (Manne 1967), the relocation problem has turned to the modellers' attention since later in the 1990's (Van Mieghem 2003). The interest in global resource management and delocalization has been reviewed by Prasad and Babbar (2000) from 1986 to 1997 and then by Meixell and Gargeya (2005) from 1980s to 2003. Then, Melo et al. (2009), Klibi et al. (2010) and Farahani et al. (2010) have reviewed more recent papers in this field. Moreover, Snyder et al. (2006) presented a valuable review paper on facility location under uncertainty.

Some different direct factors such as the lower labour costs, energy prices, tariff and trade concessions, capital subsidies and reductions in transportation costs to foreign markets have been raised as the main driving forces behind global investment in capacity (Ferdows 1997). These direct factors will be applied in the model development in chapter 4.

Other indirect factors, such as the company's policy, access to the overseas market, organisational learning through closeness to the customers and, consequently, an increase in reliability (MacCormack et al. 1994), however, cannot be easily implemented in a quantitative optimisation model, due to the subjective and qualitative nature of these factors. Therefore, the impacts of these factors on capacity decisions should be considered by users in the input data. In such cases, few options/choices, which are consistent with the company's policies, are introduced to the model as input data in order for the model to find out which one is the best solution. This approach will be used in this research in chapter 4.

Capacity design and location decisions are becoming increasingly sensitive to tax rates and tariff differences as well as governmental incentives for investment across the globe (Verter et al. 2002). In the 1990's more than 75% of the biggest American companies invested in factories outside their country, followed by more than 90% in the 2000's (Hamad et al. 2008), which shows the importance of global investment in the manufacturing industries. In the automotive industry, for example, in the 1980s and the 1990s a paradigm shift happened from merely exporting or a 'products-to-market' strategy to a 'produce-in-market' approach (Syam 2000). The profit tax, inflation rate and government incentives will be applied in the model in chapter 4.

The plant location decisions should be made in connection with the topology of the supply chain network, the location of the other manufacturing sites of a company, the sales regions' locations, investment and financial features etc. (Kauder et al. 2009). In a capacity relocation problem, to avoid a sudden financial burden on a company, the planning should be done over several time periods and this lead time should be applied in the decision making models (Melo et al. 2006).

In a capacity relocation problem, sometimes relocation happens by merging some plants or production lines, where one large plant might be created in a new location at the expense of shutting down two or more current plants. De-concentration or segregation of the current plants to smaller plants to increase differentiation, is also a scenario that may come with relocation problems. In this scenario, one or two large plants can be broken down to some smaller plants in some other locations to serve the regional market places or to increase differentiation or reduce the cost of production/supply (Melo et al. 2006).

Stochastic optimisation programming is highlighted as one of the best quantitative approaches to the model facility location/relocation problems (Klibi et al. 2010, Farahani et al. 2010). In two-stage stochastic programming, the capacity location is the first-stage decision, while the product-to-plant and product-to-market decisions are the second-stage decisions. In the multi-stage stochastic programs which will be employed in this research, the location decisions are also made in the earlier stages, before the load-planning decisions, which are made in the later stages (Snyder 2006).

2-3-4- Product Management and Planning

Due to significant competition in the current market environment, product life cycles are continuously decreasing (Ahmed et al. 2008). In the automotive industry, for example, the product life cycle is now 6 to 8 years (Fleischmann et al. 2006), which is much less than the capacity planning horizon and therefore the whole life cycle curve, from the new product development and launch to the maturity and demand decline phase, should be reflected in a capacity management model (Francas et al. 2009). Launching a new product, such as a new automotive model, in a plant is expensive and time-consuming (Inman et al. 2001) and therefore it is not easy/possible to be changed after realisation (Frausto-Hernandez et al. 2010).

The product management problem comprises some distinct steps, which should all be applied in the modelling practice:

1- *Demand forecast:* The sales features in the planning horizon should be forecasted for each current and future product, considering the life cycle of each product (Papageorgiou et al. 2001). This demand forecast is stochastic, since the market environment is uncertain (Alfieri et al. 2005).

2- *Price portfolio:* The price forecast for each product in the planning horizon. The discounted price is often expected to reduce by time (on its life cycle), when the product becomes mature (Papageorgiou et al. 2001). Uncertainty in the product price should be applied in a capacity planning model (Eppen et al. 1989).

3- *New Product Development (NPD):* New product development (NPD) can be divided into two complementary stages of the design phase (R&D) and launching phase (NPL):

    a. R&D Phase: The design phase for a new product in a multi-national company can be done in a research/engineering centre or in the company’s headquarters (Fleischmann et al. 2006).

b. New Product Launch (NPL) phase: In this phase a product is launched in a current or new plant for the first time. This launch needs some product-specific investment in facilities (Fleischmann et al. 2006, Chandra et al. 2005, Papageorgiou et al. 2001).

4- *Setup time:* Both R&D and NPL phases are time-consuming, and their investment lead time should be implemented in the product management modelling (Papageorgiou et al. 2001).

The cost and lead time for R&D part of NPD has been successfully applied in strategic capacity planning for the pharmaceutical industry by Colvin and Maravelias (2009). In the manufacturing industries however, to our knowledge no previous capacity management model has considered the cost and lead time for R&D and NPL simultaneously. In the model which is developed in this research in chapter 4, this approach will be employed.

2-3-5- Flexibility and Technology Management

The manufacturing technology has experienced an evolution in recent decades. Nowadays technology selection for the manufacturing industries is within the scope of strategic decisions, due to the highly competitive market, dynamic demand change, short product life cycles and changing product-mixes (Ahmed et al. 2008). The technology acquisition decision has to be made by analysing a trade-off between “economies of scale” and “economies of scope” (Verter et al. 2002). With regards to this trade-off, and some other considerations such as the firm’s cost structure, demand characteristics, market characteristics and the firm’s risk management policy, an optimal portfolio of flexible and/or dedicated technologies is acquired for the company (Ceryan et al. 2009, Bish 2005, Beach et al. 2000).

Manufacturing flexibility, in the context of capacity planning, means the ability of a system or production line to change its capacity over time, quickly and economically (Ceryan et al. 2009), which can be generally categorised into two different types of product-mix and volume flexibilities (Karnik et al. 2009).

Matta et al. (2005) highlighted some characteristics for differentiating the dedicated and flexible technologies:

- *Rigidity / Flexibility level*: A dedicated technology is able to produce one or limited product types of a family group and cannot easily be expanded to other products, while a flexible technology is designed to produce all products of a family group, or even different families.
- *Production rate*: Dedicated technology, which is designed for some particular products, usually has a higher production rate (faster/cheaper) than flexible technology.
- *Skilled Work force Requirement:* For a dedicated technology, where managing the system is straightforward and easy to manipulate and the maintenance of the whole system is relatively trouble-free, the need for ‘highly skilled employees’ is less than it is for a flexible technology.
- *Capital Investment:* Comparing with a flexible system, where technology, robots, computers and CNC equipment are required, a dedicated system is much cheaper in terms of investment.

- *Excess/Shortage capacity:* Excess or shortage of the capacity cannot be easily managed in a dedicated system, since this system is designed for certain products, and is not flexible to switch to other products.

Having in mind that the acquisition cost of a flexible system is typically three times higher than that of a dedicated technology (Claro et al. 2012), based on the above characteristics, neither a dedicated nor a flexible technology has a distinct advantage over the other and choosing the right technology portfolio is a compromise between several factors. In capacity planning models, usually few options/choices based on the available technologies for a required application are defined as input data to the model (Elkins et al. 2004). Then, all abovementioned characteristics of each option will be defined as input to the model. The 'flexibility level of equipment' is also defined by the 'possibility matrix' for each technology. Then, based on the demand forecast and other terms and constraints, an optimisation model suggests one or a mix of solution(s), as the best possible solution. The 'possibility matrix' reflects both product and process flexibilities. In fact, it shows how flexible the production line is to produce a variety of product types and families, while at the same time it defines how the products are flexible to be produced in different production lines. However, having a complete product-mix flexibility, in many industries such as the automotive industry, is neither necessary nor feasible (Chandra et al. 2005). Instead, if one plant shares a product with another plant, then these plants form a chain. If all plants of a company are linked together in one chain, its benefit is almost equal to having a complete flexibility in that company (Inman et al. 2001). The possibility-matrix approach is successfully employed by some researchers to apply the product-mix flexibility in their capacity planning models (Kauder et al. 2009, Fleischmann et al. 2006, Karnik et al. 2009, Inman et al. 2001, Barahona et al. 2005).

In the automotive industry, for example, the traditional approach was to adapt the dedicated technology to benefit from high productivity and low capital investment. However, as a result of the increase in product differentiation, the globalised and high competitive market, and a continuous decline in the products' life cycles, a sharp drop in capacity usage took place in the 1990s and 2000's, according to figure 2-2 (Francas et al. 2009). This figure shows that the global capacity for the light vehicles increased, while the total capacity utilisation declined dramatically. This resulted in a sharp increase in the excess capacity.

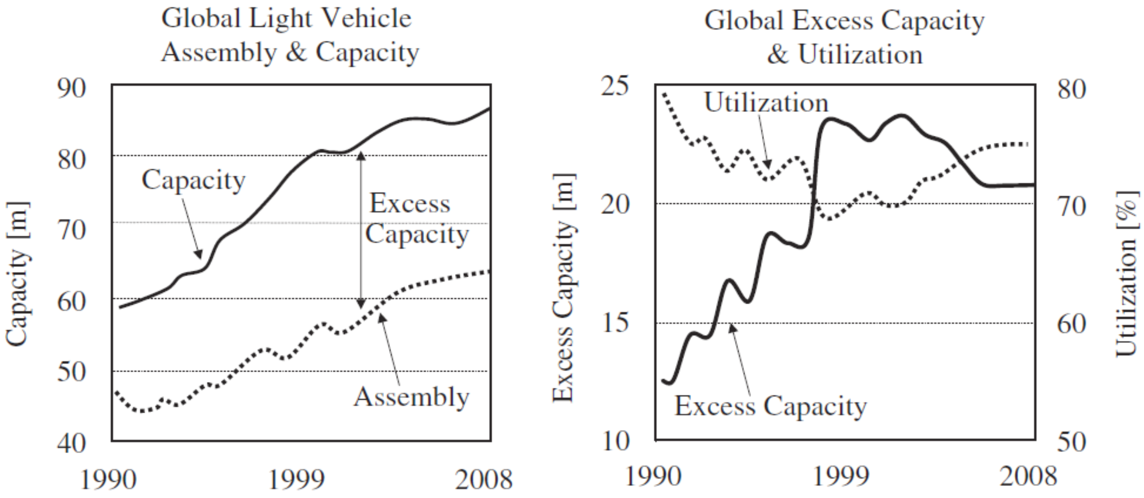


Figure 2-2: Excess capacity and capacity utilisation in the automotive industry

Source: (Francas et al. 2009)

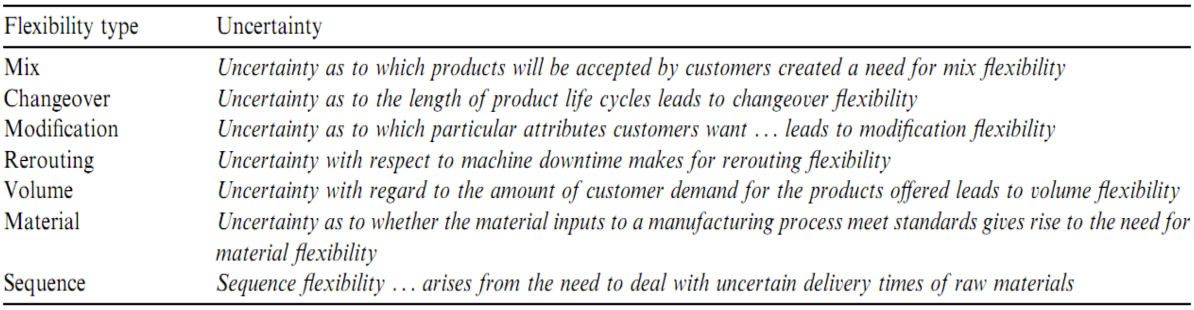
In the automotive industry, such as in any other capital-sensitive sectors, the operation margin is highly dependent on the capacity utilisation level. Being aware of this problem, the managers of the automotive industry have started to revise their manufacturing strategies and most of them found the solution is “flexibility” (Francas et al. 2009). In 2000, Chrysler experienced a huge loss of more than $2 billion on two of its products, “Town & Country” and “Voyager”, due to an overestimation of the expected market demand (Goyal et al. 2007). To reflect this loss, in 2003 the vice president of Daimler-Chrysler stated: “With so much competition, the days of one product one plant are starting to diminish”. Consequently, the group invested in changing the existing plants into “World-class, flexible manufacturing facilities”. Daimler-Chrysler, in 2005, started to invest in Sterling Stamping Plant and Sterling Heights Assembly Plant to make them flexible and capable to produce multiple products (Francas et al. 2009). In 2002, Volkswagen announced that flexible plants and the capability of shifting products between the plants is one of the main approaches to implement the company’s risk management policy (Volkswagen 2002). The Japanese carmakers have also adapted flexible technologies and, for example, in Nissan’s site in Mississippi three different car families can easily be launched in the same assembly line, with no problem or conflict. Therefore, they can keep their plant busy regardless of market changes (Bish 2005). In another study on the level of required flexibility in the automotive industry, Elkins et al. (2004) developed a simple model for the General Motors Company, which showed the merit of employing a flexible technology in an uncertain market (Elkins et al. 2004).

Chandra et al. (2005) identified the major manufacturing flexibility terms for a strategic capacity planning model in the automotive industry, including expansion flexibility, volume flexibility, new product flexibility and finally product-mix flexibility. Using the possibility matrix, capacity rates and investment lead times as well as giving the options of overutilisation, underutilisation, expansion, mothball, new plant establishment and capacity shutdown in the model, all of these flexibility types will be inherent in our model in chapter 4.

Flexibility vs. Uncertainty:

The level of uncertainty has significant effect on the optimum level of flexibility. Unplanned changes (uncertainty) have five different dimensions, including size, novelty, frequency, probability and rates and acquiring a different level of flexibility in the manufacturing process is one of the most empirical solutions to cope with these changes, according to table 2-1 (Beach et al. 2000).

Table 2-1: Association of flexibility type and uncertainty



Flexibility type	Uncertainty
Mix	*Uncertainty as to which products will be accepted by customers created a need for mix flexibility*
Changeover	*Uncertainty as to the length of product life cycles leads to changeover flexibility*
Modification	*Uncertainty as to which particular attributes customers want … leads to modification flexibility*
Rerouting	*Uncertainty with respect to machine downtime makes for rerouting flexibility*
Volume	*Uncertainty with regard to the amount of customer demand for the products offered leads to volume flexibility*
Material	*Uncertainty as to whether the material inputs to a manufacturing process meet standards gives rise to the need for material flexibility*
Sequence	*Sequence flexibility … arises from the need to deal with uncertain delivery times of raw materials*

source (Beach et al. 2000)

With reference to table 2-1, many of these flexibility types have a time-related aspect, which should be applied to the quantitative models. To survive in an uncertain market and to achieve the first-to-market strategy, companies are becoming increasingly interested in more agile technologies, which should be acquired in the lowest possible lead time (Erlenkotter et al. 1989). Most of the current models on technology selection and flexibility issues, however, have failed to consider the investment lead time and have just focused on cost-related factors (Kauder et al. 2009, Chen et al. 2002, Karnik et al. 2009, Chandra et al. 2005, Hood et al. 2003, Claro et al. 2012, Barahona et al. 2005).

Van Mieghem (2003) highlighted scenario-based stochastic programming as the best method to model the flexibility level in the capacity planning models under uncertainty. Moreover, a very long planning horizon is recommended for a strategic technology acquisition planning (Ahmed et al. 2008, Francas et al. 2009). Chandra et al. (2005), in their model on strategic capacity management for the automotive industry, have measured the value of flexibility indirectly by measuring the profitability of the company in different scenarios with different levels of product-mix and volume flexibility. In their model, three levels of product-mix flexibility, including the marginal, standard, and higher levels of product-mix flexibility were considered. Further in their result, they showed that the profitability has risen by an increase in the level of flexibility in the Ford Motors Company, in case of demand increase (Chandra et al. 2005). However, they reported no result on demand fluctuation and/or decrease scenarios.

Their approach (inputting different flexible options into the model’s database) will be replicated in the model development practice in this study, but under demand fluctuations (increase/decrease) in chapter 4.

2-3-6- Financial parameters

For a global capacity and production planning model, custom duties (tariff), taxes, exchange rates and finally transfer payments between producing country, selling country, and holding company should be considered (Fleischmann et al. 2006). As mentioned earlier, global investment decisions are significantly sensitive to tax rates and custom duties (Verter et al. 2002). In this section, these financial parameters, which should be applied in the model, are explained in detail.

Profit tax

Despite a strong need for applying taxation in the optimisation model for capacity planning (Verter et al. 2002), to avoid complexity in modelling many researchers have failed to take it into account (Fleischmann et al. 2006). Just very few modellers managed to implement profit tax in their studies (Chakravarty 2005, Naraharisetti et al. 2010, Kauder et al. 2009, Hammami et al. 2009, Papageorgiou et al. 2001, Hamad et al. 2008).

When customers of a company are end users of the products, or, in other words, when the company produces the final products and sells them directly to the market, value added tax (VAT) should also be implemented in the modelling practice. Value added tax is different from country to country (Giesecke et al. 2010, Gordon et al. 1997). Very few modellers have managed to simultaneously apply both VAT and profit tax in a capacity model (Hamad et al. 2008). This model, however, was a deterministic model in the chemical-agribusiness field.

In the model which is developed in chapter 4, both profit tax and value added tax are considered in the formulations.

Custom Duty and Inflation Rates in Different Countries

Various restrictions on foreign products are imposed by countries to protect their own industries (Stoop et al. 1996). These restrictions are often reflected in tariff rates and custom duties, and are different from product to product and country to country. Countries may have different tariffs for the same product type which it imports from different countries, depending on different mutual agreements (Bhutta et al. 2003). A high custom duty in the countries which can also be the significant potential markets persuades companies to invest in those target countries and change their policy of make-to-market to make-in-market to avoid the high tariff rates and become competitive (Bhutta et al. 2003). Therefore, custom duty should be implemented in capacity design and location models (Chakravarty 2005). However, very few researchers (Chakravarty 2005, Bhutta et al. 2003) have managed to apply tariff rates in their strategic capacity management model. The inflation rate of the country, where production is taking place, is another important factor which is applied in very few resource planning models (Naraharisetti et al. 2008).

Custom duties and inflation rates are both applied in the modelling approach in chapter 4.

Exchange rate

The exchange rate is highly important for multinational companies in their money transfers from the head department to the manufacturers, manufacturers to suppliers and distributers/sellers to the headquarter (Fleischmann et al. 2006), and also for the investment and capacity expansion decisions (Mohamed 1999) as well as the relocation decisions (Farahani et al. 2010). Using a numerical example on the effect of the initial capacity and the effect of the exchange rate, Mohamed (1999) illustrated that the profit margin of a multinational manufacturing company can be declined by 46% in the worst case scenario.

Changing the exchange rates, however, are random variables and economists have had long disputes to model and forecast them. Yet there is still no widely accepted forecasting model on exchange rates (Bhutta et al. 2003). Very few previous researchers managed to apply exchange rates in their capacity management models (Chakravarty 2005, Bhutta et al. 2003, Hamad et al. 2008). Moreover, none of them applied uncertainty on exchange rates in their models. In other words, the current models which implement the exchange rates only use a fixed rate (Chakravarty 2005, Hamad et al. 2008), or a fixed linear formulation (Bhutta et al. 2003) for the exchange rate, which is unavoidable, due to the fact that there is no generally accepted exchange rate forecasting model.

Budget Constraint

In most cases, during the planning time horizon, the financial department of a company estimates the upper-bound for the annual investment budget, (Fleischmann et al. 2006), which should be taken into account in the investment planning. This upper limit should cover all costs of managing the capacity level and technology, as well as capacity depreciation and new product development (Fleischmann et al. 2006). Many modellers have successfully employed budget constraints in their models (Naraharisetti et al. 2010, You et al. 2009, Frausto-Hernandez et al. 2010, Fleischmann et al. 2006, Chandra et al. 2005, Gatica et al. 2003, Papageorgiou et al. 2001, Hood et al. 2003, Azaron et al. 2008, Zhang 2007, Wagner et al. 2009, Melo et al. 2006, Barahona et al. 2005). This constraint will be considered in the modelling practice in chapter 4.

2-3-7- Other terms

Capacity depreciation and replacement

The replacement problem regards the question when the current capacity should be renewed due to depreciation of the facilities (Luss 1982). Availability and development of a new technology is another motivation for replacement (Luss 1982). Although capacity depreciation refers to diminishing financial value as well as operating capacity level over time (Van Mieghem 2003), it is traditionally modelled by a financial loss to the value of the fixed assets in a long-term scope (Naraharisetti et al. 2010, Papageorgiou et al. 2001, Zhang 2007, Chauhan et al. 2004, Bhutta et al. 2003). Another factor which has a strong impact on capacity obsolescence and depreciation is the products' life cycles (Pangburn et al. 2009), which is successfully applied by Wu and Chaung (2010). Considering the product life cycle, product-related investment and overhaul costs at the same time in a capacity management model, as well as NPV and the modelling objective, capacity depreciation will be applied in the model, as will be practiced in this study in chapter 4.

Inventory management

Van Mieghem (2003) explained that no inventory management is required in a strategic capacity plan, due to the purely tactical nature of inventory management vs. the strategic concept of capacity design and management. Time intervals in a strategic capacity design model are longer than the intervals for inventory management (Eppen et al. 1989) and therefore the inventory management part should be removed from long-term strategic capacity design and planning models (Chen et al. 2002). The idea of no inventory planning in capacity management models is also supported by many other authors (Chakravarty 2005, Eppen et al. 1989, Eppen et al. 1989, Fleischmann et al. 2006, Francas et al. 2009). In some long-term capacity management models for the automotive industry, Eppen (1989), Inman and Gonsalvez (2001) for the General Motors Company; Fleischmann et al. (2005) and Kauder and Meyr (2009) for BMW; Francas et al. (2009) and Bihlmaier et al. (2010) for Dimler-Chrysler; and finally Chandra et al. (2005) for the Ford Company have neglected inventory management in their long-term capacity design and planning models, which will be replicated in this study as well.

Unmet Demand

Many of the strategic capacity planning models suffer from the assumption of neglecting the unmet demand penalty (Chakravarty 2005, Naraharisetti et al. 2010, Kauder et al. 2009, You et al. 2009, Chen et al. 2002, Hammami et al. 2009, Fleischmann et al. 2006, Chandra et al. 2005, Lin et al. 2010, Zhang 2007, Wagner et al. 2009, Chauhan et al. 2004, Bhutta et al. 2003, Melo et al. 2006, Syam 2000, Hamad et al. 2008, Snyder et al. 2007). In such models it is supposed that the production should fulfil the demand. Such an assumption forces the optimisation model to acquire a demand-production match strategy. And because of the lumpiness of the capacity (Olhager et al. 2001), it might cause significant changes at the capacity level which imposes very high fixed capitals to cover even a tiny fluctuation at the demand level, which could be restrained by an acceptable unmet demand (Eppen et al. 1989).

The most common way to cope with this problem is allowing models to have excess or unsatisfied demand. For the models which minimise cost-related objective, a penalty should be defined for unsatisfied demand to avoid the unrealistic solution of 100% unmet demand (Aghezzaf et al. 2010, Nagar et al. 2008, Karnik et al. 2009, Azaron et al. 2008, Claro et al. 2012, Lusa et al. 2011, Dehayem Nodem et al. 2008). This penalty should be at least as much as the net profit of the product. However, the unmet demand not only causes a loss in the profit, but also has a negative impact on the customers’ loyalty, and the brand image (Eppen et al. 1989). This is why the decision makers usually estimate these penalties higher than the net profit of the product, in order to apply the lost opportunity costs to the models and make the models more sensitive to the unmet demand. In the profit maximisation models, no unrealistic solution arises if the unmet demand penalty is not applied in the model. However, some modellers insist on applying this penalty in the models to make their models more sensitive to the unmet demand in different markets (Geng et al. 2009b, Frausto-Hernandez et al. 2010). This penalty option will be available to the model users in our model in chapter 4.

Economies of Scale

For the investment sensitive industries such as the automotive, electronics and manufacturing industries in general, the competitive advantage and the final product price of the company are directly related to the order quantity and economies of scale (Johnson et al. 2008). To employ the economies of scale in capacity planning models not only fixed investment costs, but also other fixed costs such as operations cost, maintenance cost, work force cost, utility cost, overhaul costs, etc. should be considered in the modelling cost formulations (Hsu et al. 2009). However, many researchers have just applied the unit-based operations cost and ignored economies of scale to simplify their models (Geng et al. 2009b, Frausto-Hernandez et al. 2010, Karnik et al. 2009, Inman et al. 2001, Chandra et al. 2005, Colvin et al. 2009, Hood et al. 2003, Azaron et al. 2008, Wagner et al. 2009, Chauhan et al. 2004, Claro et al. 2012, Barahona et al. 2005, Syam 2000, Hamad et al. 2008, Snyder et al. 2007, Lusa et al. 2011, Dehayem Nodem et al. 2008, Silva Filho et al. 2007). In this research, the economies of scale will be reflected in the formulation in chapter 4, as explained above.

Chapter 3 : Methodology and Methods

As described in chapter 2, a quantitative approach is the most dominant methodology for long-term resource and capacity planning problems, due to the fact that these problems are fairly parametric (Julka 2008, Pidd 2003). In this chapter we review the applied quantitative methods to find the most suitable method for this research.

3-1- Applied Quantitative Methods on Resource Planning Under Uncertainty

Four quantitative modelling approaches are categorised by Peidro et al (2009), who reviewed 103 models within the scope of resource planning under uncertainty from 1988 to 2009. These approaches include: analytical models, artificial intelligence-based models, simulation models and finally hybrid models, which are based on the integration of analytical and simulation models. All of these approaches have different methods and sub-sets, as mentioned below (Peidro et al. 2009):

- Analytical models: stochastic programming, robust optimisation, linear programming, parametric programming and the game theory
- Artificial intelligence-based models: multi-agent system, fuzzy linear programming, fuzzy multi-objective programming, fuzzy goal programming, fuzzy numbers, reinforcement learning, evolutionary programming and genetic algorithm
- Simulation models: discrete event simulation and system dynamics
- Hybrid models: linear programming and simulation, model predictive control (MPC), stochastic dynamic programming, mixed integer linear programming (MILP) and discrete event simulation, the genetic algorithm and simulation and MILP and system dynamics

Peidro et al. (2009) concluded that in this broad area of research, and among the abovementioned four groups of quantitative methods, the analytical approach has been appreciated more and had the fastest growth in the last two decades. They also observed that the analytical approach has had more success in the strategic and tactical modelling, while the artificial intelligence-based approach received more attention in the operational level of modelling in the field of resource planning. Recalling from Peidro et al. (2009), in table 3-1 the advantages and disadvantages of each method within the scope of resource planning are summarised. According to this table, the analytical approaches cannot model very complex scenarios. Furthermore, due to the restricting hypotheses and constraints, their solutions could be limited. However, this approach is still capable of providing an optimal solution for such problems in real scales with affordable input data and reasonable computing time.

Table 3-1: General advantages and disadvantages of employing different methods in resource planning

	Advantages	Limitations
Analytical Models	Right adaption for managing random uncertainties (based on probability distribution)	Not powerful enough to model complex scenarios. Solutions provided could be limited in their application fields because of preliminary restricting hypotheses.
Models based on Artificial Intelligence	Appropriate for solving optimisation problems. The fuzzy set theory could provide an alternative approach for dealing with SC uncertainties wherever statistical data are unreliable or even unavailable. Multi-agent systems constitute a very useful solution for decentralised SC management The application of techniques based on meta-heuristics, evolutionary and bio-inspired algorithms to obtain valid approximations with a right computational efficiency	Low computational efficiency The application of the fuzzy set theory requires defining more input data for considering uncertain parameters In multi-agent systems, a theoretical optimum could not be guaranteed because there is no global view of the system The application of techniques based on meta-heuristics, evolutionary and bio-inspired algorithms could only obtain approximation to the optimum
Simulation Models	More capable of capturing scenarios of complex system behaviour	Not adequate for solving optimisation problems Complex simulation models required, large amount of developing and running time
Hybrid Models	Integrate the best capabilities of both analytical and simulation models	Complex coordination of the information provided by the models.

Source: Peidro at al. (2009)

Mula et al. (2006), who have reviewed 87 models on production planning from the 1980’s to the 2000’s, also showed that the analytical approach has been one of the most successful methods in this field. They also classified the broad concept of production planning into the 7 sub-groups of: 1- Aggregated planning; 2- Hierarchical production planning; 3- Material requirement planning; 4- Capacity planning; 5- Manufacturing resource planning; 6- Inventory management; and finally 7- Supply chain planning (Mula et al. 2006). Then, they managed to show the most common quantitative approaches for these different production planning sub-groups, as reflected in table 3-2.

Table 3-2: Common and efficient methods for different types of production planning.

	Research Topic	Method
1	Aggregate planning	Artificial intelligence models, Simulation models
2	Hierarchical production planning	Analytical models,
3	Material requirement planning	Conceptual models, analytical models, Simulation Models
4	Capacity planning	Analytical models, simulation models
5	Manufacturing resource planning	Analytical models, artificial intelligence models, simulation models
6	Inventory management	Analytical models, artificial intelligence models
7	Supply chain planning	Conceptual models, analytical models, artificial intelligence models

Source: Mula at al. (2009)

Referring to this table, the most common approaches for capacity planning are the analytical method and simulation modelling. Analytical methods employ mathematical techniques to directly solve problems, while simulation models are not directly manipulated by a mathematical approach, though equations and distributions may be employed in this approach (Curwin et al. 2008).

Back to table 3-1, although the simulation method is capable of handling more complex scenarios, this method is more complex in nature, and is also inadequate for optimisation problems. On the other hand, as discussed in chapter 2, for the capacity management issue, the aim is how to plan the size, location and type of capacity, as well as when to invest in capacity (Hayes et al. 1984). Therefore, the analytical method and optimisation technique is the best approach in resource and capacity management, and has been supported by many other peer scholars in this field (Van Mieghem 2003, Mula et al. 2006, Melo et al. 2006, Hvolby et al. 2010).

3-2- Scenario-Based Stochastic Programming (SB-SP)

In the real scale optimisation practice, often one or some of the input parameters are not known for sure (Graves 2011). The traditional technique to deal with such data was to replace unknown parameters by expected value or the value for the most probable scenario. This method is called ‘deterministic approach’.

In capacity management models, traditionally, uncertainty is seldom considered because it would increase the modelling and solution complexity (Zhang 2007). As a result of global market competition, however, capacity planning is subject to a vast diversity and uncertainty and simple estimations are no longer sufficient to cope with the contemporary situation. Planning the capacity of an organisation, if it is done based on a single demand set with a deterministic approach, may cause a huge gap between required capacity and planned capacity (Barahona et al. 2005). Therefore, uncertainty should be directly applied in the models (Engell et al. 2010), as was explained in section 2-3-1.

Stochastic programming is a method of implementing uncertain parameters in an analytical optimisation model (Huang et al. 2009, Baron et al. 2008, Wu 2011). This technique was developed in the 1950’s by many authors independently, as a probabilistic generalization of mathematical programming and deterministic optimisation (Charnes et al. 1959, Beale 1955, Dantzig 1955, Ferguson et al. 1956). Therefore, this framework is the natural candidate for capacity design and planning under uncertainty (Alfieri et al. 2005).

The advantages of employing the stochastic programming, over the deterministic models are: 1- Model robustness: the result from scenario-based stochastic programming is feasible for realisation of all (or many of) the scenarios; 2- Solution robustness, which is defined as the solution proximity to the optimality for any scenario realisation (Lusa et al. 2011). The benefit of employing stochastic optimisation over deterministic models is assessed by calculating the Value of Stochastic Solution

(VSS), which comes from the difference of the final objective value of two methods (Frausto-Hernandez et al. 2010).

3-2-1- Stochastic Modelling: Methods

Stochastic optimisation is mostly divided into two methods, including two-stage programming (TSP) and multi-stage programming (MSP) (Nagar et al. 2008). In the two-stage stochastic programming approach, the problem formulation is divided into two distinct categories, based on whether a particular task needs to be carried out before or after the uncertainty realisation. For example, in a long term planning some activities such as the raw material procurement, capacity utilisation and sometimes final production are modelled as "here-and-now" decisions, which need to be made before demand (uncertainty) realisation. The post-production activities such as outsourcing, inventory management, transportation and distribution, on the other hand, can be modelled as the "wait-and see" decisions, which would be managed after the demand realisation (Nagar et al. 2008, Nagurney et al. 2005, Shapiro 2004). TSP models are much easier and less time-consuming to solve than the multi-stage programming (MSP), because they have less scenarios, variables and constraints (Huang et al. 2009). Many two-stage stochastic models have been developed for resource design and planning (Kuttner 2008). Employing the stochastic method has been proven to have a significant reduction on the over-design and safety factors and therefore reduces final cost. You et al. (2009) observed that replacing a deterministic model with a two-stage stochastic one leads to a 5.7% saving in the final costs of the company's products and reduces the probability of high cost risk to less than 3% (You et al. 2009).

Multi-stage models, on the other hand, extend the two-stage stochastic programming models. In other words, the multi-stage stochastic method is a dynamic approach and one can apply a multi-layer scenario tree in it to implement a set of different scenarios with different possibilities. Although the solution algorithms are much more complicated for MSP models (Cheon et al. 2006) and solutions are more time-consuming and consequently expensive (Van Mieghem 2003), the accuracy and efficiency of this approach is much higher (Geng et al. 2009a). The merits of the MSP over the TSP have been highlighted by Ahmed (2002). He maintained that this merit would be increased by increasing the number of stages and the number of decision variables per stage (Ahmed 2002). It is addressed by Nagar and Jain (2008) that replacing a TSP model with an MSP would help the decision makers to design their resource chain to save more than 5 % of the final cost. In addition, Gebennini et al. (2009) managed to develop a multi-stage stochastic model in the context of the location and allocation problem and inventory management to decrease the global cost of logistics by at least 10% (in comparison with deterministic models). This advantage was achieved by a significant reduction of the safety stock level (about 20%) and number of distribution centres as well as an optimisation of the transportation procedure (Gebennini et al. 2009). Moreover, Huang and Ahmed (2009), using an approximation algorithm method, observed that even an approximation solution to a multi-stage method can be superior to any optimal solution from a two-stage stochastic model (Huang et al. 2009), which is also supported by Geng and Jiang (2009). Due to the merits of using multi-stage stochastic programming over a two-stage one, this approach is employed in chapter 4, where the model for this study will be developed.

The stochastic parameters can appear in both objective and constraints of an optimisation model (Frausto-Hernandez et al. 2010). Two main formats have been developed for applying uncertain coefficients in stochastic programming: 1- random parameters with known probability distributions (Charnes et al. 1959); or 2- different alternative values from different scenarios with different probabilities (Walsh 2005).

The probability distribution method is based on the assumption of having access to adequate historical data to extrapolate and estimate the future prospect (Kempf et al. 2011a). However, this approach is restricted because: 1- Comprehensive and reliable historical data are not always available (Escudero et al. 1995); 2- Not all possible future prospects can be drawn from historical data, especially with regard to the contemporary market environment (Escudero et al. 1995, Kempf et al. 2011b).

The merits of a scenario-based approach over the probability distribution technique are: 1- This approach is more tractable (Snyder 2006); 2- The uncertain parameters in this approach can be statistically dependent, which is often not applicable in the other technique (Snyder 2006). 3- There is no need for very detailed historical data; a general scope is sufficient to shed light on a prospect for the future (Karnik et al. 2009) 4-The scenario-based technique is generally more reliable in long-term planning models (Lin et al. 2010).

In practice, statistical data for the demand uncertainty in terms of probability distribution are not always available and therefore manufacturing firms rely on point forecasts of demand (Karnik et al. 2009), which is the concept of scenario planning (Geng et al. 2009b). Therefore employing the scenario planning technique to implement uncertainty into stochastic programming is appreciated wider than the probabilistic approach in general (Escudero et al. 1995, Kempf et al. 2011b, Geng et al. 2009a), particularly for long-term resource management (Escudero et al. 1995, Kempf et al. 2011b, Lin et al. 2010, Geng et al. 2009a). Therefore, this technique will be employed in this study.

3-2-2- Stochastic Modelling: Scenario Generation

In the scenario-based method a set of possible scenarios are defined, based on the outlook of the firm and the prospect for the market, and then a probability and values of stochastic parameters will be assigned to each scenario (Geng et al. 2009b). In other words, scenarios should explain and figure out the future state of the business. These factors may come from a broader analysis, such as PESTEL or Porter Five Forces (Johnson et al. 2008), and/or some key aspects which are recognised by the managers of the companies (Eppen et al. 1989). Several factors, such as existing products mix, technology choices and market prospect should be considered by decision makers in creating scenarios (Barahona et al. 2005). Apart from the mechanism of defining the scenarios, the output of a scenario planning is a set of realistic values for stochastic parameters in each scenario, with a realisation probability for each scenario (Johnson et al. 2008).

There are different ways of generating scenarios, including a scenario tree, enumerated scenarios and a Monte Carlo simulation (Hood et al. 2003). In another classification, two types of scenario construction, including independent and arbitrary, are identified by Geng et al. (2009a). Independent scenarios are defined when no prior information is assumed, and there is no dependency and relationship between the scenarios. Arbitrary scenarios, on the other hand, reflect the dependency between scenarios (Geng et al. 2009a). This approach can be organised in the format of a scenario tree (Sen 2001), as is illustrated in figure 3-1. An arbitrary scenario approach is designed for 'what if' or sensitivity analysis (Geng et al. 2009a). Figure 3-1 shows how scenarios in each stage depend on the scenarios in the earlier stages. This format depicts the information evaluation over the stages. In such a format, two scenarios that have the same history until stage (t) are not recognisable until that stage. For example in figure 3-1, the SC_7 and SC_8 nodes have the same path until stage t_2. Every certain scenario represents a particular path from the first stage (current time), to a leaf node in the last stage (future). In multi-stage stochastic programming, at the beginning of each stage, decisions are made based on incomplete and uncertain information, while at the end of the stage, some of the aspects of uncertain information are realised, and then, the set of scenarios will be reduced (Lusa et al. 2011).

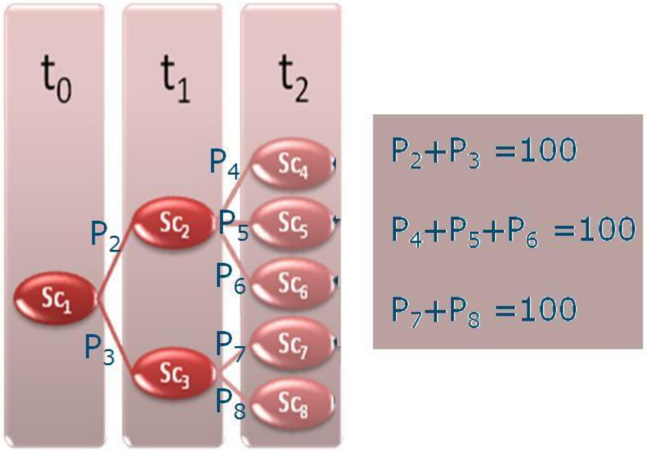


Figure 3-1: Arbitrary scenarios in the format of a scenario tree.

The scenario tree approach (dependent scenarios) has two main disadvantages: difficulty in defining scenarios and their probabilities as well as complex programming and long computation time for a large number of scenarios (Snyder 2006). Scenario trees can be extremely large and difficult to manage, if no appropriate approximation approach is employed (Sen 2001). Therefore to make a scenario-based stochastic model easy to handle, either an approximation technique or an enumerated scenario method should be employed (Sen 2001).

In the enumerated (Hood et al. 2003), or in another word independent (Geng et al. 2009a), scenario approach, the whole business environment is analysed by the decision makers and a set of limited possible independent scenarios for the future will be defined. Then, for each scenario, distinct values for uncertain parameters will be suggested for each stage, as well as its probability (Lin et al. 2010). Traditionally, at least three scenarios, including optimistic, pessimistic and realistic (neutral) scenarios, are considered in scenario planning (Johnson et al. 2008). However, the total number of scenarios may be much higher than three , depending on the decision makers' viewpoint. Figure 3-2 shows a typical enumerated or independent scenario plan, including five scenarios and five time periods or stages. In this figure, each scenario has its independent and distinct path and probability. Since the whole scenarios show the state of the future for the planner, the summation of the probabilities of all scenarios should be 100%.

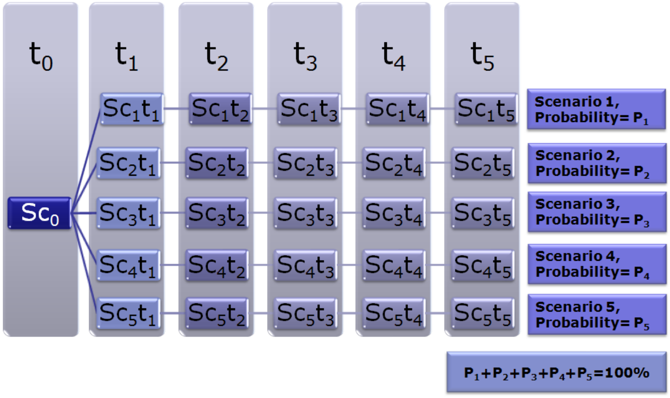


Figure 3-2: A typical enumerated or independent scenario plan, including five scenarios and five future stages.

In practice, an empirical and common approach to scenario planning is defining limited possible scenarios with higher expected values (e.g. more probable or higher impact), by the top managers and decision makers of a company (Lin et al. 2010). This common method, in general, is the independent enumerated approach, as described above. The enumerated scenario approach is also supported by many other researchers in capacity design and planning models, including in the electronic and semiconductor industries (Hood et al. 2003, Barahona et al. 2005), and chemical productions (Dal-Mas et al. 2011, You et al. 2009). In an empirical approach to the automotive industry, Eppen et al. (1989) tried to find a modelling framework that can achieve the following three aims: 1- Fit in the actual framework of the managers' forecasting method; 2- Produce a reasonable size of information; and 3- Provide a more appropriate representation of reality. They finally came up with the enumerated scenario planning approach (Eppen et al. 1989). Therefore this approach is adapted as the uncertainty implementation method in the scenario-based stochastic program which will be used in chapter 4 of this research.

3-2-3- Stochastic Modelling: Formulation

In practice, for solving a stochastic optimisation problem, it should be transferred into an equivalent deterministic model directly or by using an approximation and decomposition solution algorithm. Then it will be solved by a simple algorithm or commercial software. In other words, most of the solution algorithms for this method are paired with linear programming. When the number of scenarios is not large, these solution algorithms can be directly applied in programming (Sen 2001); otherwise, an approximation method should be employed (Baron et al. 2008).

Capacity planning problems are typically involved with integer variables, such as capacity amount, demand, decision variables (Binary variables) and time intervals (Engell et al. 2010). The optimisation-based method, which can manipulate such models, is called mixed-integer optimisation and in linear cases, it is called mixed-integer linear programming (MILP) (Heyman et al. 1984). When stochastic parameters are applied in these models in order to implement uncertainty in optimisation programming, mixed-integer stochastic programming will be developed (Yang 2009).

Since in the optimisation problem under uncertainty, one or some of the variables are stochastic, the optimised solution will also be random, and therefore impractical. Consequently, even in case of uncertainty and when the variables are random, we are looking for a unique optimal value as the final answer. One logical solution to such a problem is employing expected value to be optimised under different scenarios. This paradigm is called the resource stochastic model (Birge, John, R, 1997).

To transfer a resource stochastic model to a deterministic format and solve it, the easiest approach is to have an independent/enumerated scenario-based stochastic model. However, even if the scenario tree is employed, this format can be split into an enumerated scenario approach (Nagar et al. 2008), as described in figure 3-3.

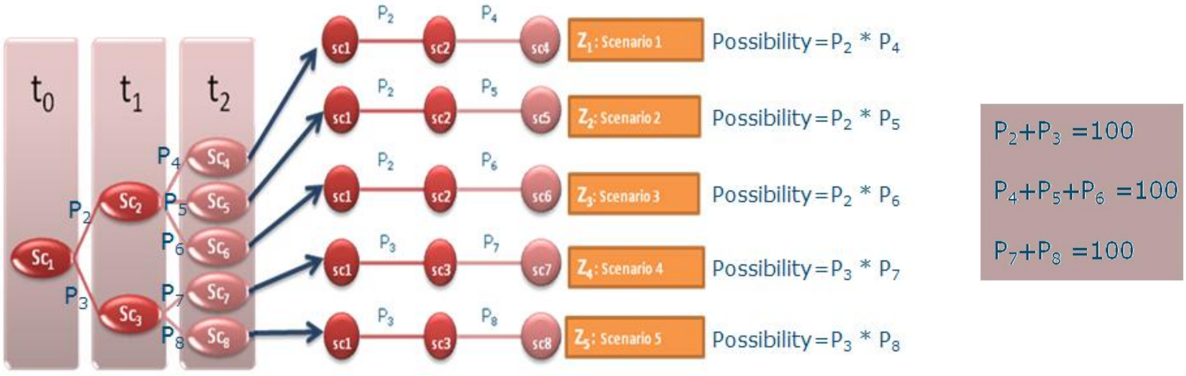


Figure 3-3: The procedure of splitting a scenario tree into separate enumerated scenarios

Finally, a set of independent scenarios with distinct probability for each scenario will result and values of the stochastic parameter for each scenario in each stage are known as input data in a database. The objective of the model is then optimising a function under the whole scenario plan. Therefore, the model objective can be formulated in general format of:

$$Max \sum_{z} P_z \sum_{t=0}^{T} F(X_{z,t}) \qquad z \in Z$$

In this objective, (z) represents the scenario number which belongs to the scenario set of Z, while P_Z is the probability of the scenario z. The variable $X_{z,t}$ shows the decision variable of the model in the time period (t) and under the scenario (z) and $F(X_{z,t})$ signifies the stochastic objective function.

Sets of constraints, including logical constraints, non-negative constraints, non-anticipative constraints, etc. should also be applied in the model to limit the solutions, as will be described in chapter 4 in detail.

3-2-4- Stochastic Modelling: Application in the Manufacturing Industry

Although employing the Stochastic technique in planning under uncertainty goes back to the 1960's (Dantzig 1955, Ferguson et al. 1956), using it in manufacturing capacity design and planning is relatively novel (Snyder 2006) and goes back to the 1990's (Frausto-Hernandez et al. 2010, Geng et al. 2009a). This novelty is mainly due to the previous limitation in computation power and suitable solution algorithms (Baron et al. 2008). Van Mieghem (2003) maintained that employing this approach in capacity planning turns up the brightness on the direct effect of uncertainty. Thanks to the soaring in computational abilities in recent years, solving stochastic programming (SP) models is becoming increasingly feasible and therefore, gaining more popularity in capacity design and planning models (Geng et al. 2009a). Snyder (2006) in the capacity location/relocation problems, and Azaron et al. (2008) in the investment decision making issues, illustrated how SP technique can offer a more robust result in the capacity design concept.

In their very recent successful work, Claro and Sousa (2012) developed a scenario-based multi-stage stochastic programming for capacity management, which was capable of considering demand uncertainty and financial risk at the same time as technology flexibility. They did not, however, adapt their model to any industry, or validate it with a real scale manufacturing problem (Claro et al. 2012). Nevertheless, many other successful scenario-based multi-stage stochastic optimisation models have been recently developed and employed in some manufacturing industries, such as the *automotive industry* (Bihlmaier et al. 2010), *electronics and semiconductor industry* (Geng et al. 2009b), *chemical industry* (Dal-Mas et al. 2011) and *pharmaceutical industry* (Colvin et al. 2009). These recent publications support the fact that developing scenario-based multi-stage stochastic optimisation models is a relatively new topic in manufacturing capacity management and this field is still hot for researchers.

3-2-5- Stochastic Modelling: Solution Algorithms and Programming Approach

The computational problem, solving time and solution algorithms are referred to by many reviewers as the solution challenges in this field (Chen et al. 2002). These issues for a real scale problem in the automotive industry (Ford Motor) are also reported by Chandra et al. (2005). In their model, which was not a very complex model and in which no product-to-plant allocation nor economies of scale were considered, a problem with 8 plants and 14 vehicles took 15 hours to solve (Chandra et al. 2005).

The size of the problem exponentially grows with the number of stages as well as the number of scenarios and stochastic parameters, especially for the mixed-integer stochastic programs such as capacity planning models (Yang 2009). Since a long-term capacity management model is aimed for by this research, a large number of stages (10-20 years) should be applied in a mixed-integer scenario-based stochastic optimisation framework (Eppen et al. 1989, Bhutta et al. 2003, Stray et al. 2006). Therefore, the size of the problem will be large, and directly depend on the number of scenarios and stochastic parameters. However, as discussed in chapter 2, rather than a single source of uncertainty, two sources of demand and sale price uncertainties have been chosen for this research, which soar the size of the problem.

Although the enumerated scenario approach will limit the number of scenarios, some other techniques should also be employed to reduce the problem size to a manageable scope. Another empirical way is to write the extended equations by using a programming and coding, rather than the more common compact format. In the extended format, exploiting a computer programing all the objective terms and constraints will be regenerated, using the database and actual values for each parameter. By adopting this approach, rather than expanding all equations for the whole parameters, only effective equations for non-zero parameters will be generated in programming. The effective equations are those which are defined by constraints and possibility matrixes. For example in this format, if a product is currently in production, no NPL-related formulations will be generated for that particular product; or if a product cannot be produced in a plant (based on the possibility matrix), no formulation for production, transportation, supply, etc. will be generated for this particular product in that particular plant. In this way, the total number of formulations, including the objective function and constraints, will be significantly reduced to a moderate and realistic size.

Using an extended format rather than a compact one, not only reduces the size and solution time of the problem, but also gives the opportunity to implement some extra parameters and constraints into the model such as the capacity expansion lead time (Naraharisetti et al. 2010, Fleischmann et al. 2006, Stray et al. 2006), the product development lead time (Papageorgiou et al. 2001, Colvin et al. 2009), the product lifetime (Fleischmann et al. 2006, Gatica et al. 2003, Papageorgiou et al. 2001), the possibility matrix (Kauder et al. 2009, Fleischmann et al. 2006, Karnik et al. 2009, Inman et al. 2001, Papageorgiou et al. 2001, Barahona et al. 2005), etc.

Relaxing the information by non-anticipative constraints is another method of decomposition algorithms, which is widely employed to solve multi-stage stochastic programming (Sen 2001). Non-anticipative constraints are employed in multi-stage stochastic programming to limit the sequential decisions to the known information (Fernandez et al. 1996). In other words, non-consequential decisions are those which, if made in earlier stages, cannot be easily modified in later stages in a rolling horizon basis (Escudero et al. 1995). Non-anticipative constraints cannot be applied to non-consequential decisions. An example of consequential and non-consequential decisions in a capacity design and planning model are production scheduling and capacity shutdown respectively, of which the former can be modified in later stages, while if a plant shutdown happens, it cannot be reopened later. In multi-stage problems, the choice between a sequential and a non-sequential decision depends on (Colvin et al. 2009):

1- The importance level of the decision being made in earlier stages.
2- Whether or not a rolling horizon approach is employed.
3- If a decision is taken in one stage, what source of modifying actions (decisions) can be made later. On the other hand, how easy is it to recover or modify the consequence of an early decision in a rolling horizon plan?

Non- anticipative constraints in this study will be developed and explained in chapter 4.

3-3- Computation

In the computation stage, the model logic and formulations should be coded into a programming language to let the user input data in the model, run the model and get the result. Therefore, an input database, solution software and a result generator are the three main elements of the computation phase. Microsoft Access® is very common commercial software for creating a database, and it has been previously employed in capacity management modelling (Silva Filho et al. 2007).

For the optimisation solution, on the other hand, commercial optimisation software called GAMS (General Algebraic Modelling System) is the most common software in this field of research, which is employed by many peer authors (Chakravarty 2005, Chen et al. 2002, Fleischmann et al. 2006, Verter et al. 2002, Gatica et al. 2003, Papageorgiou et al. 2001, Zhang 2007, Bhutta et al. 2003, Melo et al. 2006, Barahona et al. 2005, Ahmed et al. 2008, Silva Filho et al. 2007).

GAMS is an optimisation solver for large scale and complex modelling applications, which has its own programming language and compiler (GAMS 2011). As will be explained in chapter 4, the model in this study will be converted to a mixed-integer linear, after applying a series of non-anticipative constraints. Therefore, CPLEX module of GAMS software, which is argued to be the most powerful tool for such problems (GAMS 2011), will be employed in this study. The outcome from GAMS are numerical results, which show the optimised value of all decision making variables. This format of the result, however, is not easy to manipulate and understand by non-OR specialists (Fleischmann et al. 2006). Therefore, Microsoft Excel® is selected to export and visualise the result, as it is the most common software for general numerical application. GAMS provides this ability to export the result to Excel (GAMS 2010) and it facilitates this application.

However, to connect Microsoft Access®, GAMS® and Microsoft Excel® together, a new interim-application (software) should be generated. Such an interim-application makes the model easier to use for managers and decision makers, and closes the gap highlighted by Fleischmann et al. (2006). On top of commercialising the model and making it user-friendly, to generate an extended form of formulation, writing this interim-application is unavoidable (Fleischmann et al. 2006).

Visual Basic® compiler, due to its compatibility with Microsoft Office® (Mansfield 2008), is the best option to develop such an application. Although Fortran® has also been used for programming in strategic capacity management modelling (Verter et al. 2002), Visual Basic® has already established its function as a strong compiler to develop application/software for this purpose (Silva Filho et al. 2007, Wu et al. 2010). Therefore, Visual Basic 2008® was chosen to develop this interim-application in this project. However, it should be admitted that the programming approach for this purpose suffers from the important disadvantage of significant effort to write the codes, as will be described in chapter 4 and shown in appendix B.

3-4- Validation

Pidd (2003) stated: "A model is representation of the real world, or at least part of it. All we have to do is check that model behaves as the real-world does under the same conditions. If it does, then the model is valid". However, validation is a complex practice in nature and it is not always easy to compare the model with the 'reference system' (Pidd 2003). Moreover, the outcome data from the reference system are not always available for different circumstances to compare with the results from the model (Pidd 2003). That is why, "Validation is the most incomprehensive part of developing a model", despite the fact that it is an inevitable part of a model development, which brings creditability to the model (Martis 2006).

The following statements are highlighted for identifying the characteristics of a validation process:

- "A model should be judged for its usefulness rather than its absolute validity" (Martis 2006).
- A model will develop for a particular application and under distinct circumstances. These applications and circumstances should be considered when it comes to validation (Kempf et al. 2011a).
- Validation should be a continuous procedure throughout the model development to help the modellers to continuously revise their modelling approach and methods (Pidd 2003).
- Validation should be done at least in some distinct phases, including component level, whole-system level and benchmark cases (Oberkampf et al. 2004).

- There is no single set of tests to validate a model; but, the level of confidence gradually increases as the model passes more tests (Galanakis 2002).
- Rejecting a model for its failure to generate an exact result of past data or a specific future event is not acceptable, because of the fact that social systems operate in wide noise frequencies (Martis 2006).

The model validation approaches can be categorised in two main groups of black-box and open-box (white-box) validations (Pidd 2003).

Black-Box Approach: In this approach, the model is assumed as an input-output system, with unknown internal architecture. In such an approach the model will be validated by the degree of the result's conformity with the expected outcomes from the real system, under the same circumstances. Therefore the black-box validation reflects the perspective power of the model, aside from which details are implemented in the model (Pidd 2003). "The aim of the black-box validation is not to test whether a model and its reference system produce the same results. Rather, the aim is to test whether the two sets of observations are close enough to be confident that the model has adequate validity" (Pidd 2003). The validations of quantitative models are relatively easy, if dummy data are employed. Different simplified cases with a variety of input data should be run and the results should be checked in terms of rationality (Pidd 2003), because real data for one single case under different circumstances in strategic business-related subjects is rare and expensive or even impossible to generate (Troitzsch 2004).

Although the black-box validation procedure is complex and sometimes impossible for the techniques such as system dynamic, simulation, etc. (Martis 2006), in case of optimisation models with simplified cases, this type of validation procedure is often quite straightforward (Pidd 2003, Martis 2006).

Open-Box Approach: The opposite extreme to the black-box approach is open-box validation, which maintains that the internal structure of the models is known at least to the modellers. In this approach, the detailed internal structure of the model should be compared with the key features and perspectives of the reference system (Pidd 2003). The open-box validation is not a test to validate a final model but it is a part of the modelling development, which should be taken into account when the logic and method of the model is being established, with relation to its application (Pidd 2003). In the open-box approach, to establish an acceptable level of confidence in the model structure, Martis (2006) suggests the following tests to be done:

- **Test of Suitability:** Including the following tests:
    - *Structure verification tests:* There should not be a major conflict between the structure of the model and the reference system's structure.

    - *Dimensional consistency tests:* The dimensions of variables should be balanced on both sides of each equation.
    - *Extreme condition & Boundary adequacy tests:* Every equation should make sense, even in extreme (but possible) cases.
- **Test of Consistency:** Including the following tests:
    - *Face validity tests:* The model should recognisably represent the reference system.
    - *Parameter Verification tests:* The parameters and their values should have correspondent equivalents in the reference system.
- **Test of Utility and Effectiveness:** Including the test:
    - *Appropriate for audience*: "Is the size of the model, its simplicity or complexity, and its level of aggregation or richness of detail appropriate for the audience of the study? … The more appropriate a model for the audience the more will be the audience's perception of model validity."

As mentioned earlier, open-box validation and testing the model structure with the abovementioned questions is a continuous practice in the model development phase, and gives a road-map and an instruction to develop a robust model, rather than to test a ready-made model (Pidd 2003).

In case of optimisation models, "The solution procedure is elegant and correct"; and as far as the optimisation model keeps its descriptiveness of the reference system, it is easy to validate the optimisation models (Martis 2006). In other words, model descriptiveness is a very good indicator to validate such models (Moss 2001). It implies the relative importance of the open-box approach in the validation procedure for the optimisation-based models in comparison to the black-box validation. Very few recent optimisation-based models in the scope of capacity planning have been validated by real data, and the rest of the modellers have just sufficed to hypothetical data and simplified cases for black-box validation (Naraharisetti et al. 2010, Aghezzaf et al. 2010, Kauder et al. 2009, You et al. 2009, Frausto-Hernandez et al. 2010, Colvin et al. 2009, Lusa et al. 2011).

The concept of the open-box paradigm will be employed in this research to develop the logic and model formulations in chapter 4, from the strategic terms and reference system which are explained in chapter 2. Then in Chapter 5, employing the black-box approach, a set of structured hypothetical cases will be used to verify and validate the final model. The ability of the model to deal with real-scale industrial cases will then be demonstrated in chapter 6 for an automotive reference system.

Chapter 4 : The Model Framework

4-1- Model's Outline and Conceptual Framework

Having reviewed the major strategic terms for an integrated global capacity management model in chapter 2 as well as the best possible modelling technique and programming approach in chapter 3, in this section an outline of a successful capacity planning model is analysed. The *Input*, *Controls, Output* and *Mechanism* framework (Matta et al. 2005), which was introduced in chapter 2, is employed in this section to match the modelling framework to the purpose of this research. This outline is illustrated in figure 4-1. This framework establishes a road-map for the whole modelling development concept and demonstrates a logical backbone of the formulations, which come later in this chapter. Details of each box in this figure have been expanded, checked and continuously improved in a dynamic procedure to be verified by an open-box approach, as explained in chapter 3. In this open-box approach, the output results, constraints and required database have been frequently updated with the aims and objectives of this research as well as the highlights from the literature review and methodology chapters.

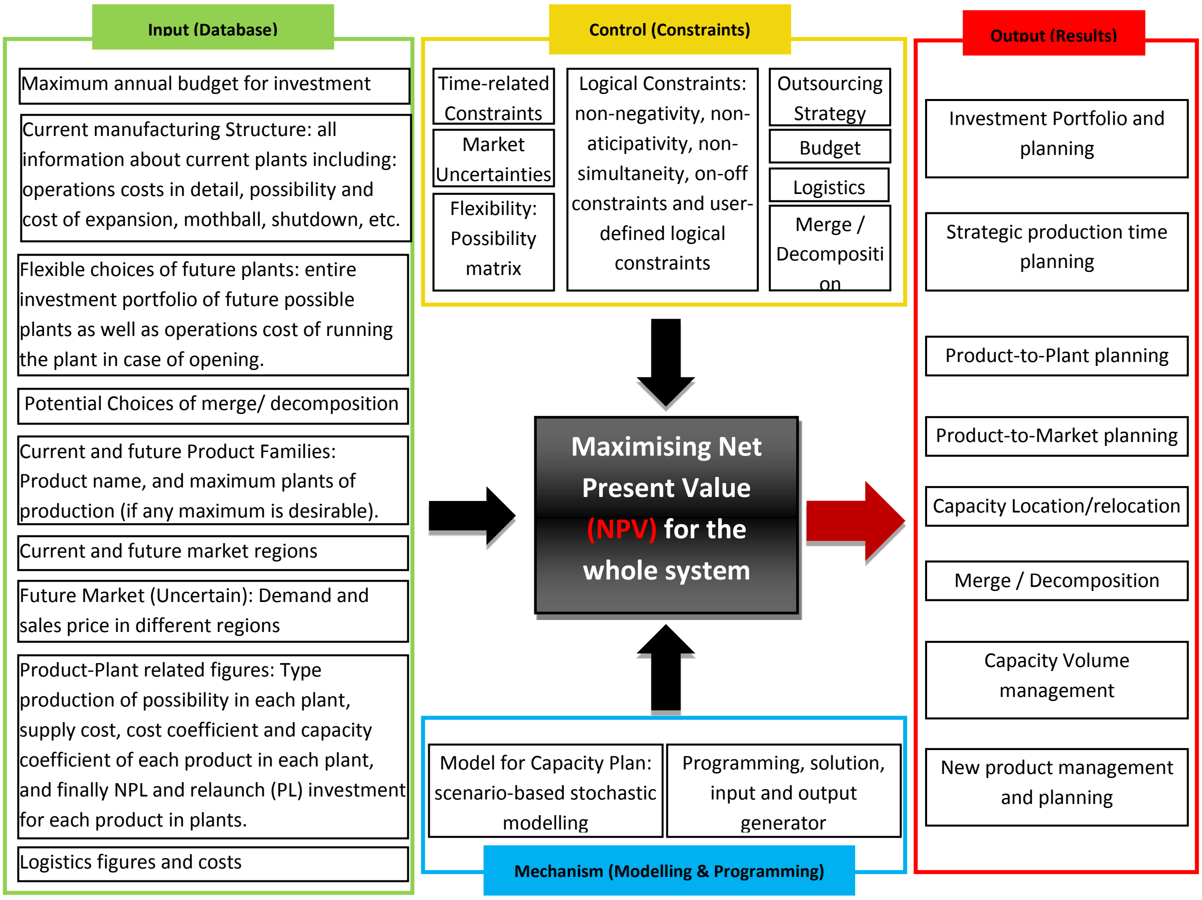


Figure 4-1: The Model's Framework in an *ICOM logic*

Having the list of inputs and outputs in figure 4-1, a table of nomenclatures is presented in table 4-1 for further reference in the model development. This list is also represented in appendix A, with more details and explanations.

Table 4-1: Nomenclatures list for the model formulation. More details are given in Appendix A.

Indices			
z	Scenario	i	plant
t	time interval	j	product
r	sales region		
Parameters (inputs)			
ρ	Discount rate	$\mu_{i_i}^{Max}$	Normal capacity ratio (out of maximum cap.)
σ_i^{Tax}	Profit tax rate in plant i location	γ_{ij}	$\in [0,2]$ Cap. volume rate of product j in plant i
σ_r^{VAT}	Value added tax in region r	C_{ij}^{Sup}	Unit cost of supply for product j in plant i
σ_{ri}^{Tariff}	Tariff rate of import from plant i to region r	C_{rij}^{D}	Unit cost of transp. product j from plant i to region r
Δ^{oper}	Inflation rate on operations cost	$C_{rj}^{Penalty}$	Unit unmet demand penalty for product j in region r
Δ^{Inv}	Inflation rate on investment cost	C_{ij}^{Unit}	Any other unit cost of producing product j in plant i
Δ^{Sup}	Inflation rate on supply cost	$C_{z,t,r,j}^{Sale}$	Unit sales price of product j in region r in year t and scenario z
Δ^{D}	Inflation rate on transportation cost	η_i^{New}	Investment timetable to establish plant i
Δ^{Unmet}	Inflation rate on unmet demand penalty	η_i^{Exp}	Investment timetable to expand plant i
I_i^{New}	Capital investment to establish new plant i	η_{ij}^{NPL}	Timetable of launching product j in plant i for the first time
I_i^{Exp}	Capital investment to expand plant i	$\eta_j^{R\&D}$	Investment timetable to design the new product (j)
I_i^{Fr}	Capital investment to mothball plant i	E_i	Maximum number of times for possible expansion for plant i
I_i^{Re}	Capital investment to reopen plant i, if it has been mothballed	$\vartheta_i^{E-\min}$	Min. capacity expansion rate of plant i, out of nominal cap.
I_i^{On}	Capital investment to overutilise plant i	$\vartheta_i^{E-\max}$	Max. capacity expansion rate of plant i, out of nominal cap.
$I_i^{Workforce}$	Annual work force cost of plant i	ε_i^{OnA}	Increase rate on labour cost, in case of overutilisation
I_i^{Opr}	Annual operations cost of plant i	ε_i^{Exp}	Increase rate on labour cost, in case of plant expansion
I_i^{OprExp}	Extra annual operations cost of plant i, if it has been expanded	ε_i^{Fr}	Redundancy rate on labour cost, in case of plant mothball
I_i^{OperFr}	Annual maintenance cost of plant i, if it has been mothballed	l_i	Maximum number of plants to produce product j
$I_{i,j}^{NPL}$	Cost of launching product j in plant i for the first time	$n_i^{\max}$	Maximum possible products to be produced in plant i
$I_{i,j}^{PL}$	Cost of relaunching product j in plant i, after a production break	d_{ztrj}	Demand for product j in region r in year t under scenario z
$I_j^{R\&D}$	Cost of designing product j in research centre/headquarter	b_t	Maximum investment budget in year t
I_i^{Cl}	Fixed cost of shutting down plant i	M	A very large number
$K_i^{Initial}$	Nominal capacity of plant i, before any volume change	P_z	Probability of scenario z
n_i^{merge}	How many plants should be merged together to form plant i	P_i^{merge}	The combination of the plants that should be merged (see Cons.21)
Decision variables (outputs)			
X_{ztij}^{A}	Production no. of product j in plant I in year t, under scenario z	K_{zti}^{Re}	Reopened cap. amount of plant i in year t under scenario z
Y_{ztij}^{A}	Binary decision variable corresponding to X_{ztij}^{A}	Y_{zti}^{Re}	Binary decision variable corresponding to K_{zti}^{Re}
X_{ztrij}^{D}	Transp. no. of product j from plant i to region r in year t, scenario z	K_{zti}^{Exp}	Expanded cap. amount of plant i in year t under scenario z
X_{ztrj}^{Unmet}	Unmet number of product j in region r in year t under scenario z	Y_{zti}^{Exp}	Binary decision variable corresponding to K_{zti}^{Exp}
Y_{zti}^{On}	Binary Dec. Var.: if in year t and scenario z plant i is overutilised	$Y_{zti}^{ExpOveral}$	Binary var. showing whether plant i has ever been expanded
K_{zti}^{Max}	Nominal cap. of plant i in year t under scenario z	K_{zti}^{FrAll}	Available amount of mothballed capacity for plant i in year t
K_{zti}^{Cl}	Shutdown cap. amount of plant i in year t under scenario z	Y_{zti}^{FrAll}	Binary decision variable corresponding to K_{zti}^{FrAll}
Y_{zti}^{Cl}	Binary decision variable corresponding to Y_{zti}^{Cl}	Y_{ztij}^{NPL}	Binary var. showing if NPL happens for product j in plant i
K_{zti}^{Fr}	Mothballed cap. amount of plant i in year t under scenario z	Y_{ztij}^{PL}	Binary var. showing if PL happens for product j in plant i
Y_{zti}^{Fr}	Binary decision variable corresponding to K_{zti}^{Fr}	$Y_{ztj}^{R\&D}$	Binary var. if product j is designed in year t & scenario z
Y_{zti}^{Opr}	Binary var. showing if plant i is in use in year t and scenario z	$Y_{zti}^{ExpWforce}$	Binary var. if in-use plant i has ever been expanded earlier
Z_{zti}^{New}	Binary var. showing if plant i is established in year t & scenario z	Y_{ztj}^{Dep}	Binary var. if the plant is open or frozen (subject to depreciation)

Having this framework (figure 4-1) and the list of indices, outputs and inputs (table 4-1), the mechanism with which the model works is established and illustrated in figure 4-2. This figure provides a structural picture of the modelling approach in this research.

As can be seen from this figure, the model, which is set in a ‘scenario-based stochastic’ format, is managed by the programming driving force. This analytical model, then, drives the whole system to make it optimised. This system consists of the model’s objective (NPV), which is constrained and controlled by flexibility options, time-related constraints, market uncertainties, and some other logical constraints. Logical constraints comprise non-negativity, non-anticipativity, non-simultaneity, on-off constraints and user-defined logical constraints.

With reference to this outline of the model’s mechanism, when the constrained objective is optimised by the analytical model and programming method, the results will be generated and released to the user. These results show the balanced figures of the output terms and decision variables in an optimised situation. It is noticeable that these optimised figures may be changed by changing inputs and the model’s system. Therefore, one can optimise and see the best possible results for different sets of input, including different market scenarios, products and plants inputs, logical constraints, etc. This would provide some strategic perspectives for top managers of a company to see the effect of implementing different policies and making possible changes.

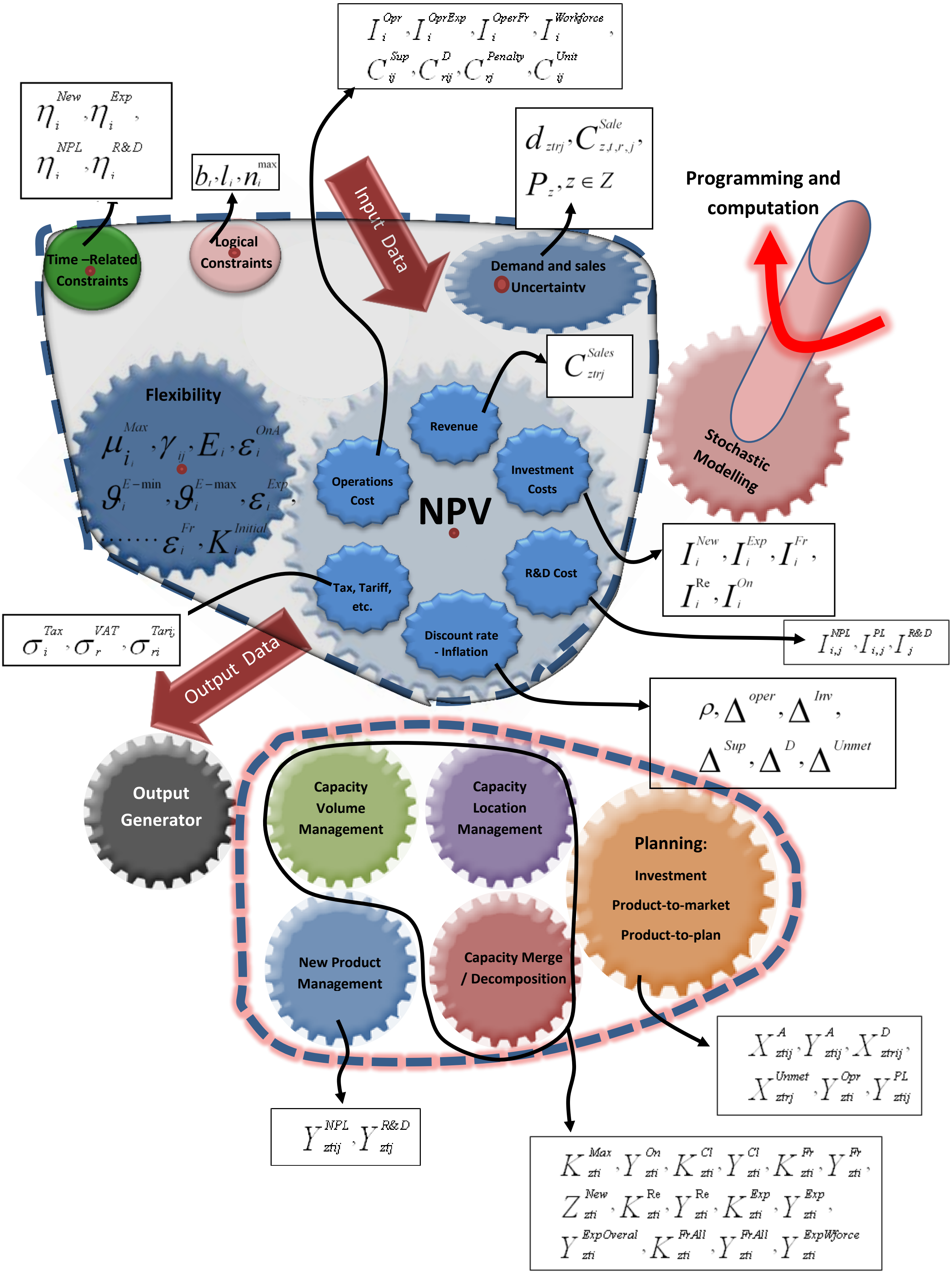


Figure 4-2: The model's working mechanism

4-2- Objective Function

As targeted in chapter two, the net present value (NPV) under uncertainty is identified as the best possible objective for this scenario-based stochastic capacity planning model. The time interval for strategic capacity planning should be long enough so that production levels can be altered within the time period to satisfy the demand level, as closely as possible (Verderame et al. 2010). A one-year interval is suggested for strategic capacity planning by many researchers (Verderame et al. 2010, Fleischmann et al. 2006). Furthermore, capacity planning should be done in a long-term horizon (Eppen et al. 1989). If a short or mid-time planning horizon is considered for capacity planning, the decisions are directed towards more tactical solutions such as temporary overutilisation, rather than investment, which causes sub-optimal results (Stray et al. 2006). A 10-year time plan is highlighted as a typical time horizon for a high technology manufacturing capacity (Bhutta et al. 2003). In the automotive industry Kauder and Meyr (2009) support a ten years' time horizon, while Fleischmann et al. (2006) employed a 12-year horizon. Therefore it is better to set *T* in this objective formula in the range of 10 to 15 years, depending on the product life cycle and setup lead times.

All the costs but the R&D cost of the NPD can be grouped in a plant-based category. In other words, except for the R&D investment and the design phase, which can be carried out in research centres or headquarters, all other production or investment costs will be done in the plants. Having said that, it should be noted that the major proportion of the NPD cost, which is the new product launch cost (NPL), is a plant-based cost. The NPL includes purchasing new production lines, tooling, technology, changing production layout, staff training, etc.

Since the R&D costs are not plant-based costs, we have to ignore the tax on this part of NPD costs to simplify the formulations and computation. Due to the fact that many countries have tax-free incentives on R&D centres and also since this cost constitutes a very small proportion of the NPD cost, this assumption has no significant effect on the final result.

Therefore, the objective function of this model is formulated in general format of 'Interim Obj.1:

Interim Obj.1

$$\text{Max(NPV)} = Max\sum_{z} P_z \sum_{t=0}^{T} \left(1+\rho\right)^{-t} .\{ [\sum_{i} \overset{\text{Profit tax}}{(1-\sigma_i^{Tax})}.(\overset{\text{Revenue}}{\mathrm{Re}\,v_{z,t,i}} - \overset{\text{Investment Costs}}{Inv_{z,t,i}} - \overset{\text{Operations Costs}}{Oper_{z,t,i}})] - \overset{\text{R\&D Costs}}{R\&D_{z,t}} \}$$

In this formula, P_z is the probability of scenario (z), ρ is the discount rate, σ_i^{Tax} is the tax rate in each plant (i), *t* is the time interval, and *T* is the maximum time interval. According to table 4-1 and appendix A, $\mathrm{Re}\,v_{z,t,i}$, $Oper_{z,t,i}$ and $Inv_{z,t,i}$ are revenue, operations costs and investment costs, respectively, in time interval *t* and under scenario *z* and in plant *i*.

$R\&D_{z,t}$, on the other hand, is the product design-related part of the NPD in year *t* and under scenario *z*, which is a plant-independent cost, as explained earlier.

Now every term of the objective function will be extended, as per below.

4-2-1- Total Sales and Revenue

Revenue ($\mathrm{Re}\,v_{z,t,i}$) comes from the sales price[1] ($C^{Sale}_{z,t,r,j}$) of products (*j*), which are produced in plant (i), to be sold in sales region[2] (*r*) in year (t) and under scenario (z), which is an input in the model, according to table 4-1 and appendix A.

$$\mathrm{Re}\,v_{z,t,i} = \sum_{r,j} (C^{Sale}_{z,t,r,j} \cdot X^{D}_{z,t,r,i,j}) \qquad \forall t,z,i$$

Formula 01

$X^{D}_{z,t,r,i,j}$ is a product-to-market decision variable[3]. In other words, it shows the model's suggestion for the number of products (*j*) which should be transported from plant (*i*) to the sales region (*r*) in year (*t*) under scenario (*z*). [4]

---

[1] Sales price in one of two uncertain inputs (the other one is demand). This is why (z) has appeared in this input.

[2] Such as Fleischmann et al. (2006), we divided the global market into some sales regions to consider the strategic effect of distribution costs on capacity design and management. These regions will be defined by the model users. However, sales regions can be simply the countries where the company sells its products.

[3] Strategic decisions of YES/NO involve binary variables, and many tactical decisions such as load-planning decisions are described by integer values (Bihlmaier et. al. 2010)

[4] This decision-making variable covers one of the main aims of a successful aggregated capacity planning model (Van Mieghem 2003).

4-2-2- Investment Costs

The investment-related cost ($Inv_{z,t,i}$) and decision consist of:

- **Investment in establishing a new capacity:** The investment cost of establishing a brand new plant includes all required capital investment for the land, buildings, production lines and facilities, fixed cost of hiring and training employees etc. Such an investment might be done over some years and needs an investment lead time.

$I_{ti}^{New} \cdot \eta_i^{New} \cdot Z_{zti}^{New}$	Inputs: 1- I_{ti}^{New}, capital cost of establishment; 2- η_i^{New} , Investment lead time (schedule)	Decision variable: Z_{zti}^{New}, binary variable saying whether or not the plant (i) is established in year (t)

- **Capacity expansion:** The investment to expand a plant includes all required capital investment for land, new buildings, new production facilities, training of the new employees, etc.

$I_{ti}^{Exp} \cdot \eta_i^{Exp} \cdot Y_{zti}^{Exp}$	Inputs: 1- I_{ti}^{Exp}, capital cost of Expansion; 2- η_i^{Exp} , Investment lead time (schedule) for expansion	Decision variable: Y_{zti}^{Exp}, binary variable saying whether or not the plant (i) is expanded in year (t)

- **Temporary Capacity Mothballing:** The fixed cost of mothballing a current capacity includes the fixed cost of redundancy, terminating the suppliers' contracts and any other cost which is directly or indirectly imposed on the company with the mothballing decision. Mothball decisions do not need a lead time over one year.

$I_{ti}^{Fr} \cdot Y_{zti}^{Fr}$	Inputs: 1- I_{ti}^{Fr} , Fixed cost of mothballing plant (i) in year (t)	Decision variable: Y_{zti}^{Fr}, binary variable saying whether or not the plant (i) is being mothballed in year (t)

- **Overutilisation Fixed Cost:** Utilising a plant near its maximum (nominal) capacity requires a fixed cost (investment) in possible changes in layout, training the staff, etc and some extra annual operations costs. This annual investment and operations costs, however, is not a one-off cost and is required every year the plant goes overutilised. It is, however, lead time free and no over one-year planning on investment is required. In other words, a one year time period is enough to make the plant ready for overutilisation.

$I_{ti}^{OnA} \cdot Y_{zti}^{OnA}$	Inputs: 1- I_{ti}^{OnA} , Fixed cost of overutilising plant (i) in year (t)	Decision variable: Y_{zti}^{OnA} , binary variable saying whether or not the plant (i) is being overutilised in year (t)

- **Reopening a Mothballed Capacity:** The cost of reopening a mothballed capacity includes training new employees, any updates and changes in process layout and machineries, etc. This decision, however, does not need an investment lead time of more than a year.

$I_{ti}^{\mathrm{Re}} \cdot Y_{zti}^{\mathrm{Re}}$	Inputs: 1- I_{ti}^{Re} , Fixed cost of reopening mothballed plant (i) in year (t)	Decision variable: Y_{zti}^{Re}, binary variable saying whether or not the mothballed plant (i) is being reopened in year (t)

- **Permanent Shutdown of a Capacity:** Very seldom, capacity can be disinvested with no cost (reversible/frictionless investment), and mostly a fixed cost is required for capacity reduction

(Van Mieghem 2003). However, if a plant shutdown decision is made, part or all of the cost can be covered by salvaging the machineries, selling the equipment, building and land etc. The shutdown cost, however, includes redundancy costs, costs of terminating suppliers' contracts and any other direct or indirect costs of a plant shutdown. One of the indirect costs of closing down a plant is the cost of damaging the brand image.

$I_{ti}^{Clo} \cdot Y_{zti}^{Clo}$	Inputs: I_{ti}^{Clo}, Fixed cost of shutting down plant (i) in year (t)	Decision variable: Y_{zti}^{Clo}, binary variable saying whether or not plant (i) is being shut down in year (t)

- **New Product Launch:** If a product is launched in an existing facility for the first time, a first-time launch cost will be applied. It includes all required product-related investment, including new lines, tooling, machines, settings, training, scrap costs in the first year, etc. Launching a product in a plant for the first time may need an over one-year investment plan.

$\sum_j I_{tij}^{NPL} \cdot \eta_{i,j}^{NPL} \cdot Y_{ztij}^{NPL}$	Inputs: 1- I_{tij}^{NPL}, investment cost of launching product (j) in plant (i) in year (t) for the first time; 2- η_{ij}^{NPL} : Investment lead time	Decision variable: Y_{zti}^{NPL}, binary variable saying whether or not the product (j) is subject to NPL in plant (i) in year (t)

- **Re-launch a Product:** If a product is being launched in a production plant after more than a one year production-break, a reset cost of relaunching will be applied to the production site. This setting, however, can be done within one year and does not need any investment lead time. Since in the case of a first-time launch, the model recognises the situation as 'production after break' and makes Y_{ztij}^{PL}=1, in the below formulation $(Y_{ztij}^{PL} - Y_{ztij}^{NPL})$ has been applied to avoid applying a relaunch cost for first-time launch cases.

$\sum_j I_{tij}^{PL} . (Y_{ztij}^{PL} - Y_{ztij}^{NPL})$	Inputs: I_{tij}^{PL}, investment cost of relaunching product (j) in plant (i) in year (t) after a production-break of over one year	Decision variable: Y_{zti}^{PL}, binary variable saying whether or not the product (j) is subject to NPL in plant (i) in year (t)

Bringing all these terms together, 'Formula 02' below expands $Inv_{z,t}$ from the main NPV objective equation. This part not only brings a comprehensive set of investment terms, but also implements the investment lead time in the model.[5]

Formula 02

New capacity Investment | Invest to expand capacity | Invest to mothball | Over normal utilization Fixed cost

$$Inv_{z,t} = \sum_i [I_{ti}^{New} \cdot \eta_i^{New} \cdot Z_{zti}^{New} + I_{ti}^{Exp} \cdot \eta_i^{Exp} \cdot Y_{zti}^{Exp} + I_{ti}^{Fr} \cdot Y_{zti}^{Fr} + I_{ti}^{OnA} \cdot Y_{zti}^{OnA}$$
$$+ I_{ti}^{Re} \cdot Y_{zti}^{Re} + I_{ti}^{Clo} \cdot Y_{zti}^{Clo} + \sum_j (I_{tij}^{NPL} \cdot \eta_{i,j}^{NPL} \cdot Y_{ztij}^{NPL} + I_{tij}^{PL} . (Y_{ztij}^{PL} - Y_{ztij}^{NPL}))]$$

Invest to reopen a frozen capacity | Invest to Close down a capacity | Invest to Launch a product in a new line | Re-launch cost of products

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[5] Lead time (as a dimension of flexibility/agility) of both capacity acquisition and product launch should be implemented in the capacity management models (Elkins et. al. 2004)

Since capacity increase/upgrade is time-consuming (Matta et al. 2005), $\eta_i^{New}, \eta_i^{Exp}, \eta_i^{NPL}$ are respectively defined as investment timetables/schedules for the new plant establishment, capacity expansion and finally new product launch. Table 4-1 illustrates an input example for more clarification. η defines the investment schedule for each year before and after the running year. In this table, $\eta_{i,t}^{Exp}$, for instance, shows that investment lead time for expanding plant (i) to start to be utilised in year (t) is 4 years, including 2 years before (t) the year (t) itself and one year after running. This table also explains how investment scheduling and distribution will be done for this decision: 15% of the total investment will be done in (t-3), 35% in (t-2) and so forth.

Table 4-2: An example of investment timetables. The features are proportions of the total required investment

	5 years before running	**4 years before running**	**3 years before running**	**2 years before running**	**1 year before running**	**Running Year**	**1 year after running**	**2 years after running**	**Total**
$\eta_{i,t}^{New}$	5%	10%	15%	30%	25%	10%	5%	0	100%
$\eta_{i,t}^{Exp}$	0	0	15%	35%	50%	5%	0	0	100%
$\eta_{i,t}^{NPL}$	0	0	0	15%	55%	20%	10%	0	100%

4-2-3- Operations costs

Operations costs consist of:

- **Transportation cost:** unit-based cost of transportation of the products from the production plant to the sales region.

$C_{trij}^{D} \cdot X_{ztrij}^{D}$	Inputs: C_{trij}^{D}, unit cost of transporting product (j) from plant (i) to sales region (r) in year (t).	Decision variable: X_{ztij}^{D}, integer variable showing the number of product (j) which is transferred from plant(i) to sales regions (r) in year (t) Under scenario (z)

- **Work force cost:** This is the total annual cost of the work force for the plant, which makes the model sensitive to strategic work force decisions. This cost consists of:
    - Annual work force cost of normal production

$I_{t,i}^{Workforce} \cdot Y_{zti}^{Dep}$	Inputs: $I_{t,i}^{Workfor}$, Annual work force cost of plant (i) in year (t).	Decision variable: Y_{zti}^{Dep}, binary variable showing if plant (i) in year (t) and under scenario (z) is subject to depreciation (open or mothballed but not closed or optional)

- Additional annual work force cost in case of overutilisation

$\varepsilon_{i}^{OnA} \cdot I_{t,i}^{Workforce} \cdot Y_{zti}^{OnA}$	Inputs: 1- $I_{t,i}^{Workforc}$, Annual work force cost of plant (i) in year (t); 2- ε_{i}^{OnA} work force increase rate of overutilisation for plant (i)	Decision variable: Y_{zti}^{OnA}, binary variable showing if plant (i) in year (t) and under scenario (z) is overutilised.

- Additional annual work force cost in case of plant expansion

$\varepsilon_{i}^{Exp} \cdot I_{t,i}^{Workforce} \cdot Y_{zti}^{ExpWforce}$	Inputs: 1- $I_{t,i}^{Workforce}$, Annual work force cost of plant (i) in year (t); 2- ε_{i}^{Exp} work force increase rate of expanding plant (i)	Decision variable: $Y_{zti}^{ExpWforce}$, binary variable showing if plant (i) has ever been expanded before year (t) and under scenario (z) and has not been closed or mothballed earlier.

- Annual work force cost reduction due to redundancy in case of plant mothball

$-\varepsilon_{i}^{Fr} \cdot I_{t,i}^{Workforce} \cdot Y_{zti}^{FrAll}$	Inputs: 1- ε_{i}^{Exp}, Annual work force cost of plant (i); 2- ε_{i}^{Fr} work force redundancy rate of for plant (i) in case of mothball	Decision variable: Y_{zti}^{FrAl}, binary variable showing if plant (i) has been mothballed before or in year (t) and has not been opened earlier, under scenario (z)

- **Value added tax and custom duty costs**: Custom duty[6] and VAT[7] calculated on the total sales figures, in different sales regions.
    - *Custom duty:*

$\sigma_{ri}^{Tariff} \cdot C_{ztrj}^{Sale} \cdot X_{ztrij}^{D}$	Inputs: 1- C_{ztrj}^{Sale}, unit price of product (j) in sales region(r) in year (t) under scenario (z); 2- σ_{rj}^{Tariff} tariff rate from plant (i) to region (r)	Decision variable: X_{ztrij}^{D}, integer variable showing the number of transported (sold) product (j) from plant (i) to region (r) in year(t), under scenario (z).

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[6] Custom duty is one of the most important factors in investment and location/relocation decisions (Chakravarty 2005).

[7] If the direct customer of the company is the end user of the product, the VAT rate should be input in the model. Otherwise, VAT=0 will be inputted.

- *VAT after tariff:*

$$\sigma_r^{VAT}(1+\sigma_r^{Tariff}).C_{ztrj}^{Sale}\cdot X_{ztrij}^{D}$$

Inputs: 1- σ_{rj}^{Tariff}, unit price; 2- σ_{rj}^{Tariff} tariff rate from (i) to region (r); 3- VAT σ_r^{VAT} rate in region (r)

Decision variable: C_{ztrj}^{Sale}, integer variable showing the number of transported (sold) product (j) from plant (i) to region (r) in year(t), under scenario (z).

- **Operation, maintenance and overhead costs:** Excluding work force, transportation, overutilisation and supply costs, which are already discussed in the other terms, any other annual fixed cost will be implemented here. This cost may include costs of utilities, maintenance, overhead, quality, marketing, etc. for every plant in operation (but not for mothballed or closed plant

$$I_{ti}^{Opr}\cdot Y_{zti}^{Opr}$$

Inputs: I_{ti}^{Opr}, annual operations cost of plant (i) in year (t), including: Utilities, overhaul, overhead, marketing, etc.

Decision variable: Y_{zti}^{Opr}, binary variable showing if plant (i) is in operation (not mothballed or closed and not optional) in year (t) under scenario (z)

- **Operation, maintenance and overhead costs of expanded capacity:** Any expanded plant has got two parts. The first one is the original capacity and the second one is the expanded capacity. The operations cost of the original capacity has been explained earlier. This part, however, explains the operations cost of the expanded part. However, this cost should only be applied to the in-use expanded capacities, not to any plant which has been expanded earlier and is now mothballed or closed (just like what was discussed for extra work force for an expanded capacity).

$$I_{ti}^{OperExp}\cdot Y_{zti}^{ExpWforce}$$

Inputs: I_{ti}^{OprE}, annual operations cost of plant (i) in year (t), including: Utilities, overhaul, overhead, marketing, etc.

Decision variable: $Y_{zti}^{ExpWforce}$, binary variable showing if plant (i) has ever been expanded before year (t) and under scenario (z) and has not been closed or mothballed earlier.

- **Annual holding cost of the mothballed plants:** Any cost of holding and maintaining a mothballed plant.

$$I_{ti}^{OperFr}\cdot Y_{zti}^{FrAll}$$

Inputs: I_{ti}^{OperFr}, annual holding and maintaining cost of mothballed plant (i) in year (t).

Decision variable: Y_{zti}^{FrAll}, binary variable showing if plant (i) has been mothballed at some point before (t) and not reopened earlier, under scenario (z).

- **Supply Cost and other Unit-Based Costs:** This model is not aimed at designing the supply chain network. However, the location sensitive supply cost of material will be applied in the model.[8]
In addition to supply costs, any other unit-based cost of production, which has not been counted in any earlier term can be applied to a separate input parameter for production of each

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[8] To avoid unrealistic simplification of ignoring supply chain network design on capacity location and planning, the location sensitive supply cost of material has been supported by many researchers to be implemented in the modelling procedure (Dal-Mas et. al. 2011).

product in each plant. This parameter opens up a free-hold parameter for the model users to input any unit-based costs that they are willing to add.

$$(C^{Sup}_{tij} + C^{Unit}_{tij}) \cdot X^{A}_{ztij}$$

Inputs: 1- C^{Sup}_{tij}, unit supply cost of material and subassemblies for product (j) to plant (i) in year (t); 2- C^{Unit}_{tij}, any other unit-based cost of production.

Decision variable: X^{A}_{ztij}, integer variable showing the number of product(j) to be produced in plant (i), in year (t), scenario (z)

- **Unmet demand Penalty (cost):** Any unit-based penalty for unsatisfied demand should be applied here to make the model more sensitive to the unmet orders. Without this term (=0), the decisions would be neutral to unmet demand.[9] We assume that unmet demand is lost, or goes to the competitors. Moreover, since this cost is rather a fortune cost than a real cost, no tax-related calculations can be done on this cost, which should be noticed in the final objective expansion.

$$C^{Unmet}_{trj} \cdot X^{Unmet}_{ztj}$$

Inputs: C^{Unm}_{trj}, unit penalty cost of unmet demand for product (j) in sales region (r) in year (t).

Decision variable: X^{Unm}_{ztj}, integer variable showing the number of unmet demand for product (j)in sales regions (r) in year (t) Under scenario (z)

Bringing all these terms together, 'Formula 03' below expands $Oper_{z,t}$ from the main NPV objective equation.

Formula 03

Transportation costs

Work force cost of normal utilisation

Work force cost of overutilisation

Work force cost of expanded Capacity

Work force cost cut due to mothball

$$Oper_{z,t} = \sum_{i} [\sum_{rj} C^{D}_{trij} \cdot X^{D}_{ztrij} + I^{Workforce}_{t,i} \cdot (Y^{Dep}_{zti} + \varepsilon^{OnA}_{i} Y^{OnA}_{zti} + \varepsilon^{Exp}_{i} Y^{ExpWforce}_{zti} - \varepsilon^{Fr}_{i} Y^{FrAll}_{zti})$$

$$+ \sum_{r,j} (\sigma^{Tariff}_{ri} + \sigma^{VAT}_{r} (1 + \sigma^{Tariff}_{ri})) \cdot C^{Sale}_{ztrj} \cdot X^{D}_{ztrij}$$

VAT and Tariff Costs

$$+ I^{Opr}_{ti} \cdot Y^{Opr}_{zti} + I^{OperExp}_{ti} \cdot Y^{ExpWforce}_{zti} + I^{OperFr}_{ti} \cdot Y^{FrAll}_{zti} + \sum_{j} (C^{Sup}_{tij} + C^{Unit}_{tij}) \cdot X^{A}_{ztij}] + \sum_{j,r} C^{Unmet}_{trj} \cdot X^{Unmet}_{ztj}$$

Annual operations costs of Expanded plant

Annual operations costs

Annual Holding costs of mothballed plant

Unit-based Costs (Supply and any other)

Unmet demand Penalty

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[9] This penalty should be at least equal to the net profit margin of the product (*j*) to be sold in region (*r*) in year (*t*). But it may also cover the opportunity costs (Eppen et. al. 1989).

4-2-4- R&D Costs

These include the design and engineering costs of the NPD procedure which is product-based only and independent from the plant in which the product may be launched later. This entirely design-based activity usually happens not in individual plants but in headquarters or R&D centres. The major parts of the NPD cost, which is called the new product launch (NPL) cost, has already been applied in the investment costs in the last section. Here is the formulation for the R&D cost of the NPD:

$$R\&D_{z,t} = \sum_{j} I_{tj}^{R\&D} \cdot \eta_{j}^{R\&D} \cdot Y_{ztj}^{R\&D}$$

Formula 04

Inputs: 1- $I_{tj}^{R\&D}$, investment cost for Research and engineering/design of product (j), in year (t); 2- $\eta_{j}^{R\&D}$ R&D Investment lead time

Decision variable: $Y_{ztj}^{R\&D}$, binary variable saying whether or not the product (j) is being designed in year (t), scenario (z)

4-1-5- Final Objective Formulation

Since it is not practical to ask the model users to provide all the cost-related parameters for all future years individually, we need to define an annual increase/decrease rate (inflation/deflation rate) on the costs.[10] Then, all the cost-related parameters are defined for the first year of the planning (the current year) and the future costs will be calculated by the model, based on the inflation rates. To make the model more accurate and realistic, different increase and interest rates can be defined by the user for operations cost, investment cost, supply cost, distribution cost, and finally for the sales price.[11] Inflation/increase rates in this model are shown by Δ .

Δ^{Oper} shows the inflation rate on operation production costs. Δ^{Sup} and Δ^{D} imply the increase rate on the supply cost of materials and distribution/transportation costs, respectively. Finally, Δ^{Inv} demonstrates the inflation rate on the investment costs.

Considering the abovementioned assumptions, the time dimension of all input parameters will be replaced by an inflation term. For example, $C_{z,t,\ldots} = (1+\Delta)^{t} \cdot C_{z,\ldots}$ and $I_{z,t,\ldots} = (1+\Delta)^{t} \cdot I_{z,\ldots}$

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[10] This is why the inflation rate of the country where production is taking place is an important factor to be implemented in capacity design models (Naraharisetti et. al. 2008).

[11] In this case, the managers can apply their different views on inflation and increase rates in different input parameters. This makes the model more accurate and it provides the ability to apply possible investment risks in the model.

Replacing the time-dependent input parameters with inflated parameters in formula 1 to 4 and putting these formulas in the main objective function, the final extended objective function will be achieved:

$$
\begin{aligned}
& Max(NPV) = \\
& Max\sum_{z} P_z \sum_{t=0}^{T} \left(1+\rho\right)^{-t} .\{\sum_{r,i,j}(1-\sigma_i^{Tax}).(C_{z,t,r,j}^{Sale}\cdot X_{z,t,r,i,j}^{D}) && \text{Revenue} \\
\text{Investment Costs} \quad & -[\sum_{i}(1-\sigma_i^{Tax}).\left(1+\Delta^{Inv}\right)^{t}.(I_i^{New}\cdot\eta_i^{New}\cdot Z_{zti}^{New}+I_i^{Exp}\cdot\eta_i^{Exp}\cdot Y_{zti}^{Exp}+I_i^{Fr}\cdot Y_{zti}^{Fr})] \\
\text{Operations costs 1} \quad & -[\sum_{i}(1-\sigma_i^{Tax}).\left(1+\Delta^{Inv}\right)^{t}.(I_i^{OnA}\cdot Y_{zti}^{OnA}+I_i^{\mathrm{Re}}\cdot Y_{zti}^{\mathrm{Re}}+I_i^{Clo}\cdot Y_{zti}^{Clo})] \\
\text{Product Launch Costs} \quad & -[\sum_{i,j}(1-\sigma_i^{Tax}).(I_i^{NPL}\cdot\eta_{i,j}^{NPL}\cdot Y_{ztij}^{NPL}+I_i^{PL}\cdot(Y_{ztij}^{PL}-Y_{ztij}^{NPL}))] \\
\text{Transportation Costs} \quad & -[\sum_{r,i,j}(1-\sigma_i^{Tax}).\left(1+\Delta^{D}\right)^{t}\cdot C_{rij}^{D}\cdot X_{ztrij}^{D}] \\
\text{Workforce Costs} \quad & -[\sum_{i}(1-\sigma_i^{Tax}).\left(1+\Delta^{oper}\right)^{t}\cdot I_i^{Workforce}.(Y_{zti}^{Dep}+\varepsilon_i^{OnA}Y_{zti}^{OnA}+\varepsilon_i^{Exp}Y_{zti}^{ExpWforce}-\varepsilon_i^{Fr}Y_{zti}^{FrAll})] \\
\text{Taxes (Tariff and VAT)} \quad & -[\sum_{r,i,j}(1-\sigma_i^{Tax}).(\sigma_{ri}^{Tariff}+\sigma_{r,i}^{VAT}(1+\sigma_r^{Tariff})).C_{zrj}^{Sale}\cdot X_{ztrij}^{D}] \\
\text{Operations costs 2} \quad & -[\sum_{i}(1-\sigma_i^{Tax}).\left(1+\Delta^{Oper}\right)^{t}.(I_i^{Opr}\cdot Y_{zti}^{Opr}+I_i^{OperExp}\cdot Y_{zti}^{ExpWforce}+I_i^{OperFr}\cdot Y_{zti}^{FrAll})] \\
\text{Unit-base operation costs} \quad & -[\sum_{i,j}(1-\sigma_i^{Tax}).\left(1+\Delta^{oper}\right)^{t}\cdot C_{ij}^{Unit}\,X_{ztij}^{A}] \\
\text{Supply costs} \quad & -[\sum_{i,j}(1-\sigma_i^{Tax}).\left(1+\Delta^{Sup}\right)^{t}\cdot C_{ij}^{Sup}\cdot X_{ztij}^{A}] \\
\text{Unmet demand penalty} \quad & -[\sum_{r,j}\left(1+\Delta^{Unmet}\right)^{t}C_{rj}^{Unmet}\cdot X_{ztij}^{Unmet}] \\
\text{Product design and R\&D costs} \quad & -[\sum_{j}\left(1+\Delta^{Inv}\right)^{t}\cdot I_j^{R\&D}\cdot\eta_i^{R\&D}\cdot Y_{z,j,t}^{R\&D}]\}
\end{aligned}
$$

4-3- Constraints and Controls

Having defined the extended objective of the model and considering the model's framework and mechanism (figure 4-1 and 4-2), in this section constraints and controls will be developed.

4-3-1- Capacity Volume

The maximum available capacity of each plant (K_{zti}^{Max}) in each year and under each scenario is a function of capacity volume decision variables, as expanded in Cons.01. This equation explains that the maximum available capacity of each plant in the beginning of a year is equal to the maximum available capacity of the plant at the beginning of the year before, plus/minus the capacity changes during the year before.

Maximum Available capacity in plant (i) in the year before

Volume of capacity expansion for each plant in this year

Volume of capacity closedown this year

Cons.01

$$K_{z,t+1,i}^{Max} = K_{z,t,i}^{Max} + Z_{z,t,i}^{New} \cdot K_{i}^{Initial} + K_{z,t,i}^{Exp} - K_{z,t,i}^{Fr} - K_{z,t,i}^{Cl} + K_{z,t,i}^{\mathrm{Re}}$$

Whether it is a new plant subject to establishment

Volume of temporary capacity mothball in this year

Volume of reopened capacity of this plant in this year (from frozen capacity)

Assumptions:

- *(t) means the beginning of the year of (t)*
- *All decisions (such as freeze, closedown, reopening and new product launch, etc.) take place at the beginning of the next year (t+1), when decisions are made at (t).*

In this equation, variables $K_{zti}^{Exp}, K_{zti}^{Fr}, K_{zti}^{Cl}, K_{zti}^{\mathrm{Re}}$ are decision variables showing the volume of expanded, mothballed, closed or reopened capacity for the plant (i) in year (t) and under scenario (z), respectively and $Y_{zti}^{Exp}, Y_{zti}^{Fr}, Y_{zti}^{Cl}, Y_{zti}^{\mathrm{Re}}$ are their corresponding binary variables. [12]

---

[12] The equations below establish a link between each pair. These equations show that if (and only if) the integer variables are not zero, the binary variables are equal to 1. Otherwise, the binary variables are zero.

$Y_{zti}^{Exp} \le K_{zti}^{Exp} \le Y_{zti}^{Exp}.M$ ==> If $K_{zti}^{Exp} \succ 0$ then $Y_{zti}^{Exp} = 1$, otherwise $Y_{zti}^{Exp} = 0$ $\forall z,t,i$

$Y_{zti}^{Fr} \le K_{zti}^{Fr} \le Y_{zti}^{Fr}.M$ ==> If $K_{zti}^{Fr} \succ 0$ then $Y_{zti}^{Fr} = 1$, otherwise $Y_{zti}^{Fr} = 0$ $\forall z,t,i$

$Y_{zti}^{Cl} \le K_{zti}^{Cl} \le Y_{zti}^{Cl}.M$ ==> If $K_{zti}^{Cl} \succ 0$ then $Y_{zti}^{Cl} = 1$, otherwise $Y_{zti}^{Cl} = 0$ $\forall z,t,i$

$Y_{zti}^{\mathrm{Re}} \le K_{zti}^{\mathrm{Re}} \le Y_{zti}^{\mathrm{Re}}.M$ ==> If $K_{zti}^{\mathrm{Re}} \succ 0$ then $Y_{zti}^{\mathrm{Re}} = 1$, otherwise $Y_{zti}^{\mathrm{Re}} = 0$ $\forall z,t,i$

M is a very large number in the scope of this modelling. In this mode **M=1,000,000,000**

Every plant (i) which is open and in production is subject to annual operations costs (I_i^{Oper}), including utility cost, maintenance cost, overhead cost, marketing cost, and other annual-based costs, as explained in section 4-2-3. Y_{zti}^{Oper} is a binary decision variable, which implies whether or not the plant (i) in year (t) under scenario (z) has any in-production capacity. This binary variable is a corresponding variable of the capacity volume integer variable (K_{zti}^{Max}).[13]

Having the general capacity equation (Cons.01), in the rest of this subsection, constraints and controls for each volume-related decision will be expanded and explained.

4-3-1-1- Normal / Over-normal Utilisation & Possibility Matrix

Not all products can be produced in all plants. Therefore, a possibility matrix should be defined to link products and plants, as explained in section 2-3-5. Moreover, the normal production rate for each plant may be different from product to product (Elmaghraby 2011). In other words, the maximum volume of the plant (i) for every possible product (*j*) may be different, based on the product configuration and its match-ability to the plant. The maximum capacity rate which was formulated in Cons.01 shows the average rate. $\gamma_{ij} \in [0,2]$ shows the capacity rate for each product (j) in plant (i). This rate also covers the possibility matrix.[14]

If $\gamma_{ij} = 1$, which means the maximum capacity for producing product (*j*) in plant (*i*) equals the nominal capacity of the plant (Cons.01). However, if for instance $\gamma_{ij} = 1.25$, it means the maximum capacity for manufacturing product (*j*) in plant (*i*) is 25% more than the nominal capacity of the plant (this product match is better in this line than the normal products).

The maximum production of all possible products in a plant should be less than the maximum capacity of that plant. Also, if product (*j*) cannot be produced in plant (*i*), no manufacturing of this product should be planned for this plant in the whole planning horizon. These two logics are formulated in Cons.02 and Cons.03, respectively.

$$\sum_j \gamma_{ij} \cdot X_{ztij}^{A} \le K_{zti}^{Max} \qquad \forall i,t,z$$

Cons.02

If γ_{ij} =0, then $\sum_t X_{ztij}^{A}$ =0 $\forall z, i, j$

Cons.03

---

[13] $Y_{zti}^{Opr} \le K_{zti}^{Max} \le M.Y_{zti}^{Opr} \qquad Y_{zti}^{Opr} \in [0,1] \qquad \forall z,t,i$ M=1,000,000,000

[14] If the capacity rate for the product (j) in plant (i) is equal to 0, it means the product cannot be produced in the plant.

Employing the possibility matrix and volume/product flexibility, Cons.02 and 03 explain the maximum capacity. Figure 4-3, on the other hand, establishes a logical link between maximum and normal utilisation rates.

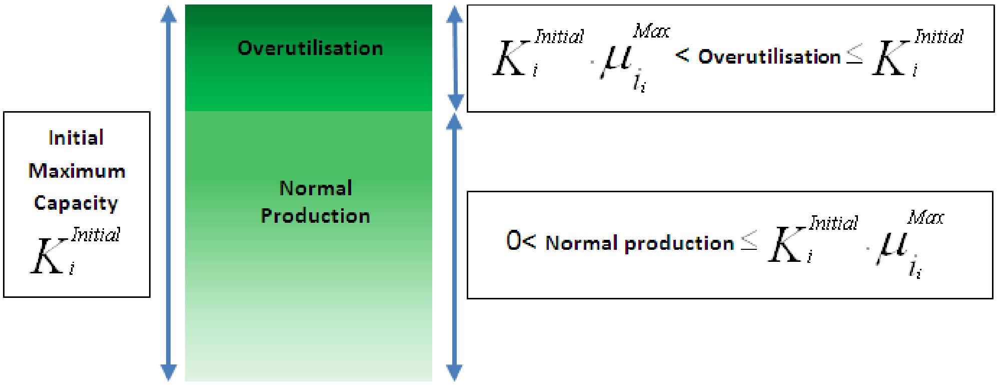

Figure 4-3: A link between normal and over-normal utilisation.

Now, applying the capacity rate logic (earlier mentioned) in the abovementioned normal/over-normal utilisation concept, Cons.04 and 05 establish a link between maximum and normal utilisations, based on different capacity rates for different possible productions. If production in plant (*i*) exceeds $\mu_{i_i}^{Max}\cdot K_{zti}^{Max}$ (normal capacity), then $Y_{zti}^{OnA}=1$, which means plant (*i*) in year (*t*) under scenario (*z*) is overutilised.

$$\sum_j(\gamma_{ij}\cdot X_{ztij}^{A}) - M.Y_{zti}^{OnA} \le (\mu_{i_i}^{Max}\cdot K_{zti}^{Max}) \qquad \forall z,t,i$$

Cons.04

$$\sum_j(\gamma_{ij}\cdot X_{ztij}^{A}) + M.(1-Y_{zti}^{OnA}) \ge (1.00001\,\mu_{i_i}^{Max}\cdot K_{zti}^{Max}) \qquad \forall z,t,i$$

Cons.05

4-3-1-2- New Capacity Establishment

In case of new plant establishment, the initial capacity of the plant is defined by the model's user as an input ($K_i^{Initial}$), as well as an investment time schedule (η_i^{New}). Having implemented a binary variable as the new plant decision function (Z_{zit}^{New}) in the model, it suggests whether or not and when to open this plant.

Moreover, every optional (new) capacity can be opened once.

$$\sum_{t=0}^{T} Z_{zit}^{New} \le 1 \qquad \forall i,z$$

Cons.06

4-3-1-3- Capacity Expansion

Capacity expansion in this model is limited to distinct number(s) of times, which is input to the model (E_i).If *E_i=2*, for instance, capacity (i) can only be expanded up to two times. Moreover, to address the lumpy nature of capacity expansion, every expansion is limited to a certain range, as explained in figure 4-4. The expanded plant, then, will have an extended normal and over-normal utilisation range, as illustrated in figure 4-4.

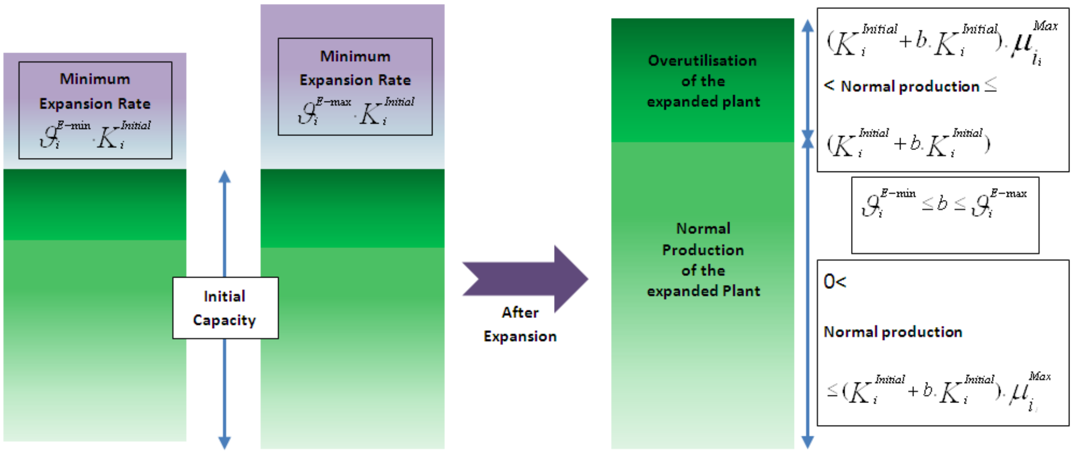

Figure 4-4: Capacity expansion mechanism

As shown in figure 4-4, each expansion should be done in a range of ($\vartheta_i^{E-\min}$ and ϑ_i^{E-Max}) of the initial capacity. Cons.07 to 09 formulate these logics and establish a link between the corresponding decision variables of K_{zti}^{Exp} and Y_{zti}^{Exp} .

$$\sum_t Y_{zti}^{Exp} \leq E_i \qquad \forall i,t,z \qquad \textbf{Cons.07}$$

$$K_{zti}^{Exp} \leq Y_{zti}^{Exp} \cdot \vartheta_i^{E-Max} \; K_{t=0,i}^{Max} \qquad \forall i,t,z \qquad \textbf{Cons.08}$$

$$\vartheta_i^{E-\min} \; K_{i,t=0}^{Max} \cdot Y_{zti}^{Exp} \leq K_{zti}^{Exp} \qquad \forall i,t,z \qquad \textbf{Cons.09}$$

4-3-1-4- Capacity Mothball

In this model, it is assumed that if a mothball decision is taken for a plant, all available capacity of this plant will be frozen. The constraints below fulfil this logic and establish a link between the corresponding integer and binary mothball decision variables of K_{zti}^{Fr} and Y_{zti}^{Fr}.

$$K_{zti}^{Fr} + M.(1 - Y_{zti}^{Fr}) \geq K_{zti}^{Max} \qquad \textbf{Cons.10}$$

$$K_{zti}^{Fr} \leq K_{zti}^{Max} \qquad \textbf{Cons.11}$$

The mothballed capacity, however, is not permanently closed and can be opened at any point in the future.

4-3-1-5- Capacity Re-open

The reopening of a mothballed plant can be carried out, knowing how much mothballed capacity is available to reopen. The availability of a mothballed capacity is defined by the binary variable of $Y_{z,t,i}^{FrAll}$ and its available volume is termed by $K_{z,t,i}^{FrAll}$.[15]

Cons.12 says the available mothballed capacity in each year equals its available capacity in the year before plus the new mothball capacity minus whatever mothballed capacity was reopened during the year before.

$$K_{z,t+1,i}^{FrAll} = K_{zti}^{FrAll} + (K_{zti}^{Fr} - K_{zti}^{\mathrm{Re}}) \quad \forall i,t,z \qquad \textbf{Cons.12}$$

For reopening a mothballed capacity, there can be two practices: 1- The decision can be made on a proportion of mothballed capacity (at least a minimum rate of $\vartheta_i^{R-\min}$) like the capacity expansion approach in this model. 2- The decision can be made on the whole mothballed capacity (open or not open, but the whole mothballed capacity). Although the first approach is feasible in terms of formulation, it is not practical for the purpose of this model. In many manufacturing practices, reopening a mothballed plant is only practical when the whole plant is subject to reopening, due to the sequential nature of the production lines. Therefore, in this model the second approach is acquired.

Cons.13 and 14, below, establish this logic and create a link between the corresponding decision variables of capacity reopening (K_{zti}^{Re} and Y_{zti}^{Re})

$$K_{zti}^{\mathrm{Re}} + M.(1 - Y_{zti}^{\mathrm{Re}}) \geq K_{zti}^{FrAll} \qquad \textbf{Cons.13}$$

$$K_{zti}^{\mathrm{Re}} \leq K_{zti}^{FrAll} \qquad \textbf{Cons.14}$$

4-3-1-6- Capacity Shutdown

Shutdown of a plant can happen once.

$$\sum_{t=0}^{T} Y_{zti}^{Cl} \leq 1 \qquad \forall z,t,i \qquad \textbf{Cons.15}$$

If the plant closure happens, it never reopens. When a capacity is closed down in year (t), the maximum capacity volume of that plant in the year after will be zero and it means that expansion, mothball or reopening will be out of the question afterwards. This is the main difference between capacity shutdown and mothball. The three constraints below establish a link between $K_{z,i,t}^{Cl}$ and its corresponding binary variable $Y_{z,i,t}^{Cl}$, and guarantee that if capacity shutdown happens, all of the in-use capacity will be closed:

$$K_{z,i,t}^{Cl} + (1 - Y_{zti}^{Cl}).M \geq K_{z,i,t}^{Max} \quad \forall z,t,i \qquad \textbf{Cons.16}$$

---

[15] $Y_{zti}^{FrAll} \leq K_{zti}^{FrAll} \leq Y_{zti}^{FrAll}.M \qquad \forall z,t,i$ M=1,000,000,000

$$K_{z,i,t}^{Cl} - M.Y_{zti}^{Cl} \leq K_{z,i,t}^{Max} \qquad \forall z,t,i$$

Cons.17

$$K_{zti}^{Cl} \leq K_{zti}^{Max} \qquad \forall z,t,i$$

Cons.18

Meanwhile, no mothballed capacity should be closed at any time. In other words, if a capacity would not be needed in the future at all, it should be closed down, not mothballed:

$$(1-Y_{zti}^{Cl}).M \geq K_{zti}^{FrAll} \qquad \forall i,t$$

Cons.19

Y^{Cl} for all plants and under all scenarios in the last year of the planning should be equal to zero to avoid closing capacity at the end of the planning. It is considered in the boundary conditions in the programming section.

4-3-2- Relocation and Merge Constraints

Relocation of a plant means opening a new plant in a new location and closing the current one. Similarly, in the case of merging plants, some distinct plants should be merged together to create one new plant. It means these plans should be closed down, in order to open the new one. Merging portfolio(s) should be defined by the model user in the model database. It includes how many (n_i^{merge}) and which plants/lines (p_i^{merge}) should be merged to open the new one, how much money should be invested and what the merging/relocation lead time is. In modelling practice, the plants which should be merged/relocated can be closed at any time before the year in which the new one is opened. The constraints below formulate the abovementioned logic for both relocation and merging cases. In case of relocation with no merge, $n_i^{merge} = 1$.

$$Z_{zti}^{New} \cdot n_i^{merge} \leq \sum_{\tau=0}^{\tau=t} p_i^{merge} \qquad \forall z,t,i$$

Cons.20

$$p_i^{merge} = \underbrace{Y_{zt,R_1}^{Cl} + Y_{zt,R_2}^{Cl} + Y_{zt,R_3}^{Cl} + Y_{zt,R_4}^{Cl}}_{n_i^{merge}} \qquad R_1,R_2,R_3,R_4 \in I \qquad \forall z,t,i$$

Cons.21

In these constraints, if $n_i^{merge} = 2$, for instance, constraint 21 will be changed to $p_i^{merge} = Y_{zt,R_1}^{Cl} + Y_{zt,R_2}^{Cl}$.

On the other hand, since merge and relocation depend on closing the current plants/lines, Z_{zti}^{New} in t=0 should be equal to zero. In other words, merge/relocation happens just for the current plants, not for optional ones. The following constraint formulates this logic:

If $n_i^{merge} \geq 0 \quad \Rightarrow \quad Z_{zti}^{New} = 0$ for t=0 and $\forall z,i$

Cons.22

Like investment lead time and possibility matrix, applying these three constraints can only be carried out in the programming phase and they cannot be directly applied in a compact modelling framework, because of the programming logic involved in these constraints (if, then format).

4-3-3- New Product Development (NPD) Constraints

As discussed earlier in the objective function, new product development activity can be divided into two separate phases of R&D and new product launch (NPL).

4-3-3-1- Product Launch (NPL and PL):

Launching a product in plant (*i*) for the first time in year (*t*) needs some product-related costs for the company. This product can be a completely new product (which will be subject to both NPL and R&D costs), or a current product which is new to a certain plant (which will be subject to only NPL costs in this plant). The following binary variable (Y^{NPL}_{ztij}) defines whether or not product (j) is produced in plant (i) in year (t) for the first time under scenario (z). If yes, the plant is subject to NPL costs to launch the product in this year, as explained in section 4-2-2:

$$[(Y^{A}_{ztij} - \sum_{\tau=0}^{\tau=t-1} Y^{A}_{z,\tau,i,j}) - 1] + M.(1 - Y^{NPL}_{ztij}) \geq 0$$

$$(Y^{A}_{ztij} - \sum_{\tau=0}^{\tau=t-1} Y^{A}_{z,\tau,i,j}) \leq Y^{NPL}_{ztij}$$

Cons.23

Where Y^{A}_{ztij} is the corresponding binary decision variable of X^{A}_{ztij}.[16]

On the other hand, after a long production break, if the production is again planned to be produced in a plant, it costs the company to reset the production lines for changeover. The binary variable of Y^{PL}_{ztij}, defined below, indicates whether the product is produced in plant (i) in year (t), after at least one year with no production. It may consist of production after a break or NPL. Therefore, in the objective equation in section 4-2-2, $Y^{PL}_{ztij} - Y^{NPL}_{ztij}$ is applied, which means production after a break, excluding NPL for changeover costs of re-production.

$$[(Y^{A}_{ztij} - Y^{A}_{z,t-1,i,j}) - 1] + M.(1 - Y^{PL}_{ztij}) \geq 0$$

$$(Y^{A}_{ztij} - Y^{A}_{z,t-1,i,j}) \leq Y^{PL}_{ztij}$$

Cons.24

4-3-3-2- R&D and Product Design:

Designing a new product (as one part of the NPD procedure) costs the headquarter of the company, as explained earlier.To formulate this logic, first we need to know whether product (*j*) has ever been produced in one of the production sites of the company, or not. Y^{h}_{ztj} in constraint 25 answers this question.

---

[16] $Y^{A}_{ztij} \leq X^{A}_{ztij} \leq Y^{A}_{ztij}.M \qquad \forall z,t,i,j$ M=1,000,000,000

$$Y^{h}_{ztj} \le \sum_{i,\tau=0}^{\tau=t} Y^{A}_{z,\tau,i,j} \le M.Y^{h}_{ztj} \quad \forall j,t$$

Cons.25

Now, based on this binary variable (Y^{h}_{ztj}), a new binary variable for R&D ($Y^{R\&D}_{ztj}$) can be defined in constraints 26 and 27, which shows whether or not a product (j) is subject to R&D costs in year (t) under scenario (z). These constraints explain that, if a product has never been produced in any production line before year (t), but is being produced in at least one plant in this year, the product has been designed to be launched in this year and should be subject to R&D cost in this year and under this scenario. The investment portfolio and time schedule, however, may be set to start some years in advance of the actual launch year, as explained in section 4-2-2.

$$[(Y^{h}_{ztj} - Y^{h}_{z,t-1,j}) - 1] + M.(1 - Y^{R\&D}_{ztj}) \ge 0$$

Cons.26

$$(Y^{h}_{ztj} - Y^{h}_{z,t-1,j}) \le Y^{R\&D}_{ztj}$$

Cons.27

4-3-4- Non-Simultaneous and Non-Anticipative Constraints

Reopening, expansion and new product launch can be done for the same plant simultaneously, like new capacity establishment and new product launch. However, freezing and reopening, freezing and expansion, reopening and closing down, closing down and expansion, new product launch and capacity closedown and finally new product launch and capacity freezing cannot be done simultaneously for the same plant. The following set of formulations constrain the model in this regard.

$$\boxed{\begin{array}{lll} (Y^{\mathrm{Re}}_{zti} + Y^{Fr}_{zti}) \le 1 & & \\ & (Y^{Exp}_{zti} + Y^{Fr}_{zti}) \le 1 & \\ (Y^{\mathrm{Re}}_{zti} + Y^{Cl}_{zti}) \le 1 & & \\ & (Y^{Cl}_{zti} + Y^{Fr}_{zti}) \le 1 & \forall z,t,i \\ (Y^{Exp}_{zti} + Y^{Cl}_{zti}) \le 1 & & \end{array}}$$

Cons.28

Moreover, non-anticipative constraints are also required to be defined for stochastic modelling (Ruszczyński et al. 2003). The strategic decisions suggested by the model are obtained from an optimised solution for the whole system, considering the effect of all the scenarios. While these strategic decisions are taken, change will be almost impossible.[17]

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[17] Planning for capacity is not a "wait and see" decision and should be done in advance for the whole time horizon of the planning, considering all scenarios. Tactical decisions such as load-planning, however, can be adjusted for each scenario in each year, regarding the resources, capacities, and realised demands. In other words, load-planning is a "wait and see" decision.
In other words, some of the decisions are irreversible decisions which means that changing them in the future costs a lot for the company. Capacity change is expensive (Frausto-Hernandez et. al. 2010) and time-consuming (Matta et. al. 2005). Some decisions such as new plant establishment, capacity expansion, capacity closedown, new product development (both R&D and NPL phases), capacity mothball and plant reopening are

In other words, it is not possible to adjust these decisions later, when the uncertainty is realised by time. However, some tactical decisions such as overutilisation of the capacity, as well as load-planning, product-to-market and transportation decisions are adjustable decisions and can be changed over time. These changes, however, may create cost for the company.

Irreversible decisions should be applied in the model in the form of non-anticipative constraints. These decisions are capacity expansion, shutdown, new plant establishment, new product launch decision, product design (R&D), plant mothball and finally plant reopening, as formulated below:

$$
\begin{array}{ll}
K^{Exp}_{t,i,z_q} = K^{Exp}_{t,i,z_l} & l \neq q, \forall t, i, z_q, z_l \\
Y^{Cl}_{t,i,z_q} = Y^{Cl}_{t,i,z_l} & l \neq q, \forall t, i, z_q, z_l \\
Z^{New}_{t,i,z_q} = Z^{New}_{t,i,z_l} & l \neq q, \forall t, i, z_q, z_l \\
Y^{NPL}_{t,i,j,z_q} = Y^{NPL}_{t,i,j,z_l} & l \neq q, \forall t, i, j, z_q, z_l \\
Y^{R\&D}_{t,j,z_q} = Y^{R\&D}_{t,j,z_l} & l \neq q, \forall t, j, z_q, z_l \\
Y^{Fr}_{t,j,z_q} = Y^{Fr}_{t,j,z_l} & l \neq q, \forall t, j, z_q, z_l \\
Y^{\mathrm{Re}}_{t,j,z_q} = Y^{\mathrm{Re}}_{t,j,z_l} & l \neq q, \forall t, j, z_q, z_l
\end{array}
$$

Cons.29

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decisions that cost massively for the company to change or in some cases, such as capacity shutdown/salvage, are completely irreversible when made.

4-3-5- Other Constraints

4-3-5-1- Work force Constraints

From the objective function, expanded capacity, if working (not closed or mothballed), would cause an extra work force cost to the plant. Constraints below guarantee that this cost will only be applied to the cases where the plant is expanded and not closed or mothballed. Only in such cases $Y_{zti}^{ExpWforce}=1$ and otherwise $Y_{zti}^{ExpWforce}$ =0.

- When capacity has been closed down anytime earlier ($\sum_{\tau=0}^{\tau=t} Y_{z,\tau,i}^{Close}=1$) or when it has got any mothballed capacity in reserve ($Y_{zti}^{FrAll}=1$)in year (t) then $Y_{zti}^{ExpWforce}$ =0

$$Y_{zti}^{FrAll}+\sum_{\tau=0}^{\tau=t} Y_{z,\tau,i}^{Close}\leq 1-Y_{zti}^{ExpWforce} \qquad \forall z,t,i$$

Cons.30

- If the plan has been expanded earlier ($Y_{zti}^{ExpOveral}=1$)[18] and not mothballed ($Y_{zti}^{FrAll}=0$) or ever closed down ($\sum_{\tau=0}^{\tau=t} Y_{z,\tau,i}^{Close}=0$) then $Y_{zti}^{ExpWforce}$ =1

$$Y_{zti}^{ExpOveral}-Y_{zti}^{FrAll}-\sum_{\tau=0}^{\tau=t} Y_{z,\tau,i}^{Close}\leq Y_{zti}^{ExpWforce} \quad \forall z,t,i$$

Cons.31

- If the plant has never been expanded ($Y_{zti}^{ExpOveral}=0$)[18] then $Y_{zti}^{ExpWforce}$ =0

$$Y_{zti}^{ExpOveral}\geq Y_{zti}^{ExpWforce} \quad \forall z,t,i$$

Cons.32

---

[18] To find out whether plant (i) has ever been expanded before the year (t), a binary variable of Y_{zti}^{ExpAll} can be defined as follows, which will later be used in work force constraints.

$$Y_{zti}^{ExpOveral}\leq \sum_{\tau=0}^{t} K_{z\tau i}^{Exp}\leq M.Y_{zti}^{ExpOveral} \qquad \forall i,t,z$$

If $Y_{zti}^{ExpOveral}=1$, it means the plant (i) has been expanded at least once, before year (t) under scenario (z).

4-3-5-2- Maximum Plant and Maximum Product Constraints

Following constraint we fulfil the policy of the company to launch each product (*j*) in a certain maximum number of plants (l_{tj}), even if more plants are capable of producing the product. It often happens, when the company wishes to restrict the number of plants which are engaged with one product, in order to improve the efficiency, quality and production lead time, or to restrict technology distribution.

$$\sum_{i} Y^{A}_{ztij} \le l_{j} \qquad \forall j,t$$

Cons.33

Likewise, there could be another constraint to limit the maximum products which are allowed to launch in a certain plant, in each period of time. Constraint 34 formulates this policy. Sometimes, companies have this policy to avoid producing several products in one plant (even if the production lines are capable/flexible), to reduce the risk of quality problems or to control the setup costs and change over time.

$$\sum_{j} Y^{A}_{ztij} \le n_{i}^{\max} \qquad \forall i,t$$

Cons.34

4-3-5-3- Budget Constraints

Most often, companies define a maximum annual budget of investment. The simplest budget allocation, which is defined by a maximum annual limit for investment, is formulated here:

$$\sum_{z} \sum_{t} [\sum_{i} Inv_{zti} + \sum R\&D_{ztj}] \le b_{t} \qquad \forall z,t$$

Cons.35

However, if the company is self-funded for new investment, we can write the budget constraint of each year as a function of the total of sold products of the previous year.[19]

4-3-5-4- Demand and Distribution Constraints

The main input to strategic capacity planning models is demand forecast (Olhager et al. 2001). Demand forecast is uncertain (Dangl 1999). Furthermore, the product life cycle is also reflected in the product demand curve. The product life cycle should be applied in technology selection and capacity acquisition problems (Francas et al. 2009). Applying this life cycle while considering the product-related cost of NPL, helps us to implement capacity depreciation in the modelling practice, as explained in section 2-4-7.

Moreover, as explained in chapter 2, unmet demand should be allowed in a capacity planning model (Hammami et al. 2008).

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[19] $Inv_{zt} \le \sum_{j} \xi^{I}_{j} \sum_{ir} X^{D}_{zijr,t-1} \qquad \forall z,t$ This constraint, however, is not applied in this programming.

Constraint 36 explains that the demand of each product (j) in each sales region (r), in each year (t) and under each scenario (z), is the summation of the number of products of this type which are transported to the sales region in the same year and under the same scenario, plus the possible amount of unmet demand.

$$[\sum_{i}(X_{ztrij}^{D}) + X_{ztrj}^{Unmet}] = d_{ztrj} \qquad \forall z,t,j,r$$

Cons.36

All production should be transported in the same period (no inventory, over the period of one year)[20]:

$$\sum_{r} X_{ztrij}^{D} = X_{ztij}^{A} \qquad \forall i,t$$

Cons.37

4-4- Model Summary

Figures 4-5 and 4-6 provide a summary of the modelling logic and formulations. Figure 4-5 shows how capacity volume management and planning is manipulated by the model. In each box, the relevant part of the objective function and its constraints has been highlighted. Likewise, in figure 4-6, capacity location, relocation, merge and decomposition as well as product management concepts have been explained. Other factors such as work force related objectives and constraints, sales and demand objectives and constraints and finally, supply, logistics and other operations costs have also been reflected in figure 4-6.

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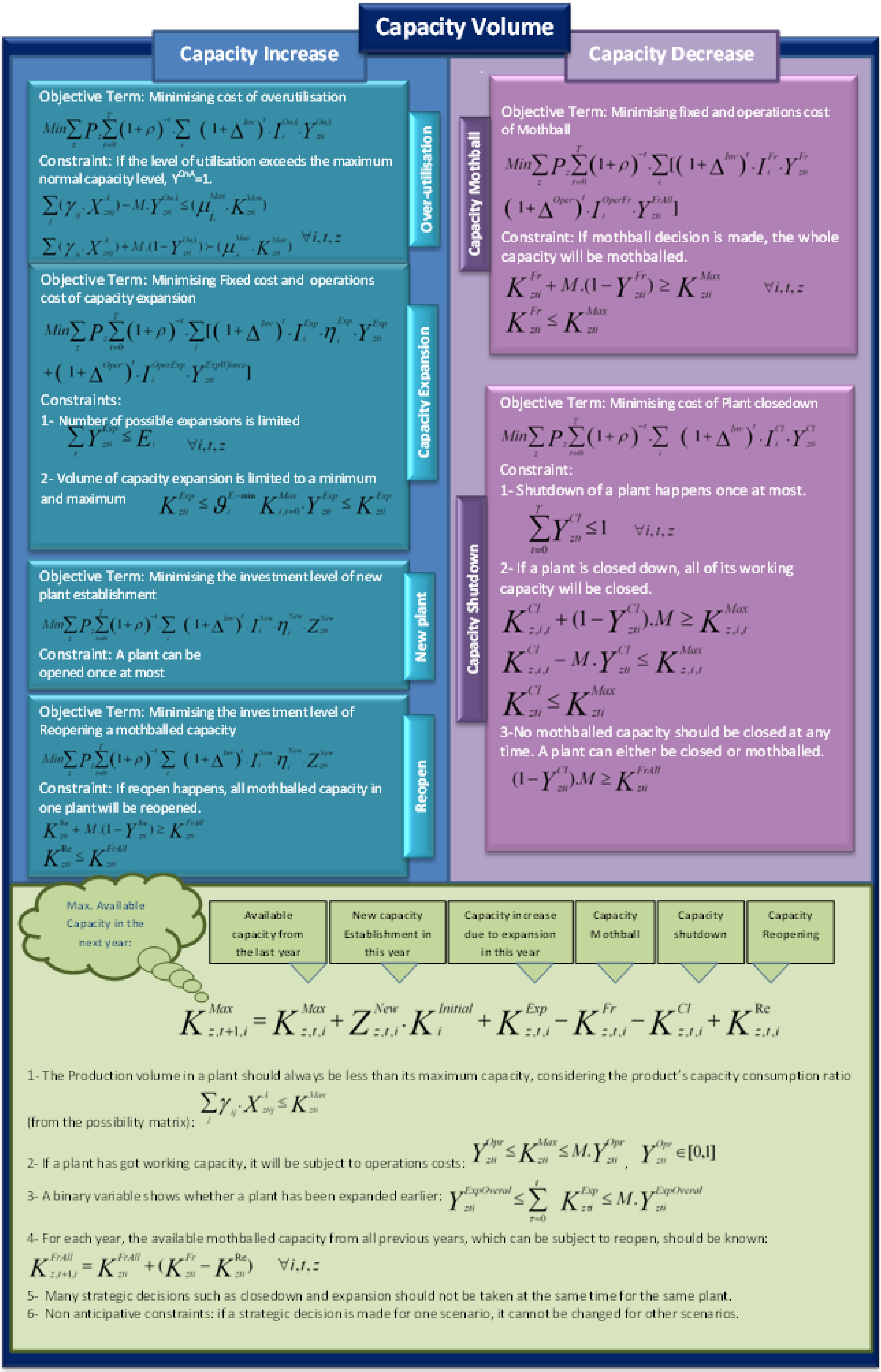
[20] Since this model is an annual-based strategic planning model, no inventory is forecasted in the model's structure (Chen et. al. 2002). To our knowledge, no manufacturing industry, which employs a "First in First out" system of inventory, manages a buffer of more than a year warehouse.



Objective Term: Minimising cost of overutilisation

$$Min\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} \cdot \sum_{i} (1+\Delta^{Inv})^{t} \cdot I_i^{OnA} \cdot Y_{zti}^{OnA}$$

Constraint: If the level of utilisation exceeds the maximum normal capacity level, $Y^{OnA}=1$.

$$\sum_{j} (\gamma_{ij} \cdot X_{ztij}^{A}) - M.Y_{zti}^{OnA} \le (\mu_i^{Max} \cdot K_{zti}^{Max})$$

$$\sum_{j} (\gamma_{ij} \cdot X_{ztij}^{A}) + M.(1-Y_{zti}^{OnA}) > (\mu_i^{Max} \cdot K_{zti}^{Max}) \quad \forall i,t,z$$

Objective Term: Minimising Fixed cost and operations cost of capacity expansion

$$Min\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} \cdot \sum_{i} [(1+\Delta^{Inv})^{t} \cdot I_i^{Exp} \cdot \eta_i^{Exp} \cdot Y_{zti}^{Exp}$$
$$+(1+\Delta^{Oper})^{t} \cdot I_i^{OperExp} \cdot Y_{zti}^{ExpWforce}]$$

Constraints:

1- Number of possible expansions is limited

$$\sum_{t} Y_{zti}^{Exp} \le E_i \qquad \forall i,t,z$$

2- Volume of capacity expansion is limited to a minimum and maximum

$$K_{zti}^{Exp} \le \vartheta_i^{E-\min} K_{i,t=0}^{Max} \cdot Y_{zti}^{Exp} \le K_{zti}^{Exp}$$

Objective Term: Minimising the investment level of new plant establishment

$$Min\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} \cdot \sum_{i} (1+\Delta^{Inv})^{t} \cdot I_i^{New} \cdot \eta_i^{New} \cdot Z_{zti}^{New}$$

Constraint: A plant can be opened once at most

Objective Term: Minimising the investment level of Reopening a mothballed capacity

$$Min\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} \cdot \sum_{i} (1+\Delta^{Inv})^{t} \cdot I_i^{New} \cdot \eta_i^{New} \cdot Z_{zti}^{New}$$

Constraint: If reopen happens, all mothballed capacity in one plant will be reopened.

$$K_{zti}^{Re} + M.(1-Y_{zti}^{Re}) \ge K_{zti}^{FrAll}$$

$$K_{zti}^{Re} \le K_{zti}^{FrAll}$$

Objective Term: Minimising fixed and operations cost of Mothball

$$Min\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} \cdot \sum_{i} [(1+\Delta^{Inv})^{t} \cdot I_i^{Fr} \cdot Y_{zti}^{Fr}$$
$$(1+\Delta^{Oper})^{t} \cdot I_i^{OperFr} \cdot Y_{zti}^{FrAll}]$$

Constraint: If mothball decision is made, the whole capacity will be mothballed.

$$K_{zti}^{Fr} + M.(1-Y_{zti}^{Fr}) \ge K_{zti}^{Max} \qquad \forall i,t,z$$

$$K_{zti}^{Fr} \le K_{zti}^{Max}$$

Objective Term: Minimising cost of Plant closedown

$$Min\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} \cdot \sum_{i} (1+\Delta^{Inv})^{t} \cdot I_i^{Cl} \cdot Y_{zti}^{Cl}$$

Constraint:

1- Shutdown of a plant happens once at most.

$$\sum_{t=0}^{T} Y_{zti}^{Cl} \le 1 \qquad \forall i,t,z$$

2- If a plant is closed down, all of its working capacity will be closed.

$$K_{z,i,t}^{Cl} + (1-Y_{zti}^{Cl}).M \ge K_{z,i,t}^{Max}$$

$$K_{z,i,t}^{Cl} - M.Y_{zti}^{Cl} \le K_{z,i,t}^{Max}$$

$$K_{zti}^{Cl} \le K_{zti}^{Max}$$

3-No mothballed capacity should be closed at any time. A plant can either be closed or mothballed.

$$(1-Y_{zti}^{Cl}).M \ge K_{zti}^{FrAll}$$

Max. Available Capacity in the next year:

Available capacity from the last year	New capacity Establishment in this year	Capacity increase due to expansion in this year	Capacity Mothball	Capacity shutdown	Capacity Reopening

$$K_{z,t+1,i}^{Max} = K_{z,t,i}^{Max} + Z_{z,t,i}^{New} \cdot K_i^{Initial} + K_{z,t,i}^{Exp} - K_{z,t,i}^{Fr} - K_{z,t,i}^{Cl} + K_{z,t,i}^{Re}$$

1- The Production volume in a plant should always be less than its maximum capacity, considering the product's capacity consumption ratio (from the possibility matrix): $\sum_{j} \gamma_{ij} \cdot X_{ztij}^{A} \le K_{zti}^{Max}$

2- If a plant has got working capacity, it will be subject to operations costs: $Y_{zti}^{Opr} \le K_{zti}^{Max} \le M.Y_{zti}^{Opr}$, $Y_{zti}^{Opr} \in [0,1]$

3- A binary variable shows whether a plant has been expanded earlier: $Y_{zti}^{ExpOverall} \le \sum_{\tau=0}^{t} K_{z\tau i}^{Exp} \le M.Y_{zti}^{ExpOverall}$

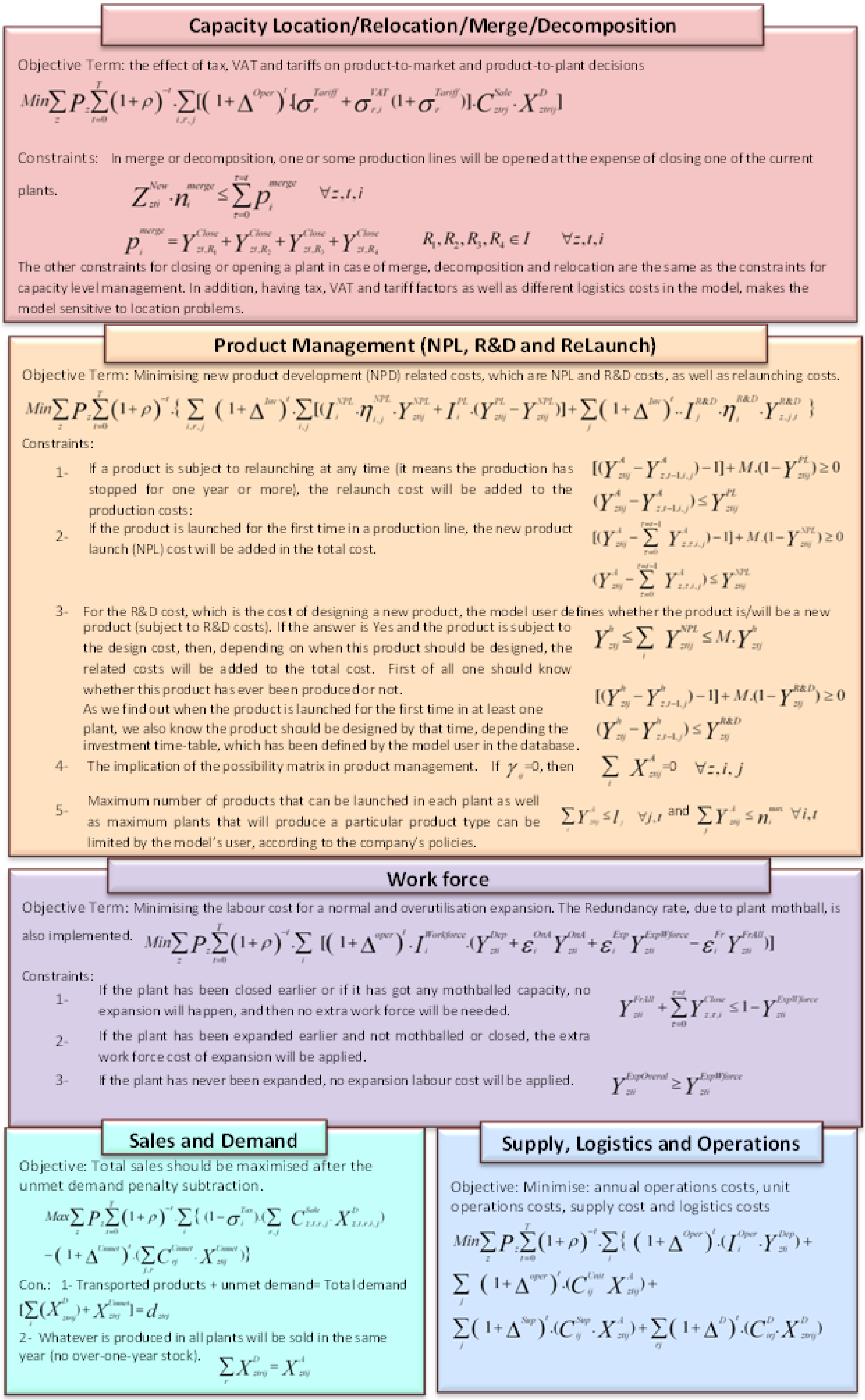
4- For each year, the available mothballed capacity from all previous years, which can be subject to reopen, should be known:

$$K_{z,t+1,i}^{FrAll} = K_{zti}^{FrAll} + (K_{zti}^{Fr} - K_{zti}^{Re}) \qquad \forall i,t,z$$

5- Many strategic decisions such as closedown and expansion should not be taken at the same time for the same plant.

6- Non anticipative constraints: if a strategic decision is made for one scenario, it cannot be changed for other scenarios.

Figure 4-5: Model summary: Capacity volume management and control



Capacity Location/Relocation/Merge/Decomposition

Objective Term: the effect of tax, VAT and tariffs on product-to-market and product-to-plant decisions

$$Min\sum_{z} P_z \sum_{t=0}^{T}(1+\rho)^{-t}\cdot\sum_{i,r,j}[(1+\Delta^{Oper})^{t}\{\sigma_r^{Tariff}+\sigma_{r,i}^{VAT}(1+\sigma_r^{Tariff})\}.C_{zrij}^{Sale}\cdot X_{zrij}^{D}]$$

Constraints: In merge or decomposition, one or some production lines will be opened at the expense of closing one of the current plants.

$$Z_{zti}^{New}\cdot n_i^{merge}\le\sum_{\tau=0}^{\tau=t}p_i^{merge}\qquad\forall z,t,i$$

$$p_i^{merge}=Y_{zt,R_1}^{Close}+Y_{zt,R_2}^{Close}+Y_{zt,R_3}^{Close}+Y_{zt,R_4}^{Close}\qquad R_1,R_2,R_3,R_4\in I\qquad\forall z,t,i$$

The other constraints for closing or opening a plant in case of merge, decomposition and relocation are the same as the constraints for capacity level management. In addition, having tax, VAT and tariff factors as well as different logistics costs in the model, makes the model sensitive to location problems.

Product Management (NPL, R&D and ReLaunch)

Objective Term: Minimising new product development (NPD) related costs, which are NPL and R&D costs, as well as relaunching costs.

$$Min\sum_{z}P_z\sum_{t=0}^{T}(1+\rho)^{-t}\{\sum_{i,r,j}(1+\Delta^{Inv})^{t}\cdot\sum_{i,j}[(I_i^{NPL}\cdot\eta_{i,j}^{NPL}\cdot Y_{zij}^{NPL}+I_i^{PL}\cdot(Y_{zij}^{PL}-Y_{zij}^{NPL})]+\sum_{j}(1+\Delta^{Inv})^{t}\cdot I_j^{R\&D}\cdot\eta_i^{R\&D}\cdot Y_{z,j,t}^{R\&D}\}$$

Constraints:

1- If a product is subject to relaunching at any time (it means the production has stopped for one year or more), the relaunch cost will be added to the production costs:
$$[(Y_{zij}^{A}-Y_{z,t-1,i,j}^{A})-1]+M.(1-Y_{zij}^{PL})\ge 0$$
$$(Y_{zij}^{A}-Y_{z,t-1,i,j}^{A})\le Y_{zij}^{PL}$$

2- If the product is launched for the first time in a production line, the new product launch (NPL) cost will be added in the total cost.
$$[(Y_{zij}^{A}-\sum_{\tau=0}^{\tau=t-1}Y_{z,\tau,i,j}^{A})-1]+M.(1-Y_{zij}^{NPL})\ge 0$$
$$(Y_{zij}^{A}-\sum_{\tau=0}^{\tau=t-1}Y_{z,\tau,i,j}^{A})\le Y_{zij}^{NPL}$$

3- For the R&D cost, which is the cost of designing a new product, the model user defines whether the product is/will be a new product (subject to R&D costs). If the answer is Yes and the product is subject to the design cost, then, depending on when this product should be designed, the related costs will be added to the total cost. First of all one should know whether this product has ever been produced or not.
$$Y_{zj}^{b}\le\sum_{i}Y_{zij}^{NPL}\le M.Y_{zj}^{b}$$
As we find out when the product is launched for the first time in at least one plant, we also know the product should be designed by that time, depending the investment time-table, which has been defined by the model user in the database.
$$[(Y_{zj}^{b}-Y_{z,t-1,j}^{b})-1]+M.(1-Y_{zj}^{R\&D})\ge 0$$
$$(Y_{zj}^{b}-Y_{z,t-1,j}^{b})\le Y_{zj}^{R\&D}$$

4- The implication of the possibility matrix in product management. If $\gamma_{ij}=0$, then $\sum_{t}X_{zij}^{A}=0\quad\forall z,i,j$

5- Maximum number of products that can be launched in each plant as well as maximum plants that will produce a particular product type can be limited by the model's user, according to the company's policies. $\sum_{i}Y_{zij}^{A}\le l_j\quad\forall j,t$ and $\sum_{j}Y_{zij}^{A}\le n_i^{max}\quad\forall i,t$

Work force

Objective Term: Minimising the labour cost for a normal and overutilisation expansion. The Redundancy rate, due to plant mothball, is also implemented.

$$Min\sum_{z}P_z\sum_{t=0}^{T}(1+\rho)^{-t}\cdot\sum_{i}[(1+\Delta^{oper})^{t}\cdot I_i^{Workforce}\cdot(Y_{zti}^{Dep}+\varepsilon_i^{OnA}Y_{zti}^{OnA}+\varepsilon_i^{Exp}Y_{zti}^{ExpWforce}-\varepsilon_i^{Fr}Y_{zti}^{FrAll})]$$

Constraints:

1- If the plant has been closed earlier or if it has got any mothballed capacity, no expansion will happen, and then no extra work force will be needed.
$$Y_{zti}^{FrAll}+\sum_{\tau=0}^{\tau=t}Y_{z,\tau,i}^{Close}\le 1-Y_{zti}^{ExpWforce}$$

2- If the plant has been expanded earlier and not mothballed or closed, the extra work force cost of expansion will be applied.

3- If the plant has never been expanded, no expansion labour cost will be applied.
$$Y_{zti}^{ExpOverall}\ge Y_{zti}^{ExpWforce}$$

Sales and Demand

Objective: Total sales should be maximised after the unmet demand penalty subtraction.

$$Max\sum_{z}P_z\sum_{t=0}^{T}(1+\rho)^{-t}\cdot\sum_{i}\{(1-\sigma_i^{Tax})(\sum_{r,j}C_{z,t,r,i,j}^{Sale}\cdot X_{z,t,r,i,j}^{D})$$
$$-(1+\Delta^{Unmet})^{t}\cdot(\sum_{j,r}C_{rj}^{Unmet}\cdot X_{zrj}^{Unmet})\}$$

Con.: 1- Transported products + unmet demand= Total demand
$$[\sum_{i}(X_{zrij}^{D})+X_{zrj}^{Unmet}]=d_{zrj}$$

2- Whatever is produced in all plants will be sold in the same year (no over-one-year stock). $\sum_{r}X_{zrij}^{D}=X_{zij}^{A}$

Supply, Logistics and Operations

Objective: Minimise: annual operations costs, unit operations costs, supply cost and logistics costs

$$Min\sum_{z}P_z\sum_{t=0}^{T}(1+\rho)^{-t}\cdot\sum_{i}\{(1+\Delta^{Oper})^{t}\cdot(I_i^{Oper}\cdot Y_{zti}^{Dep})+$$
$$\sum_{j}(1+\Delta^{oper})^{t}\cdot(C_{ij}^{Unit}X_{zij}^{A})+$$
$$\sum_{j}(1+\Delta^{Sup})^{t}\cdot(C_{ij}^{Sup}\cdot X_{zij}^{A})+\sum_{rj}(1+\Delta^{D})^{t}\cdot(C_{irj}^{D}\cdot X_{zrij}^{D})$$

Figure 4-6: Model Summary: location/relocation, product management work force and other terms

4-5- Model Programming and Solution

Finally, after developing the model, as described in section 3-4, to apply the model in the decision making practice, programming and encoding the equations in an expanded format are required. It includes developing an input database, establishing a compiler, running an optimisation algorithm and finally generating visualised results. Microsoft Access®, Visual Basic®, CPLEX and finally Microsoft Excel® have been employed for these purposes, respectively.

Writing more than 18,000 lines of codes in Visual Basic®, an application/software was developed to create and manage a link between Microsoft Access®, GAMS ®, and Microsoft Excel®, in an integrated visualised framework. Figure 4-7 shows the framework of this application. As described in this figure, this application simply consists of three main sub-groups of input (database), run (optimisation) and finally result. We called this application/software NBS-DMM-CI (Nottingham Business School - Decision making Model – Capacity Investment).

4-5-1- Input Design and Database Collection

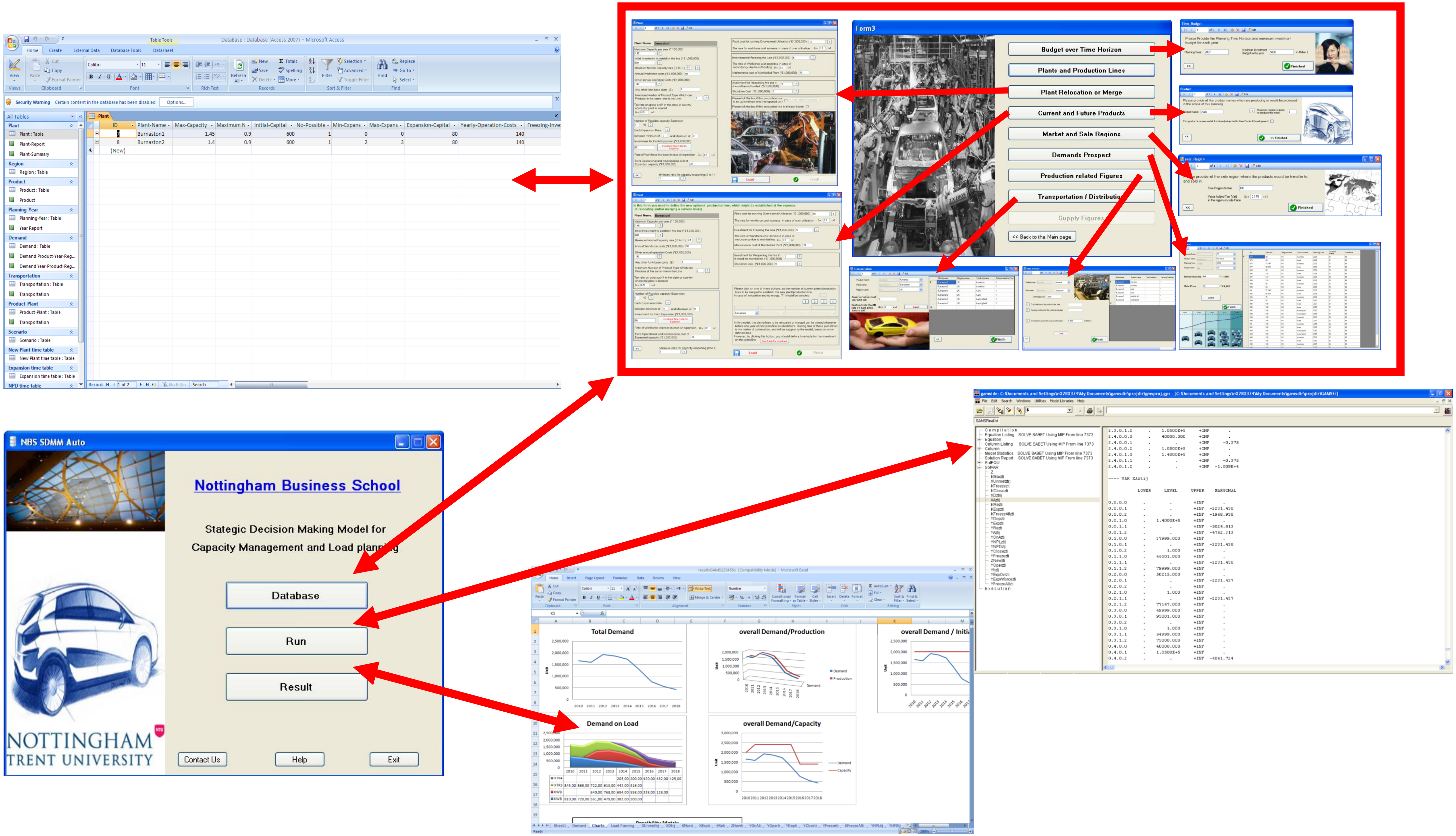
The first phase of the NBS-DMM-CI Application is the collection of data and the creation of the database, as shown in figure 4-8. Input data are categorised in the different sections of: 1- time horizon, annual budget limits and financial features of inflations; 2- information about the plants including all fixed costs of investment, running, operations, lead times, variable costs etc.; 3- required information for the cases of merging the plants; 4- product-related features, R&D costs and lead time; 5- sales regions and VAT information; 6- demand forecast for different products in various regions; 7- possibility matrix, product launch costs and lead times; and finally 8- transportation costs. This application communicates with an Access® file to save and restore the database, as demonstrated in figure 4-7. Moreover, figure 4-8 links the data collection forms to the models' nomenclatures.

4-3-2- Solution and Optimisation

Based on the model framework and the input database, the extended formulations should be generated and programmed in GAMS® language. Then, GAMS will run the formulations and find the optimal solution. However, to extend the formulations in connection with the database, and to write the equivalent equations in GAMS language, massive coding is required in Visual Basic®. This step is embedded in the second major command of the NBS-DMM-CI Application, Run, as shown in figure 4-7. Clicking on this button, the entire database is recalled from the Access® file and the extended formulations in GAMS language will be generated and exported. Appendix B shows this procedure in detail. In this appendix, every equation from section 4-2 and 4-3 is addressed and the programming logic and the link to the database are explained in detail.

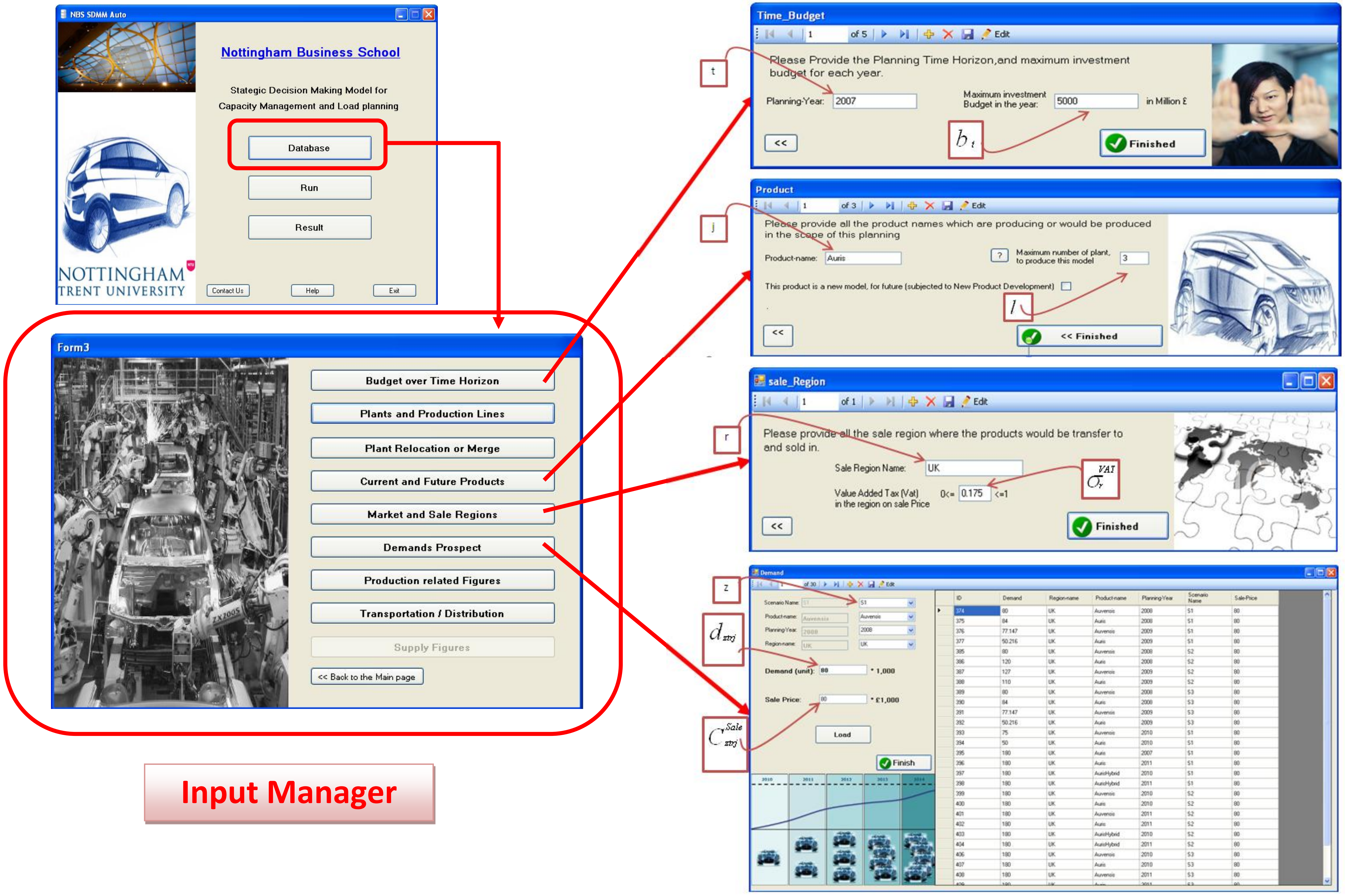
4-3-3- Output Design and Post Solution

Although the results generated by GAMS are clear for OR specialists, the NBS-DMM-CI Application provides an option for non-OR users to generate more user-friendly results in Microsoft Excel ®, by clicking on the 'Result' command, after running the GAMS (see figure 4-7). It exports the result from GAMS to Excel, and automatically generates tables and charts, which make the result easier to understand and analyse.



	ID	Plant-Name	Max-Capacity	Maximum N	Initial-Capital	No-Possible	Min-Expans	Max-Expans	Expansion-Capital	Yearly-Operation-Costs	Freezing-Inve
⊞	7	Burnaston1	1.45	0.9	600	1	0	0	80	140	
⊞	8	Burnaston2	1.4	0.9	600	1	2	3	80	140	
*	(New)										

Figure 4-7: The flow chart for information transfer in the application/software developed in this project. How the application manages the communication between different parts of the database input (Microsoft Access®), the optimisation software (GAMS®) and the result demonstration (Microsoft Excel®)



NBS SDMM Auto

Nottingham Business School

Stategic Decision Making Model for Capacity Management and Load planning

Form3

Input Manager

Time_Budget

Please Provide the Planning Time Horizon,and maximum investment budget for each year.

Planning-Year: 2007

Maximum investment Budget in the year: 5000 in Million £

Product

Please provide all the product names which are producing or would be produced in the scope of this planning

Product-name: Auris

Maximum number of plant, to produce this model: 3

This product is a new model, for future (subjected to New Product Development) ☐

sale_Region

Please provide all the sale region where the products would be transfer to and sold in.

Sale Region Name: UK

Value Added Tax (Vat) in the region on sale Price: 0<= 0.175 <=1

Demand

Scenario Name: S1

Product-name: Auvensis

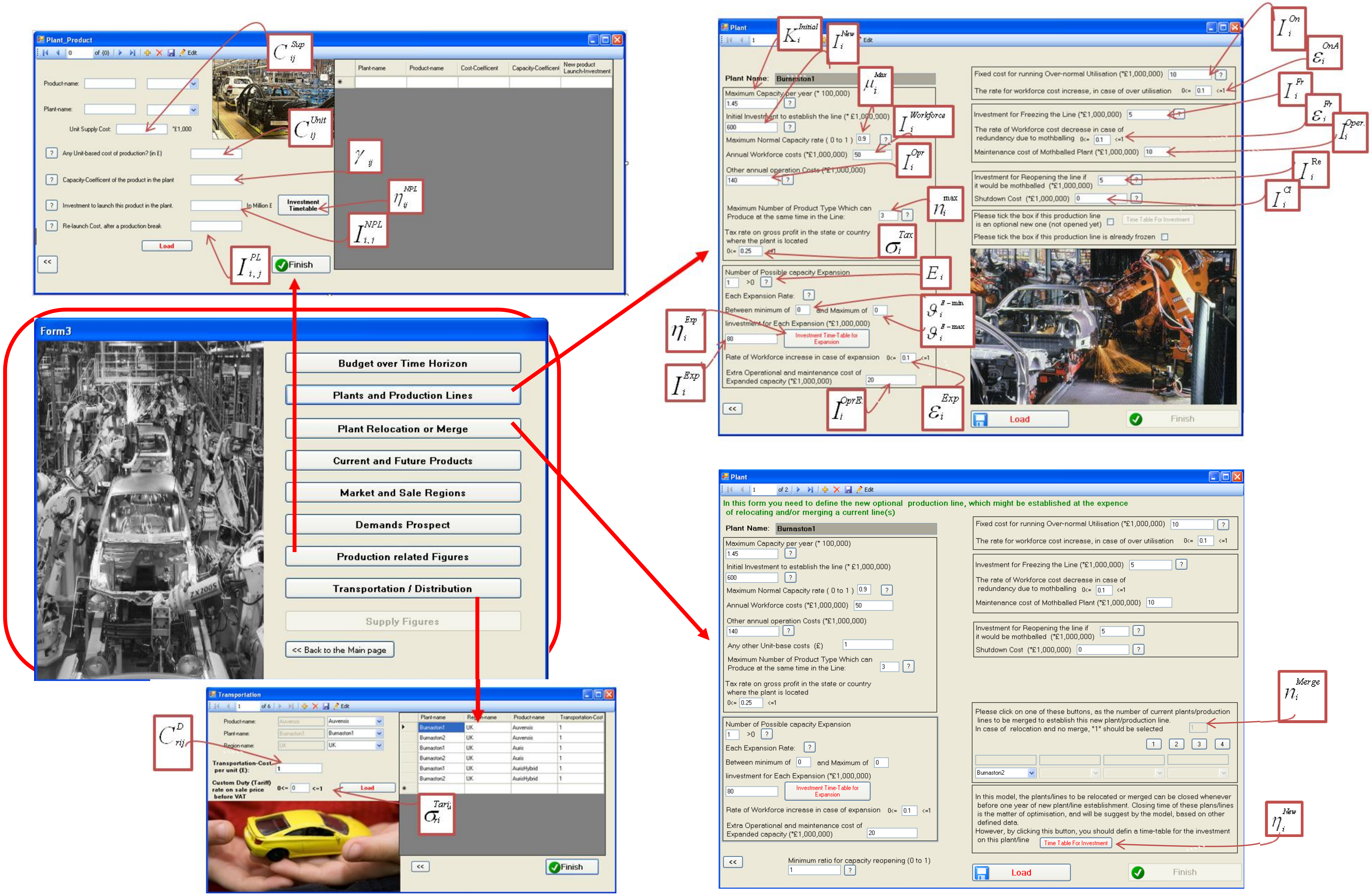
Planning-Year: 2008

Region-name: UK

Demand (unit): 80 * 1,000

Sale Price: 80 * £1,000

Figure 4-8: Data collection section of the NBS-DMM-CI Application. The input manager consists of different forms and each form collects the data and saves them in a specific form in an Access file (continues on the next page)



Plant_Product

Product-name:

Plant-name:

Unit Supply Cost: *£1,000

? Any Unit-based cost of production? (in £)

? Capacity-Coefficent of the product in the plant

? Investment to launch this product in the plant. In Million £

? Re-launch Cost, after a production break

Plant-name	Product-name	Cost-Coefficent	Capacity-Coefficent	New product Launch-Investment

Form3

Plant

Plant Name: Burnaston1

Maximum Capacity per year (* 100,000) 1.45

Initial Investment to establish the line (* £1,000,000) 600

Maximum Normal Capacity rate (0 to 1) 0.9

Annual Workforce costs (*£1,000,000) 50

Other annual operation Costs (*£1,000,000) 140

Maximum Number of Product Type Which can Produce at the same time in the Line: 3

Tax rate on gross profit in the state or country where the plant is located 0<= 0.25 <=1

Number of Possible capacity Expansion 1 >0

Each Expansion Rate:

Between minimum of 0 and Maximum of 0

Iinvestment for Each Expansion (*£1,000,000) 80

Rate of Workforce increase in case of expansion 0<= 0.1 <=1

Extra Operational and maintenance cost of Expanded capacity (*£1,000,000) 20

Fixed cost for running Over-normal Utilisation (*£1,000,000) 10

The rate for workforce cost increase, in case of over utilisation 0<= 0.1 <=1

Investment for Freezing the Line (*£1,000,000) 5

The rate of Workforce cost decrease in case of redundancy due to mothballing 0<= 0.1 <=1

Maintenance cost of Mothballed Plant (*£1,000,000) 10

Investment for Reopening the line if it would be mothballed (*£1,000,000) 5

Shutdown Cost (*£1,000,000) 0

Please tick the box if this production line is an optional new one (not opened yet) ☐

Please tick the box if this production line is already frozen ☐

Plant

In this form you need to define the new optional production line, which might be established at the expence of relocating and/or merging a current line(s)

Plant Name: Burnaston1

Maximum Capacity per year (* 100,000) 1.45

Initial Investment to establish the line (* £1,000,000) 600

Maximum Normal Capacity rate (0 to 1) 0.9

Annual Workforce costs (*£1,000,000) 50

Other annual operation Costs (*£1,000,000) 140

Any other Unit-base costs (£) 1

Maximum Number of Product Type Which can Produce at the same time in the Line: 3

Tax rate on gross profit in the state or country where the plant is located 0<= 0.25 <=1

Number of Possible capacity Expansion 1 >0

Each Expansion Rate:

Between minimum of 0 and Maximum of 0

Iinvestment for Each Expansion (*£1,000,000) 80

Rate of Workforce increase in case of expansion 0<= 0.1 <=1

Extra Operational and maintenance cost of Expanded capacity (*£1,000,000) 20

Minimum ratio for capacity reopening (0 to 1) 1

Fixed cost for running Over-normal Utilisation (*£1,000,000) 10

The rate for workforce cost increase, in case of over utilisation 0<= 0.1 <=1

Investment for Freezing the Line (*£1,000,000) 5

The rate of Workforce cost decrease in case of redundancy due to mothballing 0<= 0.1 <=1

Maintenance cost of Mothballed Plant (*£1,000,000) 10

Investment for Reopening the line if it would be mothballed (*£1,000,000) 5

Shutdown Cost (*£1,000,000) 0

Please click on one of these buttons, as the number of current plants/production lines to be merged to establish this new plant/production line. In case of relocation and no merge, "1" should be selected 1

Burnaston2

In this model, the plants/lines to be relocated or merged can be closed whenever before one year of new plant/line establishment. Closing time of these plans/lines is the matter of optimisation, and will be suggest by the model, based on other defined data.
However, by clicking this button, you should defin a time-table for the investment on this plant/line

Transportation

Product-name: Auvensis

Plant-name: Burnaston1

Region-name: UK

Transportation-Cost per unit (£): 1

Custom Duty (Tariff) rate on sale price before VAT 0<= 0 <=1

Plant-name	Region-name	Product-name	Transportation-Cost
Burnaston1	UK	Auvensis	1
Burnaston2	UK	Auvensis	1
Burnaston1	UK	Auris	1
Burnaston2	UK	Auris	1
Burnaston1	UK	AurisHybrid	1
Burnaston2	UK	AurisHybrid	1

Data collection section of the NBS-DMM-CI Application. The input manager consists of different forms and each form collects the data and saves them in a specific form in an Access file (continuation from the last page)

Chapter 5 : Validation

5-1- Validation Plan

In this section a series of validations with hypothetical data will be done to test all the terms, characteristics and essential abilities of the model and their interactions. To design these hypothetical cases, a validation plan with verification considerations is required. This plan should provide a road-map for doing the hypothetical tests, with regard to all the model's terms and interactions. The outline of this plan is given in figure 5-1 and then pinpointed in detail in figure 5-2.

Figure 5-1 shows the highlights of the validation and verification plan, which links the test series' outlines to the chapter's sections and provides the big picture of the validation logic. Using the same structure but in more detailed format, figure 5-2 links the validation plan to the input-control-output-mechanism (ICOM) framework of each test series and establishes the inter-connections and interactions of the test series.

As illustrated in figure 5-1, the validation plan covers all the strategic terms and abilities which have been highlighted in section 2-3 as musts for a strategic capacity planning model, namely uncertainty, capacity volume, capacity location/relocation, product management and finally flexibility management. Financial and other terms are also embedded in these early-mentioned main terms. As can be seen from figure 5-1, not only will capacity volume and location problems under deterministic and stochastic markets be individually validated in this plan; also the effect of local and global strategy on capacity volume management in both deterministic and stochastic markets will be interactively validated and compared which then highlights the value of the stochastic solution (VSS). To create this interrelationship between the test series to see the VSS, as demonstrated in figure 5-2, the same input data and market scenarios are considered for some of the cases to see how different strategies (global or local) in different market environments (deterministic or stochastic) cause different optimum solutions and why a lack of a global strategy or ignoring market uncertainty leads to sub-optimal solutions. Since the model is based on a stochastic framework, to generate equivalent deterministic cases (cases 1 to 5 and 6 to 8), the expected demand as well as expected sales price under just one scenario (z=1) will be applied to the model. This one-scenario format represent a deterministic case.

Once the capacity volume and location/relocation cases in both the deterministic and stochastic market are validated in the abovementioned individual cases, and once the interactions are established in a more interrelated test series, in the rest of the validation plan flexibility choices and the product management ability of the model are tested in a series of more complex (global) hypothetical tests, as shown in figure 5-1 and 5-2.

Although the model can be used for a wide range of production industries, here, to make the cases more dedicated, just the production plants for the automotive industries are considered in the hypothetical data. The input data are therefore, adjusted to average figures for non-luxury passenger car manufacturers, which can be compared with the case of TMUK in chapter 6.

The rest of this chapter has been organised as follows: In section 5-2 and 5-3 respectively, capacity volume management and location/relocation management in a Business-as-usual (BAU) framework will be validated, as shown in figure 5-1. Business-as-usual (BAU) is an approach used to find the most probable scenario, and to run the deterministic program for the scenario to find the solutions of the optimum product-mix, load-planning, and capacity planning (Hood et al. 2003). This is the deterministic approach that has been employed by many researchers to simplify the cases (Chakravarty 2005, Naraharisetti et al. 2010, Kauder et al. 2009, Hammami et al. 2009, Fleischmann et al. 2006, Melo et al. 2006, Hamad et al. 2008). In section 5-4 the model will be validated in an uncertain market for volume and location problems, with more complex cases. The effect of market uncertainty on global strategic capacity management will be explained in these sections. Subsequently, in sections 5-5 and 5-6, flexibility choices and product management abilities will be validated. Each section may contain one or more hypothetical tests as shown in figure 5-2. Each test is designed to validate one or more abilities of the model. The cases start from much simpler cases in the beginning (section 5-2), and, validating the basic abilities of the model, section by section and case by case, the hypothetical cases become more complex and larger. Therefore, the last cases (case 12, 13 and 14 in section 5-5 and 5-6) not only validate the model for certain abilities, but also show the applicability of the model to the large-scale hypothetical cases. The demand changes and input data are designed in a way that the optimised solutions are not easily anticipated or obvious to the decision makers as to not only validate the model in near-boundary situations, but to also show the merits of using the model in such cases. As the general complexity of the cases increases step by step, this near-boundary and anticipation complexity will also increase section by section and case by case.

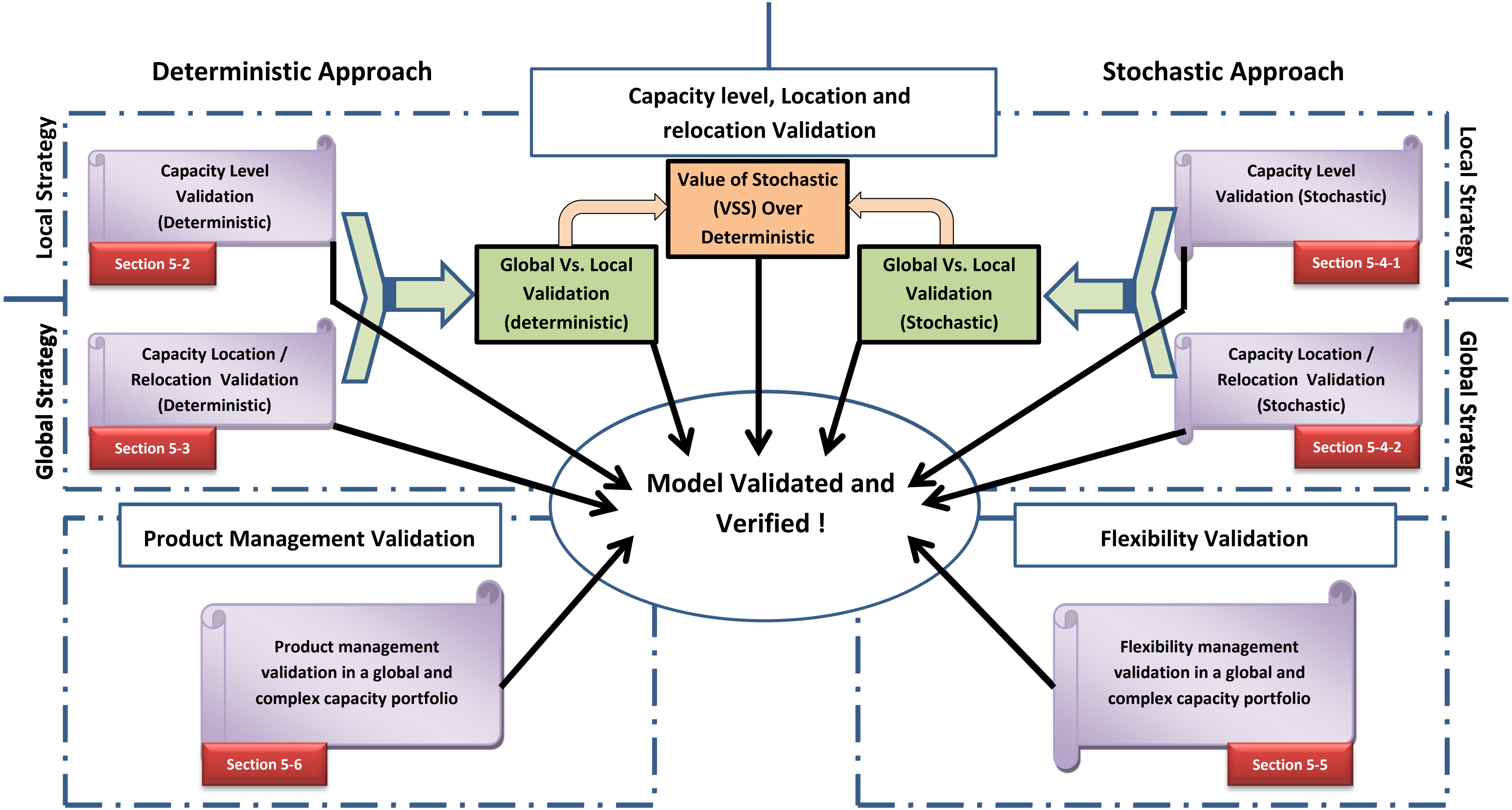


Figure 5-1: The outline of the validation and verification plan

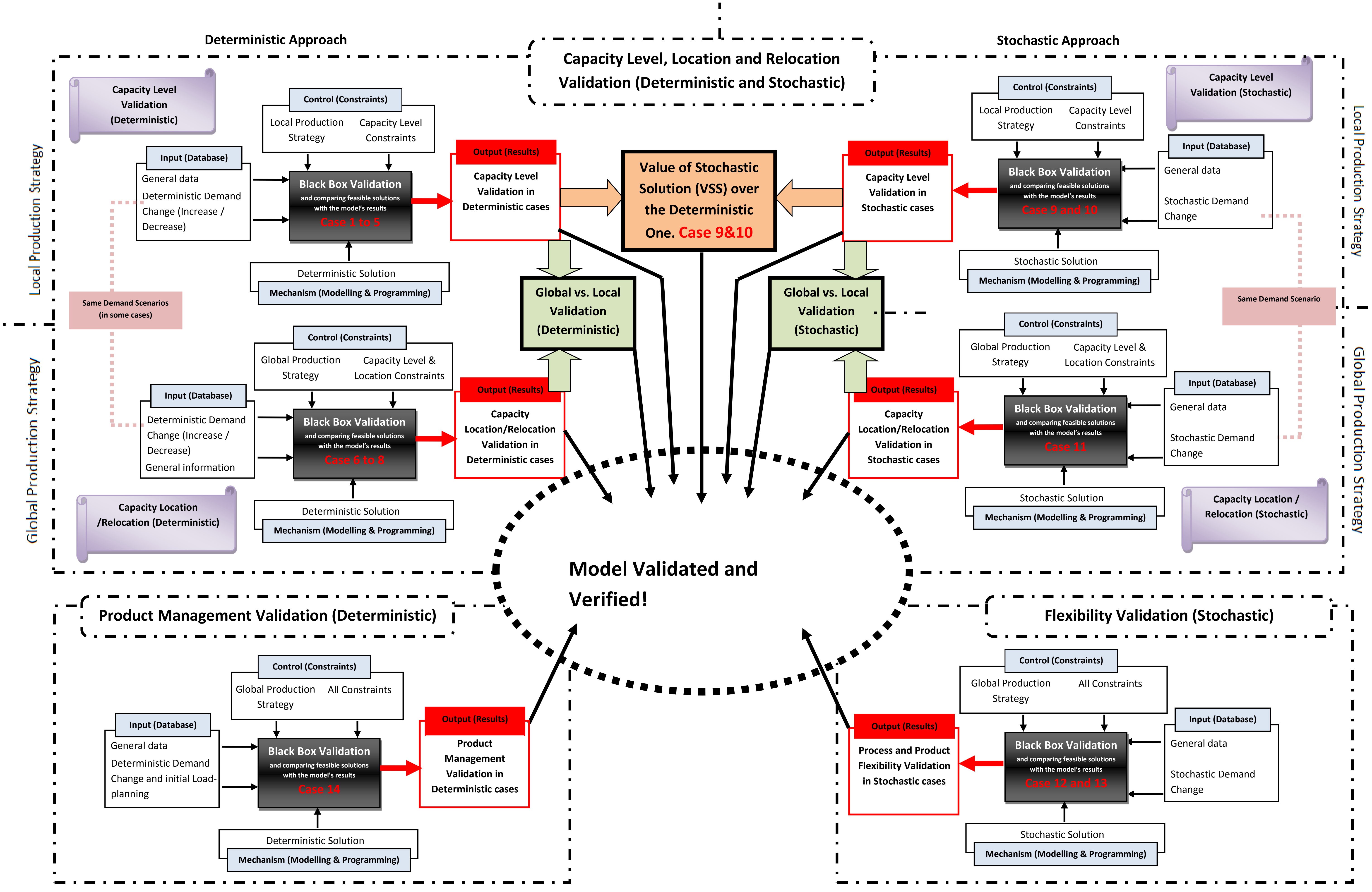


Figure 5-2: Details of validation plan and verification procedure, based on ICOM framework

5-2- Capacity Level Management

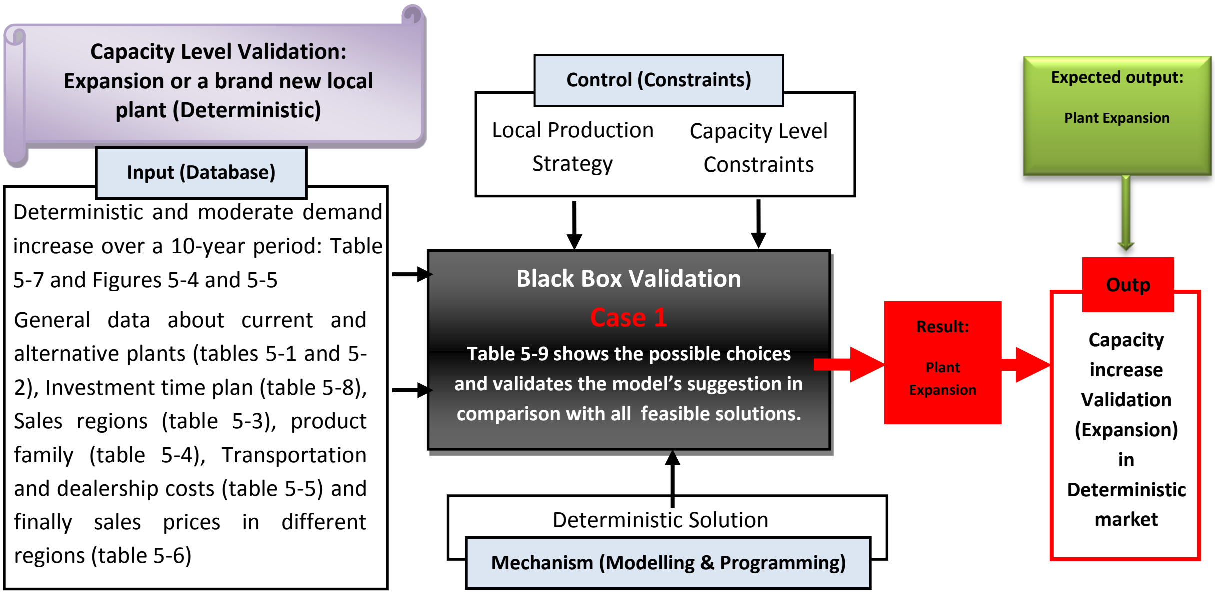
In this section, the model's ability to manage different demand changes will be validated in a business-as-usual framework. This section is divided into the two main subsections of demand increase and demand decrease. At the beginning of each subsection the required data and initial information is explained, followed by problem statements and results.

Demand Increase Series:

In this category the demand is designed to increase slightly or moderately and options for overutilisation, capacity expansion and new capacity establishment are available options for the model.

Case1: Moderate Demand Increase. Expansion or New Plant in the UK?

Case Brief: In this case, there is one plant in the UK, supplying all the current demand. However, a moderate demand increase is expected in the scope of the next 10 years for the company. Although this excess demand is beyond the current nominal capacity of the plant, the factory is capable of expansion to cover this demand. Another option to the decision makers, however, is establishing a brand new production site in the UK, close to the current plant to benefit from the training, same suppliers, sharing management etc. Therefore the question is which choice is more beneficial in this case. Adapting the same input-output-mechanism-control (ICOM) framework, which was explained in the methodology chapter and then expanded on in the last section (figure 5-2), figure 5-3 summarises this case.



Deterministic and moderate demand increase over a 10-year period: Table 5-7 and Figures 5-4 and 5-5

General data about current and alternative plants (tables 5-1 and 5-2), Investment time plan (table 5-8), Sales regions (table 5-3), product family (table 5-4), Transportation and dealership costs (table 5-5) and finally sales prices in different regions (table 5-6)

Table 5-9 shows the possible choices and validates the model's suggestion in comparison with all feasible solutions.

Figure 5-3: ICOM framework for case 1 of the validation plan

Input Data: Table 5-1 reflects some general information about both the current and optional plants in the UK. Table 5-2, on the other hand, provides more details about expansion and overutilisation of these plants.

Table 5-1: General information about the current and optional plants in case 1

	Plant No.	Plant Location	Maximum Capacity (*1,000)	Maximum normal capacity rate	Initial Capital Investment (million pounds)	Annual Operations cost (million pounds)	Annual normal Work force Cost (million pounds)	Any unit-based cost of production excluding supply	Profit Tax rate
Plant 1	1	UK	300	0.7	200	150	130	500	0.2
Alternative Plant	2	UK	200	0.8	150	100	100	500	0.2

Table 5-2: Expansion and Overutilisation details of the plants in case 1

	Plant No.	Capacity Expansion					Overutilisation	
		Number of possible Expansions	Maximum Expansion rate	Capital investment for Expansion (million pounds)	Extra operations cost in case of expansion (million pounds)	Extra work force cost in case of expansion (million pounds)	Extra work force cost in case of overutilisation (million pounds)	Extra operations cost in case of overutilisation (million pounds)
Plant 1	**1**	1	0.4	70	40	39	26	30
Alternative Plant	**2**	1	0.4	50	20	30	20	15

Three market regions for the products are considered in this case: EU, USA and Asia. Table 5-3 identifies the VAT in these regions, as well as tariff rates for the products coming from each plant. Since both plants are located in the UK, the tariffs remain the same for them.

Table 5-3: VAT and tariff rates for different sales regions in case 1

Sales Region	**EU**	**USA**	**Asia**
VAT in Market	20%	18%	17%
Tariffs Plant 1	0	10%	20%
Tariffs Plant 2	0	10%	20%

Six different product families have been planned for this 10-year scope, including 4 current families and two new products. Table 5-4 illustrates more details about these product families to be produced in each plant.

Table 5-4: Product families and required R&D and NPL investment to launch them, in case 1

Product Name	**If R&D applies, what is the Cost (£million)**	**Plant-related figures for PLANT 1**				**Plant-related figures for PLANT 2**			
		NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 1	Capacity Coefficient in plant 1	NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 2	Capacity Coefficient in plant 2
KX1	-	-	£17,000	1	1	5	£17,000	1	1
KX2	-	-	£18,000	1	1	5	£18,000	1	1
KX3	-	-	£19,000	1	1	5	£19,000	1	1
TY2	-	-	£16,000	1	1	5	£16,000	1	1
TY3	1.5	10	£17,000	1	1	10	£17,000	1	1
TX5	1.5	10	£18,000	1	1	10	£18,000	1	1

This table shows that the last two product families are new products which will be subject to the cost of NPD, including £1.5 million for design of the products and £10 million to launch them in either the current or the new plant. For producing the current products in the current plant, no launch investment is required, since the investment is already made and the plant is capable of this production. However, since the second plant would be a new one, launching the current products in this line requires NPL investment (£5M for each product launch, as shown in table 5-4). Because the optional plant will be located in the UK, close to the current one, the supply cost is identical for each product to both plants. The transportation and warehouse costs as well as the dealership expense are also the same for both plants, depending on the sales regions (table 5-5). Sales prices for the product families are also set in table 5-6.

Table 5-5: Transportation, warehouse and dealership expenses for case 1

	Plant 1	Plant 2
EU	£1,000	£1,000
USA	£4,000	£4,000
Asia	£8,000	£8,000

Table 5-6: The product family sales price in different sales regions for case 1

	KX1	KX2	KX3	TY2	TY3	TX5
EU	£31,000	£32,000	£33,000	£29,000	£31,000	£32,000
USA	£32,000	£33,000	£34,000	£30,000	£32,000	£33,000
Asia	£33,000	£34,000	£36,000	£32,000	£33,000	£34,000

To simplify this case no inflation, interest rate or discount rate is assumed in this case. Demand details and the product life cycle for each product family in each sales region and each planning year is set in table 5-7.

Table 5-7: Demand details for each product family in each sales region in each year for case 1.

			KX1	KX2	KX3	TY2	TY3	TX5
2012	**t=0**	**EU**	60	30	20	10	0	0
		USA	35	20	10	10	0	0
		Asia	20	15	10	10	0	0
2013	**t=1**	**EU**	60	30	20	20	0	0
		USA	30	20	15	15	0	0
		Asia	25	15	15	15	0	0
2014	**t=2**	**EU**	50	40	20	35	0	0
		USA	20	20	15	25	0	0
		Asia	20	15	15	20	0	0
2015	**t=3**	**EU**	30	40	25	45	0	0
		USA	20	20	20	30	0	0
		Asia	10	20	20	30	0	0
2016	**t=4**	**EU**	20	30	30	55	0	0
		USA	20	20	20	40	0	0
		Asia	10	15	20	40	0	0
2017	**t=5**	**EU**	10	30	30	40	40	0
		USA	5	15	20	30	20	0
		Asia	5	10	20	30	20	0

2018	**t=6**	**EU**	0	15	30	40	60	0
		USA	0	5	20	30	35	0
		Asia	0	5	20	30	30	0
2019	**t=7**	**EU**	0	0	10	30	60	40
		USA	0	0	5	20	45	25
		Asia	0	0	0	20	45	25
2020	**t=8**	**EU**	0	0	0	15	60	60
		USA	0	0	0	10	50	40
		Asia	0	0	0	5	50	40
2021	**t=9**	**EU**	0	0	0	0	65	70
		USA	0	0	0	0	55	50
		Asia	0	0	0	0	55	40

The budget planning for each investment is shown in table 5-8. This table shows how much and how far in advance the investment for the new plant establishment and capacity expansion should be carried out, as well NPL and R&D investment for each product.

Table 5-8: Investment time planning requirement

	3 years before	2 years before	1 year before	Running year	1 year after	2 years after
Plant 1 Expansion	-	-	80%	10%	10%	-
Plant 2 Establishment	-	50%	30%	10%	10%	-
Plant 2 Expansion	-	-	80%	10%	10%	-
TY3 Product NPD investment	-	50%	30%	10%	10%	-
TX5 Product NPD investment	-	50%	30%	10%	10%	-
TY3 Product NPL in Plant 1	-	-	80%	20%	-	-
TX5 Product NPL in Plant 1	-	-	80%	20%	-	-
KX1 Product NPL in Plant 2	-	-	80%	20%	-	-
KX2 Product NPL in Plant 2	-	-	80%	20%	-	-
KX3 Product NPL in Plant 2	-	-	80%	20%	-	-
TY2 Product NPL in Plant 2	-	-	80%	20%	-	-
TY3 Product NPL in Plant 2	-	-	80%	20%	-	-
TX5 Product NPL in Plant 2	-	-	80%	20%	-	-

Case Result and analysis: Figure 5-4 illustrates the accumulative cycle planning for each product. In this case, it is assumed that both the current plant and the new (alternative) one are capable of producing all of these products and the 'capacity ratios' of all the products in both plants are equal to one. In other words, they are all standard products for both plants.

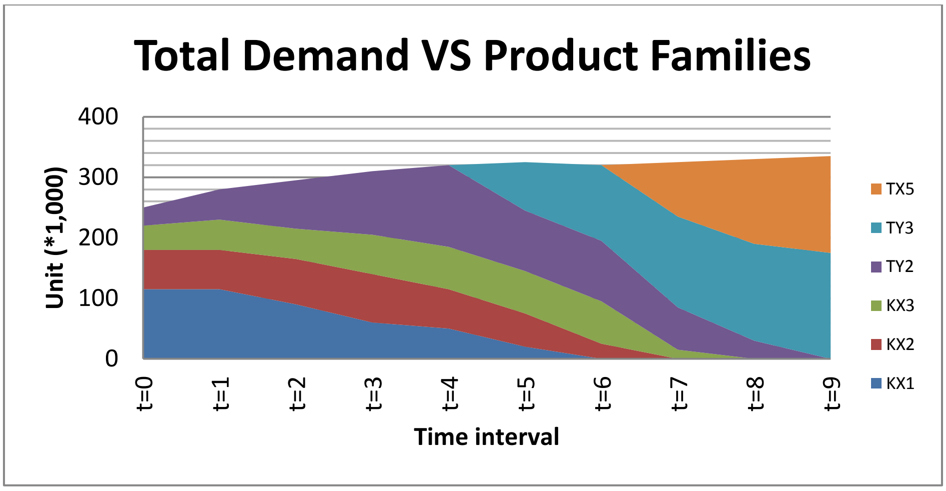


Figure 5-4: Production/demand cycle time for product families in case 1.

Total demand vs. available and alternative capacity is shown in figure 5-5, which shows the large picture demand-wise to compare the potential solutions.

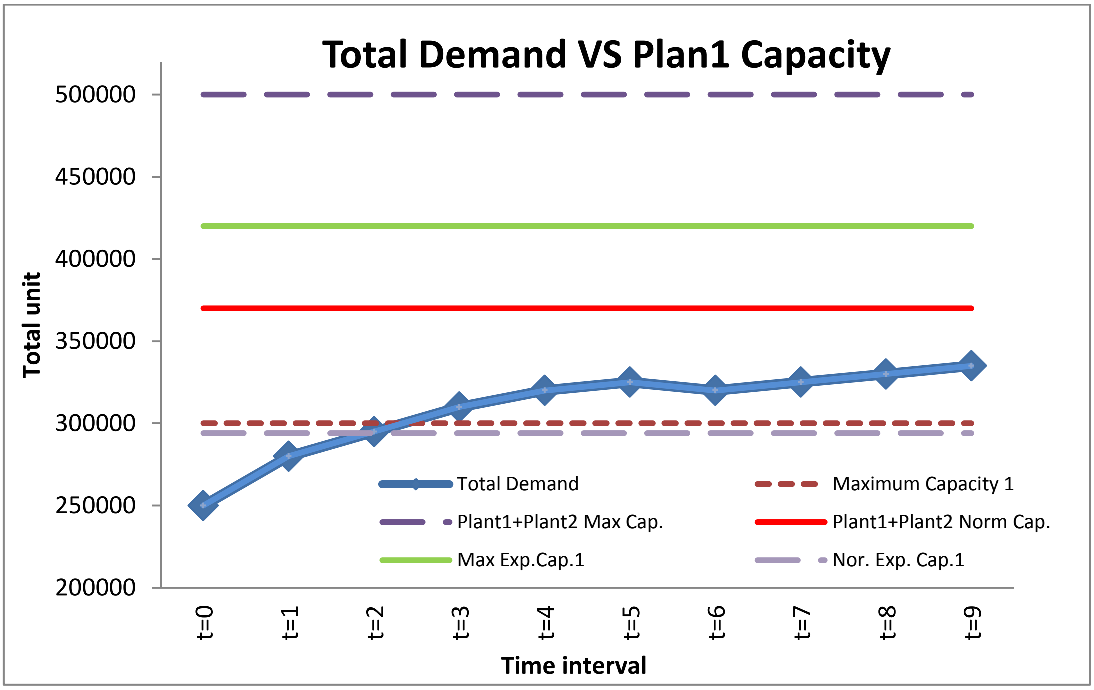


Figure 5-5: Total demand change vs. different options in Case 1.

According to this diagram, both options of capacity expansion and new plant establishment are feasible for this demand increase. In case of a new capacity establishment, both plants would work reasonably below their normal capacity, while in the case of capacity expansion, the plant will be working overutilised just one year after expansion until the end of the planning period.

Putting all abovementioned information into the model and running it, the model suggests expanding the current plant, rather than investing in the new one. In this case the current plant will be overutilised in the whole planning period. Table 5-9, which shows the different amount of investment for these two choices, supports the decision taken by the model. In this simple case, it is easy to trace down the options and calculate the differences.

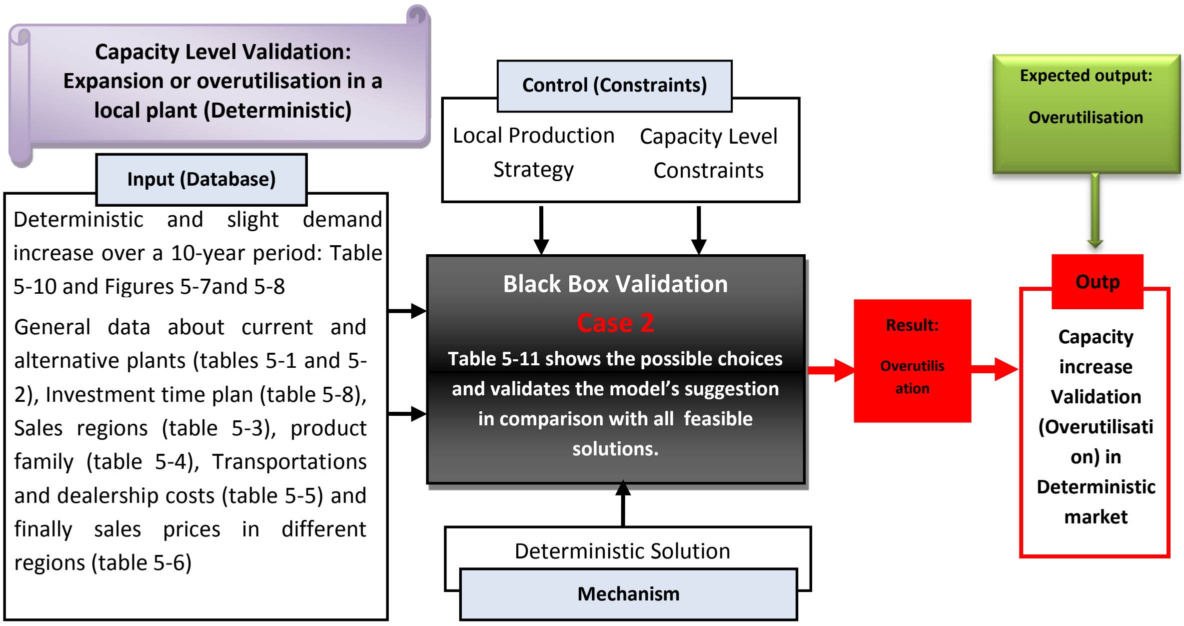
Table 5-9: Differences in investment amount for two feasible options in case 1, which support the model's suggestion (numbers are in million£)

Expansion	**Expansion Fixed Cost**	**Extra Annual Operations cost of expansion**	**Extra Annual Work force Cost of expansion**	**Annual Overutilisation fixed cost x 10**	**Annual Overutilisation Work force cost x 10**	**Sum**
	70	280	273	260	300	**1,183**
New Plant	**New plant Capital**	**Operations cost of Plant 2**	**Work force Cost of Plant 2**	**NPL for 4 product families**	**-**	**Sum**
	150	700	700	20	-	**1,570**

One may think about other possible options, such as establishing the new plant in China to reduce the costs, enjoying a larger market and avoiding tariffs, transportation costs and reducing dealership costs. Such complicated cases will be discussed in section 5-3. For this section, however, the result shows, basically, unless the demand overtakes the maximum expanded capacity of the current plant, establishing the new plant in the UK is not the optimal solution. However, if the running cost of the overutilised capacity increases significantly or if demand surpasses the expanded capacity, establishing the new plant becomes more feasible/desirable. Although both cases have been tested by the author, the results were fully consistent with expectations and will therefore not be repeated here.

Case2: Slight Demand Increase. Expansion or Overutilisation?

Case Brief: In this case a slight demand increase will be analysed and the model will be validated for this demand change. Recalling from case 1, the current plant with all early-mentioned financial data will be assumed in this case. Demand increase is in the scope of plant overutilisation or expansion and the question is which decision is the best. Sales regions, product families and budget planning remain the same as in case 1. Therefore, tables 5-1 to 5-6 and 5-8 are valid for this case so they are applied in figure 5-6, where the ICOM framework for this case has been shaped.



Deterministic and slight demand increase over a 10-year period: Table 5-10 and Figures 5-7and 5-8

General data about current and alternative plants (tables 5-1 and 5-2), Investment time plan (table 5-8), Sales regions (table 5-3), product family (table 5-4), Transportations and dealership costs (table 5-5) and finally sales prices in different regions (table 5-6)

Table 5-11 shows the possible choices and validates the model's suggestion in comparison with all feasible solutions.

Figure 5-6: ICOM framework for case 2 of the validation plan

Input data: In this case the plant and its information remain the same as the current plant in the UK in case 1. All other investment-related and operations related costs, as well as product families, market regions, etc. are also recalled from case 1. Demand change, however, is designed differently to test the model for overutilisation or expansion choices. This demand change is shown in table 5-10.

Table 5-10: Demand details for each product family in each sales region in each year for case 2.

			KX1	KX2	KX3	TY2	TY3	TX5
2012	**t=0**	**EU**	60	40	20	10	0	0
		USA	35	25	10	10	0	0
		Asia	20	15	10	10	0	0
2013	**t=1**	**EU**	55	30	20	20	0	0
		USA	30	20	15	15	0	0
		Asia	25	15	15	15	0	0
2014	**t=2**	**EU**	40	40	20	35	0	0
		USA	20	20	15	25	0	0
		Asia	20	15	15	20	0	0

2015	**t=3**	**EU**	30	40	25	45	0	0
		USA	10	20	20	30	0	0
		Asia	10	13	20	30	0	0
2016	**t=4**	**EU**	10	35	30	55	0	0
		USA	5	20	20	40	0	0
		Asia	5	15	20	40	0	0
2017	**t=5**	**EU**	0	25	30	40	40	0
		USA	0	13	20	30	20	0
		Asia	0	10	20	30	20	0
2018	**t=6**	**EU**	0	0	30	40	60	0
		USA	0	0	20	30	35	0
		Asia	0	0	20	30	30	0
2019	**t=7**	**EU**	0	0	0	30	60	40
		USA	0	0	0	20	45	25
		Asia	0	0	0	10	45	25
2020	**t=8**	**EU**	0	0	0	15	60	60
		USA	0	0	0	10	35	40
		Asia	0	0	0	5	30	40
2021	**t=9**	**EU**	0	0	0	0	55	60
		USA	0	0	0	0	50	40
		Asia	0	0	0	0	50	40

Illustrating from this table, figure 5-7 shows the total production cycle time for each product. In this case, it is assumed that the current plant is capable of producing all of these products and capacity ratios for these products in this plant are equal to one.

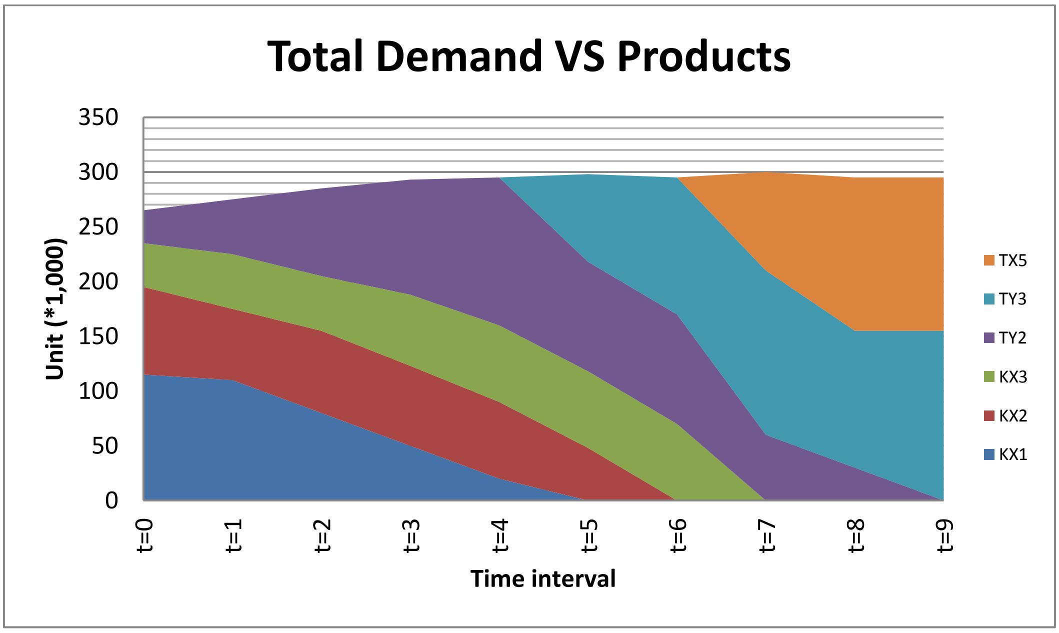


Figure 5-7: Production/demand cycle time for product families in case 2.

Case Result and analysis: Possible options vs. demand change is shown in figure 5-8. These choices are: 1- expanding the current capacity; or 2-overutilising the plant nearly to its maximum capacity.

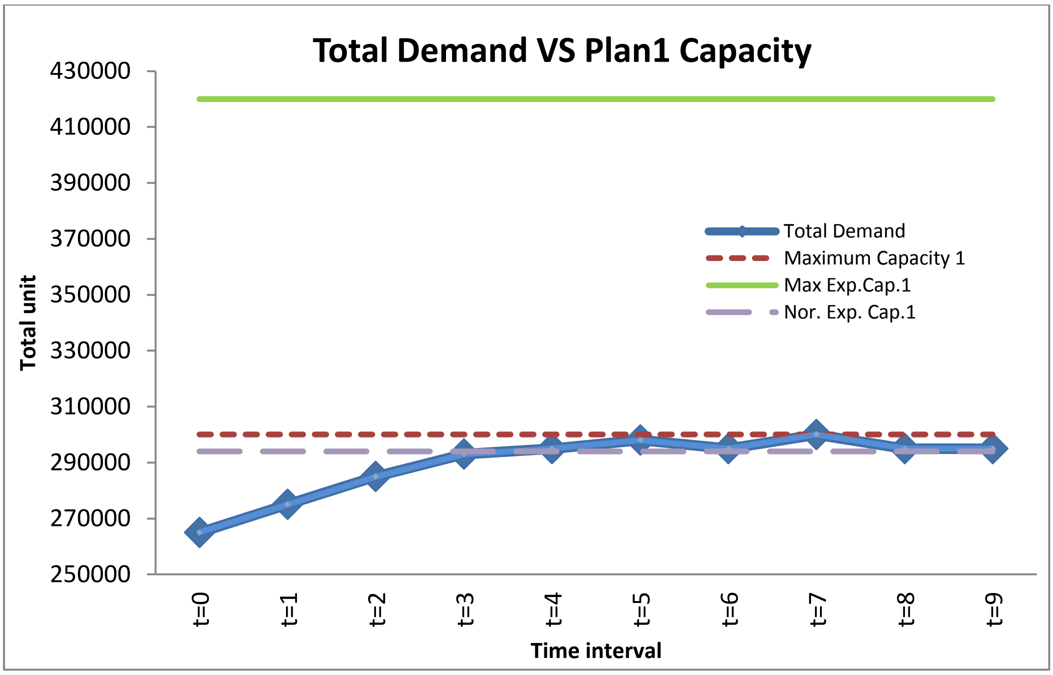


Figure 5-8: Total demand change vs. different options in case 2.

This figure shows that both capacity overutilisation and expansion can be feasible solutions to chase the slight demand increase. The maximum demand in this case is just below the maximum capacity of the current plant, and just above the normal capacity rate for the expanded capacity.

Putting all this information into the model and running it, the model suggests overutilising the current capacity without any expansion. Table 5-11, which shows the differences in investment and costs between the two possible options, supports this decision.

Table 5-11: Differences in investment amount for two feasible options in case 2, which support the model's suggestion (numbers are in million£)

Expansion	**Expansion Fixed Cost**	**Extra Annual Operations cost of expansion x7**	**Extra Annual Work force Cost of expansion x7**	**Annual Overutilisation fixed cost x 7**	**Annual Overutilisation Work force cost x 7**	**Sum**
	70	240	234	156	180	**880**
Overutilisation	**Annual Overutilisation fixed cost x 10**	**Annual Overutilisation Work force cost x 10**	**-**	**-**	**-**	**Sum**
	260	300	-	-	-	**560**

One may think about other possible options, such as establishing the new plant in China rather than overutilising the current plant in the UK for 10 years. This case will also be discussed in section 5-3. For this section, however, the result shows, unless the demand overtakes the maximum capacity of the current plant, plant expansion is not the best answer. However, if the running cost of the overutilised capacity increases significantly or demand surpasses the maximum capacity, expanding the plant might become feasible/desirable. Although both cases have been tested by the author, the results are in total consistent with the expectations and are not repeated here.

Demand Decrease Series:

In this section the demand is designed to decrease slightly or moderately and the options are: underutilisation, capacity mothball and capacity shutdown. There are two open plants in the UK, supplying all the current demands. However, the company needs to decide to close or mothball one of their plants in the UK, or leave them underutilised. The information for the plants remains the same as in case 1, except for the fact that the 'Alternative plant' in table 5-1 and 5-2 is supposed to be an open plant ('plant 2') in this case. On top of that, table 5-12 provides more information about the required investment and operational costs to close or mothball the plants.

Table 5-12: Mothball and shutdown information for the plants

		Capacity Mothball				Capacity Shutdown
	Plant No.	Fixed cost of mothballing (million pounds)	Redundancy rate in case of mothball	Fixed cost of reopening (million pounds)	Operations cost for mothballed plant (million pounds)	Fixed cost of shutdown (million pounds)
Plant 1	**1**	20	0.4	5	10	80
Plant 2	**2**	17	0.4	5	8	60

Information for the market regions as well as the cost of transportation, warehouse and dealerships can also be extracted from case 1 in tables 5-3, 5-5 and 5-6.

Since plant 2 is an open plant in this case and it is already producing the products, no NPL is assumed for the current products in plant 2. Figures for NPD will be different from case one, which is reflected in table 5-13.

Table 5-13: Product families and required R&D and NPL investment to launch them

Product Name	**If R&D applies, what is the Cost (£million)**	**Plant-related figures for PLANT 1**				**Plant-related figures for PLANT 2**			
		NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 1	Capacity Coefficient in plant 1	NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 2	Capacity Coefficient in plant 2
KX1	-	-	£17,000	1	1	0	£17,000	1	1
KX2	-	-	£18,000	1	1	0	£18,000	1	1
KX3	-	-	£19,000	1	1	0	£19,000	1	1
TY2	-	-	£16,000	1	1	0	£16,000	1	1
TY3	1.5	10	£17,000	1	1	10	£17,000	1	1
TX5	1.5	10	£18,000	1	1	10	£18,000	1	1

Case3: Moderate and Long-Term Demand Decrease. Shutdown, Mothball or Underutilisation?

Case Brief: In this case a moderate demand decrease and a long-term downturn in the market is designed to validate the model in a recession situation. Having all abovementioned input data, the decision makers of the company have three options: Shutdown, Mothball and Underutilisation. Figure 8-9 establishes an ICOM framework for this case, showing what the inputs, outputs, controls and mechanisms are in this case.

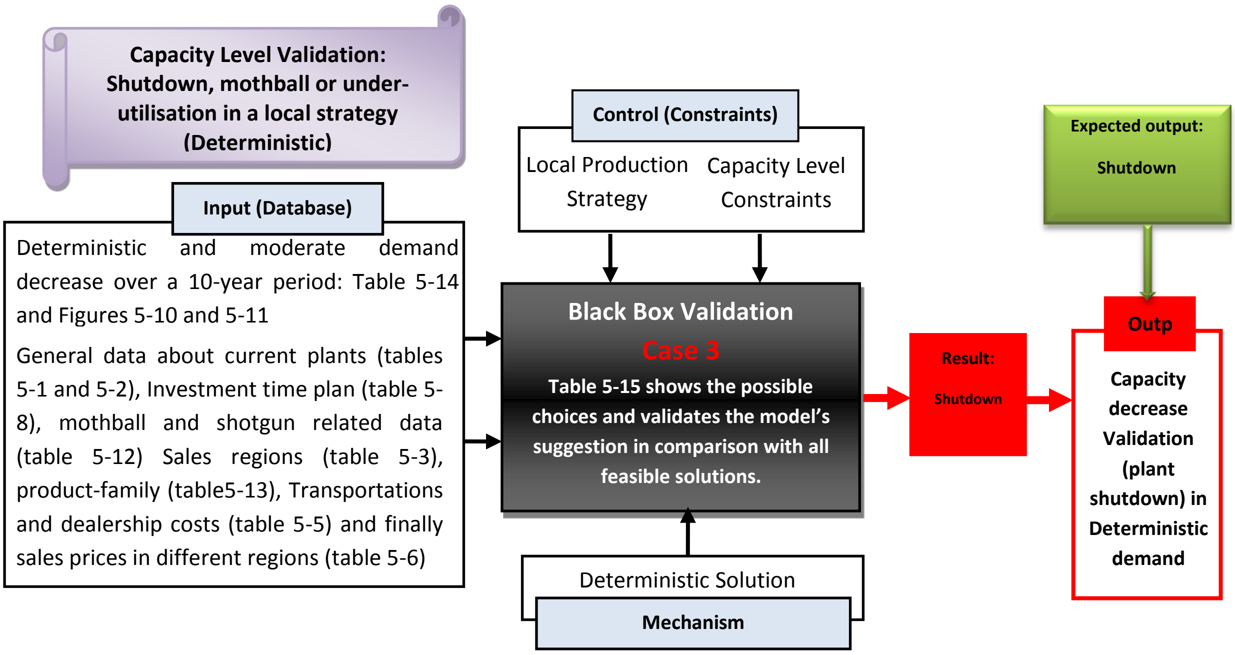


Figure 5-9: ICOM framework for case 3 of the validation plan

Input data: As mentioned earlier, in this case both plants in the UK are assumed open and their general data can be retrieved from table 5-1 and 5-2. Shutdown and mothball information about these plants has also been set in table 5-12. The sales region from table 5-3, product families from table 5-13, transportation and dealership costs from table 5-5 and finally sales prices from table 5-6 can be recalled.

Demand change, however, is applied in this case to validate the model in a long-term recession market and to test the demand decrease choices of shutdown, mothball or underutilisation. This moderate demand decrease is set in table 5-14 and illustrated in figure 5-10.

Table 5-14: Demand details for each product family in each sales region in each year for case 3.

			KX1	KX2	KX3	TY2	TY3	TX5
2012	t=0	EU	40	40	30	30	0	0
		USA	30	20	20	20	0	0
		Asia	30	30	10	20	0	0
2013	t=1	EU	40	40	30	30	0	0
		USA	30	20	20	15	0	0
		Asia	30	30	10	15	0	0
2014	t=2	EU	40	30	20	35	0	0
		USA	30	20	15	25	0	0
		Asia	30	15	15	20	0	0
2015	t=3	EU	30	30	25	45	0	0
		USA	20	15	10	30	0	0
		Asia	20	15	10	30	0	0
2016	t=4	EU	20	25	30	40	0	0
		USA	15	15	20	35	0	0
		Asia	10	10	20	30	0	0
2017	t=5	EU	15	20	30	35	30	0
		USA	5	10	10	25	20	0
		Asia	5	10	10	25	20	0
2018	t=6	EU	0	20	20	35	50	0
		USA	0	10	10	25	35	0
		Asia	0	5	10	25	30	0
2019	t=7	EU	0	15	20	20	50	30
		USA	0	5	10	10	40	20
		Asia	0	5	10	10	20	15
2020	t=8	EU	0	0	0	0	50	60
		USA	0	0	0	0	45	50
		Asia	0	0	0	0	30	45
2021	t=9	EU	0	0	0	0	40	90
		USA	0	0	0	0	30	50
		Asia	0	0	0	0	25	45

Based on this table, figure 5-10 shows the overall products' life cycles in the scope of the time plan for this case.

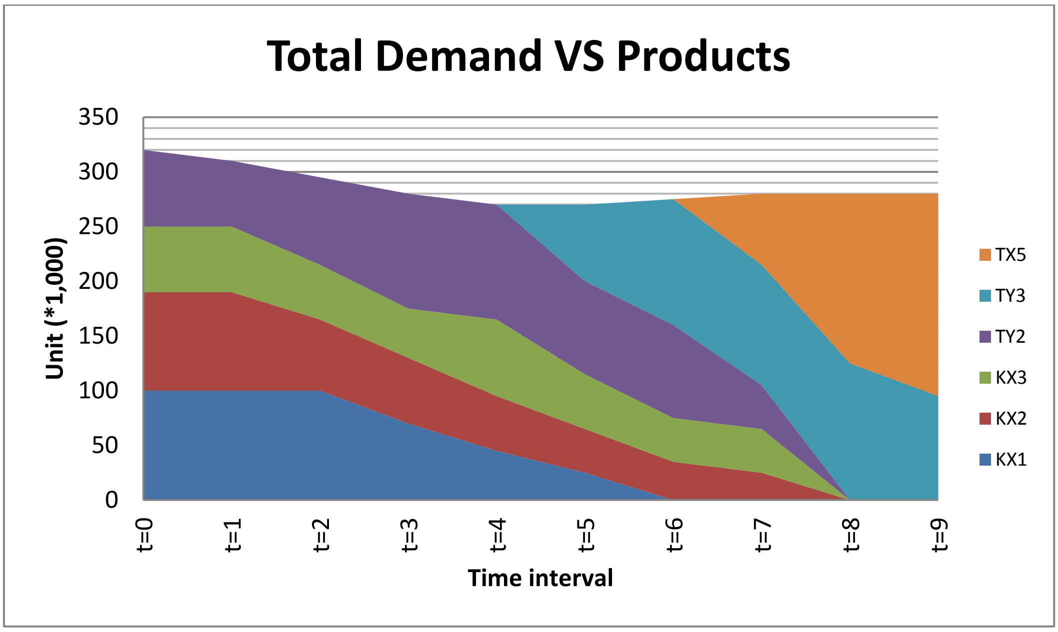


Figure 5-10: Production/demand cycle time for product families in case 3

Case Result and analysis: Considering figure 5-10 and the general information of the open plants, and assuming that all products can be produced in both plants, figure 5-11 illustrates the demand vs. available capacity.

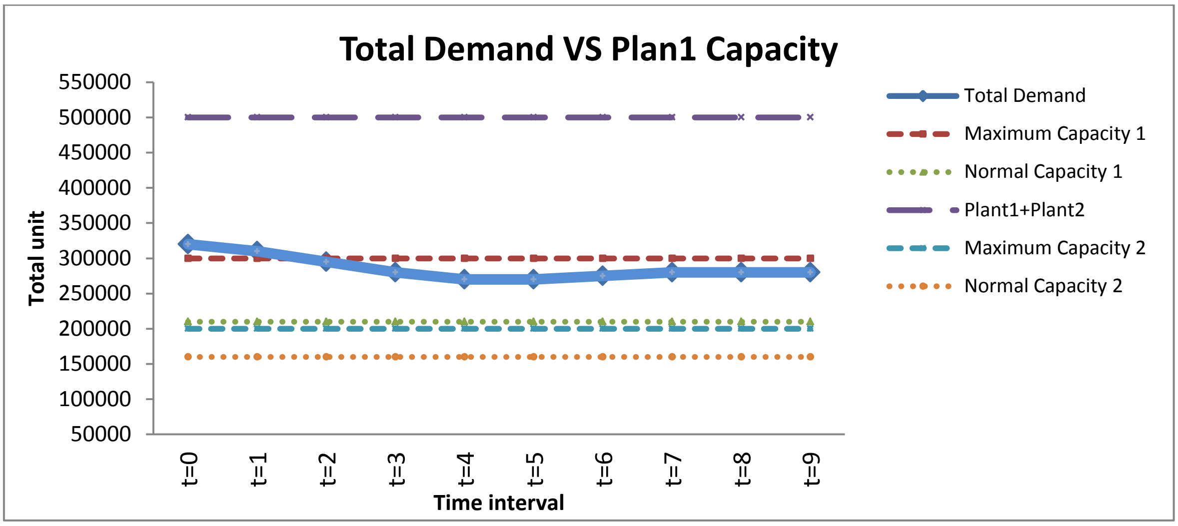


Figure 5-11: Total demand change vs. capacity in case 3

In this case, a moderate demand decrease is expected, where the demand drops from normal capacity of the company (Plant1 +Plant2) to just above maximum capacity of plant 1. Therefore, the three options of shutdown or mothball of plant 2, or of leaving both plants underutilised for the whole planning period can all be considered as feasible solutions. However, putting all this information into the model, it has been suggested to close down plant 2 and overutilise plant 1. Table 5-15, which shows the cost differences between these three feasible solutions also supports the model's suggestion. Regarding this table, shutting down plant 2 is the less expensive and therefore the best solution to the problem.

Table 5-15: Differences in investment amount for three feasible options in case 3, which support the model's suggestion (numbers are in million£)

Under Utilisation	**Plant 2 operations costs**	**Plant 2 work force cost**				**Sum**
	1000	1000				**2,000**
Capacity Shutdown	**Shutdown fixed cost of plant 2**	**Plant1 extra annual operations cost x 8**	**Plant1 overutilised work force x 8**		**-**	**Sum**
	60	120	160	-	-	**340**
Capacity Mothball	**Mothball fixed cost of plant2**	**Plant2 maintenance cost of mothball x8**	**Plant2 work force cost of mothball (after redundancy) x8**	**Plant1 extra annual operations cost x8**	**Plant1 overutilised work force x8**	**Sum**
	0	0	480	120	160	**760**

Case4 and Case5: Moderate but Mid-Term Demand Decrease. Mothball or Underutilisation?

Case Brief: In these two cases a mid-term and short-term recession is supposed for the company to validate the mothball decision. Since after the depression the demand is designed to return to the current situation, a shutdown option is not feasible unless one decides to shut down one of the plants and relocate it to another country when the demand recovers (this case will be discussed later in section 5-3). Therefore, the question is: Mothball or Underutilisation?

Case 4 is designed for a deeper recession, while case 5 represents a better situation. The expected result, however, is mothball for both recessions. The ICOM framework for these cases has been developed in figure 5-12.

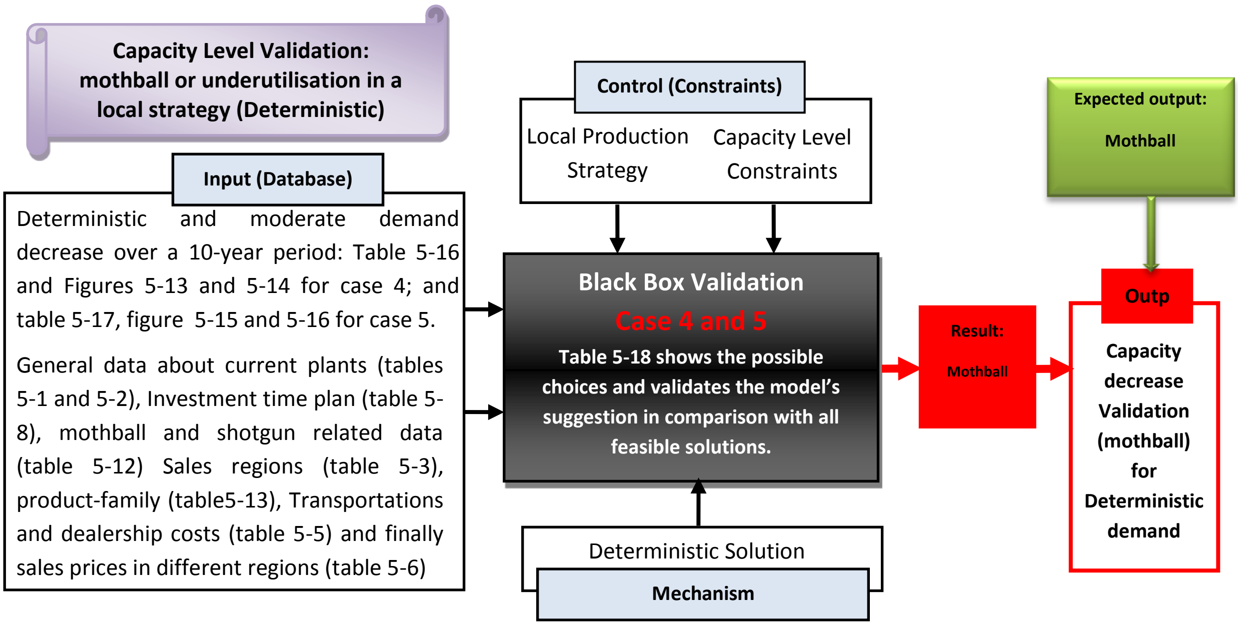


Figure 5-12: ICOM framework for case 4 and 5 of the validation plan

Input data: Demand detail and product life cycle for case 4 are shown in table 5-16 and figure 5-13, while table 5-17 and figure 5-14 show a better demand prospect for case 5. The general input data from both cases, however, stay the same as in the previous cases. Both plants are assumed to be in the UK, while tables 5-1, 5-2 and 5-12 illustrate all required plant-related data. Meanwhile table 5-3 on sales regions, table 5-13 on product families, table 5-5 on transportations and dealership costs and finally table 5-6 on sales prices provide other required input data, as explained in the ICOM framework (figure 5-12) for these two cases.

Table 5-16: Demand details for each product family in each sales region in each year for case 4.

			KX1	KX2	KX3	TY2	TY3	TX5
2012	**t=0**	**EU**	50	40	30	30	0	0
		USA	30	20	20	20	0	0
		Asia	30	30	10	20	0	0
2013	**t=1**	**EU**	40	40	30	30	0	0
		USA	30	20	20	15	0	0
		Asia	30	30	10	15	0	0
2014	**t=2**	**EU**	40	30	20	35	0	0
		USA	30	20	15	25	0	0
		Asia	30	15	15	20	0	0
2015	**t=3**	**EU**	30	30	25	45	0	0
		USA	20	15	15	30	0	0
		Asia	15	15	15	30	0	0
2016	**t=4**	**EU**	20	25	40	40	0	0
		USA	5	15	30	35	0	0
		Asia	5	10	25	30	0	0
2017	**t=5**	**EU**	5	20	30	35	45	0
		USA	0	10	10	25	30	0
		Asia	0	10	10	25	30	0
2018	**t=6**	**EU**	0	5	20	35	60	0
		USA	0	5	10	25	55	0
		Asia	0	5	10	25	40	0
2019	**t=7**	**EU**	0	0	20	20	50	50
		USA	0	0	10	20	40	30
		Asia	0	0	10	15	20	25
2020	**t=8**	**EU**	0	0	0	10	40	80
		USA	0	0	0	5	30	65
		Asia	0	0	0	0	30	60
2021	**t=9**	**EU**	0	0	0	0	50	90
		USA	0	0	0	0	35	65
		Asia	0	0	0	0	30	55

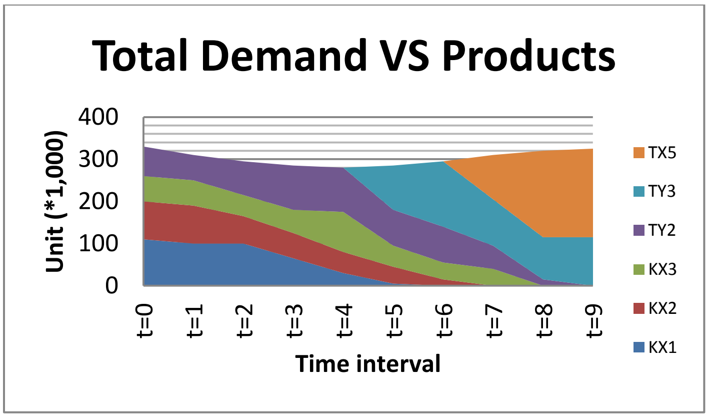


Figure 5-13: Production/demand cycle time for product families in case 4

Table 5-17: Demand details for each product family in each sales region in each year for case 5.

			KX1	KX2	KX3	TY2	TY3	TX5
2012	**t=0**	**EU**	50	40	30	30	0	0
		USA	40	20	20	20	0	0
		Asia	40	30	10	20	0	0
2013	**t=1**	**EU**	40	40	30	30	0	0
		USA	30	20	20	15	0	0
		Asia	30	30	10	15	0	0
2014	**t=2**	**EU**	40	30	20	35	0	0
		USA	30	20	15	25	0	0
		Asia	30	15	15	20	0	0
2015	**t=3**	**EU**	30	30	25	45	0	0
		USA	20	15	15	30	0	0
		Asia	20	15	15	30	0	0
2016	**t=4**	**EU**	20	25	40	40	0	0
		USA	15	15	30	35	0	0
		Asia	10	10	25	30	0	0
2017	**t=5**	**EU**	15	20	30	35	45	0
		USA	5	10	10	25	30	0
		Asia	5	10	10	25	30	0
2018	**t=6**	**EU**	0	20	20	35	60	0
		USA	0	10	10	25	55	0
		Asia	0	5	10	25	40	0
2019	**t=7**	**EU**	0	15	20	20	50	50
		USA	0	5	10	10	40	30
		Asia	0	5	10	10	20	25
2020	**t=8**	**EU**	0	0	0	0	50	80
		USA	0	0	0	0	45	65
		Asia	0	0	0	0	30	60
2021	**t=9**	**EU**	0	0	0	0	50	90
		USA	0	0	0	0	45	65
		Asia	0	0	0	0	30	55

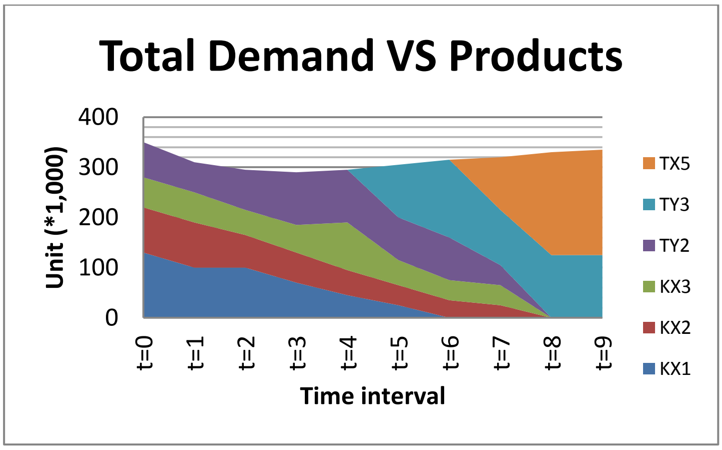


Figure 5-14: Production/demand cycle time for product families in case 5

Case Result and analysis: Based on all abovementioned information, demand vs. available capacity for case 4, in figure 5-15, and for case 5, in figure 5-16, is summarised. From these diagrams, it is clear that case 4 represents a mid-term depression for the company, while case 5 is set for a short-term decline in demand. In both cases, current demand as well as after-recession demand is well above the maximum capacity of plant 1, but in the normal production zone for Plant 1+ Plant 2.

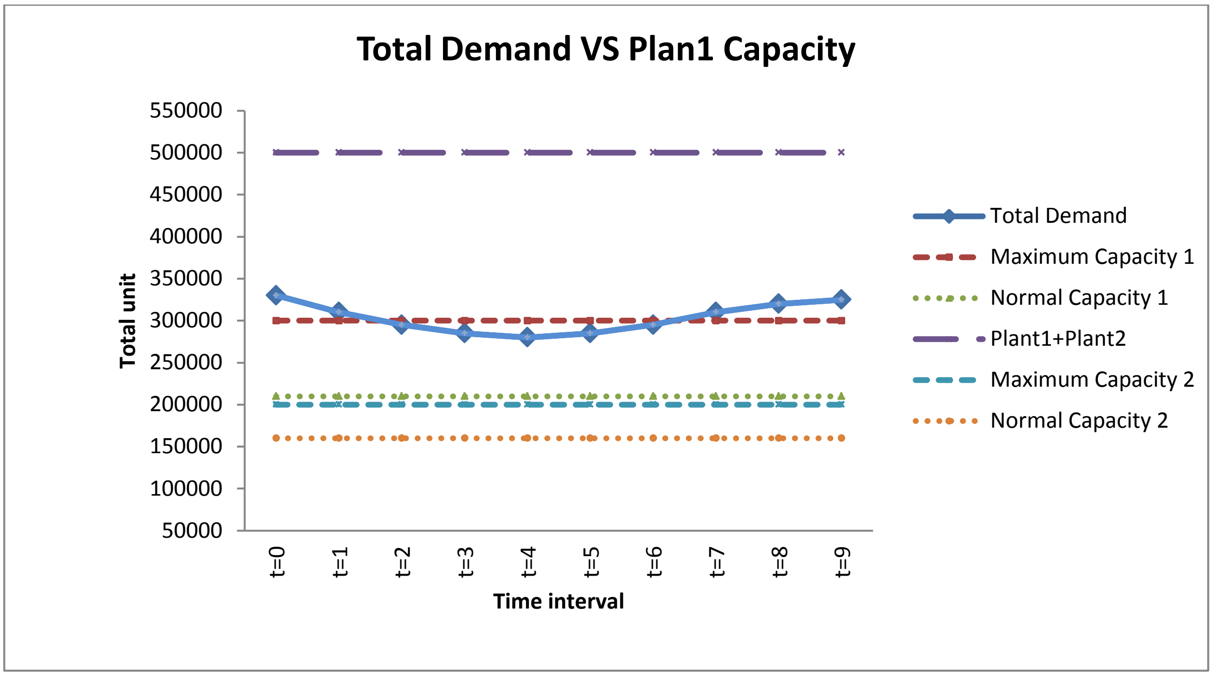


Figure 5-15: Total demand change vs. capacity in case 4

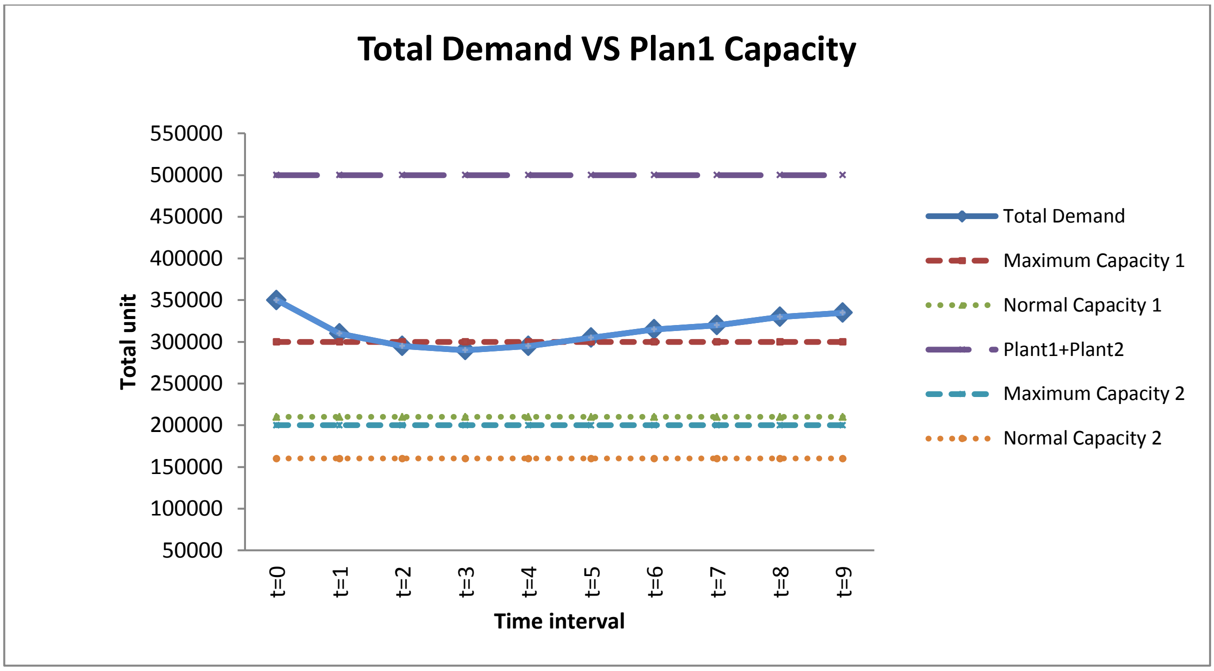


Figure 5-16: Total demand change vs. capacity in case 5

Finally, running the model with the information for both cases, capacity mothball is suggested as the optimal solution for both cases of 4 and 5, when a mid- or short-term recession is expected. This decision is also supported and validated by calculations which are shown in table 5-18. This table shows that in both mid- and short-term recessions the total amount of required investment for mothballing and then reopening plant 2 during and after the recession is far less than underutilisation of both plants in recession time.

Table 5-18: Differences in investment amount for feasible options in case 4 and 5, which support the model's suggestion (numbers are in million£)

Under Utilisation in Case 4	**Plant 2 operations costs of 5 years**	**Plant 2 work force cost of 5 years**	**-**	**-**	**-**	**-**	**Sum**
	500	500	-	-	-	-	**1,000**
Mothball in case 4	**Mothball fixed cost of plant 2**	**Operations cost of Mothballed plant in 5 years**	**Work force cost of plant2 after redundancy in 5 years**	**Reopening fixed cost of plant2 after downturn**	**Overutilisation operations cost of plant1 in 5 years**	**Overutilisation work force cost of plant1 in 5 years**	**Sum**
	17	40	300	5	75	125	**562**
Under Utilisation in Case 5	**Plant 2 operations costs of 3 years**	**Plant 2 work force cost of 3 years**	**-**	**-**	**-**	**-**	**Sum**
	300	300	-	-	-	-	**600**
Mothball in case 5	**Mothball fixed cost of plant 2**	**Operations cost of Mothballed plant in 3 years**	**Work force cost of plant2 after redundancy in 3 years**	**Reopening fixed cost of plant2 after downturn**	**Overutilisation operations cost of plant1 in 3 years**	**Overutilisation work force cost of plant1 in 3 years**	**Sum**
	17	24	180	5	45	75	**346**

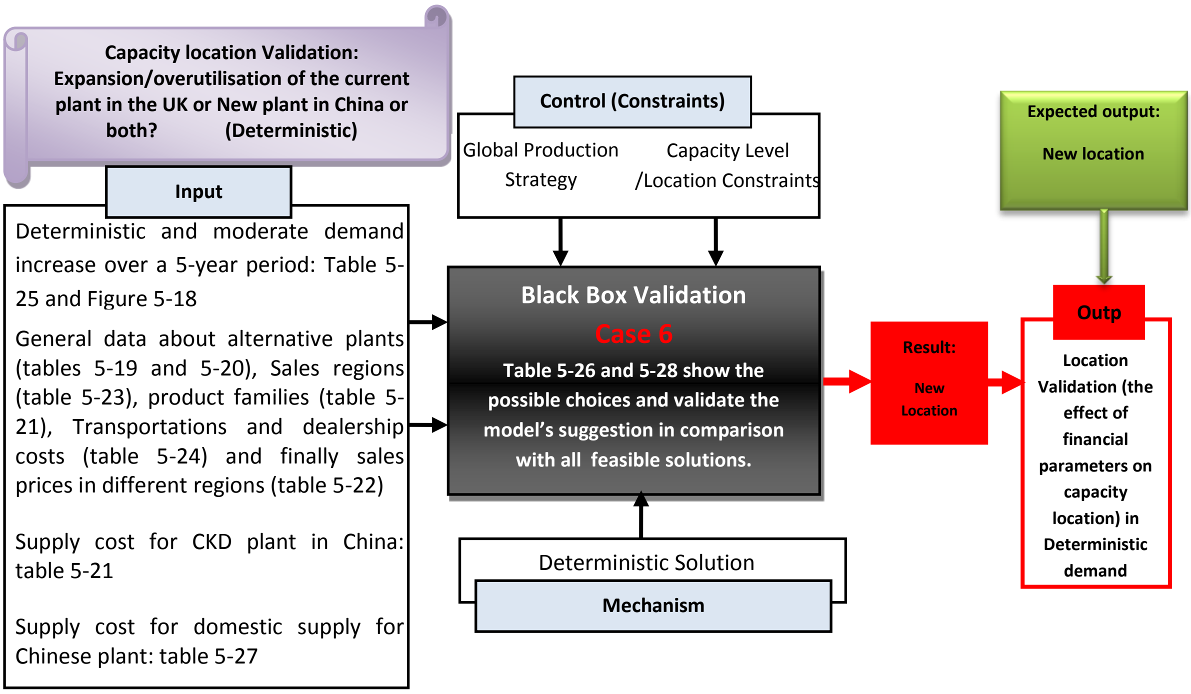
5-3- Location/Relocation Problem

In this section the location and relocation problems will be discussed and the model will be validated by some simplified hypothetical cases. Firstly, the effect of financial parameters in the location problem will be studied and validated in case 6.

Case 7 shows how a global strategy to invest in low-cost countries (LCCs) can be modelled and validated in this research. Relocating a current plant (in the UK) to an LCC is also validated in case 8. The advantage of a global approach to capacity planning, then, will be studied using a comparison between case 4 and 8. This comparison establishes a link between a local and a global approach as well as capacity level and location management, as was shown in the validation plan in figure 5-2.

Case6: The Effect of Financial Terms on the Location Problem

Case Brief: In this case two alternative plants for new capacity expansion are considered, one in the UK and the other one in China. The question, therefore, is which one is the best choice for future products, with reference to different demands in the sales region, operations costs, total fixed investment, transportation cost and financial terms such as tariff, VAT and inflation rates. With realistic figures for financial data (custom duty and governmental incentives for foreign investment, in particular) and considering a promising market both in China and in the western countries, the expected answer is an investment in China on a production plant for the Chinese market, as well as in the UK for the domestic market. The ICOM framework for this case has been established in figure 5-17.



Deterministic and moderate demand increase over a 5-year period: Table 5-25 and Figure 5-18

General data about alternative plants (tables 5-19 and 5-20), Sales regions (table 5-23), product families (table 5-21), Transportations and dealership costs (table 5-24) and finally sales prices in different regions (table 5-22)

Supply cost for CKD plant in China: table 5-21

Supply cost for domestic supply for Chinese plant: table 5-27

Table 5-26 and 5-28 show the possible choices and validate the model's suggestion in comparison with all feasible solutions.

Location Validation (the effect of financial parameters on capacity location) in Deterministic demand

Figure 5-17: ICOM framework for case 6 of the validation plan

Input data: The input data for this case are set to demonstrate a promising market for the company, and to give the model of flexibility to globally design and plan the capacity. Table 5-19 and 5-20 depict the input data for both alternative plants for the future market.

5-19: General information about alternative plants in case 6

	Plant No.	Plant Location	Maximum Capacity (*1,000)	Maximum normal capacity rate	Initial Capital Investment (million pounds)	Annual Operations cost (million pounds)	Annual normal Work force Cost (million pounds)	Any unit-based cost of production excluding supply	Profit Tax rate
Plant1	1	UK	200	0.8	150	100	100	500	0.2
Plant2	2	China	200	0.8	100	80	60	500	0

5-20: Expansion and Overutilisation details of the alternative plants in case 6

	Plant No.	Capacity Expansion					Overutilisation	
		Number of possible Expansions	Maximum Expansion rate	Capital investment for Expansion (million pounds)	Extra operations cost in case of expansion (million pounds)	Extra work force cost in case of expansion (million pounds)	Extra work force cost in case of overutilisation (million pounds)	Extra operations cost in case of overutilisation (million pounds)
Plant1	**1**	1	0.4	70	40	35	25	15
Plant2	**2**	1	0.4	40	30	21	15	10

Table 5-19 shows that the plant in China benefits from governmental investment incentives of free tax on profit. This plant also enjoys the significant lower work force cost and annual operations cost. Referring to table 5-20, moreover, the plant in China requires less investment to expand or overutilise.

Recalling from table 5-4, there are only two future new products, which will be planned for these alternative plants to produce. Table 5-21 shows more detail on supply, R&D and NPL costs of these products in the plants. Supposing that the supply is carried out from the UK, and the Chinese plant is based on CKD (Complete Knock Down) procedure, the cost of supply to the Chinese plant will be higher than its cost to the British one, because of the transportation cost of parts and a 10% tariff on automotive parts in China (PWC 2011).

5-21: Product families, supply costs and required R&D and NPL investment in alternative plants for case 6

Product Name	If NPD applies, what is its Cost (£million)	Plant-related figures for PLANT 1				Plant-related figures for PLANT 2			
		NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 1	Capacity Coefficient in plant 1	NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 2	Capacity Coefficient in plant 2
TY3	1.5	10	£17,000	1	1	5	£19,000	1	1
TX5	1.5	10	£18,000	1	1	5	£20,000	1	1

The sales price for all product families in different sales regions is shown in table 5-22 and VAT and tariff details of import from different plants to each sales region are illustrated in table 5-23.

Table 5-22: The product family sales price in different sales regions in case 6

	TY3	TX5
EU	£31,000	£32,000
USA	£32,000	£33,000
Asia	£33,000	£34,000

Table 5-23: VAT and tariff rates for different sales regions in case 6

Sales Region	EU	USA	Asia
VAT in Market	0.20	0.18	0.17
Tariffs Plant 1	0.00	0.10	0.20
Tariffs Plant 2	0.20	0.20	0.00

Transportation and warehouse costs as well as dealership expenses are different to each plant. In other words, if the company exports to China from the alternative plant in the UK, transportation and dealership costs would be significantly more expensive than its cost in case of producing in the country. This fact is reflected in table 5-24.

Table 5-24: Transportation, warehouse and dealership expenses for both alternative plants in case 6

	Plant 1	Plant 2
EU	£1,000	£4,000
USA	£4,000	£6,000
Asia	£8,000	£2,000

In this case, demand for the new products starts from the 5th year of the planning horizon, as shown in table 5-25 and summarised in figure 5-18.

Table 5-25: Demand details for each product family in each sales region in each year for case 6.

		TY3	TX5
2017	**EU**	60	0
	USA	45	0
	Asia	45	0
2018	**EU**	60	0
	USA	50	0
	Asia	50	0
2019	**EU**	50	35
	USA	30	15
	Asia	30	15
2020	**EU**	40	50
	USA	20	30
	Asia	20	30
2021	**EU**	30	50
	USA	10	40
	Asia	10	40

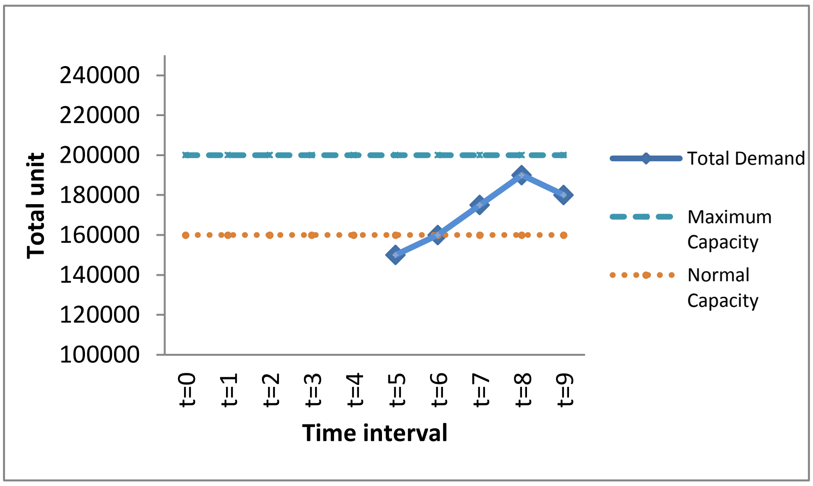


Figure 5-18: Total demand of new products vs. normal and maximum capacity of the alternative plants in case 6

As shown in table 5-19 and figure 5-18, both alternative plants are set to have the same maximum and normal capacity. Moreover, the total demand is below the maximum capacity level of each of these plants. Therefore, opening either one of those two alternative plants or both can be feasible solutions to fulfil the demand and consequently the problem has three possible options: opening plant 1, opening plant 2 or opening both plants.

Case Result and analysis: Since opening one plant is adequate to cover the demand and because of a lower required capital investment for the Chinese plant, as well as lower operational and labour costs and tax-free incentives, one may think that the answer to this problem is opening this plant only.

However, running the model with all abovementioned information, opening both plants is suggested by the model, which might be the least favourable option at first glance. The model suggests opening both plants at the same time, no overutilisation and launching both products in both plants.

In load-planning, the model suggests producing the domestic demand for China in the Chinese plant. However, demands for the EU and the US are suggested to be produced in the British plant.

To validate this result, the objective function for these three options should be manually calculated and compared. Since the total revenue is the same for all three options, only total costs of different options should be calculated and compared. Table 5-26 reflects the cost breakdown analysis for these three options. Option one is the option which is suggested by the model. In this option both plants will be opened and normally utilised. The demand for the Chinese market is locally supplied by the Chinese plant (plant 2) and the rest of the demand is covered by plant 1 in the UK. This table validates the result from the model, and shows that the cost of investment and production for the first option is the lowest one.

Table 5-26: Cost breakdown analysis for 3 options in case 6, which validates the model's results.

			Tax on profit	Unit Cost	Supply Cost	Transportation …	Operations cost in 5y	Work force Cost in 5y	Tariff and VAT	NPL Cost	Capital cost of establishment	R&D cost of product design	Total Cost
Opt. 1	2017	Plant1	0.2	53	1,785	240	100	100	801	10	250	3	**25,572**
		Plant2	0.0	23	855	90	80	60	252	5			
	2018	Plant1	0.2	55	1,870	260	100	100	849	0			
		Plant2	0.0	25	950	100	80	60	281	0			
	2019	Plant1	0.2	65	2,260	265	100	100	968	10			
		Plant2	0.0	23	870	90	80	60	255	5			
	2020	Plant1	0.2	70	2,460	290	100	100	1,054	0			
		Plant2	0.0	25	980	100	80	60	286	0			
	2021	Plant1	0.2	65	2,300	280	100	100	995	0			
		Plant2	0.0	25	990	100	80	60	287	0			
Opt. 2	**2017**	**Plant1**	0.2	75	2,550	600	100	100	1,401	10	150	3	**27,595**
	2018		0.2	80	2,720	660	100	100	1,515	0			
	2019		0.2	88	3,040	625	100	100	1,574	10			
	2020		0.2	95	3,340	690	100	100	1,732	0			
	2021		0.2	90	3,190	680	100	100	1,677	0			
Opt. 3	**2017**	**Plant2**	0	75	2,850	600	80	60	1,670	10	100	3	**30,986**
	2018		0	80	3,040	640	80	60	1,765	0			
	2019		0	88	3,390	700	80	60	2,035	10			
	2020		0	95	3,720	760	80	60	2,213	0			
	2021		0	90	3,550	720	80	60	2,083	0			

Apart from tariff, transportation, warehouse and dealership costs, the other factor which opposes selecting option 3 (the Chinese plant only), is supply figures. As explained earlier, the assembly line in China is based on CKD and therefore the supply cost for this plant is more than the supply costs for plant 1, due to transportation and tariff rates for sub-assemblies and parts. Now, to release this assumption and study the pour effect of financial parameters of export, domestic supply with no extra investment in facilities is designed. Therefore, no changes in input data, except supply costs which are shown in table 5-27, are expected. In this new supply design, the domestic supply from the Chinese supplier to Plant 2 (in China) is even cheaper than the domestic supply for Plant 1 in the UK, as is expected in the real world.

Table 5-27: New supply cost (domestic supply) for case 6

Product Name	If NPD applies, what is its Cost (£million)	Plant-related figures for PLANT 1				Plant-related figures for PLANT 2			
		NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 1	Capacity Coefficient in plant 1	NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 2	Capacity Coefficient in plant 2
TY3	1.5	10	£17,000	1	1	5	£16,000	1	1
TX5	1.5	10	£18,000	1	1	5	£17,000	1	1

However, when adjusting the supply cost in the model and running it for the new database, again, option one is being suggested by the model.

Table 5-28: Cost breakdown analysis for 3 options with domestic supply in case 6.

			Tax on profit	**Unit Cost**	**Supply Cost**	**Transportation …**	**Operations cost in 5y**	**Work force Cost in 5y**	**Tariff and VAT**	**NPL Cost**	**Capital cost of establishment**	**R&D cost of product design**	**Total Cost**
Opt. 1	2017	Plant1	0.2	53	1,785	1,785	100	100	801	10	250	3	**24,852**
		Plant2	0.0	23	855	720	80	60	252	5			
	2018	Plant1	0.2	55	1,870	1,870	100	100	849	0			
		Plant2	0.0	25	950	800	80	60	281	0			
	2019	Plant1	0.2	65	2,260	2,260	100	100	968	10			
		Plant2	0.0	23	870	735	80	60	255	5			
	2020	Plant1	0.2	70	2,460	2,460	100	100	1,054	0			
		Plant2	0.0	25	980	830	80	60	286	0			
	2021	Plant1	0.2	65	2,300	2,300	100	100	995	0			
		Plant2	0.0	25	990	840	80	60	287	0			
Opt. 2	**2017**	**Plant1**	0.2	75	2,550	2,550	100	100	1,401	10	150	3	**27,595**
	2018		0.2	80	2,720	2,720	100	100	1,515	0			
	2019		0.2	88	3,040	3,040	100	100	1,574	10			
	2020		0.2	95	3,340	3,340	100	100	1,732	0			
	2021		0.2	90	3,190	3,190	100	100	1,677	0			
Opt. 3	**2017**	**Plant2**	0	75	2,850	2,400	80	60	1,670	10	100	3	**28,421**
	2018		0	80	3,040	2,560	80	60	1,765	0			
	2019		0	88	3,390	2,865	80	60	2,035	10			
	2020		0	95	3,720	3,150	80	60	2,213	0			
	2021		0	90	3,550	3,010	80	60	2,083	0			

Using the objective formulation and breaking down the total cost of investment and operations for the new situation, table 5-28 is generated, which again supports this result, despite a total significant drop in supply cost. This also reemphasises the importance of custom duty rates, governmental incentives and dealership costs, which can all be applied in this model. This makes the model globally capable of capacity design and planning, which is not only based on low operations costs but also on more strategic and comprehensive factors. This link between local and global capacity design is highlighted in the validation plan in figure 5-1 and 5-2.

Case7: Moderate/Slight Demand Increase. Expansion or New Plant in China?

Case Brief: In case 1, where demand is expected to increase moderately, the two optional solutions of a new plant in the UK or an expansion of the current plant were considered. Running the model, plant expansion was taken by the model as the optimal one. However, in this case, on top of the abovementioned options, a new global solution of establishing a new plant in China is also introduced to the model. The aim of this case is to validate the model's output for a more complicated global case, where the capacity level problem and the location problem are combined. The ICOM framework for this case is expanded in figure 5-19, where all inputs to the model are introduced.

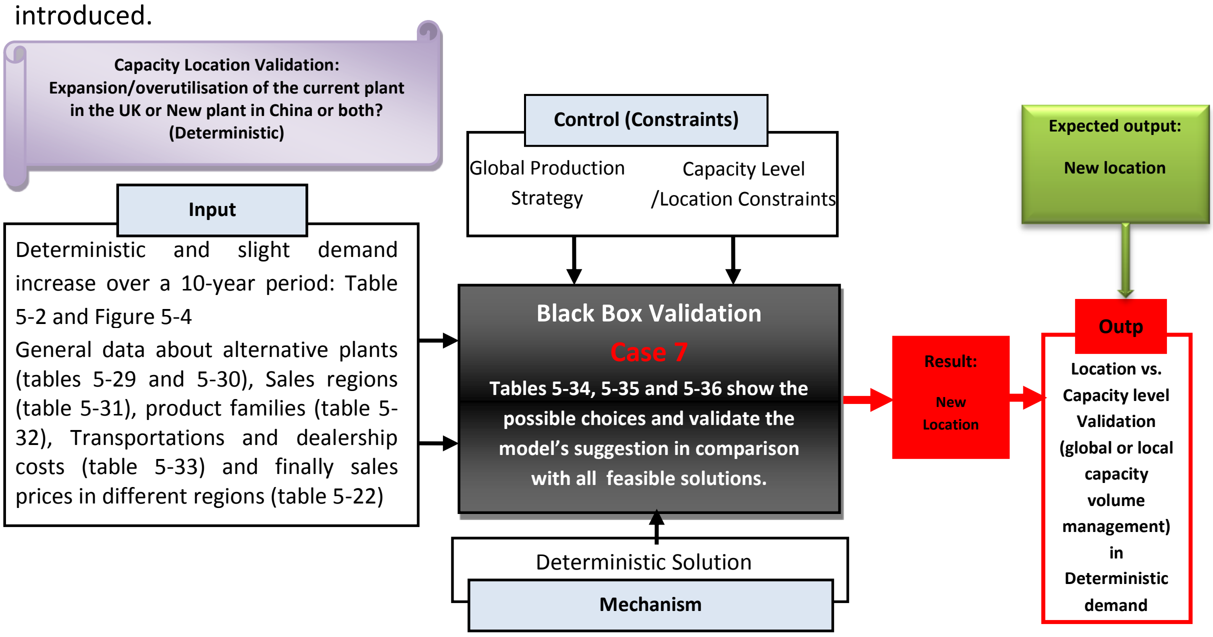


Figure 5-19: ICOM framework for case 7 of the validation plan

Input data: All the general information for the current plant in the UK and the optional plant in China remain the same as in case 1 and 6, respectively. This information is replicated in tables 5-29 and 5-30.

5-29: General information about current and alternative plants in case 7

	Plant No.	Plant Location	Maximum Capacity (*1,000)	Maximum normal capacity rate	Initial Capital Investment (million pounds)	Annual Operations cost (million pounds)	Annual normal Work force Cost (million pounds)	Any unit-based cost of production excluding supply	Profit Tax rate
Plant1	1	UK	300	0.7	150	130	100	500	0.2
Plant2 (optional)	2	China	200	0.8	100	80	60	500	0

5-30: Expansion and Overutilisation details of the alternative plants in case 7

	Plant No.	Capacity Expansion					Overutilisation	
		Number of possible Expansions	Maximum Expansion rate	Capital investment for Expansion (million pounds)	Extra operations cost in case of expansion (million pounds)	Extra work force cost in case of expansion (million pounds)	Extra work force cost in case of overutilisation (million pounds)	Extra operations cost in case of overutilisation (million pounds)
Plant1	**1**	1	0.4	70	40	39	30	26
Plant2 (optional)	**2**	1	0.4	40	30	21	15	10

VAT and custom duties for these plants are shown in table 5-31, which are basically the same as the figures for case 6. The supply figures and NPD details for the products in both plants are also reflected in table 5-32, followed by transportation, warehouse and dealership costs, which are illustrated in table 5-33.

Table 5-31: VAT and tariff rates for different sales regions in case 7

Sales Region	EU	USA	Asia
VAT in Market	0.20	0.18	0.17
Tariffs Plant 1	0.00	0.10	0.20
Tariffs Plant 2	0.20	0.20	0.00

Table 5-32: Product families, supply costs and required R&D and NPL investment in alternative plants for case 7

Product Name	If NPD applies, what is its Cost (£million)	Plant-related figures for PLANT 1				Plant-related figures for PLANT 2			
		NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 1	Capacity Coefficient in plant 1	NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 2	Capacity Coefficient in plant 2
KX1	-	-	£17,000	1	1	5	£19,000	1	1
KX2	-	-	£18,000	1	1	5	£20,000	1	1
KX3	-	-	£19,000	1	1	5	£21,000	1	1
TY2	-	-	£16,000	1	1	5	£18,000	1	1
TY3	1.5	10	£17,000	1	1	5	£19,000	1	1
TX5	1.5	10	£18,000	1	1	5	£20,000	1	1

The Chinese plant is set to be an assembly line based on CKD basis and therefore assembly supply is supposed to be done by British suppliers (such as case 6). This is why the supply cost for plant 2 is slightly more than its cost for plant 1, as shown in table 5-32.

Table 5-33: Transportation, warehouse and dealership expenses for both alternative plants in case 7

	Plant 1	**Plant 2**
EU	£1,000	£4,000
USA	£4,000	£6,000
Asia	£8,000	£2,000

The demand detail in this case remains the same as in case 1, in order to evaluate the model in the same demand prospect and to establish a link to the local capacity management strategy of case 1, as discussed in the validation plan and demonstrated in figure 5-1 and 5-2. Therefore, table 5-7 and figure 5-3 reflect the demand details and product life cycle in this case.

Case Result and analysis: From this information and considering tables 5-29 and 5-30, it is clear that the possible solutions for fulfilling this demand are either expanding the current capacity in the UK, or opening the Chinese plant and keeping the UK plant overutilised but not expanded. Putting all the above information into the model's database and running the model, the second option is suggested by the model. Table 5-34 shows the model's load-planning result for plant 2 (in China).

Table 5-34: Model's suggestion for load-planning plant 2 in case 7

		2015			2016			2017			2018			2019			2020			2021		
		EU	USA	Asia	EU	USA	Asia	EU	USA	Asia	EU	USA	Asia	EU	USA	Asia	EU	USA	Asia	EU	USA	Asia
Plant 1	KX1		10	10			10			10			5									
	KX2			15			15			15			15			10			5			
	KX3			20			20			20			20			10			5			
	TY2			30			40			30			30			20			15			10
	TY3									20			30			45			50			55
	TX5															25			40			45

Having compared this table and the demand details, it is highlighted that the model suggests opening this plant to cover the domestic demand in China. All production in this plant, except one production batch in 2015, will cover domestic sales in China. The model also suggests overutilisation of plant 1 in all years except 2012 and 2015. In 2012 the demand does not exceed the normal capacity of the plant, and in 2015, only 10,000 units of the demand exceed the normal capacity of plant 1, which will be produced in Plant 2, as shown in the table above. In this solution, although producing in China is subject to a higher custom duty to be exported to the US, this very short-term solution is more profitable than overutilisation of plant 1 for quite a small amount of excess demand. This decision also reflects the economies of scale in the model.

To validate the result, the model’s suggestion for this case is compared with the validated results of case 1. Tables 5-35 and 5-36 show the cost breakdown analysis of the solutions. These tables only show the limited items which are different for those two solutions. Table 5-35 reflects the major investment and operational cost differences and table 5-36 shows the differences in exporting and logistics figures. Table 5-36 represents the effect of financial terms in global capacity planning. If one ignores these factors, capacity expansion in the UK is less costly than establishing a new plant in China for this level of demand increase, as shown in table 5-35. However, taking table 5-36 into account, the model’s suggestion of running plant 2 to cover the Chinese market is supported by significant savings in tariff and logistic costs.

Table 5-35: Cost breakdown differences for two solutions, ignoring the export costs in case 7

Expansion of Plant 1	**Expansion Fixed Cost**	**Extra Annual Operations cost of expansion x7**	**Extra Annual Work force Cost of expansion x7**	**Annual Overutilisation fixed cost x 10**	**Annual Overutilisation Work force cost x 10**
	70	280	273	260	300
New Plant in China	**New plant Capital**	**Operations cost of Plant 2 x7**	**Work force Cost of Plant 2**	**NPL for 4 product families**	
	100	560	420	30	-

Table 5-36: Export cost breakdown differences, caused by different rates of tariff, transportation, warehouse and dealership cost in case 7

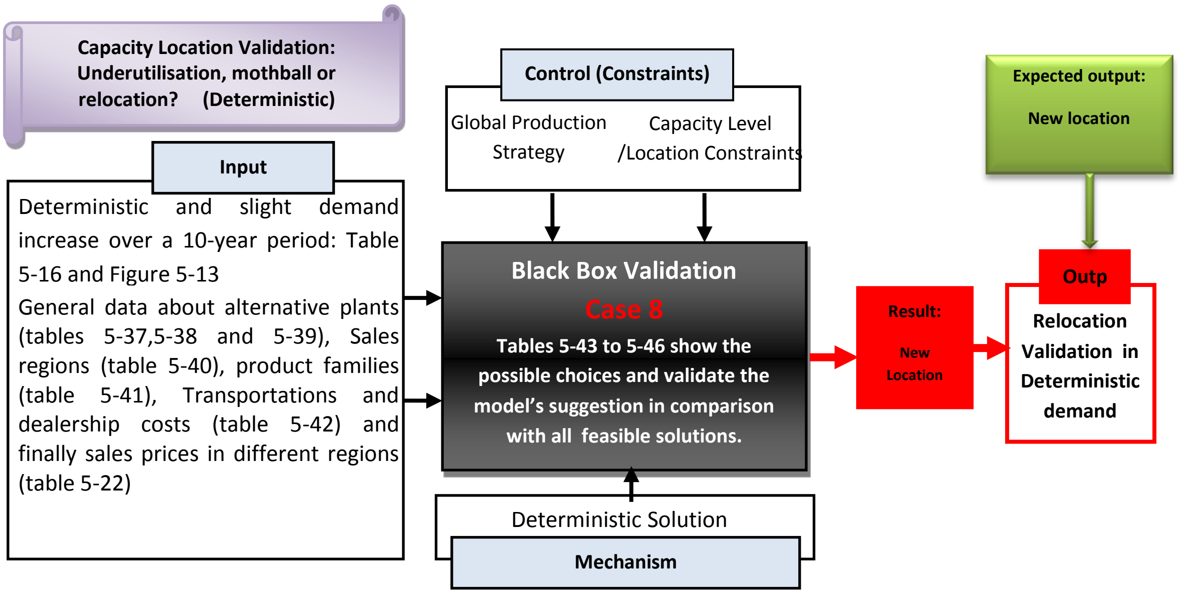
	Tariff	**Transportation**	**Sum (£million)**
KX1	235.62	4140	**8845.26**
KX2	520.2		
KX3	697.68		
TY2	1142.4		
TY3	1346.4		
TX5	762.96		

In an experience equal to the one with data from case 2, where a slight demand increase is expected which is in the scope of overutilisation of the current plant in the UK, opening the new plant in China for covering the Chinese demand is, again, suggested by the model. Likewise, this decision is justifiable because of a significant saving prospect for producing in China for China, which comes from tariff, transportation, warehouse and dealership costs.

This result shows that the expansion solution in case one or overutilisation in case 2 can be sub-optimal solutions, in the absence of a global approach to capacity planning. This interrelationship was explained in the validation plan (figures 5-1 and 5-2). It emphasises the importance of having an integrated strategic model with global design ability to avoid sub-optimal strategic solutions.

Case8: Mid-Term and Short-Term Recession. Underutilisation, Mothball, Shutdown or Relocation?

Case Brief: In this case, recalling the demand detail from case 4 and 5, a recession is expected for the company. In case 4 and 5, the model was limited to the local solutions, which were underutilisation of both open plants in the UK or mothballing one of them. The result in case 4 and 5 showed that mothball was the optimal solution in those circumstances. In this case, however, like in case 7, integrating the capacity level and capacity location, a new optional plant in China is introduced to the model as an alternative relocation solution. The ICOM framework for this case (figure 5-20) highlights how the input is set for this case and what the outputs are.



Deterministic and slight demand increase over a 10-year period: Table 5-16 and Figure 5-13

General data about alternative plants (tables 5-37,5-38 and 5-39), Sales regions (table 5-40), product families (table 5-41), Transportations and dealership costs (table 5-42) and finally sales prices in different regions (table 5-22)

Tables 5-43 to 5-46 show the possible choices and validate the model's suggestion in comparison with all feasible solutions.

Figure 5-20: ICOM framework for case 8 of the validation plan

Input data: Tables 5-37 to 5-39 show the information for both open plants in the UK and the alternative plant in China. VAT and tariff rates for different market destinations are set in table 5-40. Supply costs as well as NPD investments for products in different plants are also highlighted in table 5-41, followed by transportations, warehouse and dealership costs of export from each plant to the sales regions in table 5-42.

Table 5-37: General information about the current and alternative plants in case 8

	Plant No.	Plant Location	Maximum Capacity (*1,000)	Maximum normal capacity rate	Initial Capital Investment (million pounds)	Annual Operations cost (million pounds)	Annual normal Work force Cost (million pounds)	Any unit-based cost of production excluding supply	Profit Tax rate
Plant1	1	UK	300	0.7	200	150	130	500	0.2
Plant2	2	UK	200	0.8	150	100	100	500	0.2
Alternative Plant	3	China	200	0.8	100	80	60	500	0

Table 5-38: Expansion and overutilisation details of the alternative plants in case 8

	Plant No.	**Capacity Expansion**					**Overutilisation**	
		Number of possible Expansion	Maximum Expansion rate	Capital investment for Expansion (million pounds)	Extra operations cost in case of expansion (million pounds)	Extra work force cost in case of expansion (million pounds)	Extra work force cost in case of overutilisation (million pounds)	Extra operations cost in case of overutilisation (million pounds)
Plant1	**1**	1	0.4	80	60	45.5	32.5	30
Plant2	**2**	1	0.4	70	40	35	25	15
Alternative Plant	**3**	1	0.4	40	30	21	15	10

Table 5-39: Mothball and shutdown data for the plants in case 8

	Plant No.	**Capacity Mothball**				**Capacity Shutdown**
		Fixed cost of mothballing (million pounds)	Redundancy rate in case of mothball	Fixed cost of reopening (million pounds)	Operations cost for mothballed plant (million pounds)	Fixed cost of shutdown (million pounds)
Plant1	**1**	20	0.4	5	10	80
Plant2	**2**	17	0.4	5	8	60
Alternative Plant	**3**	15	0.4	5	5	50

Table 5-40: VAT and tariff rates for different sales regions in case 8

Sales Region	**EU**	**USA**	**Asia**
VAT in Market	20%	18%	17%
Tariffs Plant 1	0	10%	20%
Tariffs Plant 2	20%	20%	0

Table 5-41: Product families, supply costs and required R&D and NPL investment in alternative plants for case 8

Product Name	**If NPD applies, what is its Cost (£million)**	**Plant-related figures for PLANT 1 & 2**				**Plant-related figures for PLANT 3**			
		NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 1	Capacity Coefficient in plant 1	NPL Cost (£Million) if it applies	Supply cost in Plant1	Cost Coefficient in plant 2	Capacity Coefficient in plant 2
KX1	-	-	£17,000	1	1	5	£19,000	1	1
KX2	-	-	£18,000	1	1	5	£20,000	1	1
KX3	-	-	£19,000	1	1	5	£21,000	1	1
TY2	-	-	£16,000	1	1	5	£18,000	1	1
TY3	1.5	10	£17,000	1	1	5	£19,000	1	1
TX5	1.5	10	£18,000	1	1	5	£20,000	1	1

Table 5-42: Transportation, warehouse and dealership expenses for both alternative plants in case 8

	Plant 1	Plant 2	Plant 3
EU	£1,000	£1,000	£4,000
USA	£4,000	£4,000	£6,000
Asia	£8,000	£8,000	£2,000

In this case, demand details remain the same as in case 4 (table 5-16) to evaluate the result of a global option in the same case and to highlight the merits of a global decision making model, besides validating the model in this case.

Case Result and analysis: Running the model with this series of information, closing plant 1, which is the larger plant in the UK, in the third operation year, followed by opening the new plant in China, in the same year, is suggested by the model. The model also suggests expanding the Chinese plant and overutilising it from the first running year and mothballing the plant 2 for two years, when the recession is in its worst situation (2016 and 2017). Within these two years, the Chinese plant will be overutilised to fulfil the demand from the UK and the US.

Table 5-43 shows the maximum available capacity of each plant in each planning year, which is suggested by the model as the optimal solution. Moreover, the model’s load-planning output is also revealed in table 5-44.

Table 5-43: The model’s output for the plants’ utilisation status and maximum available capacity in each year in case 8

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Plant 1	**Plant Utilisation**	Normal	Normal	Normal	Shutdown	-	-	-	-	-	-
	Maximum Cap.	300,000	300,000	300,000	0	0	0	0	0	0	0
Plant 2	**Plant Utilisation**	Normal	Normal	Normal	Normal	Mothballed	Mothballed	Normal	Normal	Normal	Normal
	Maximum Cap.	200,000	200,000	200,000	200,000	0	0	200,000	200,000	200,000	200,000
Plant 3	**Plant Utilisation**	-	-	-	Over	Exp+Over	Exp+Over	Exp+Over	Exp+Over	Exp+Over	Exp+Over
	Maximum Cap.	-	-	-	200,000	280,000	280,000	280,000	280,000	280,000	280,000

Table 5-44: The model’s output for the plants’ load-planning in case 8

		EU						USA						China					
		KX1	KX2	KX3	TY2	TY3	TX5	KX1	KX2	KX3	TY2	TY3	TX5	KX1	KX2	KX3	TY2	TY3	TX5
2012	P1	50			30			30			20			30			20		
	P2		40	30					20	20					30	10			
	P3																		
2013	P1		40	30	30				20	20	15				30	10	15		
	P2	40						30						30					
	P3																		
2014	P1			20	35					15	25					15	20		
	P2	40	30					30	15					30	15				
	P3																		
2015	P1																		
	P2	30	10		45														
	P3		20	25				20	15	15	30			15	15	15	30		
2016	P1																		
	P2																		
	P3	20	25	40	40			5	15	30	35			5	10	25	30		
2017	P1																		
	P2																		
	P3	5	20	30	30	45		10	10	25	30			10	10	25	30		
2018	P1																		
	P2																		
	P3	5	20	35	45			5	10	25	55			5	10	25	40		
2019	P1																		
	P2					30													
	P3			20	20	20	50			10	20	40	30			10	15	20	25
2020	P1																		
	P2					40													
	P3				10		80				5	30	65					30	60
2021	P1																		
	P2					45													
	P3				5		90					35	65					30	55

To validate this outcome, the validated results from case 4 will be compared with these suggestions, accordingly. Table 5-45 shows the differences between these two solutions in terms of investment and operational costs, while table 5-46 highlights the cost of export. With reference to these tables, the model’s suggestion will be validated. This result, again, highlights the importance of global location ability in an integrated capacity management model.

Table 5-45: Cost breakdown analysis for differences in case 4 and 8 in terms of investment and operational costs

		Case 4		Case 8		
		Plant1	Plant2	Plant1	Plant2	Plant3
Capital investment	**Establishing**	-	-	-	-	100
	Expanding	-	-	-	-	40
	Overutilising	75	-	-	-	70
	Mothballing	-	17	-	17	-
	Reopening	-	5	-	5	-
	Shutdown	-	-	80	-	-
Operational Cost	**Operations cost**	1500	500	450	800	560
	Normal Work force cost	1300	500	390	700	420
	Overutilisation operation	150	-	-	-	70
	Overutilisation Work force	162.5	-	-	-	105
	Extra Operations cost of expanded Cap.	-	-	-	-	210
	Work force cost of Expanded Cap.	-	-	-	-	147
	Maintenance cost of Mothballed Cap.	-	40	-	16	-
	Work force cost of Mothballed Cap.	-	300	-	120	-
SUM		**4,550**		**4,300**		

Table 5-46: Export cost differences for case 4 and 8

	Case4	Case8
Transportation, Dealership and Warehouse	22,770	10,780
Tariffs and VAT	25,587	29,049
Sum	**48,357**	**39,829**

5-4- Decision Making under Uncertainty

The Effect of Uncertainty on Capacity Level Management

In this section the effect of uncertainty on strategic capacity planning will be studied and the model will be validated with some simplified cases. Three basic scenarios of the worst case, the best case and the normal scenario (pessimistic, optimistic and realistic) will be employed for all cases in this section to apply uncertainty in the model and to replicate the decision making procedure in the real world (Escudero et al. 1995, Kempf et al. 2011b, Geng et al. 2009a). To see the value of the stochastic solution (VSS) case 9 and 10 are designed in a way to expand case 2 and 5 respectively in a stochastic framework. In other words, in these two cases the expected demand is the same as what was developed for deterministic cases in the previous section, to allow a direct comparison and to calculate the 'value of the stochastic solution' (VSS). The last case in this section (case 11), however, is designed to validate the model in an uncertain global market and to highlight VSS in such a case.

Case9: Stochastic Demand Increase: Overutilisation or Expansion?

Case Brief: This case is designed to highlight the value of the stochastic solution in a promising market. Like in case 2, in this case a current plant in the UK is producing products and an overall slight demand increase is expected. To simplify the case, only one product family and one sales region is assumed in this case. The model is already validated for capacity volume management in a deterministic demand prospect. Therefore, the focus in this case is on demand uncertainty, rather than on different product types or sales regions. Figure 5-21 establishes the ICOM outline for this case, establishing the link to case 2 and representing the uncertainty.

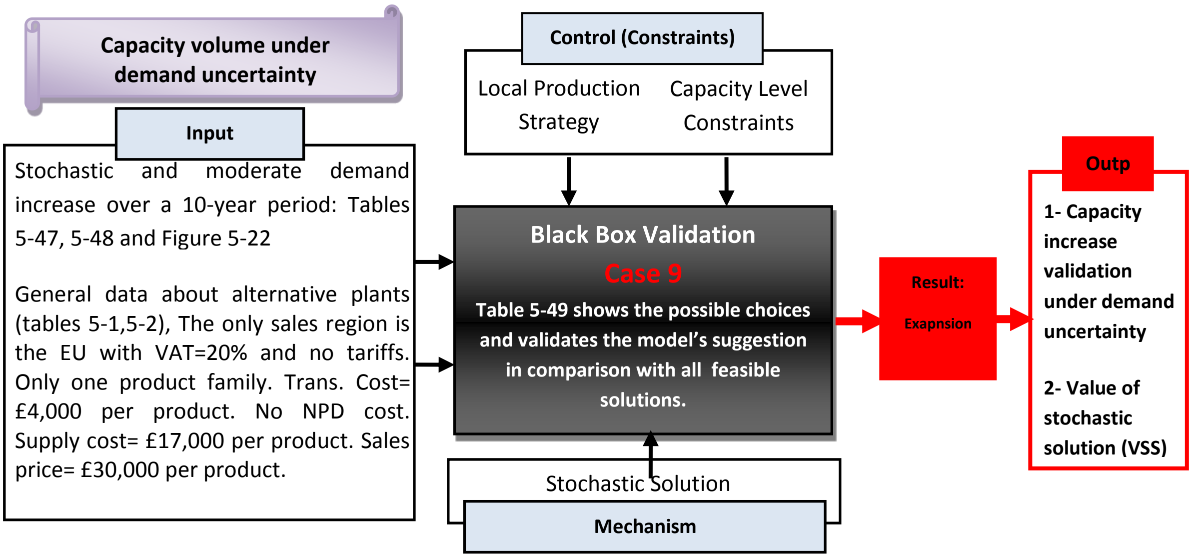


Figure 5-21: ICOM framework for case 9 of the validation plan

Input data: The required information on the current plant can be retrieved from case 2 and tables 5-1, 5-2. VAT in the sales region (the EU in this case) is assumed to be as high as 20%. Because the plant is located in the EU region, no tariff is considered in this case and transportation, dealership and warehouse cost of the product family in this sales region has been set at £4,000 per unit. Three market scenarios are designed in this case in such a way that the expected (Business-as-usual) remains exactly the same as in case 2, for further comparison. The sales price also depends on market uncertainty. In the worst case scenario, the sales price is set to be less than in other scenarios to keep the market share. The scenarios' probabilities, as well as the sales price in each scenario is highlighted in table 5-47.

Table 5-47: Scenario probabilities and sales prices in different scenarios for case 9

	Worst Scenario (S1)	Normal Scenario (S2)	Best Scenario (S3)
Scenario Probability	30%	50%	20%
Sales Price	£29,000	£31,000	£31,000
Expected Sales Price	**£30,000**		

In table 5-47, the 'Expected sales price' results from considering different sales prices and the scenarios' probabilities. Moreover, the different demand figure for each scenario in each year is highlighted in table 5-48. Again, the expected demand comes from the demand prospect for different scenarios, considering the scenarios' probabilities. The expected value for demand and sales price are the figures, which have been traditionally used by modellers in a deterministic format (BAU). However, in this case we will show how this approach can be misleading in an uncertain environment.

Table 5-48: Demand details for the product family in the sales region for all scenarios in case 9

		Scenario	Demand for each scenario	Expected Demand
2012	**t=0**	S1	265	265
		S2	265	
		S3	265	
2013	**t=1**	S1	260	275
		S2	280	
		S3	285	
2014	**t=2**	S1	255	285
		S2	290	
		S3	315	
2015	**t=3**	S1	250	293
		S2	305	
		S3	326	
2016	**t=4**	S1	252	295
		S2	308	
		S3	325	
2017	**t=5**	S1	250	298
		S2	312	
		S3	335	

2018	**t=6**	S1	255	295
		S2	308	
		S3	320	
2019	**t=7**	S1	255	298
		S2	310	
		S3	330	
2020	**t=8**	S1	260	296
		S2	305	
		S3	325	
2021	**t=9**	S1	260	296
		S2	305	
		S3	325	

The details from table 5-48 are summarised in figure 5-22, where different demand scenarios and expected demand are highlighted versus available capacity.

Case Result and analysis: This case is designed to validate the model in an uncertain market and to compare stochastic and deterministic results. Therefore, as explained earlier, uncertain demand in this case is set in such a way that the expected demand would be exactly the same as the deterministic demand in case 2. Figure 5-22 shows all market scenarios and expected demand in comparison with the available capacity.

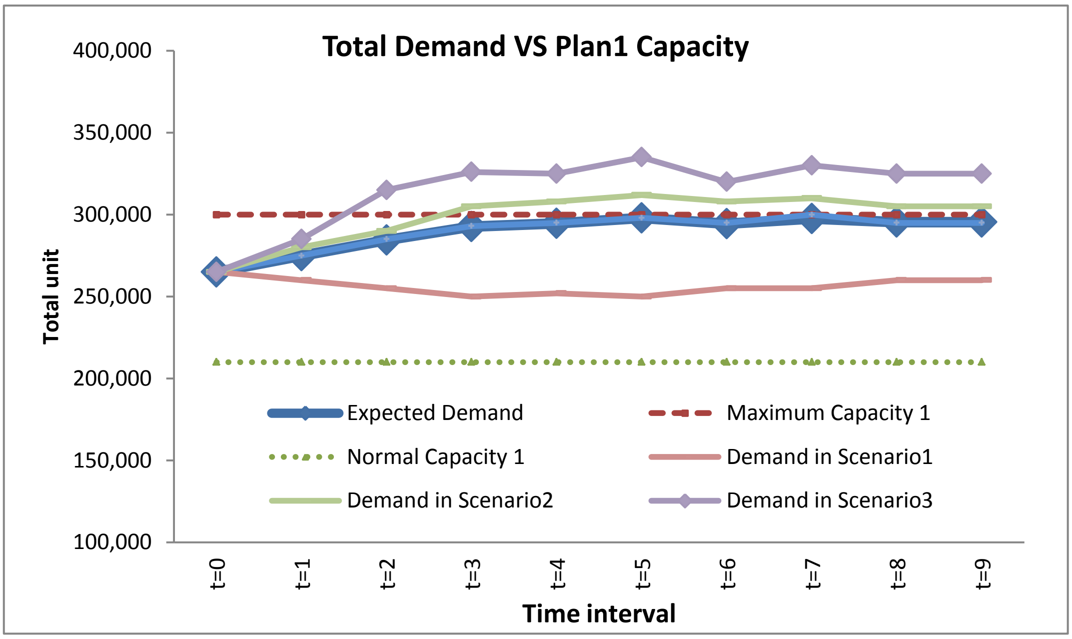


Figure 5-22: Different demand scenarios and the expected scenario vs. available capacity in case 9

It can be seen that overall a better market is expected for the company and therefore the company should get prepared for the future. In the worst case scenario, however, the demand stays more or less at the current level in the next 10 years. The overall expected demand remains just below the maximum capacity of the plant, despite a slight increase in the first years. According to case 2, where one just employs the BAU approach and considers the expected demand value, no expansion is suggested and the plant should work overutilised (near the maximum capacity) to cover the demand. However, in this case, if scenario one or two happens, the plant would not be capable of fulfilling the demand and would lose the market share. Assuming a £10,000 penalty for unmet demand and putting all abovementioned information into the model and running it, an expansion in the third year of planning is suggested by the model.

Considering the optimal solution for the deterministic approach (Case 2), which is overutilisation, and the above solution for the stochastic approach, the only differences between them are:

- The gain from producing extra products in scenarios 2 and 3, as well as the unmet demand penalty if these scenarios happen and the plant has not been expanded.
- The investment cost of expansion as well as extra operation and work force costs

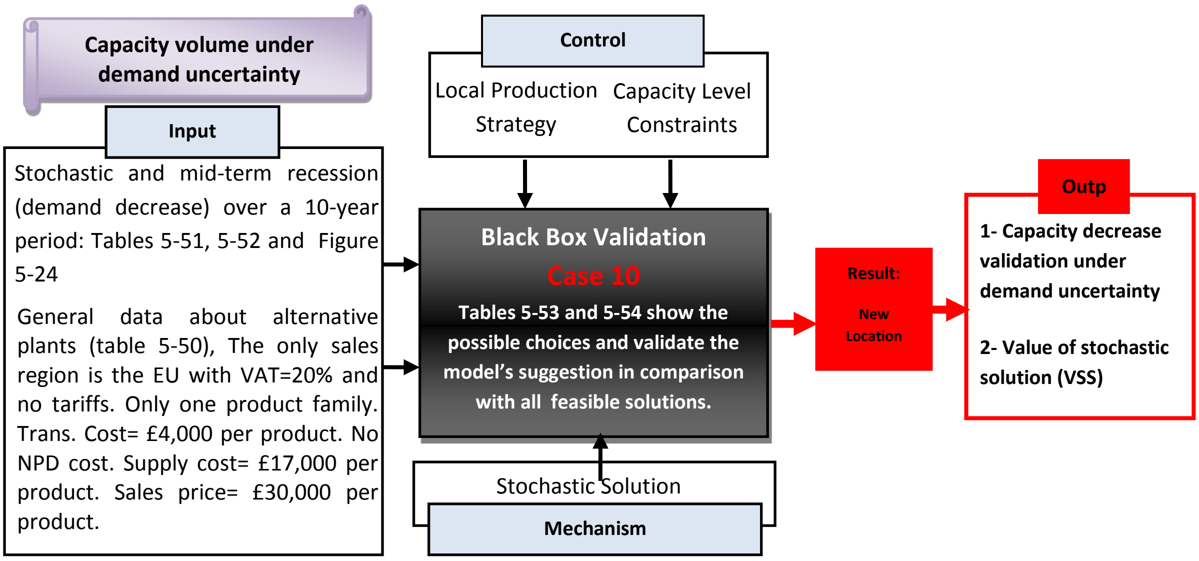
In Table 5-49 these differences are calculated and therefore it supports the solution from this stochastic approach over the deterministic one. The value of the stochastic solution can also be calculated from this difference, which is more than £500million over the ten-year horizon. However, if the unmet demand penalty is set to the real loss of the company and is taken out of the real financial equations in table 5-49, expansion of the capacity is not the optimal solution anymore and the model suggests to keep the plant overutilised and not to meet the extra demands in scenarios 2 and 3. It shows the level of importance of the strategic decision on setting a right unmet demand penalty, which reflects the marketing policy of the company.

Table 5-49: Cost breakdown of differences for stochastic and deterministic solutions in case 9

Optimal solution for case 9 (Stochastic)	**Expansion Capital**	**Extra cost of operations in 7 years**	**Extra cost of work force in 7 years**	**Gain from extra possible sales**
	-80	-420	-318.5	667
Optimal solution for case 2 (Deterministic)	**Penalty on possible unmet demand**	-	-	-
	-667	-	-	-
				VSS= £515 million

Case10: Stochastic Demand Decrease: Mothball or Underutilisation?

Case Brief: This case is designed to highlight the value of the stochastic solution in a depressed market. A demand decrease is set for this case and to simplify the case only one product family, one sales market and two identical domestic production plants will be set for the case. Also, no capacity expansion is possible for the plants and no extra overutilisation cost is required to utilise the maximum capacity. To compare the result with the deterministic case, expected demand is replicated from case 5 to show a short-term recession in the near future. With reference to case 5 in a business-as-usual approach the plant should be mothballed in the recession period. This case is designed to see the result in a stochastic case and the effect of the unmet demand penalty in an uncertain market. Figure 5-23 shows the ICOM structure for this case.



Stochastic and mid-term recession (demand decrease) over a 10-year period: Tables 5-51, 5-52 and Figure 5-24

General data about alternative plants (table 5-50), The only sales region is the EU with VAT=20% and no tariffs. Only one product family. Trans. Cost= £4,000 per product. No NPD cost. Supply cost= £17,000 per product. Sales price= £30,000 per product.

Tables 5-53 and 5-54 show the possible choices and validate the model's suggestion in comparison with all feasible solutions.

1- Capacity decrease validation under demand uncertainty

2- Value of stochastic solution (VSS)

Figure 5-23: ICOM framework for case 10 of the validation plan

Input data: Table 5-50 shows the required initial data on the plants to put into the database in this case.

Table 5-50: Required information on the plants to put into the database for case 10

	Plant Location	**Maximum Capacity (*1,000)**	**Maximum normal capacity rate**	**Annual Operations cost (million pounds)**	**Annual normal Work force Cost (million pounds)**	**Any unit-based cost of production excluding supply**	**Profit Tax rate**	**Capacity Mothball**			
								Fixed cost of mothballing (million pounds)	Redundancy rate in case of mothball	Fixed cost of reopening (million pounds)	Operations cost for mothballed plant (million pounds)
Plant 1	UK	100	1	40	50	500	0.2	20	0.4	5	2
Plant 2	UK	100	1	40	50	500	0.2	20	0.4	5	2

Since a local production strategy is adopted for this case, no import tariff is expected here, 20% is set for VAT in the UK and local transportation, warehouse cost and dealership expense for the product family is assumed to be as much as £4,000 per product unit. The average sales price in the UK for this product family is £30,000 per product.

The product family and cost-related aspects in this case remain exactly the same as in case 9 and therefore no R&D and NPL cost is expected for this product and the supply cost of the product family is as much as £17,000 per product unit. The scenarios' probability and the sales price in each scenario is set in table 5-51.

Table 5-51: The scenarios' probabilities and sales prices in different scenarios for case 9

	Worst Scenario (S1)	Normal Scenario (S2)	Best Scenario (S3)
Scenario Probability	50%	20%	30%
Sales Price	£29,000	£31,000	£31,000
Expected Sales Price	**£30,000**		

Table 5-52, on the other hand, shows the demand details for each year and each scenario. Figure 5-24 summarises the demand data and shows differences between the best, worst and normal scenarios, as well as the expected demand. All scenarios and expected demands reflect a forecasted recession in the next 4 years, which will be over by the end of the time horizon. The level and depth of the drawback is, however, different in the different scenarios. In the best case scenario, the demand level remains within the scope of the normal production capacity for both plants, despite the demand reduction in the first 4 years. For the other 2 scenarios, however, the demand is forecasted to slump under the maximum capacity of one plant for 3 years. Considering the same pattern for all scenarios and the relatively high probability of the worst case scenario, the expected demand also follows the recession pattern, as shown in figure 5-24.

Table 5-52: Demand details for the product family in the sales region for all scenarios in case 10

		Scenario	Demand for each scenario	Expected Demand
2012	**t=0**	S1	140	140
		S2	140	
		S3	140	
2013	**t=1**	S1	130	120
		S2	120	
		S3	114	
2014	**t=2**	S1	124	104
		S2	106	
		S3	92	
2015	**t=3**	S1	116	91
		S2	90	
		S3	76	

2016	**t=4**	S1	108	83
		S2	80	
		S3	70	
2017	**t=5**	S1	118	96
		S2	94	
		S3	84	
2018	**t=6**	S1	136	110
		S2	104	
		S3	96	
2019	**t=7**	S1	144	120
		S2	116	
		S3	108	
2020	**t=8**	S1	150	131
		S2	130	
		S3	120	
2021	**t=9**	S1	160	140
		S2	136	
		S3	130	

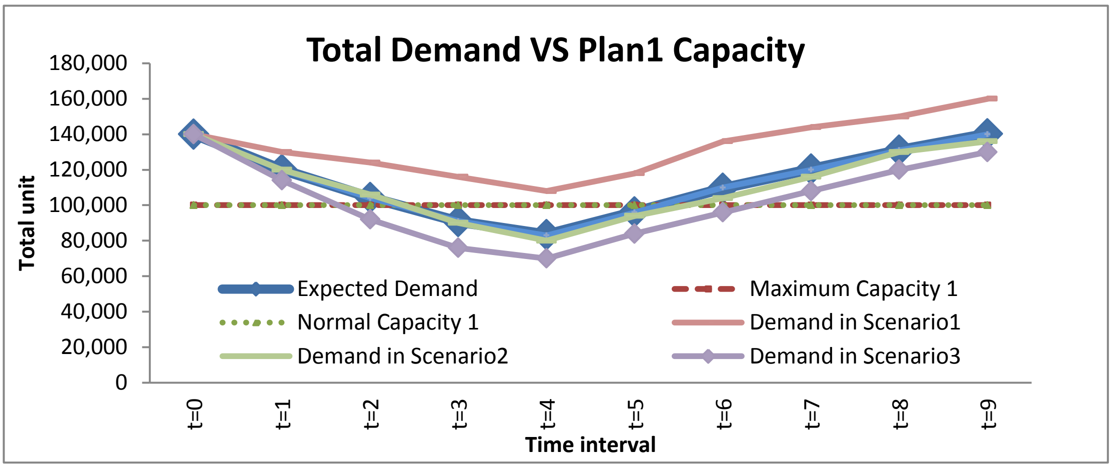


Figure 5-24: Different demand scenarios and expected scenario in case 10

Case Result and analysis: Figure 5-24 shows the demand scenarios in comparison with the plant 1 available capacity. Considering the expected demand and a deterministic approach, with reference to case 5, mothballing plant 2 during the recession time (year 3 to 5) is the best solution. In this case (stochastic) however, the best case scenario shows no demand decrease under the maximum capacity of plant 1. In other words, if a mothball decision is taken and if scenario 1 happens, all the excess demand for the company's products will be lost (will have gone to the competitors).

Running the stochastic model with all abovementioned information and applying these different scenarios, different results based on the level of the unmet demand penalty were achieved, as presented in table 5-53.

Table 5-53: The Model's outcome for the number of open plants in case 10, showing the relationship between scenarios, unmet demand penalty and solution approach

		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Deterministic		2	2	2	1	1	1	2	2	2	2
Stochastic	Penalty=<£5000/unit	2	2	2	1	1	1	2	2	2	2
	£5000/unit<Penalty<=£7000/unit	2	2	2	1	1	2	2	2	2	2
	£7000/unit<Penalty<=£10000/unit	2	2	2	2	1	2	2	2	2	2
	£10000/unit<Penalty	2	2	2	2	2	2	2	2	2	2

This table shows the impact of the unmet demand penalty on the capacity level management in a stochastic approach. According to this table, based on the input information, if the penalty for the unmet demand is set at less than £5,000 per unit, the model suggest to mothball one of the plants for 3 years, which is the same as the result for the deterministic approach. However, as the penalty increases, the tendency to capacity mothball decreases, because of the high weight of the penalty risk in case of realising scenario 1. This tendency in this case is reflected in mothball duration, according to table 5-53. Although the unmet demand penalty is not a direct cost for the company, it reflects the marketing policy of the company, which directly affects the operation strategy of the firm. If no penalty is set for the unmet demand, it means that the company is not sensible at all to losing its market share due to a possible lack of capacity. In other words, minimising the operations costs by increasing the utilisation level of the entire capacity is in the centre of attention to the company and no risk of operation is taken, while the highest risk of brand image deterioration has been acquired.

To validate the result, table 5-54 shows the differences in all possible solutions, with different unmet demand penalties. According to this table, different solutions will be raised as optional solutions for different levels of the unmet demand penalty. These calculations validate the model's output in this case.

Table 5-54: Cost breakdown of differences for the stochastic and deterministic solutions in case 10

	Mothball Duration (years)	Fixed cost of mothballing and re-opening(m£)	operations cost of mothballed plant (m£)	Proportion work force cost of mothballed plant (m£)	Total Unmet demand penalty (m£)	Lose of gain (m£)	Total cost of Mothball (m£)	No mothball (m£)	Final result	VSS
Penalty=£5,000 per Unit	**3**	25	6	90	51	96	**268**	**270**	**3 years mothballing if P=£5000**	-
	2	25	4	60	24	48	**161**	**180**		
	1	25	2	30	12	24	**93**	**90**		
Penalty=£7,000 per Unit	**3**	25	6	90	71.4	102	**294**	**270**	**2 years mothballing if P=£7000**	**100**
	2	25	4	60	33.6	48	**171**	**180**		
	1	25	2	30	16.8	24	**89**	**90**		
Penalty=£11,000 per Unit	3	25	6	90	112.2	102	**335**	**270**	**No mothballing if P=£11000**	**165**
	2	25	4	60	52.8	48	**190**	**180**		
	1	25	2	30	26.4	24	**107**	**90**		

The Effect of Uncertainty on Capacity Location Management

Case11: Stochastic Demand Increase: Overutilisation, Expansion or New Plant in China?

Case Brief: It was shown in case 9 that with an uncertain but increasing demand, when a penalty for unmet demand was defined, capacity expansion was suggested by the model in a local capacity management approach. In this case, however, giving a global option and inputting export-related financial terms into the model, the global capacity management in a stochastic market will be analysed and validated, accordingly. Figure 5-25 reveals the ICOM outline for this case.

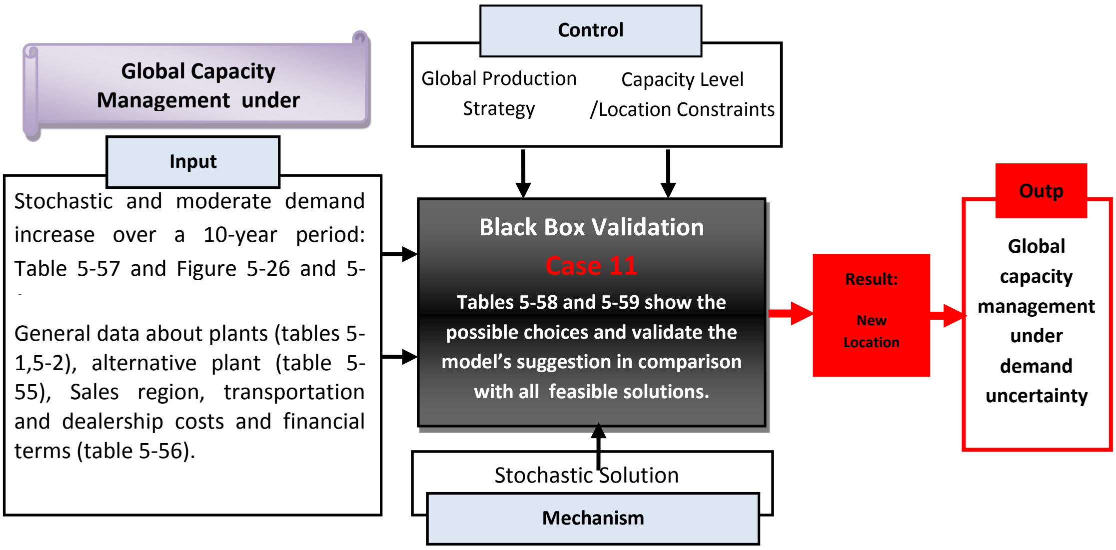


Figure 5-25: ICOM framework for case 11 of the validation plan

Input data: The current plant, product family, sales regions, demand details, scenarios' probabilities and other input data in this case remain the same as the data set for case 9. The only difference is an optional brand new plant in China. In addition to the general data for Plant 1 in the UK, which is reflected in case one (tables 5-1 and 5-2), table 5-55 discloses data on an alternative brand new plant in China.

Table 5-55: Input data for the optional plant in case 11

	Plant Location	Maximum Capacity (*1,000)	Maximum normal capacity rate	Initial Capital Investment (million pounds)	Annual Operations cost (million pounds)	Annual normal Work force Cost (million pounds)	Any unit-based cost of production excluding supply	Profit Tax rate
Optional Plant	China	200	0.8	150	100	60	500	0
	Capacity Expansion					**Overutilisation**		
	Number of possible Expansions	Maximum Expansion rate	Capital investment for Expansion (million pounds)	Extra operations cost in case of expansion (million pounds)	Extra work force cost in case of expansion (million pounds)	Capital investment for Overutilisation (million pounds)	Extra operations cost in case of overutilisation (million pounds)	Extra work force cost in case of overutilisation (million pounds)
	1	0.4	30	20	0	0.5	5	0

The product sales prices in all sales regions as well as transportation and dealership costs from different plants to each sales destination are also presented in table 5-56.

Table 5-56: Sales price, cost of transportation-related costs and tariff rates in case 11

	EU	USA	China
Sales Price in EU	£31,000	£32,000	£33,000
Transp. to Dealership From Plant 1	£1,000	£4,000	£8,000
Transp. to Dealership From Plant 2	£4,000	£6,000	£2,000
Tariff rate From Plant 1	0%	10%	20%
Tariff rate From Plant 2	20%	20%	0%

The demand in this case has been explained in 3 basic scenarios, such as in case 9. Figure 5-26 and table 5-57 show the demand level in the three sales regions for the three scenarios.

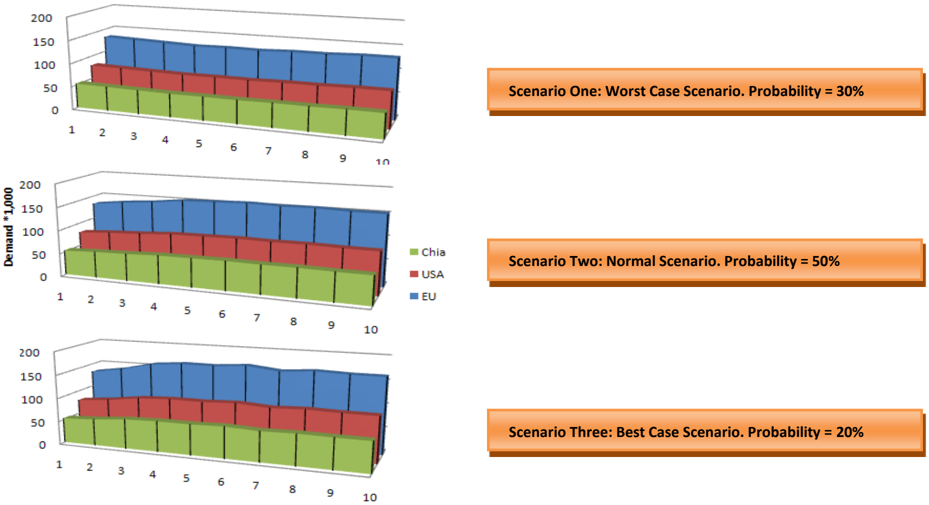


Figure 5-26: Demand detail in 3 different scenarios for different sales regions in case 11

Table 5-57: Demand detail in 3 different scenarios for different sales regions in case 11

		Scenario	Demand for each scenario in the UK	Demand for each scenario in the USA	Demand for each scenario in China	Expected Demand
2012	**t=0**	S1	133	80	53	**265**
		S2	133	80	53	
		S3	133	80	53	
2013	**t=1**	S1	130	78	52	**275**
		S2	140	84	56	
		S3	143	86	57	
2014	**t=2**	S1	128	77	51	**285**
		S2	145	87	58	
		S3	158	95	63	
2015	**t=3**	S1	125	75	50	**293**
		S2	153	92	61	
		S3	163	98	65.2	
2016	**t=4**	S1	126	76	50.4	**295**
		S2	154	92	61.6	

		S3	163	98	65	
2017	**t=5**	S1	125	75	50	**298**
		S2	156	94	62.4	
		S3	168	101	67	
2018	**t=6**	S1	128	77	51	**295**
		S2	154	92	61.6	
		S3	160	96	64	
2019	**t=7**	S1	128	77	51	**298**
		S2	155	93	62	
		S3	165	99	66	
2020	**t=8**	S1	130	78	52	**296**
		S2	153	92	61	
		S3	163	98	65	
2021	**t=9**	S1	130	78	52	**296**
		S2	153	92	61	
		S3	163	98	65	

And finally, similar to case 2 and 9, the total expected demand versus the current capacity is shown in figure 5-27. This chart is identical to figure 5-7 for case 2 and the expected demand for case 9 in figure 5-22. This similarity establishes the link which makes case 2, 9 and 11 comparable, as was discussed in the validation plan and shown in figure 5-1 and 5-2.

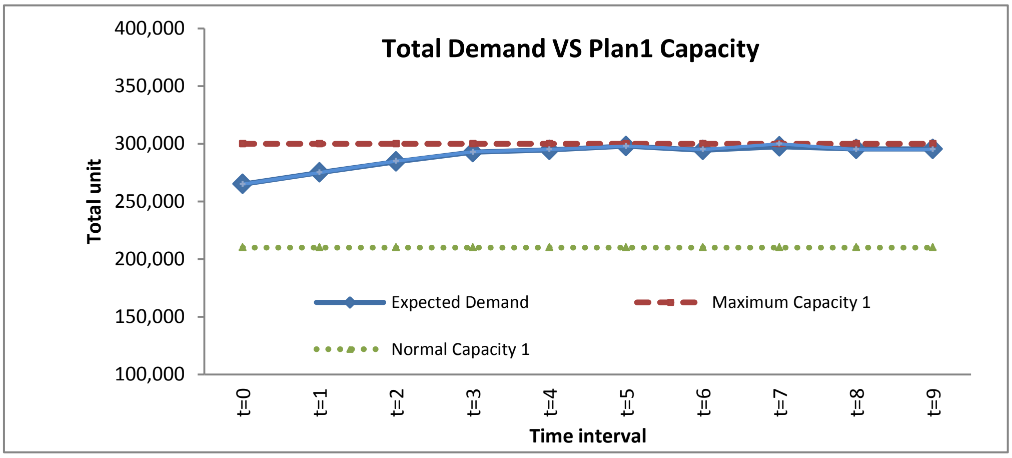


Figure 5-27: Total expected demand vs. current capacity in Case 11.

Case Result and analysis: Comparing case 2 and 9, earlier we verified that overutilisation is not the optimal solution in case of a slight demand increase, when the market is uncertain and an unmet demand penalty is assumed. Therefore the feasible choices in this case are capacity expansion or a new plant in China. Running the model with all the abovementioned information and assuming that the plant in China can be opened at any time after the first year of planning, the model suggests establishing the Chinese plant in the second year of the planning and keeping both plants open until the end of the time horizon. Moreover, to supply all demands in scenarios 2 and 3 when more demand is expected, the model proposes overutilisation for both plants. The cost breakdown analysis of the differences for both feasible solutions of capacity expansion and a new plant in China is reflected in tables 5-58 and 5-59. This cost breakdown supports and validates the model's suggestion.

While table 5-58 shows that the summation of the operational and capital investment to run the Chinese plant is higher than the figures for expanding the current plant, table 5-59 underpins the importance of export-related costs. This trade-off leads to an investment in China for the domestic market in the end. The tax-free incentive for investment in China also adds to the total cost saving and supports the decision even more, which is ignored in these tables.

Table 5-58: Operational and capital investment for each feasible solution in case 11.

Expansion Solution	Fixed Cost Of expansion (m£)	Extra Operations cost of expanded plant for 8 years (m£)		Extra Work force cost of expanded plant For 8 years (m£)		**Sum (m£)**
	80	480		364		**924**
New plant Solution	Fixed Cost of establishing the optional plant (m£)	Operations cost of running optional plant for 9 years (m£)	Work force Cost of Running optional plant for 9 years (m£)	Overutilisation Cost of optional plant for 9 years (m£)	Extra Work force cost of overutilisation of optional plant for 9 years (m£)	**Sum**
	200	900	540	45	180	**1,865**

Table 5-59: Export-related cost breakdown in Case 11.

Expansion Solution	**Scenario**	**Extra Cost of transp., warehouse and dealership for Chinese market in 9 years (m£)**	**Extra Tariff cost for export to China in 9 years (m£)**	**Sum (m£)**
	S1	2,756	3,032	**6,622**
	S2	3,268	3,594	
	S3	3,463	3,810	
New plant Solution	**Scenario**	**Extra Cost of material supply in 9 years to the Chinese plant (m£)**		**Sum (m£)**
	S1	1,378		**1,577**
	S2	1,634		
	S3	1,732		

5-5- Flexibility Choices

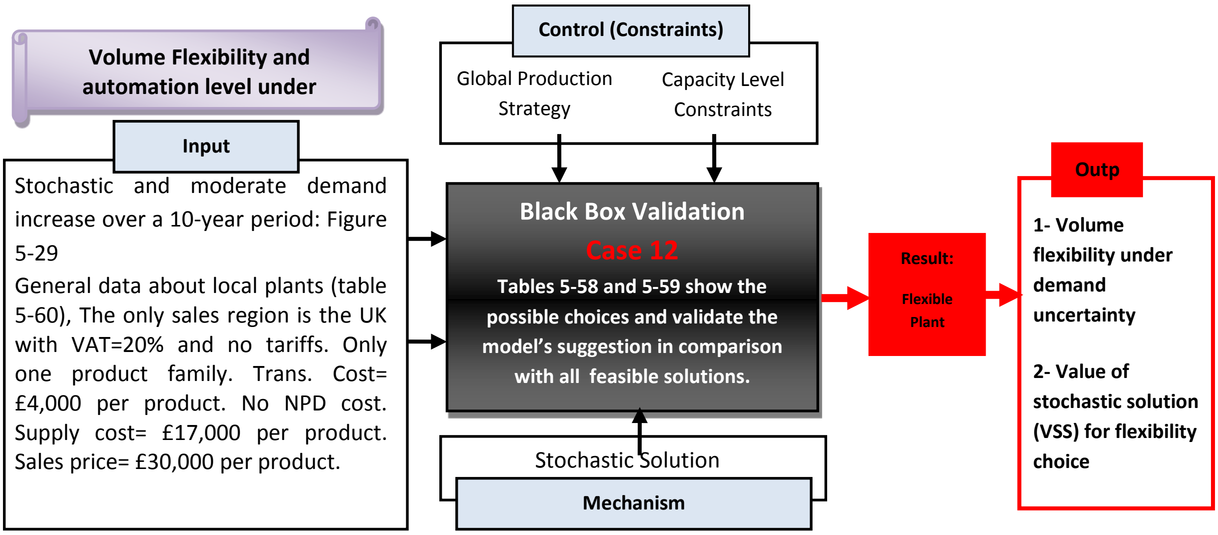
In this section, flexibility choices will be studied and the model will be validated in both stochastic and deterministic demand changes. As discussed earlier in chapter 2 and 4, the terms which identify the level of flexibility in strategic capacity modelling and particularly in this model are: 1- the possibility matrix, which shows how products are flexible to be launched in more plants and how the plants welcome a wider variety of products. Moreover, capacity ratios in the possibility matrix indicate how the production of different products in different lines is efficient in terms of capacity consumption and cost. The extra unit cost of products in different lines, as well as the NPL cost and relaunch investment also indicate how launching and relaunching a product in the different lines would be cost efficient. 2- The automation level will be reflected in the required capital investment, work force costs and operations costs. 3- The volume flexibility is also directly applied in the model, by setting capacity change lead time and cost. In other words, how quickly and cost-efficiently a plant can react to the volume change requests.

Case 12 addresses terms 2 and 3 of the abovementioned metrics and case 13 goes over item 1. The effect of uncertainty on the flexibility choice is also demonstrated in case 12, where the value of stochastic solutions (VSS) over the deterministic optimisation in the ‘flexibility choice case’ will be established.

Case12: Flexibility Choice: Automation and Volume Flexibility.

Case Brief: In this case two possible plant choices are applied in the model in a prospering market. The demand is set to be stochastic, but domestic. Both plants are located in the UK to feed the local market. The first choice (plant 1) is less automated and flexible, while the other choice is more volume adjustable. Due to the high automation in the second choice, although a higher capital investment and annual maintenance cost is expected, a lower work force level would be required to run the plant. More volume flexibility of the second choice means the plant needs no extra investment to utilise its highest capacity. It means, in other words, no higher than normal utilisation cost and this plant can quickly and cost-efficiently adjust its capacity.

Showing all required inputs for this case, figure 5-28 establishes the ICOM framework for the case.



Stochastic and moderate demand increase over a 10-year period: Figure 5-29

General data about local plants (table 5-60), The only sales region is the UK with VAT=20% and no tariffs. Only one product family. Trans. Cost= £4,000 per product. No NPD cost. Supply cost= £17,000 per product. Sales price= £30,000 per product.

Tables 5-58 and 5-59 show the possible choices and validate the model's suggestion in comparison with all feasible solutions.

1- Volume flexibility under demand uncertainty

2- Value of stochastic solution (VSS) for flexibility choice

Figure 5-28: ICOM framework for case 12 of the validation plan

Input data: Table 5-60 shows the investment figures for both choices. Only one product family with a sales price of £31,000 and a unit supply cost of £17,000 is considered in this case. The VAT in the UK is 20% and no product launch or development cost is applied in this case.

Table 5-60: Investment figures for both plant choices in case 12

	Maximum Capacity (*1,000)	Maximum normal capacity rate	Initial Capital Investment (million pounds)	Annual Operations cost (million pounds)	Annual normal Work force Cost (million pounds)	Any unit-based cost of production excluding supply	Profit Tax rate	Overutilisation	
								Extra work force cost (million pounds)	Extra operations cost (million pounds)
Plant1	200	0.8	150	100	100	500	0.2	16	11
Plant2	200	1	250	120	80	500	0.2	0	0

Using the 'business-as-usual' approach in this case, the expected demand for the product is shown in figure 5-29. This figure implies that, although the expected demand will increase, it is anticipated to be mainly in the normal production zone.

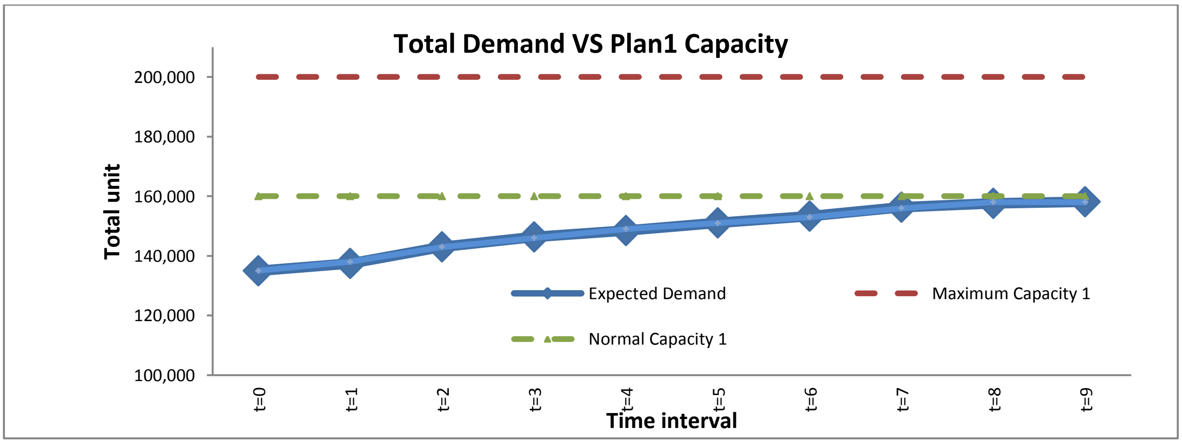


Figure 5-29: Total expected demand vs. current capacity in Case 12

Therefore the best solution seems obvious in this case: Plant 1 (less expensive, but less flexible). Running the model with all the above information in the deterministic mode, plant 1 was suggested by the model to be established, as expected. Since the only financial difference between plant 1 and 2 is listed in table 5-60, when no overutilisation is expected over the time plan, selecting plant 1 as the manufacturing site brings £90 million savings compared to the choice of plant 2.

However, if the stochastic approach is employed the results may be different. In the remainder of this case, the stochastic demand is designed in such a way that the final expected value remains the same as in figure 5-29, in order to make the case comparable with the deterministic approach and to show the value of the stochastic solution (VSS). In this case, three scenarios of optimistic, pessimistic and realistic have been designed, as shown in figure 5-30. Although the expected demand remains in the normal capacity zone of plant 1, in two scenarios, demand may exceed this zone to the overutilisation area. If these scenarios happen, the plants should be utilised at their highest level, while plant 2, which is more flexible, runs with no need to invest in overutilisation or resetting. With this level of uncertainty, which is in the range of almost 10% to 30% in different years, one may expect the model to go for the more flexible choice.

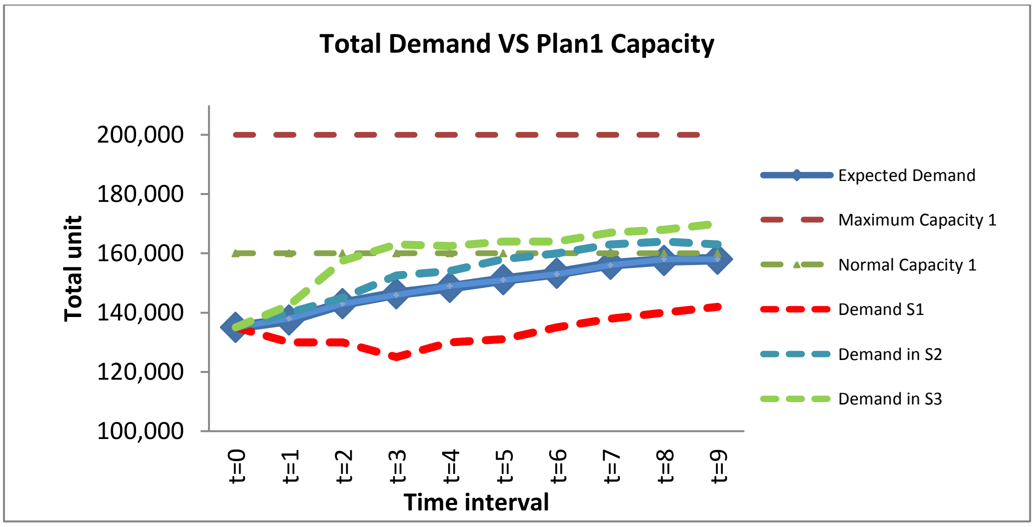


Figure 5-30: Different demand scenarios and expected demand vs. current capacity in Case 12

Case Result and analysis: Refining the model with this new stochastic demand set, this time model suggests investing in the more flexible plant to cope with this demand uncertainty more cost-efficiently, as expected.

Table 5-61 highlights the difference in total investment in different scenarios for both choices, which supports the outcome and establishes the VSS.

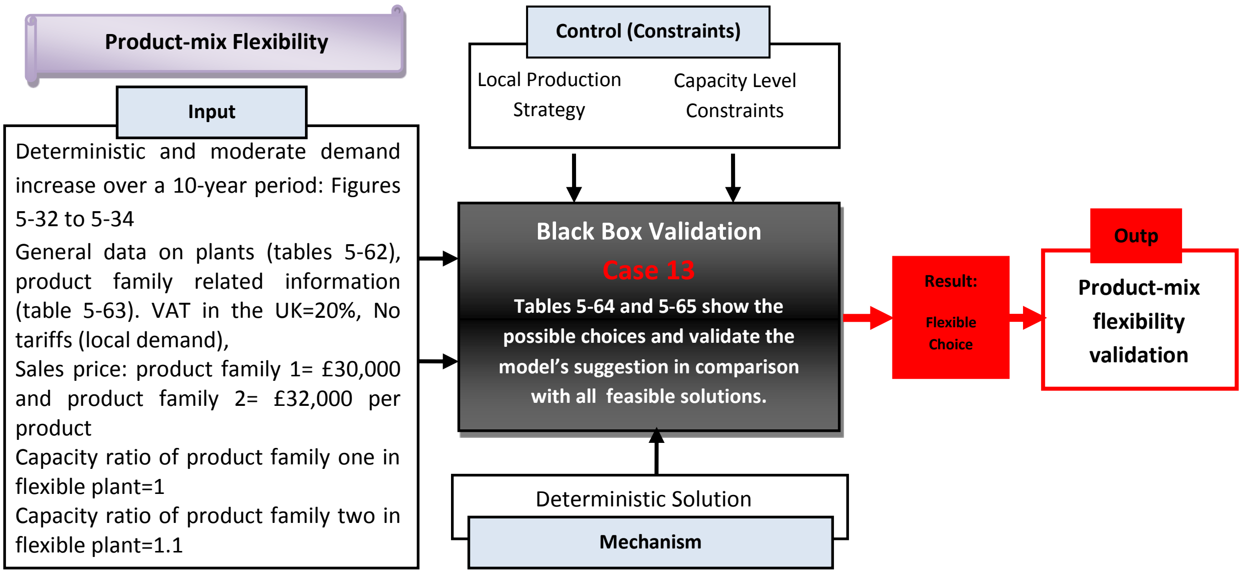
Table 5-61: Differences between two feasible choices which support the model's result

	Scenario	Initial Capital Investment (million pounds)	Operations cost in 10 years (million pounds)	Annual normal Work force Cost (million pounds)	Overutilisation		Sum (m£)
					Extra work force cost (m£)	Extra operations cost (m£)	
Plant1	scenario 1, P=0.3	150	1000	1000	0	0	**2241.8**
	scenario 2, P=0.5				=4*16	=4*11	
	scenario 3, P=0.2				=7*16	=7*11	
Plant2	scenario 1, P=0.3	110	1200	800	0	0	**2110**
	scenario 2, P=0.5						
	scenario 3, P=0.2						
							VSS
							£130.1M

This case shows that employing the stochastic approach in this case will assist decision makers to save almost 6% of their total costs over a 10-year time plan, which is as large as 130 million pound in this example.

Case13: Flexibility Choice: Product-mix Flexibility

Case Brief: In this case two dedicated plants will be compared with one equivalent flexible choice. Both plants are local UK-based plants for the domestic market. Having shown the value of the stochastic approach in the flexibility choice in the previous case, in this case the deterministic approach has been employed for reasons of simplification. Two product families have been considered and for each product family a choice of dedicated plants has been made in favour of plant 1 or 2. Plant 3, however, is the more flexible plant, which is capable of producing both product family groups, simultaneously. A prospering market is assumed for this case and demand is set to increase (but within the scope of available capacity of the plants). The question in this case is about the feasibility of dedicated and flexible plants. The ICOM outline, which is disclosed in figure 5-31, summarises this case.



Deterministic and moderate demand increase over a 10-year period: Figures 5-32 to 5-34

General data on plants (tables 5-62), product family related information (table 5-63). VAT in the UK=20%, No tariffs (local demand),

Sales price: product family 1= £30,000 and product family 2= £32,000 per product

Capacity ratio of product family one in flexible plant=1

Capacity ratio of product family two in flexible plant=1.1

Tables 5-64 and 5-65 show the possible choices and validate the model's suggestion in comparison with all feasible solutions.

Figure 5-31: ICOM framework for case 13 of the validation plan

Input data: Table 5-62 shows these three plants and their investment figures.

Table 5-62: Capacity and Investment figures for the dedicated and flexible plants in case 13

	Plant Loc.	Max. Capacity (*1,000)	Normal capacity rate	Initial Capital Inv. (£M)	Annual Operations cost (£M)	Annual normal Work force Cost (£M)	Overutilisation	
							Extra work force cost (M£)	Extra operations cost (M£)
Plant1 (dedicated to product family No.1)	UK	200	0.8	150	100	100	15	10
Plant2 (dedicated to product family No.2)	UK	200	0.8	150	100	100	15	10
Plant3 (Flexible)	UK	300	0.8	330	150	130	20	15

Table 5-63 also depicts that plant 1 is dedicated to product family one and plant 2 is designed for the other product family, while plant 3 is capable of producing both product types at the same time. According to this table, since dedicated plants are designed for a product family, producing this type in such plants is standard (capacity ratio=1) and no extra unit-based cost of production is required. Moreover, developing the products to a dedicated plant is less expensive than launching them in a flexible production line.

Table 5-63: Product/Plant-related figures in case 13

	Product Family No.1					Product Family No.2				
	Capacity Coefficient	NPL Cost (£M)	Material Supply Cost (£M)	Any Unit Cost of production (£M)	R&D Cost of NPD (£M)	Capacity Coefficient	NPL Cost (£M)	Material Supply Cost (£M)	Any Unit Cost of production (£M)	R&D Cost of NPD (£M)
Plant 1	1	50	£17,000	0	10	-	-	-	-	10
Plant 2	-	-	-	-		1	50	£18,000	0	
Plant 3	1	70	£17,000	200		1.1	70	£18,000	500	

Tax on profit and VAT in the domestic market are both set as high as 20%. The average sales prices of £30,000 and £32,000 have been applied for product families 1 and 2, respectively. Transportation and dealership costs are considered the same for both product types and for all plants.

Diagram 5-32 and 5-33 respectively illustrate the demand for product families versus the capacity of dedicated plants. Diagram 5-34, on the other hand, shows the total demand versus the normal and maximum capacity of the flexible plant. The capacity ratio of 1.1 for product family 2 in the flexible plant is set, which is also highlighted in diagram 5-34.

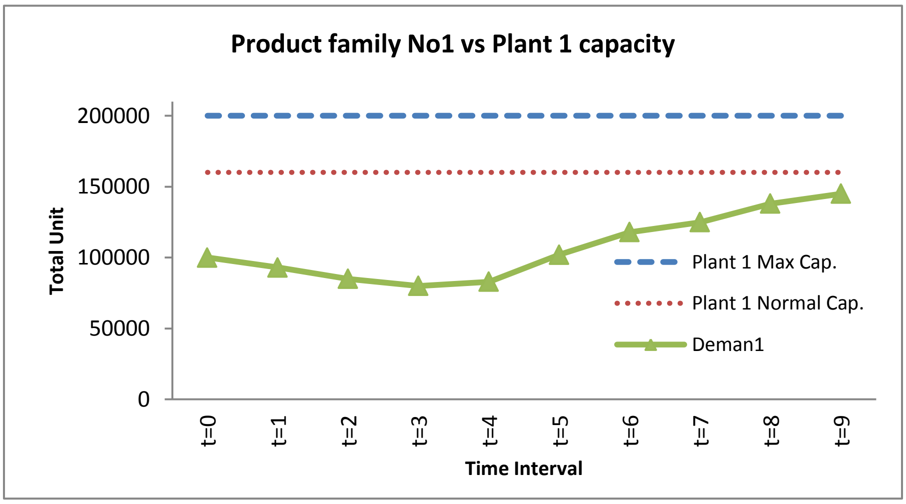


Figure 5-32: Demand for product family 1 vs. maximum and normal capacity of dedicated plant 1 in case 13

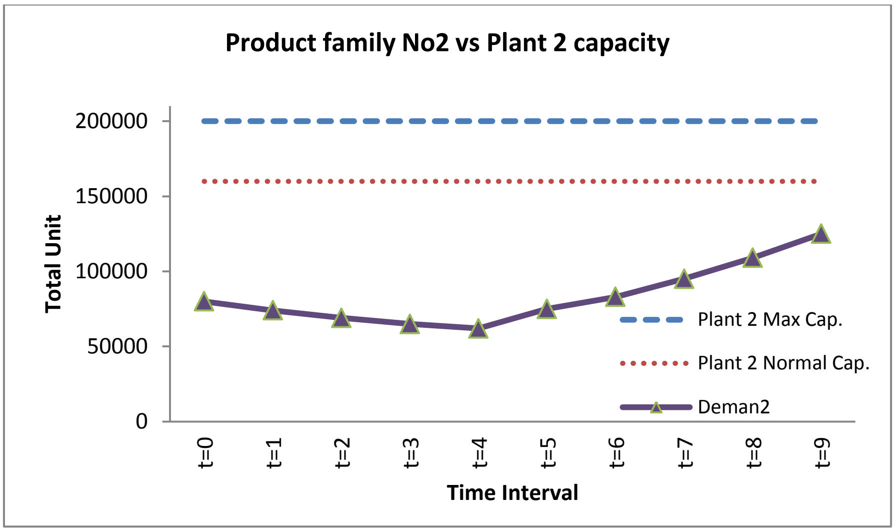


Figure 5-33: Demand for product family 2 vs. maximum and normal capacity of dedicated plant 2 in case 13

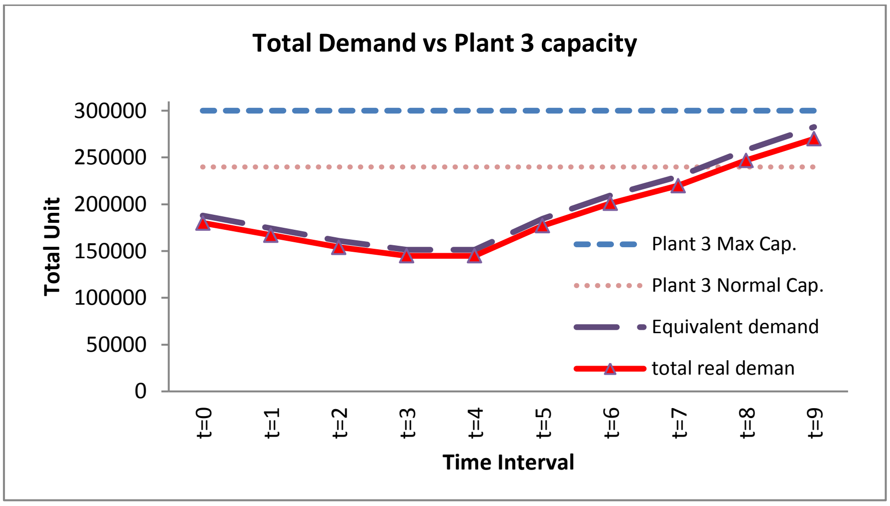


Figure 5-34: Total demand versus maximum and normal capacity of the flexible plant (plant 3) in case 13

Case Result and analysis: These diagrams imply that having either dedicated or flexible plants can be feasible solutions for the production here. The total capital investment and operations cost of the flexible plant is higher than for each individual dedicated plant but reasonably lower than for both dedicated plants, as shown in table 5-62. On the contrary, the production unit cost of both product families in the flexible plant is higher than its cost for the dedicated lines. The NPD investment to launch these products in the flexible plant is also more expensive. This trade-off brings a massive complexity to the decision making procedure, which sometimes makes the decision very difficult. Putting all data into the model's database and running it, the flexible solution is being suggested by the model as the optimal solution for this case. To find out why, table 5-64 and 5-65 break down the financial differences to be comparable. These tables support the model's outcome and validate the results.

Table 5-64: Investment and operations cost differences between two feasible solutions in case 13

	Capital Inv. (M£)	Operations cost of 10 years (M£)	Work force cost in 10 years (M£)	Overutilisation	NPL	**Sum (M£)**
Solution 1: dedicated plants (Plant 1&2)	**300**	2000	2000	0	100	**4400**
Solution 2: Flexible plant (Plant 3)	**330**	1500	1300	70	140	**3340**

Table 5-65: Extra cost of unit production in the flexible plant (solution 2) in case 13

		t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	**Sum (M£)**
Product Family1	Demand	100	93	85	80	83	102	118	125	138	145	**632.3**
	extra cost of production in plant 3	20	18.6	17	16	16.6	20.4	23.6	25	27.6	29	
Product Family2	Demand	80	74	69	65	62	75	83	95	109	125	
	extra cost of production in plant 3	40	37	34.5	32.5	31	37.5	41.5	47.5	54.5	62.5	

These tables explain how the flexible choice in this case brings a saving of almost 10% on the total costs of the company (including investment and cost of production) in the scope of this planning (10 years), which is as large as £428 million. Setting different input data, however, one may see different results. Depending on the investment figures and operations costs, the dedicated choices can also be a better solution in some cases.

5-6- Product Management Validation

In this section, the aim is to validate product-related decisions. The product-related decisions in this model are:

- Product-to-market decisions, which explain which product should be launched in which market and from which production site. Financial parameters, such as profit tax, VAT, import tariff etc. as well as transportation, warehouse and dealership costs have been highlighted in chapter 2 and 4 as the main effective parameters that may change such a decision.
- New product development (NPD) decisions, which consist of product design (R&D), first time product launch (NPL) and product relaunch, as were discussed in chapter 4.
- Strategic plant load-planning and the generic production plan

The first two aspects of product management decisions have already been covered in sections 5-2-2, 5-4 and 5-5. In this section strategic load-planning and its impacts on long-term investment planning will be discussed in case 14.

Case14: Strategic Load-Planning

Case Brief: In this case a hypothetical company with 4 manufacturing plants and 5 product families has been assumed in the European Union with its regional market. Therefore, no product-to-market, tariff and dealership costs will be part of the input in this case. Production plants in this case comprise of:

- Plant 1: A very large flexible plant, which is capable of producing 3 product families of A, B and E, at the same time
- Plant 2: A medium-size flexible plant, in which two products of C and D are being produced simultaneously
- Plant 3: A small dedicated plant, which is now producing product C, but is rather capable of producing product B instead, with some investment in production line modification
- Plant 4: A small dedicated plant for product E, which can be switched to product D, if some changes happen in the production layout.

Although dedicated plants 3&4 are capable of producing alternative products, just one product can be produced in these plants at the same time. In other words, these dedicated plants are capable of shifting from producing the main product to the alternative one if some modifications are carried out on the production lines' layout. For all but one product family, demand is expected to slightly but continuously increase over a 10-year planning horizon. Relying on this demand prospect, one may suggest expanding the more flexible plant to increase the reserved capacity, and reduce overutilisation level on other plants. However, redesigning load-planning over the long-term scope, the model has been tested in this case against this idea. Based on this problem brief, figure 5-35 represents the ICOM structure for this case.

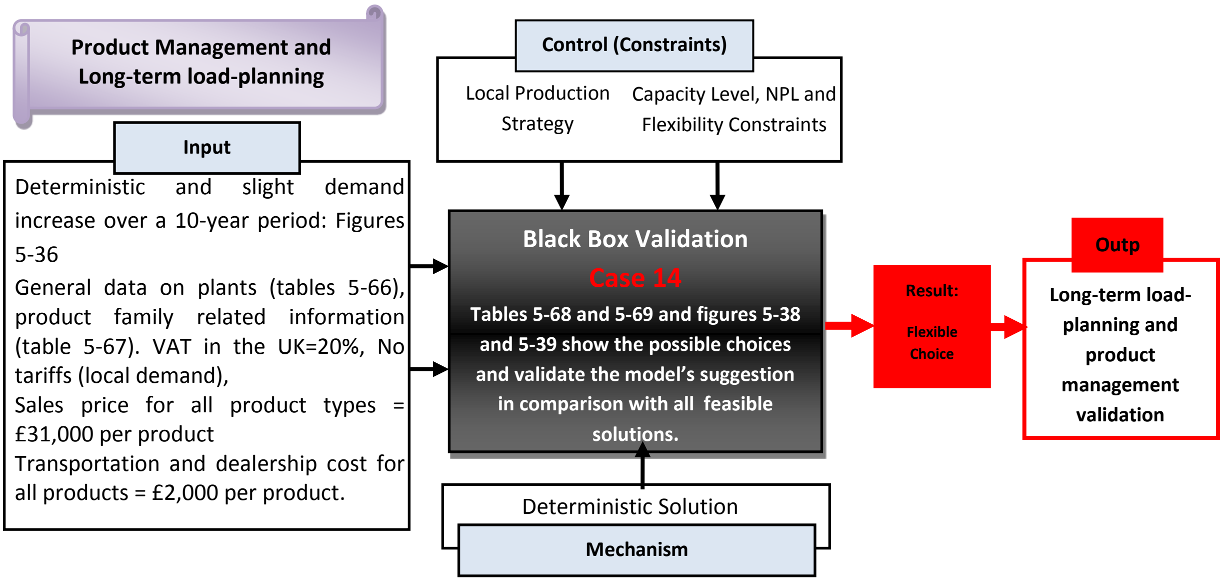


Figure 5-35: ICOM framework for case 14 of the validation plan

Input data: Table 5-66 is set to reflect some information on the operations cost of the plants as well as expansion investment, which provides us with the required information for the decision.

Table 5-66: Investment and operations data on the four current plants in case 14

	Plant Loc.	Maximum Capacity (*1,000)	Maximum normal capacity rate	Annual Operations cost (£M)	Annual normal Work force Cost (£M)	Overutilisation		Expansion			
						Extra work force costs (M£)	Extra opera-tions cost (M£)	Expansion rate	Expansion Capital Investment (M£)	Extra work force (M£)	Extra operations cost (M£)
Plant 1	UK	300	0.9	150	130	13	15	0.3	100	33	38
Plant 2	UK	200	0.9	110	90	9	11	0.3	50	23	28
Plant 3	UK	100	0.7	70	60	6	7	0.3	15	15	18
Plant 4	UK	100	0.7	70	60	6	7	0.3	15	15	18

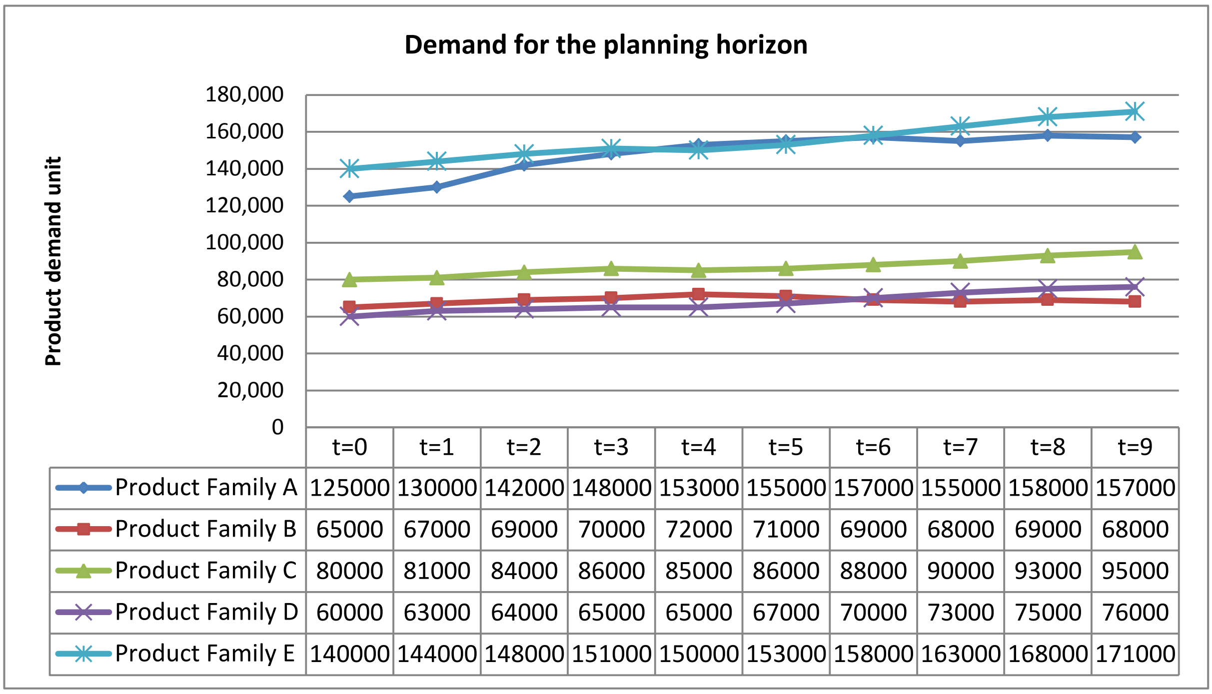
Table 5-67, on the other hand, explains how the products can be fit into different plants and how efficient the plants are to produce these products. This table shows that products A, B and E, which are already being produced in plant 1, do not cause any extra cost for launching, if the decision was taken to continue their production in this plant. However, according to section 5-5, producing these products in this flexible plant is a bit more expensive than making them in dedicated plants. For example, producing products B would cost £200 more per unit in plant 1 than in plant 3. The same is true for plant 2, with a rate of £100 per unit for products C and D, in comparison with plants 3 and 4, respectively.

Moreover, to launch the alternative products in the dedicated plants 3 and 4, according to table 5-67, a five million pound investment is required to change the production line and set up the products.

Table 5-67: Investment and operations data on the four current plants in case 14

		Plant 1	Plant 2	Plant 3	Plant 4
Product Family A	Capacity Coefficient	1	-	-	-
	NPL Cost (£M)	0	-	-	-
	Material Supply Cost (£M)	£17,000	-	-	-
	Any Unit Cost of production (£M)	0	-	-	-
	R&D Cost of NPD (£M)	0			
Product Family B	Capacity Coefficient	1	-	1	-
	NPL Cost (£M)	0	-	£5M	-
	Material Supply Cost (£M)	£17,000	-	£17,000	-
	Any Unit Cost of production (£M)	200	-	0	-
	R&D Cost of NPD (£M)	0			
Product Family C	Capacity Coefficient	-	1	1	-
	NPL Cost (£M)	-	£0	£0	-
	Material Supply Cost (£M)	-	£17,000	£17,000	-
	Any Unit Cost of production (£M)	-	100	0	-
	R&D Cost of NPD (£M)	0			
Product Family D	Capacity Coefficient	-	1	-	1
	NPL Cost (£M)	-	£0	-	£5M
	Material Supply Cost (£M)	-	£17,000	-	£17,000
	Any Unit Cost of production (£M)	-	100	-	0
	R&D Cost of NPD (£M)	0			
Product Family E	Capacity Coefficient	1	-	-	1
	NPL Cost (£M)	0	-	-	£0
	Material Supply Cost (£M)	£17,000	-	-	£17,000
	Any Unit Cost of production (£M)	200	-	-	0
	R&D Cost of NPD (£M)	0			

The demand change for the products is highlighted in figure 5-36. This figure shows that a slight demand increase is set for almost all products and products A and E are the main products for the company with an almost double demand size over products B, C and D.



	t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9
◆ Product Family A	125000	130000	142000	148000	153000	155000	157000	155000	158000	157000
■ Product Family B	65000	67000	69000	70000	72000	71000	69000	68000	69000	68000
▲ Product Family C	80000	81000	84000	86000	85000	86000	88000	90000	93000	95000
× Product Family D	60000	63000	64000	65000	65000	67000	70000	73000	75000	76000
✳ Product Family E	140000	144000	148000	151000	150000	153000	158000	163000	168000	171000

Figure 5-36: Demand prospect for all product families within the time scope of case 14

Since the long-term demand is promising, especially for product family A and E, decision makers of this hypothetical company may suggest expanding flexible plant 1. To support this suggestion, considering the growing prospect for the market and possible needs to expansion, one may emphasise on all the advantages of the company's most flexible plant. Having this expansion done, it can also be said that the company will have reserve capacity which means less overutilisation cost and more reduced operations cost.

Having has this hypothetical solution, and based on the demand details in figure 5-23, one may plan the strategic load-planning like what is shown in figure 5-24 for each plant. Except for Plant 4, which will be utilised at the highest normal capacity, all other plants (including plant 1 after an expansion) will enjoy normal utilisation and sparing a reserved capacity, as shown in figure 5-37.

Now the aim of this case study is to evaluate this suggestion, which brings us validation on product management and load-planning.

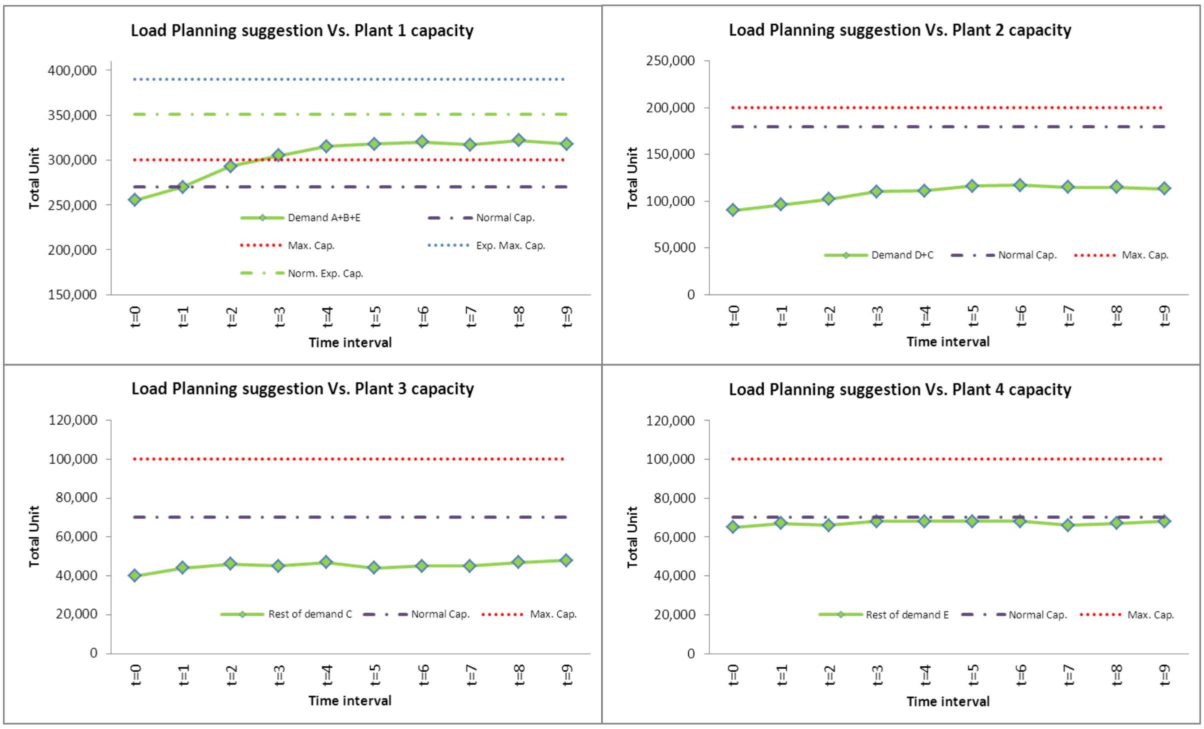


Figure 5-37: Strategic load-planning, which is suggested by the company in case 14

Case Result and analysis: Setting the model's database, using tables 5-66 and 5-67, and assuming the same sales price of £31,000 per unit for all product families as well as £2,000 per unit for transportation, warehouse and dealership costs, the model has been run and results have been generated. The model surprisingly suggests closing Plant 3 and shifting the production of product family C to flexible plant 2 in maximising the utilisation level of the plant. This suggestion is summarised in figure 5-38. In this suggestion, while plant 2 will be underutilised, Plant 1 will be expanded and plant 4 will be planned to work in the normal zone close to the overutilisation limit.

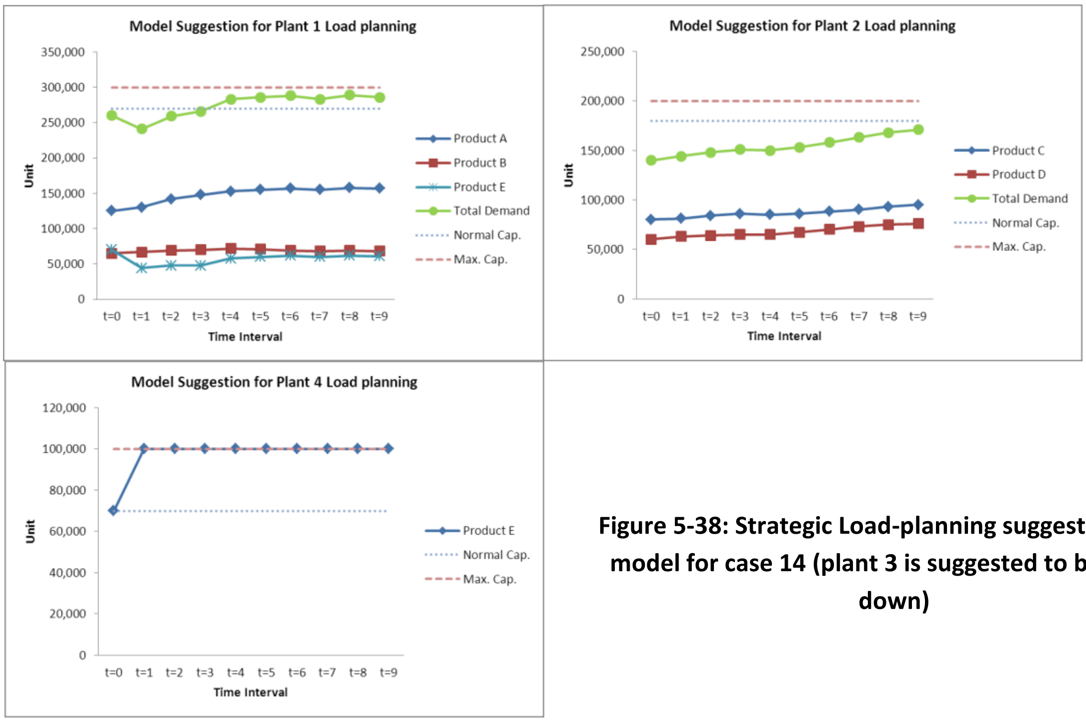


Figure 5-38: Strategic Load-planning suggested by the model for case 14 (plant 3 is suggested to be closed down)

Closing Plant 3 and increasing the other plants' utilisation level has been recognised as the optimal solution by the model whilst 40 Million pound was equally assumed as the shutdown cost for all plants. In other words, the model suggests that even expending £40M on capacity closure as well as an overutilisation cost of 2 other plants will still generate more profit within the scope of this planning, than having 4 normally and under-normally utilised plants. To support or reject this result, the differences of these two suggestions in terms of total cost should be analysed. Table 5-68 highlights these differences and supports the model's suggestion.

Table 5-68: Total differences between two suggestions, which validate the model's results in case 14

Company's Suggestion (hypothetical)	Expansion Fixed Cost (M£)	Expansion Operation*9 years (M£)	Expansion Work force Cost*9years (M£)	Plant 3 Operations cost *10 years (M£)	Plant 3 Work force Cost *10 years (M£)	Total extra cost of production B&E in plant1 (m£)	Total extra cost of production C&D in plant2 (m£)	**Total cost (M£)**	**Difference between Two suggestions (M£)**
	100	338	292.5	700	600	310.6	108.5	**2449.1**	
Model's Suggestion	Plant 3 closure cost (M£)	Plant1 Overutilisation costs *6y (M£)	Plant1 Overutilisation work force* 6y (M£)	Plant4 Overutilisation costs *9y (M£)	Plant4 Overutilisation work force* 9y (M£)	Total extra cost of production B&E in plant1 (m£)	Total extra cost of production C&D in plant2 (m£)	**Total cost (M£)**	**£1,717**
	40	90	78	63	54	252.2	154.6	**731.8**	

Now, what if capacity shutdown or mothball is not desirable for the company due to brand image or labour union considerations? In this new problem statement, increasing the total cost of closedown to a high value, the model is constrained in order to keep the plants open. Adding this constraint to the abovementioned data and running the case, a new load-planning has been suggested by the model, to keep all plants open and underutilised, but not expanded. Figure 5-39 shows this new strategic load-planning, for this case. This figure shows how the model has rearranged load-planning to launch product B in the dedicated Plant 3, instead of product C, in order to avoid expanding plant 1 and to keep all plants as busy as possible without any unnecessary overutilisation planning.

Table 5-69 compares the financial figures of this decision with the first suggestion's figure. This table implies that even the second and sub-optimal solution from the model, which was constrained to no capacity closure, is highly superior to the hypothetical suggestion raised from non-optimised qualitative discussion in the case.

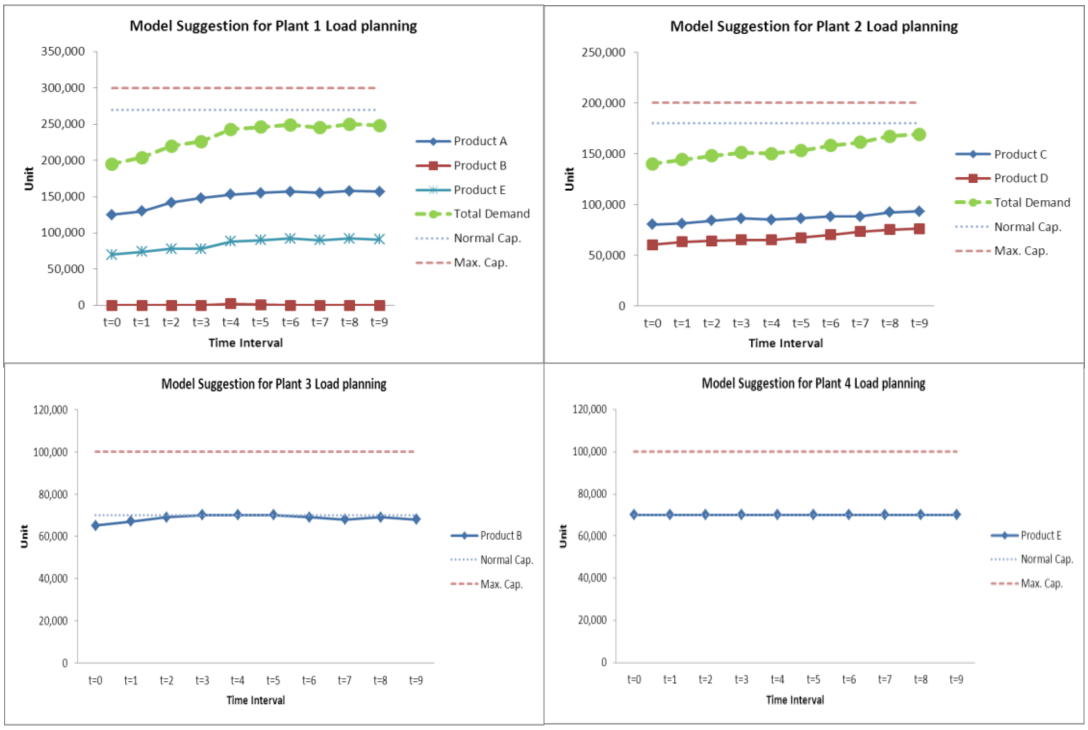


Figure 5-39: No capacity closure constraint which leads to sub-optimal strategic Load-planning in case 14

Table 5-69: Total differences between the company's suggestion and the sub-optimal solution from the model in case 14

Company's Suggestion	Expansion Fixed Cost (M£)	Expansion Operation *9years (M£)	Expansion Work force Cost*9years (M£)	Total extra cost of production B&E in plant1 (m£)	Total extra cost of production C&D in plant2 (m£)	**Total cost (M£)**	**Difference between 2 suggestions (M£)**
	100	338	292.5	310.6	108.5	**1149.1**	
Model's second Suggestion	NPL cost of Product B to Plant 3 (M£)	Total extra cost of production B&E in plant1 (m£)		Total extra cost of production C&D in plant2 (m£)		**Total cost (M£)**	**£821**
	£5	169.2		154.1		**£328**	

A comparison between tables 5-68 and 5-69 highlights that, although the second (sub-optimal) solution of the model is still superior to the early-mentioned hypothetical suggestion, the optimal solution, which suggest closing one of the plants, causes more than two times savings over the sub-optimal one.

Chapter 6 : **Case Studies in the Automotive Industry**

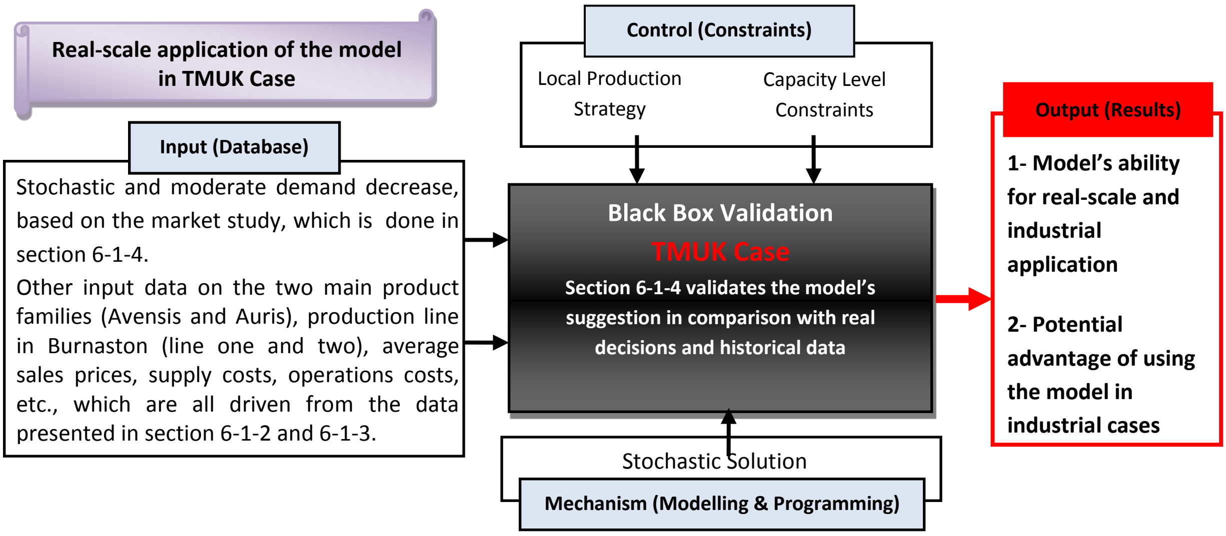
Employing the model in real-scale problems, in this chapter, two cases from the automotive industry with publicly released data will be analysed to demonstrate the ability and applicability of the model in industrial practice.

6-1- The Case of TOYOTA UK

6-1-1- Case Brief

Having two assembly lines in Burnaston, Toyota UK (TMUK), with a maximum capacity of 285,000 vehicles per year, is one of the top 5 car manufacturers in Britain (Bekker 2010). However, following the recent global recession, TMUK firstly scaled down its second production line in Burnaston and then mothballed this line by the end of 2010 (Lea 2010). Stating that having one fully utilised production line is much more feasible than having two underutilised assembly lines, TMUK supported its mothballing policy (Bawden, Lewis 2010), despite no labour lay-off happening at the time.

In this case, a set of input data is identified for the model, reviewing all the facts, publicly released data and financial figures of the company. To simulate the same decision atmosphere for that time in order to generate scenario sets, all market status and facts at the beginning of 2010 will be reviewed in this case, as these were available to the TMUK decision makers at the time they made their decision. No data released at a later point in time, therefore, will be employed. Based on the figures at the beginning of 2010, the market prospect and different scenarios for 2010 onward will be generated in this case to place in the model as the ‘future’. Then the model will be run for the case and the results will be analysed and compared. Figure 6-1 develops the ICOM (Input, output, control, mechanism) framework for this case and summarises the modelling approach.



Stochastic and moderate demand decrease, based on the market study, which is done in section 6-1-4.

Other input data on the two main product families (Avensis and Auris), production line in Burnaston (line one and two), average sales prices, supply costs, operations costs, etc., which are all driven from the data presented in section 6-1-2 and 6-1-3.

Section 6-1-4 validates the model’s suggestion in comparison with real decisions and historical data

1- Model’s ability for real-scale and industrial application

2- Potential advantage of using the model in industrial cases

Figure 6-1: ICOM framework for the Toyota UK case

6-1-2- Case Background

Toyota Motors has got 4 manufacturing sites in Europe, including the UK (TMUK), France (TMMF), Turkey (TMMT), and most recently its joint venture site in the Czech Republic (TPCA). The total production of these plants from 1997 to 2009 is shown in diagram 6-2 (Toyota Motor Annual Report 2010), which shows a dramatic production decrease in almost all European production sites during the time of the recession, after 2008.

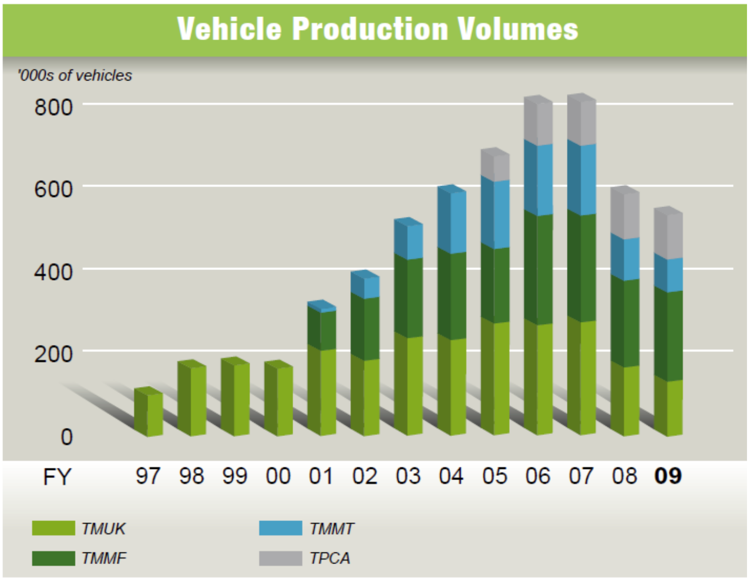


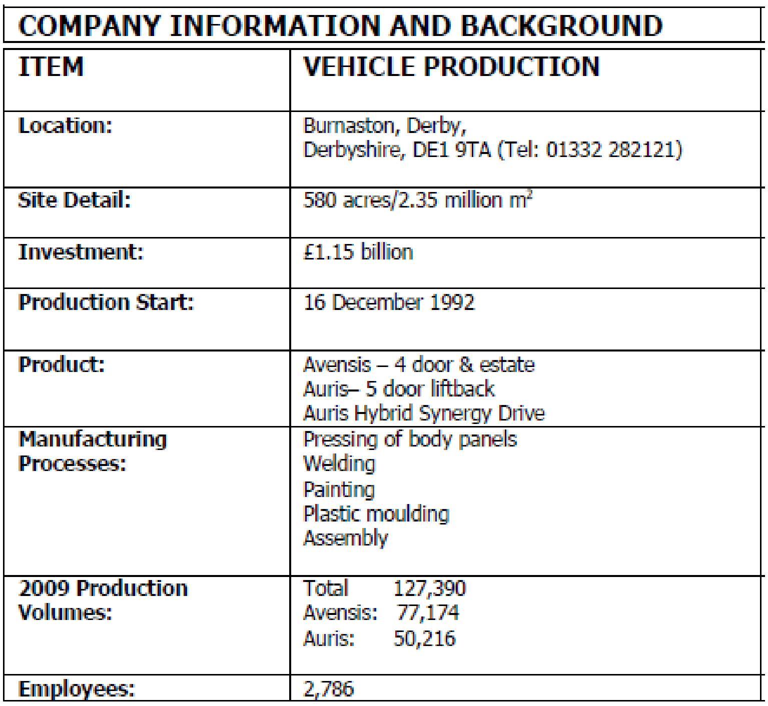
Figure 6-2: Toyota's plants in Europe and their production from 1997 to 2009

Source: (Toyota Motor Annual Report 2010)

Toyota Motor UK Manufacturing Ltd (TMUK), with its headquarters in Derby, UK, was established in December 1989. TMUK has two manufacturing plants in the UK with a total investment in excess of £1.7 billion and currently around 3,000 employees. The vehicle manufacturing plant is located at Burnaston in Derbyshire and the engine manufacturing plant is located at Deeside in North Wales. The first car, the Carina E, drove off the Burnaston production line on December 16, 1992. The Avensis replaced the Carina E in 1997 and in 2003 the new generation Avensis was launched. In 1998 the second model, the Corolla, was launched in the line and in 2001 the new generation of the Corolla family was introduced. The processes at Burnaston include stamping, welding, painting, plastic mouldings and assembly, and in Deeside machining, assembly and aluminium casting is taking place (FAME Database 2010c). Table 6-1 reveals more detailed information about this plant (Toyota Press July 2010). Having two separate assembly lines, the Burnaston plant with an annual production capacity of 285,000 vehicles manufactures the Auris and Avensis models for the European market. The Avensis is also exported to Japan.

Just over 3 million vehicles have been made since production at the plant began in 1992 (Toyota Motor Annual Report 2010). With a total of two million new passenger cars manufactured in the UK in 2009, TMUK, with 127,390 cars, was fourth in rank after Ford, Vauxhall and Volkswagen, and held more than 5% of the total market share in the UK, while it was ranked 6th in 2008 (Bekker 2010).

Table 6-1: TMUK assembly line information and background



COMPANY INFORMATION AND BACKGROUND	
ITEM	**VEHICLE PRODUCTION**
Location:	Burnaston, Derby, Derbyshire, DE1 9TA (Tel: 01332 282121)
Site Detail:	580 acres/2.35 million m^2
Investment:	£1.15 billion
Production Start:	16 December 1992
Product:	Avensis – 4 door & estate Auris– 5 door liftback Auris Hybrid Synergy Drive
Manufacturing Processes:	Pressing of body panels Welding Painting Plastic moulding Assembly
2009 Production Volumes:	Total 127,390 Avensis: 77,174 Auris: 50,216
Employees:	2,786

Source: (Toyota Motor Annual Report 2010)

However, financial information of TMUK in the FAME Database reveals the impact of the recent recession on the financial situation of the company, which is highlighted in diagram 6-3. It shows that after the recession in 2008, TMUK lost almost £1 Billion in annual sales, which dropped from £2.774 billion in 2007 to £1.82 billion in 2009 (FAME Database 2010c).

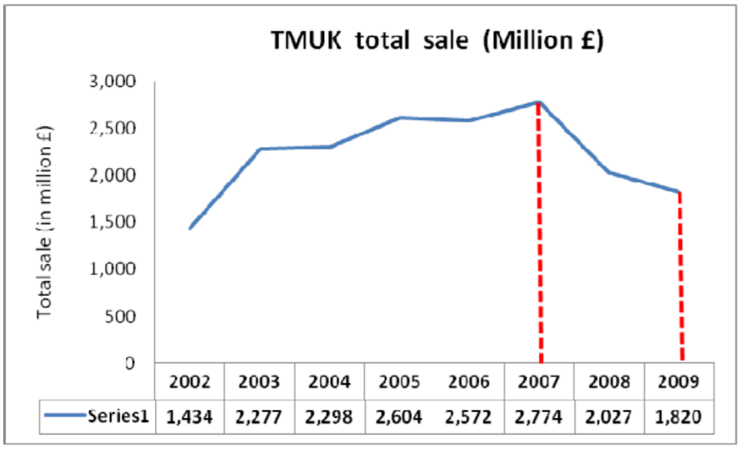


Figure 6-3: Total sales of TMUK in million £, from 2002 to 2009

Due to this dramatic fall in demand and, subsequently, in production, TMUK announced a net loss of £199 million and £80 million in 2008 and 2009 respectively, while the company made £14 million net profit in 2007 (FAME Database 2010). Therefore, dictated by the mother company, the TMUK Company implemented the strategy of reducing net profit, fixed assets, overheads and shareholder funds to cope with the crisis in 2008 (Toyota Motor Annual Report 2010).

In the first months of 2010, Toyota was faced with another disaster: "safety problems", which caused 58 deaths in the US and forced the company to recall around 8 million passenger cars all over the world, including around 200,000 cars in the UK (The Telegraph 2010).

In September 2010, TMUK scaled down its No2 production line in Burnaston from two shifts to one in order to reduce the overheads and to cope with the demand cut. Later on, although insiders suggested that TMUK in Burnaston could have had both lines open but underutilized, Toyota maintained that having one production line with full-power production is more feasible than two underutilized production lines (Bawden, Lewis 2010). At the end of June 2010, finally, TMUK decided to mothball its second line in Burnaston, which was producing only the Auris, in order to cut more overheads (Lea 2010). However, TMUK reassured its employees that there would be no redundancies and most of them would be moved to the other production line in Burnaston, until conditions improved (Lewis 2009). These cuts are part of Toyota's plan to get back to profitability by the end of March 2011 (The Telegraph 2010).

6-1-3- Data Collection: Toyota UK Financial Report

In this section, production-related information of TMUK from 2002 to 2009 is extracted from the FAME Database, Toyota annual reports and other publicly released sources of information in order to gather input data for the model.

It should be noted that all the financial data are for the Toyota Motor UK manufacturing Limited company which holds two assembly lines and one engine production site. These two assembly lines, in 2009, employed around 2800 staff, while the engine manufacturing plant had around 500 employees. Since this report is aimed at addressing the assembly line mothball decision while the engine manufacturing site remains unchanged, the input data to the model are adjusted accordingly and some estimations and simplifications have been done, as will explain later.

Extracting the volume production from the Toyota Motor Annual Report (2009) and diagram 6-2, the total sales quantity of TMUK is listed in table 6-2 for a scope of 10 years from 2000 to 2009. This table shows a drastic drop in the TMUK sales after the global recession in 2008.

Table 6-2: TMUK production quantity over a 10-year period since 2000. Data are extracted from Figure 6-2

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
TMUK Car Production (*1,000)	198	211	212	211	245	263	282	275	164	127

Table 6-3 summarises the main features of the company's balance sheet from 2002 to 2009, including total sale, total cost of goods sold, operation expenses and gross and operation profits (FAME Database 2010c). This table, then, helps us to extract the required data for the input database.

Table 6-3: Summary of the balance sheet, including total sale, total costs and profit/loss (in £ Million)

	2002	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Net Sale	*1,434*	*2,277*	*2,298*	*2,604*	*2,572*	*2,774*	*2,027*	*1,820*
Cost of goods sold	*-1,500*	*-2,204*	*-2,205*	*-2,503*	*-2,526*	*-2,738*	*-2,188*	*-1,863*
Gross Profit	*-67*	*73*	*94*	*101*	*46*	*36*	*-161*	*-44*
Operation Expenses	*-33*	*-40*	*-38*	*-39*	*-39*	*-33*	*-31*	*-22*
Operating Profit	*-100*	*33*	*56*	*62*	*6*	*2*	*-192*	*-66*

The cost of goods sold in table 6-3 includes all the costs for producing and selling the product for the company, including material and supply costs, operations costs, maintenance cost, depreciation on facilities, work force costs and marketing cost. In the financial report of the FAME Database, however, the cost of goods sold is divided into some limited subcomponents, which are presented in table 6-4.

Table 6-4: Details of cost of goods sold (in £ million)

	2002	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Cost of goods sold	***1,500***	***2,204***	***2,205***	***2,503***	***2,526***	***2,738***	***2,188***	***1,863***
Total Remuneration	*129.2*	*165.5*	*175.9*	*179.2*	*172.1*	*162.4*	*154.6*	*124.1*
Depreciation	*135.6*	*97.4*	*114.1*	*103*	*115.1*	*115.5*	*106.1*	*87.2*
Operation Expenses	*33.3*	*39.9*	*37.8*	*39.2*	*39.2*	*33.4*	*31.4*	*22*
Other costs	*1,202*	*1,902*	*1,877*	*2,181*	*2,200*	*2,426*	*1,896*	*1,630*

Source: (FAME Database 2010c)

Assuming that the supply cost of materials and sub-assemblies is around 70% of the total sale, table 6-4 can be extended to table 6-5, with more details which can then be used in the model's input database.

Table 6-5: Details of the total annual cost of the company considering supply costs (in £ million)

	2002	2003	2004	2005	2006	2007	2008	2009
Supply costs (Total)	1,004	1,594	1,609	1,823	1,800	1,942	1,419	1,267
Total Remuneration	129.2	165.5	175.9	179.2	172.1	162.4	154.6	124.1
Depreciation	135.6	97.4	114.1	103	115.1	115.5	106.1	87.2
Operation Expenses	33.3	39.9	37.8	39.2	39.2	33.4	31.4	22
Other costs of operations	198.8	307.6	267.8	358.4	399.7	484.8	476.9	363

Finally, sales volume (or demand) is another input data in the model. Considering table 6-2 and applying the last 3 years' details, diagram 6-4 shows the production quantity for the company from 2002 to 2009.

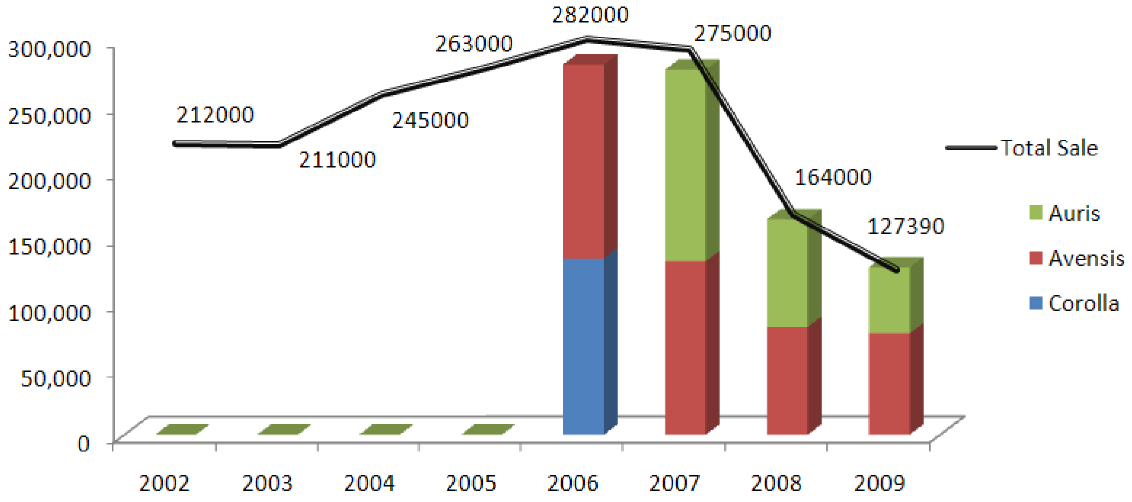


Figure 6-4: The production details of TMUK from 2002 to 2009

6-1-4- Scenario Definition

As mentioned earlier, since the mothball decision was taken in early 2010, in this case, no actual data and available information from 2010 to 2012 has been used to design the scenarios. In other words, in this section the facts and figures which were available to decision makers by early 2010, are highlighted to outline the possible scenarios.

Facts for 2010: Despite a rapid appreciation of Yen and a recall of 11 million cars, primarily in the US market, Toyota has not stopped on its way back to profitability. A substantial cost reductions plan which was introduced in 2009 was expected to save ¥470bn in Toyota's fixed costs in 2010. The Japanese carmaker estimated vehicle sales of 7.24m automobiles in the year 2010 (Ruddick 2010), while the forecast was 6.98m in the year 2009 (Toyota Press 2010). The estimation for Europe, however, expects a 19.2% decline in sales to 858 thousand units and Toyota's total production in the EU was expected to decline by 10.2%, to 433 thousand units in 2010 (Toyota Motor Corporation 2010). Figure 6-5 shows Toyota's sales and production records in the EU by 2010, and the estimations for 2010, when the mothball decision was taken.

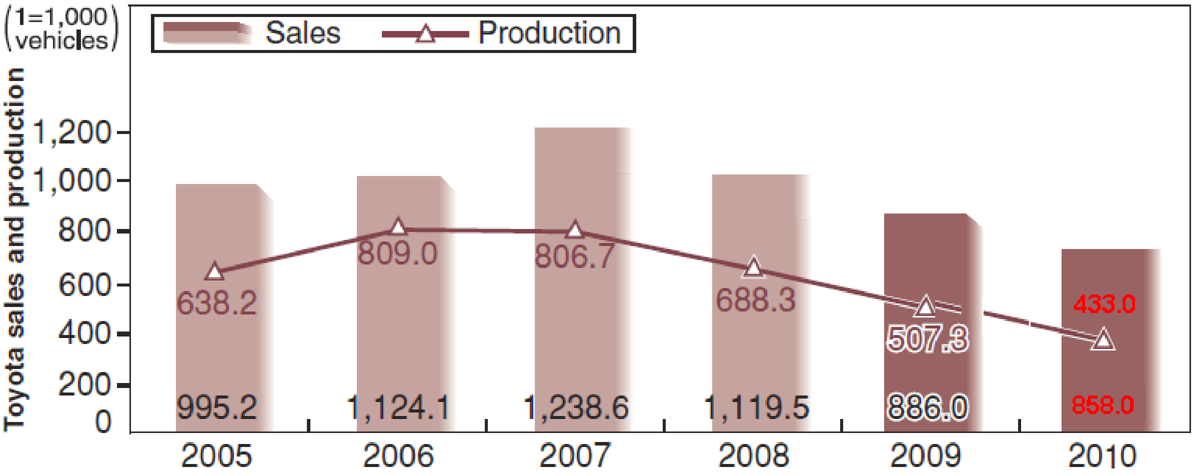


Figure 6-5: The changes in Toyota production and sales in the EU

On the other hand, TMUK planned to launch the Auris hybrid in the Burnaston production line in the first months of 2010. This car was the Toyota's first fully hybrid car in the EU. The Auris Hybrid was planned to be assembled in Burnaston alongside Toyota's Avensis. There were, however, 149 new processes, 395 new parts, 28 new pieces of production machinery and modifications to a further 40 machines and tools. It was an indication of the plant's efficiency and excellent logistics system that the hybrid were expected to take just 6.6 more minutes to build than the conventional Auris (English 2010). Burnaston has a capacity to produce a maximum of 40,000 Auris hybrids a year and by 2020 Toyota is aiming to produce a hybrid version of each one of its conventional cars (English 2010). TMUK aimed to produce 30,000 Auris hybrids for the EU market in 2010 (Roberts 2010).

Facts for 2011: Toyota's first forecast for fiscal year 2011 (ending March 31, 2011) were a vehicle sales of 7.29 million units (Toyota Motor Corporation 2010). However, due to recession recovery signs by early 2010, Toyota revised its sales forecast to 7.41m units for 2011. (Costea 2010).

Despite a slightly better prospect for Toyota's global sales in 2011, Toyota cut its sales target in Europe for this year (irishtimes 2010). Moreover, the executive vice president of the Toyota

Company, Ozawa, admitted: “We currently find ourselves in a very tough business environment, characterized by the radically and seriously appreciated Yen in recent months, the risk of slowdown in demand recovery in the United States and Europe and falling demand following the end of the eco-car subsidies in Japan. Nevertheless, we will do our utmost in order to deliver as many vehicles as possible to our customers while continuing to improve our profit structure through further fixed cost and variable cost reduction activities.” (Costea 2010).

Having done by the Society of Motor Manufacturers and Trades (SMMT), UK-made passenger cars’ forecast for 2010 was estimated at 2.026 million units. This was a sign for 1.5% sales increase compared to 2009’s figures, which was mostly down to the scrappage scheme in the UK in 2010. Finishing this scheme in 2011, SMMT’s 2011 forecast was estimated at 1.928 million units, which is 4.8% lower than the 2010’s forecasts (SMMT Oct 2010).

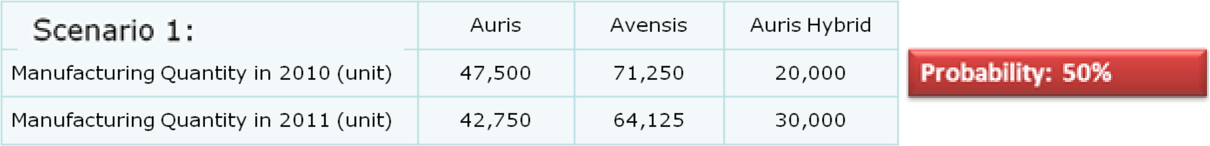
To sum up, although general worldwide sales for Toyota in 2010 was better than its sales in 2009, manufacturing and sales in Europe were expected to slightly decrease. Even launching the Auris hybrid in TMUK did not seem to boost manufacturing here in Europe. For 2011, despite a prospect of moderate increase in worldwide sales for Toyota, sales in the EU and manufacturing in TMUK was expected to experience a decrease of around 5% (SMMT Oct 2010).

Therefore, in accordance with the abovementioned facts and figures, we consider the following 3 possible scenarios for TMUK, comprising demand decrease and increase as well as stationary demand, with different possibilities.

Scenario 1: Demand Decrease

This scenario, which is the most likely scenario for the short-term production in TMUK, is highly supported by the facts mentioned in the last section. In this scenario, we presume the 20,000 and 30,000 units of their target for the Auris hybrid in 2010 and 2011 will be realised. Since production of the Auris hybrid is taking almost the same production time (English 2010), and the NPD cost is already invested, we assume no more production launch and development costs would be incurred by the company. For other conventional products (Auris and Avensis) a 5% reduction in 2010, followed by another 10% production reduction in 2011 is assumed in this scenario. In total, a slight increase in production volume is supposed for 2010, in comparison with 2009, due to the Scrappage Scheme. A short-term fall is, however, expected for 2011 because the scheme will be ceased by the government. Table 6-6 shows the production quantity in this scenario. A probability of 50% is assumed for this scenario.

Table 6-6: Details of scenario 3 for demand decrease



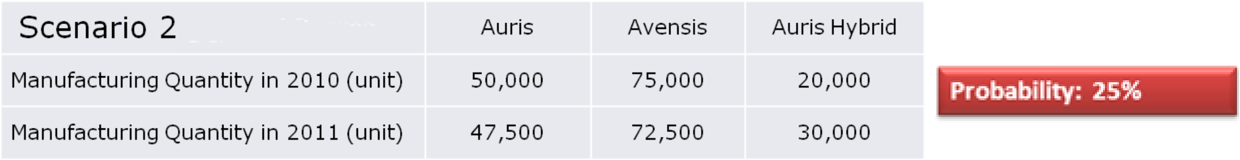
Scenario 1:	Auris	Avensis	Auris Hybrid
Manufacturing Quantity in 2010 (unit)	47,500	71,250	20,000
Manufacturing Quantity in 2011 (unit)	42,750	64,125	30,000

Probability: 50%

Scenario 2: Fairly Stable Demand

In the second scenario, we assume a 20,000 and 30,000 Auris hybrid production for 2010 and 2011, respectively. In 2010, we suppose that apart from the Auris hybrid, TMUK holds its sales features of 2009 for its two other products: the conventional Auris and Avensis. In 2011, however, these two products will experience a 5% decrease. The total demand, on the other hand, remains fairly stable, as shown in table 6-7. The probability of this scenario is estimated at 25%, as mentioned earlier.

Table 6-7: Details of scenario 2 for stable demand



Scenario 2	Auris	Avensis	Auris Hybrid
Manufacturing Quantity in 2010 (unit)	50,000	75,000	20,000
Manufacturing Quantity in 2011 (unit)	47,500	72,500	30,000

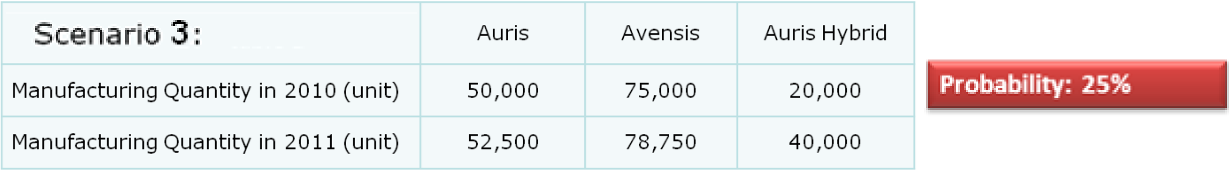
Probability: 25%

Scenario 3: Demand increase

In this scenario, it is assumed that the 20,000 of the target for producing the Auris hybrid in 2010 will be realized in the Burnaston manufacturing line, on top of keeping the same sales of 2009 in 2010. For 2011, we presume that TMUK can realize its entire production capacity for the Auris hybrid, which is 40,000 units, and still achieve an increase of 5% in its other products in TMUK.

The production volume prospect for TMUK in 2010 and 2011 under this scenario is presented in table 6-8. Since Toyota is aiming to cut its target market in Europe in its short-term planning, this scenario is not highly likely. We assume a probability of 25% for this scenario.

Table 6-8: Details of scenario 3 for demand increase



Scenario 3:	Auris	Avensis	Auris Hybrid
Manufacturing Quantity in 2010 (unit)	50,000	75,000	20,000
Manufacturing Quantity in 2011 (unit)	52,500	78,750	40,000

Probability: 25%

6-1-5- Results and Discussion

Employing all input data as well as considering the three abovementioned scenarios and their probability, the model suggests shutting down the second assembly line in Burnaston in 2010, since no market improvement prospect has been applied in the model. However, if the shutdown decision is restricted by the model's user or a back-to-normal situation is assumed for 2012 upward, the model suggests for the second production line to be mothballed in 2010, which is totally in line with the actual TMUK decision (Lea 2010). This decision has been made by the model while 2010 and 2011 are defined as 'future' to the model and therefore no decision can be made for earlier years. In other words, in this case 2010 is the earliest year that the model could take for any strategic decision.

However, if the market forecast would have been used early enough (in late 2008), when the global recession had already started, the decision might have been different. To see the difference in this case, these market figures and forecasts were put into the model to run with no time restriction. In other words, all these years were assumed 'future' in this new run. Mothball in 2009 was, then, suggested by the model, which is a year earlier than the actual decision's time. With reference to table 6-4, such an agile decision could have saved them at least half of the TMUK's operations costs, which means more than £10M in 2009.

This case study shed light on the applicability of the model in a real-scaled industrial case, which may save time, cost and risk of a strategic decision for such a large company. This model can provide the decision makers with an in-depth understanding of the implications of each possible decision as well as a suggestion of the best possible decision in each stage. The model can also be used for explanatory purposes to support the decisions which have been or are being taken.

6-2- The Case of Jaguar Land Rover Investment in China

6-2-1- Case Brief

Having a promising market in China, Jaguar Land Rover (JLR) Company, which is now part of Tata Motors, is aiming to invest in China to expand their market share in this fast-growing market. Establishing a national sales company in China, doubling the number of dealerships in this country, a general agreement to export 40,000 brand new cars in 2011 and finally, their new policy to direct investment towards manufacturing in China represents JLR's new strategy to emerge even more into one of the largest markets in the world.

In this case, their paradigm change from Produce-to-Market to Produce-in-Market will be studied and the application of our model in this strategic decision will be analysed. More specifically, JLR's decision to invest in their first assembly line in China will be evaluated in this case, using the publicly released data as the model's input and comparing the model's output with the company's actual policy. Four different possible strategic choices will be considered in this case: 1- No assembly line in China (Export-to-market Strategy); 2- Moderate investment on a CKD assembly line in China; 3- High investment on a more equipped CKD assembly line in China; 4- High investment in an assembly line, R&D, and engine centre in China. For each strategic choice three different scenarios for demand prospect and sales price will be discussed and finally the output for each choice will be revealed and compared in section 6-2-4. Following the next section where case background will be introduced, in section 6-2-3 each strategic choice will be introduced and treated as an individual case. An ICOM framework will be developed for them separately. Figure 6-6 summarises this case and highlights the structure of this case as a whole. This figure shows how these individual strategic choices will be compared and a final result will be generated and discussed.

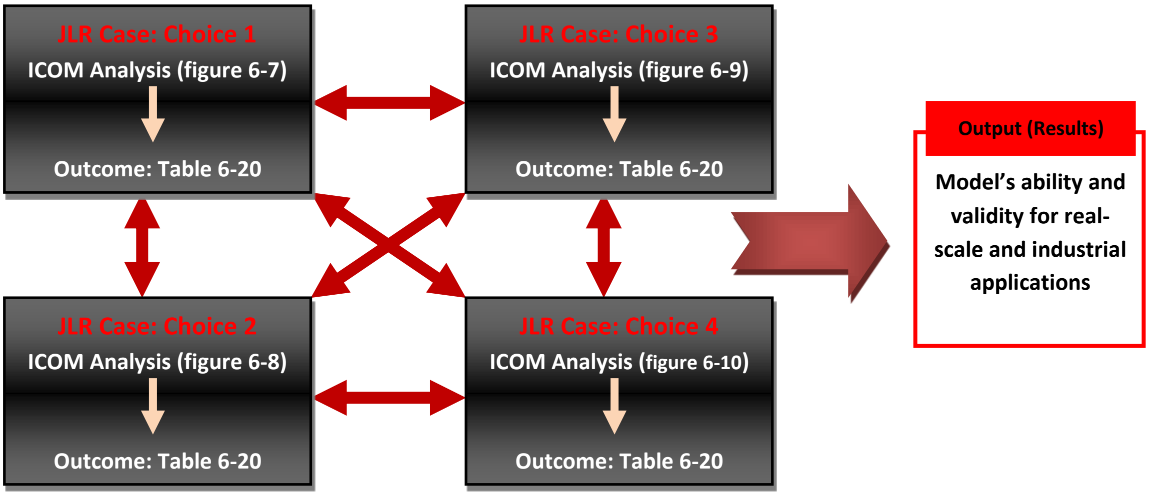


Figure 6-6: JLR case structure and output

6-2-2- Case Background

The Land Rover Company, such as many other car makers, suffered from the recent global crisis. Table 6-9 shows the main financial information of the company from its financial balance sheet (FAME Database 2010a). This table explains how the company lost part of its sales during the recession time. Moreover, table 6-10 indicates that Land Rover Export Limited has also experienced a drop in its total sales during the downturn period (FAME Database 2010b).

Table 6-9: ***Some financial information from the balance sheet of the Land Rover Company***

	31/12/2000	31/12/2001	31/12/2002	31/12/2003	31/12/2004	31/12/2005	31/12/2006	31/12/2007	31/12/2008	31/12/2009	Average
	12 months	12 months	12 months	12 months	12 months	12 months	12 months	12 months	12 months	12 months	**10 years**
	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	**th GBP**
Turnover	1,376,300	2,334,200	3,136,400	3,140,300	3,287,500	4,473,800	4,789,500	5,460,600	4,557,100	3,086,900	3,662,567
Cost of Sales	1,223,500	2,300,100	2,787,500	2,836,200	3,152,100	4,039,800	4,354,600	4,823,000	4,656,700	3,050,900	3,409,833
Remuneration	204,100	381,500	439,700	420,900	457,900	435,700	427,500	361,600	333,100	318,900	392,669
Directors' Remuneration	424	440	284	510	846	587	402	869	749	1,291	670
Administration Expenses	263,400	462,000	524,900	453,400	297,100	561,200	334,000	222,800	201,200	138,700	364,684
Depreciation	50,300	86,900	131,200	130,500	175,600	185,400	173,300	143,100	148,800	193,900	145,493
Total Amortization and Impairment	14,400	22,200	25,800	25,900	25,900	25,800	25,900	26,200	31,800	58,500	29,269
Net Tangible Assets	441,800	240,600	1,341,500	1,396,500	1,356,300	1,585,100	1,923,100	1,025,100	961,500	35,700	1,030,720
Number of Employees	12,713	11,335	11,295	11,263	10,708	10,256	9,375	8,800	7,841	7,362	10,095

Source: (FAME Database 2010a)

Table 6-10: ***Some financial information from the Balance sheet of Land Rover Export LTD***

	31/12/2000	31/12/2001	31/12/2002	31/12/2003	31/12/2004	31/12/2005	31/12/2006	31/12/2007	31/12/2008	31/12/2009	Average
	12 months	12 months	12 months	12 months	12 months	12 months	12 months	12 months	12 months	12 months	**10 years**
	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	th GBP	**th GBP**
Turnover	1,775,700	1,500,700	213,300	2,077,000	2,164,700	3,192,500	3,588,400	4,144,500	3,528,900	2,425,400	2,461,110
Cost of Sales	1,775,700	1,500,700	213,300	2,064,700	2,125,000	3,140,300	3,550,400	3,977,900	3,440,700	2,364,800	2,415,350

Source: (FAME Database 2010b)

However, in 2010 and 2011, with the global recession recovery, the Land Rover Company is also recovering and even expands its market share in the world. The company expects to sell more than 200,000 vehicles in 2011 and to generate 9.7 billion pounds, compared to 6.7 billion pounds in 2010 (Indianexpress 2010). A global investment strategy to grow the market share as well as to launch the new model of Range Rover, Evoque, is considered as the bailout plan for Land Rover. It is expected that Range Rover Evoque will soar JLR sales from 2011 onward (All About Cars 2011).

In 2010, the assembly line of the Land Rover Freelander SUV in the Maharashtra region of India was established and in May 2011 the factory started to assemble two Land Rover SUV models (Car Scoop 2011). Although their production site in India was based on a ‘complete knock down’ (CKD) assembly from their British engine maker in Liverpool, recently media report that JLR is looking into running an engine plant and R&D division in India (Car Scoop 2011).

The main sales regions for Land Rover are the UK, the US, China, Italy and Russia, with respectively 24%, 18%, 13%, 6% and 5% of total Land Rover sales in 2010 (All About Cars 2011). Although Russia has been the fifth market for the Land Rover Company in 2010 and the company has had a plan for investment in this country in a couple of years (Inside Line 2011), the growing market of China has been quite motivating to JLR (Zheng 2010). The Chinese market for Land Rover, which was about 60th in 2003, soared during recent years (All About Cars 2011). Now, it is expected that the Chinese share quickly surpasses the UK and US markets, which have been the traditional markets for Land Rover products (Chinese Car News 2010).

In the first quarter of 2010 Land Rover experienced a 192% sales increase compared to the same period in 2009. Although Land Rover has prospered in the Chinese market, Jaguar’s sales in this market also experienced a 70% rise (Chinese Car News 2010). In 2010 in general, the sales figures for Jaguar in China increased to 2,655 units, while Land Rover’s sales volume was 23,459 units in this market (Schmitt 2011). This is why JLR established a national sales company in China and also planned to double its dealerships in China by the end of 2011 (Pitalwalla 2011). However, due to the high import tariff in China and very high rates of dealerships for imported luxury cars in this country, Land Rover products cost up to three times more in China (Mullen 03/06/2011). The Rang-Rover Evoque, which is a great hope for JLR to soar the total sales of the company, is estimated to cost more than $121,000 in China (Popa 2011) to be imported, while on average it costs £40,000 in the UK.

Taxes on imported automobiles in China comprise custom duties, consumption tax and VAT, which are 25%, 40% and 17% respectively. This explains why these cars are so expensive to the end user in China (PWC 2011). Meanwhile dealers’ profits on imported luxury cars are also extraordinarily high. For example, the ‘Cadillac Escalade 2010-6.0 hybrid’, which costs US$72,500 to US$73,500 in the US, is selling for around US$216,000 in China. The cost of this car after tax and tariff in Chinese ports will be just above US$179,000, which generates more than US$45,000 profit for the dealers. Similarly, the dealer share on the ‘Range Rover 3.6 TDV8’ is more than US$114,000 (WantChinaTimes.com 2011).

Therefore, aside from raising the number of dealers in China and an expanding the export-to-market strategy, in May 2011, the JLR Company announced their produce-in-market strategy in China (Chinese Car News 2010). This investment is part of their $8 billion investment to expand their global production development over the next five years (Inside Line 2011).

This decision to establish the first Land Rover assembly line in China is estimated to cost several hundred million pounds, if an R&D facility is also planned (Pitalwalla 2011). JLR, however, has announced that at this stage an assembly line with a capacity of 50,000 cars per year and £100 million pounds investment has been planned (Zheng 2010). This plant will employ 5,000 staff in China (Indianexpress 2010). The parts and sub-assemblies will be produced in the UK and shipped to China and therefore the assembly line in China will be a CKD line (Chinese Car News 2010). Establishing this line in China, the Tata group has estimated sales of at least 20,000 Land Rovers and 5,000 Jaguars a year, which is half of the plant capacity (Chinese Car News 2010). However, to increase the possible sales in China and to enhance the utilisation level of the future line in China, JLR managed to sign a fresh deal with China to sell 40,000 cars in 2011 to establish a strong market in the country before running their assembly line (Ramanathan 2011). The agreement for this contract was signed by the UK Deputy Prime Minister, Nick Clegg, the JLR Chief Executive, Ralf Speth, and the Chinese Vice-Premier, Li Keqiang, in London in 2011 (Ramanathan 2011).

JLR is planning an investment for a 3-year period with a total capacity of 150,000 cars in this period (Zheng 2010), which will be considered in the next section where the scenarios will be defined.

Therefore, in the next section, considering all abovementioned general information and extracting some more data from publicly released sources, the two different strategies of product-to-market and produce-in-market for the Land Rover Company in the Chinese market will be analysed.

6-2-3- Strategic Choices

Four main strategic choices for the abovementioned problem are presented and explained in this section. For each choice different scenarios will be defined, accordingly. The first choice is the choice for no investment in China on manufacturing, but production in the UK to export to the Chinese market. The second and third choices, however, apply a produce-in-market strategy to invest in a CKD assembly line in China, with different capital investments. Finally, the last choice describes the case of investment in production line, engine plant and domestic suppliers development in order to reduce the supply and operations costs, and therefore, to squeeze the final sales price.

These cases are designed for a typical product, such as the new Range Rover Evoque to be sold in China. Some required data for the model, such as the annual work force and fixed operations cost for the case of production in the UK (choice one) is driven and adapted from Land Rover balance sheets (FAME Database 2010a).

According to JLR's annual report (JLR PLC 2011), the supply cost for JLR is 60-70% of the total revenue. Therefore, the cost of the CKD supply can be calculated for the product, considering the tariff rate of automotive parts (10%) in China (PWC 2011) for choices two and three. This information is reflected in table 6-12, 6-14, 6-17 and 6-19 for all choices.

Strategic Choice One: In this case a product-to-market strategy is adopted. The production will be done in their UK-based plant in Solihull and then export to china will be managed. Therefore, due to very high tax and dealership rates, the final sales price is at its highest rate. Consequently, the sales figures will be moderate to low, compared to other possible choices. Figure 6-7 shows the ICOM structure for this case.

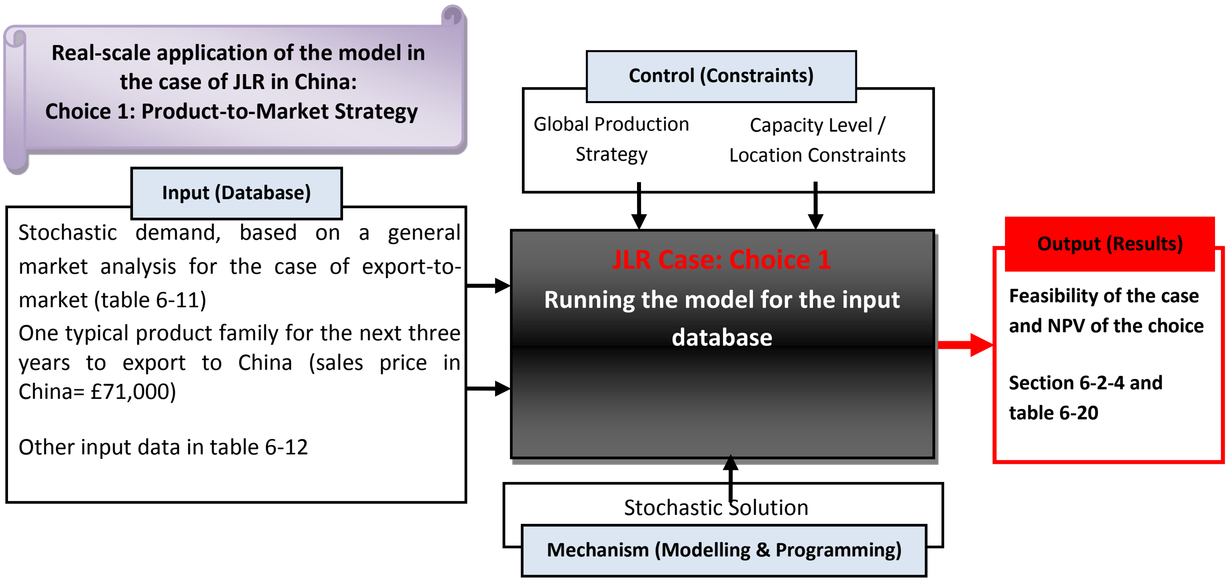


Figure 6-7: ICOM framework for the case of 'JLR in China': Strategic Choice One

Three sales scenarios of worst, best and moderate for this stream are demonstrated in table 6-11.

Table 6-11: ***Different sales scenarios for stream one, where the product-to-market strategy is adapted***

Choice one: Production in the UK and export to China, Sales price= £71,000				
	First Year	**Second Year**	**Third Year**	**Scenario Probability**
Scenario 1	25,000	27,000	30,000	**60%**
Scenario 2	25,000	30,000	35,000	**30%**
Scenario 3	35,000	45,000	50,000	**10%**

For this stream, the input data to the model are demonstrated in table 6-12. Although in this case the production will be done in the JLR plant in the UK, a plant expansion is required to increase the production capacity. The required capital investment for capacity expansion, however, is less than establishing a new plant in China. This required investment is shown in the table, along with other data, which resulted from the abovementioned discussion.

Table 6-12: ***Investment and other required data for stream one to be put into the model***

Profit Tax	VAT	Tariff	Supply Cost	Transportation & Warehouse	Agent Profit	Annual Work force Cost	Annual Operations costs	Other unit-based costs	Capital investment
20%	**25%**	**25%**	**£17,550**	**£10,000**	**£6,000**	**£129,951,000**	**£150,000,000**	**£500**	**£60,000,000**

Strategic Choice Two: In this case a production-in-market strategy will be chosen. The new assembly line in China, with an annual capacity of 50,000 units and a capital investment of £100 million is considered, which required 5,000 new staff in China (Zheng 2010). In this case the pricing strategy is also adjusted considering the fact that investment in China will dramatically reduce tariff and tax rates on the product. The ICOM framework for this case has been developed in figure 6-8.

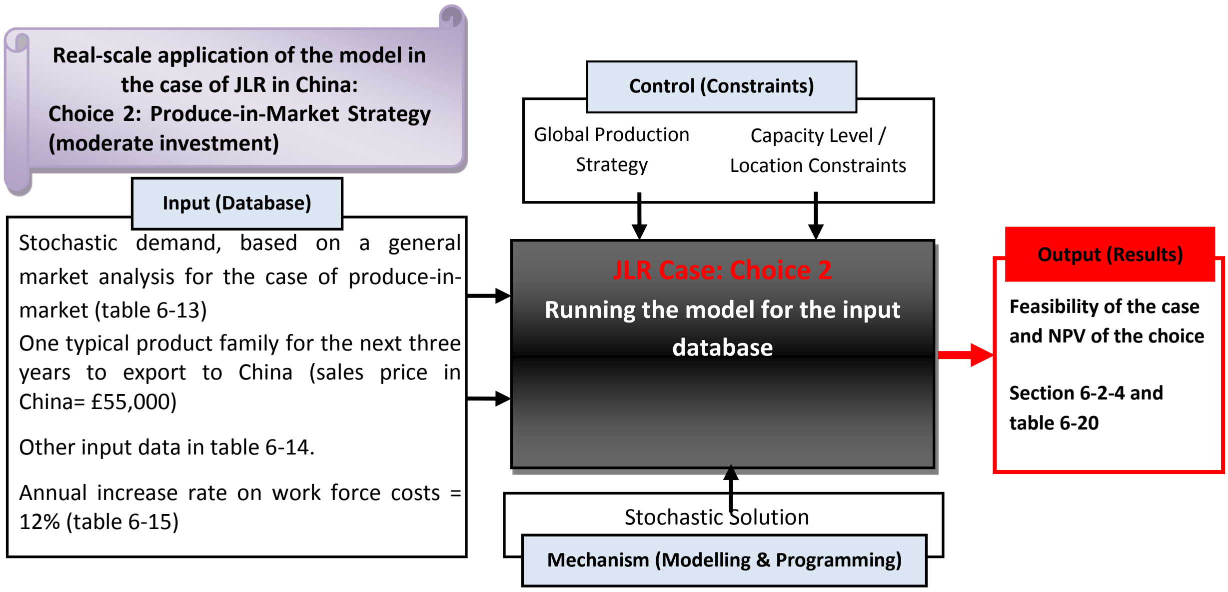


Figure 6-8: ICOM framework for the case of 'JLR in China': Strategic Choice Two

Sales figures and scenario probabilities for this case are shown in table 6-13, which shows a great sales increase due to sales price reduction. The sales price will be reduced, due to a tariff and tax cut and a reduction in operations costs, work force costs and dealers profit, as illustrated in table 6-13. Moreover, establishing the assembly line in China and investing in a national dealership will cause a significant cut in agent profit, which directly applies to the model and reflects in the sales price.

Table 6-13: ***Different sales scenarios for stream two, where the produce-in-market strategy is adapted, with a capital investment of £100 million.***

Stream Two: Production in China, £100 million investment, Sales price= £55,000				
	First Year	**Second Year**	**Third Year**	**Scenario Probability**
Scenario 1	25,000	27,000	30,000	**10%**
Scenario 2	25,000	30,000	35,000	**20%**
Scenario 3	35,000	45,000	50,000	**70%**

In this stream, income tax may be subjected to a governmental incentive for foreign investment. Therefore, two scenarios of tax-free as well as a 20% profit tax are reflected in table 6-14. Although the tariff rate on the cars will be removed due to domestic production, the supply cost of sub-assemblies from the UK will be subject to a 10% tariff as well as transportation, storage and safety stock costs (PWC 2011).

Table 6-14: ***Investment and other required data for stream two to be put into the model***

Profit Tax		**VAT**	**Tariff**	**Supply Cost (CKD)**	**Transportation, Warehouse and Agent Profit**	**Annual Work force Cost**	**Annual Operations costs (£m)**	**Other unit-based costs**	**Capital investment (m£)**
Incentive	**No Incentive**								
0%	**20%**	**25%**	**0**	**£22,815**	**£7,500**	**£60,000,000**	**£100,000,000**	**£500**	**£100,000,000**

The work force cost, moreover, will experience a massive cut, due to the lower salary rate in China. Although the wage rate for factory workers in rural provinces is still less than US$1 per hour (Average Salary Survey 2011), the rate for non-private factories and foreign enterprises is significantly higher (Le 2011). This rate was on average more than 37,000 Yuan in 2010, which meant a 13.5% increase compared to 2009. To be on the safe side in modelling, however, the work force cost in China was considered significantly higher than this average rate, due to the fact that this rate is quite sensitive to the plant location and the rate of required highly skilled workers and engineers. The annual increase rate of work force cost for different years and different categories has been shown in table 6-15. The average increase rate on work force cost will be applied in the model in the form of an inflation rate on labour cost for stream 2, 3 and 4.

Table 6-15: *Earning rates and changes in urban manufacturing units in China*

	2002	2003	2004	2005	2006	2007	2008	Sector Average Increase rate	Total Average Increase rate
All subsectors	¥11,152	¥12,671	¥14,251	¥15,934	¥18,225	¥21,144	¥24,404	**12%**	**12%**
	-	12%	11%	11%	13%	14%	13%		
Ferrous Metal Processing	¥15,032	¥17,989	¥21,074	¥24,030	¥26,999	¥30,786	¥34,482	**13%**	
	-	16%	15%	12%	11%	12%	11%		
Metal Products	¥10,075	¥11,073	¥12,451	¥15,061	¥16,287	¥18,894	¥21,757	**12%**	
	-	9%	11%	17%	8%	14%	13%		
Ordinary Machinery Manufacturing	¥10,668	¥12,777	¥14,549	¥16,628	¥19,332	¥22,845	¥26,284	**14%**	
	-	17%	12%	13%	14%	15%	13%		
Special Purpose Equipment Manufacturing	¥10,406	¥12,040	¥13,985	¥16,228	¥19,103	¥22,232	¥26,394	**14%**	
	-	14%	14%	14%	15%	14%	16%		
Transportation equipment manufacturing	¥14,409	¥16,313	¥18,485	¥20,204	¥22,990	¥26,922	¥31,658	**12%**	
	-	12%	12%	9%	12%	15%	15%		
Electrical equipment and machinery	¥12,405	¥13,435	¥14,797	¥16,438	¥18,533	¥21,141	¥24,769	**11%**	
	-	8%	9%	10%	11%	12%	15%		
Electronics and telecommunications	¥17,636	¥18,922	¥20,428	¥21,213	¥24,119	¥26,934	¥29,915	**8%**	
	-	7%	7%	4%	12%	10%	10%		
Other manufacturing	¥8,781	¥10,049	¥11,334	¥12,789	¥14,392	¥16,479	¥19,017	**12%**	
	-	13%	11%	11%	11%	13%	13%		

Source: adapted from (Banister et al. 2011)

Strategic Choice Three: This choice is basically similar to choice two. However, since some of the references mentioned that JLR may consider several hundred million pounds investment in China (Pitalwalla 2011), in this stream the capital investment is considered moderately higher than in stream two. In this case demand scenarios are exactly the same as in case two, because of the fact that the sales price, tax, tariff and dealers' profit remain the same in this stream. Figure 6-9 demonstrates the ICOM outline for this case, which is fairly similar to the ICOM structure for the second strategic choice.

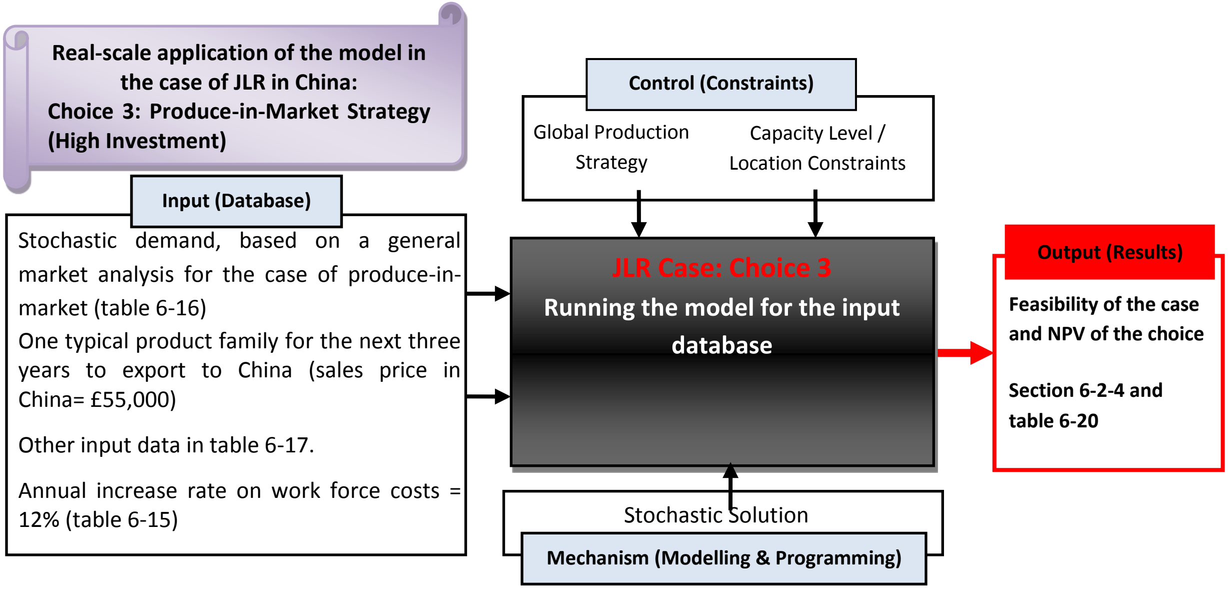


Figure 6-9: ICOM framework for the case of 'JLR in China': Strategic Choice Three

Different sales scenarios in this case are reflected in table 6-16, which are the same as the figures for the previous case, as the sales prices remain the same.

Table 6-16: ***Different sales scenarios for stream three, where the produce-in-market strategy is adapted, with a capital investment of £400 million.***

Stream Three: Production in China, £400 million investment, Sales price= £55,000				
	First Year	**Second Year**	**Third Year**	**Scenario Probability**
Scenario 1	25,000	27,000	30,000	**10%**
Scenario 2	25,000	30,000	35,000	**20%**
Scenario 3	35,000	45,000	50,000	**70%**

Investment figures, tax rates, transportations and dealership costs, supply and other costs of operations are also summarised in table 6-17, which are the main inputs in the model.

Table 6-17: ***Investment and other required data for stream three to be put into the model***

Profit Tax		**VAT**	**Tariff**	**Supply Cost (CKD)**	**Transportation, Warehouse and Agent Profit**	**Annual Work force Cost**	**Annual Operations costs (£m)**	**Other unit-base cost**	**Capital investment (m£)**
Incentive	**No Incentive**								
0%	**20%**	**25%**	**0**	**£22,815**	**£7,500**	**£60,000,000**	**£100,000,000**	**£500**	**£400,000,000**

Strategic Choice Four: In this choice, in addition to an assemble-in-market strategy, local supply is also considered. Therefore, no CKD will happen in the Chinese plant, but supply will be mostly oriented to the Chinese and Asian suppliers. The cost and therefore the final sales price, will be reduced and consequently more sales volume will be expected. The ICOM outline of this case is highlighted in figure 6-10.

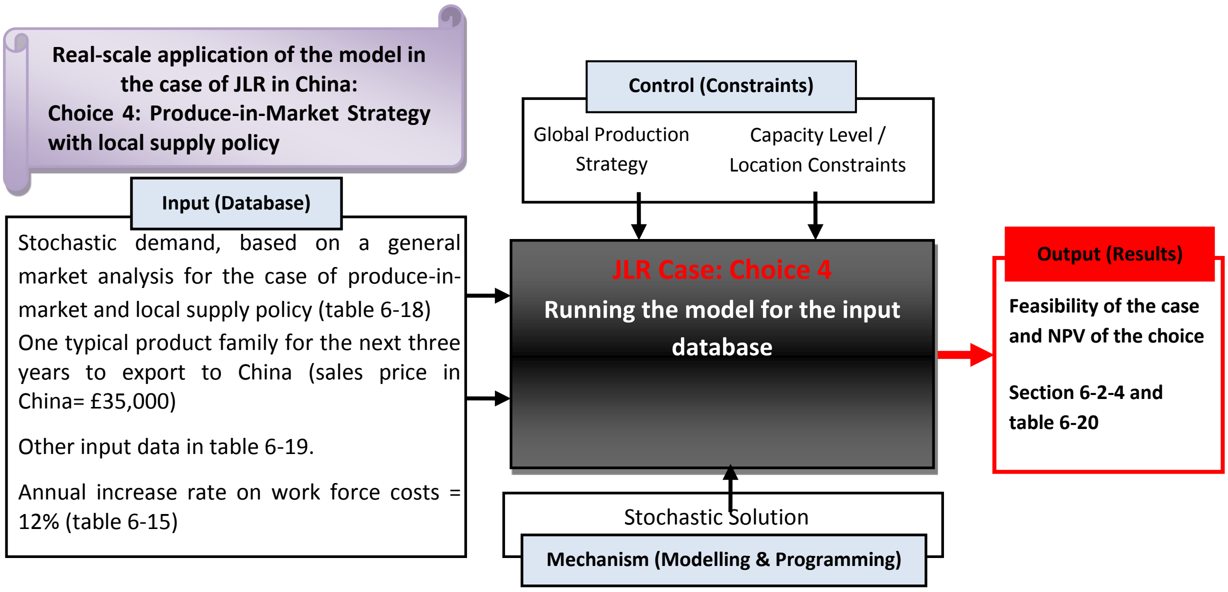


Figure 6-10: ICOM framework for the case of 'JLR in China': Strategic Choice Four

Table 6-18 shows the sales scenarios for this stream.

Table 6-18: ***Different sales scenarios for stream one, where the produce-in-market and supply-from-market strategies are adopted***

Production in China: Case 3: 400 million pound investment, Sales price= £35,000				
	First Year	**Second Year**	**Third Year**	**Scenario Probability**
Scenario 1	25,000	27,000	30,000	**5%**
Scenario 2	25,000	30,000	35,000	**10%**
Scenario 3	40,000	45,000	50,000	**85%**

In this case, the company needs to increase the capital investment in the Chinese plant as well as employing more labour to manage the domestic supply and assemblies. Despite this extra investment, not only will the 10% tariff on supply parts be cut, but also will JLR's and Tata's experience in India show that in this case they can manage to reduce the supply cost by 30-40% (Bailey 2011). At the same time, when the final price of the automotive reduces significantly due to reduction in supply cost, the dealership charge will reduce considerably, as shown in table 6-19.

Table 6-19: ***Investment and other required data for stream four to be put into the model***

Profit Tax		**VAT**	**Tariff**	**Supply Cost (Domestic)**	**Transportation, Warehouse and Agent Profit**	**Annual Work force Cost**	**Annual Operations costs (£m)**	**Other unit-based costs**	**Capital investment (m£)**
Incentive	**No Incentive**								
0%	**20%**	**25%**	**0**	**£10,530**	**£1,750**	**£72,000,000**	**£150,000,000**	**£500**	**£400,000,000**

6-2-4- Results and Discussion

Putting the abovementioned database in the model for a 3-year time scope, results for all strategic choices have been generated by the model, which are summarised in table 6-20.

Tax-free governmental incentives for foreign investment (5 years) are also reflected in this table. This table shows that all choices except choice 3 are feasible and profitable. Although a product-to-market strategy is still feasible, a produce-in-market approach is more profitable. Apart from profit, immersion into such a massive market (China) helps JLR to establish its global premium brand and increase its total revenue, as JLR Chief Executive Ralf Speth said: “The winners and losers in the world automotive industry will be determined by what happens in China,” (Indianexpress 2010).

Table 6-20: ***Model results for different streams, including the investment feasibility and NPV range over a 3-year time scope***

	Feasibility		**NPV over 3 years**	
	No Tax-free Incentives	Tax-free Incentives	No tax-free Incentives	Tax-free Incentives
Stream One	**Yes**		**NPV< £50m**	
Stream Two	**Yes**	**Yes**	**NPV <£350M**	**NPV >£350M**
Stream Three	**No**	**No**	**NPV = NA**	**NPV = NA**
Stream Four	**Yes**	**Yes**	**NPV <£200m**	**NPV >£200M**

However, comparing choice two and three in this table, the JLR decision to invest not more than US$200 million in its assembly line in China (Zheng 2010) is clearly supported.

Moreover, although JLR is considering a domestic supply programme and engine site in China, it does not seem likely for that to be implemented in the near future, which is also explainable by comparing stream 2 and 4 in the above table. Aside from the fact that the Chinese market still accepts the moderate sales price for luxury cars, JLR as a British brand also considers the home country's economic considerations to keep part of its operations in the UK, as Ralf Speth said: "This commitment to sales in China … not only signals the acceleration of our growth plans but also reflects both the importance of the Chinese market to Jaguar Land Rover and our value to the UK economy."(Ramanathan 2011).

This case-study, again, showed how this model is capable of being used for large-scale industrial cases to explore, suggest or support strategic capacity and location-related decisions.

Chapter 7 : Discussion and Conclusion

7-1- Discussion

In this section the novelty, achievements and merits of this research will be discussed, which then leads us to the contributions to knowledge that this study has made. In a search to find metrics to measure how valuable a model is, the 8 essential questions of Khazanchi (1996) appear to be more comprehensive ones to focus on. These questions are about how reasonable, feasible, effective, predictive, empirical and pragmatic the model is and how inter-subjectively and inter-methodologically the model may be explained. These questions will be expanded on and addressed in detail at the end of this section, when this discussion is summarised. However, to address the *effectiveness* of this model, which is about 'potentials of serving the scientific purposes', and the *pragmatic* side of the model, which shows 'the degree of logical self-consistency or coherence with other models in the discipline', it is necessary to conduct an inclusive comparative study, on top of what has been done in the other chapters. Such a comparative study between the model which is developed in this study and other recent analytical studies, furthermore, sheds light on the novelty of this research and its contribution to knowledge.

Therefore, in this section more than 45 new analytical papers, from 2000 to 2012, in the field of capacity management in the manufacturing industries have been selected for thematic analysis and comparison. These papers are those which have made a more significant contribution to the subject. Since the optimisation technique has been employed in this research all the models in this section are among those which have also used this method. The aim of this section is to show how the recent and more successful models have approached this research field and where the strong points and contributions of the model developed by this research are. The results from this comparative and thematic analysis are summarised in tables 7-1, 7-2 and 7-3. While the first table provides more general information on these recent models, table 7-2 and 7-3 highlight more details about the strategic terms in these models as well as the models' features and parameters, respectively. To make the discussion and conclusion easier and more graphical for readers, at the end of these three tables, a yellow highlighted column or row shows the ability of the model which is developed in this research to compare it with the other analytical models in these tables.

Table 7-1 is an abstract which underpins how this field still remains a hot research topic, how these recent modellers set their objective, how they applied uncertainty and risk in their models, how they managed to adjust their models to a manufacturing industry and finally, how they validated their models. This table also provides more details on the methodological approach of these recent models. The main facts and achievements from this comparative study are now listed and explained.

1- ***Research Topic:***

Fact: The extensive publications in highly reputable journals, as demonstrated by the literature review chapter and as summarised in table 7-1, proves the importance of the subject.

Achievement: A strong confirmation on the motivation for this research.

2- ***Model's Objective:***

Fact: Despite developing some multi-objective models, the cost-related objective is still the most dominant objective for optimisation models. Although the net present value (NPV) is the best cost-related objective (according to chapter 2), cost minimisation objectives have received more attention in these optimisation models. The NPV as an objective, however, has received more appreciation in more recent years, as shown in table 7-1.

Achievement: A confirmation on the objective selection for this research.

3- ***Uncertainty:***

Fact: Despite a high emphasis on uncertainty to be applied in capacity management models (which was explained in chapter 2), it has been applied in 63% of the models, while the rest are still deterministic. Multi-stage stochastic programming has received more attention than two-stage stochastic models to implement uncertainty in a long-term scope. In 62% of those papers which have managed to apply uncertainty, only one source of uncertainty has been applied. Demand uncertainty is the objective for more than 70% of the single uncertain-source models and the main objective for more than 80% of the multi uncertain-source models, according to table 7-1.

Achievement: This research has managed to position itself within the category which has employed uncertainty in a multi-stochastic framework. The two sources of demand and sales price uncertainty, which, according to chapter 2, are the main external sources of market instability (LI et al. 2008, Ierapetritou et al. 1996, Li et al. 2004), have been selected to apply to the model formulation.

4- ***Method & Technique:***

Fact: The scenario-based approach has been the most common technique to apply uncertainty in these stochastic models. Finally, table 7-1 indicates that all but five papers have managed to establish a linear model and that the majority of the modellers have employed CPLEX solver to solve the optimisation model.

Achievement: A confirmation of the selected method, technique and solution approach of this research.

Table 7-2 reviews the strategic aspects of these recent models, with reference to the terms which have been highlighted in the literature review. This table provides more detail on concepts such as capacity level management, flexibility and technology management, location/relocation management and product development management, and shows how these recent models have focused on some terms and failed to apply the rest. Similar to what was done above for the first table, the facts and achievements for this table are summarised below to compare the applied strategic terms in the recent models and the model developed in this research:

1- ***Load-Planning:***

Fact: All but 6 models are capable of load-planning the capacity.

Achievement: This ability has been fully implemented in peer researchers' works and has, therefore, been employed in this study.

2- ***Capacity Volume Management:***

Fact: These recent models, according to table 7-2, are more capable of managing a capacity increase than a capacity reduction. In the capacity increase category, still, none of these models are able to simultaneously manage all three empirical practices of overutilisation, capacity expansion, and new capacity establishment. On the other hand, capacity reduction management, which becomes more important in a downturn situation such as the recent recession (Zhang 2007), is widely neglected by the current studies. Underutilisation and capacity shutdown are respectively implemented in just 2 and 7 models, separately. Capacity mothball, which is an empirical solution for a mid-term capacity decline (Green 2006), is considered by none of the current modellers.

Achievement: The yellow highlighted column in table 7-2 shows how the model developed in this research has tackled all types of capacity volume management and addressed this gap.

3- ***Capacity Location & Relocation:***

Fact: In the global location/relocation problem, the location aspect received more attention than the relocation aspect (26% and 7%, respectively), as is shown in table 7-2. Still, the topic of location/relocation needs more attention in capacity management models, since not many models in the table are capable of applying location considerations. As discussed in section 2-3-3 location and relocation issues are linked with the capability of applying financial terms such as tax, tariff, VAT, inflation etc. These terms are reflected in table 7-3 for these recent models and discussed later.

Achievement: In the model developed in this research location and relocation decisions have been addressed, in a limited but more pragmatic way. In location-based decisions, quite often in industries there are not that many choices. Rather, the decision makers of a company are usually faced with very limited preferable locations. Therefore, in this strategic capacity design model, unlike the pure location-selection models, no index for the location level has been employed in the modelling logic in chapter 4 but a few limited possible choices are introduced to the input database by the decision makers to let the model find the best possible choice in balance with other strategic decisions.

4- ***Flexibility and Technology Management:***

Fact: Just below 35% of these modellers have managed to apply the strategic concept of technology selection in their models, according to table 7-2.

Achievement: In the model developed in this research flexibility and technology selection have been addressed. But, like location/relocation aspects, in industries the question of preferable technology is most often limited to very few choices in a limited but more pragmatic way. In our model, these limited choices are supposed to be entered into the database by the model's users, and then the model will offer the best possible option which makes the whole solution optimised. Therefore, in this strategic capacity design model, unlike the pure technology-selection models, no index for the technology or flexibility level has been employed in the modelling logic in chapter 4.

5- ***Product Management:***

Fact: These recent analytical papers have also failed to give enough appreciation to the product development concept, which is one of the most important strategic decisions in resource portfolio design according to section 2-3-4. While only 17% of these papers have managed to apply NPD at least partly in their models, only 11% have succeeded to manipulate the product-mix flexibility and possibility matrix in their models. The setup cost of relaunching a product in a production line after a time of production-break, which may be significant to many industries, was neglected by all reviewed papers.

Achievement: In the model developed in this research all aspects of NPD, comprising R&D and first-time launch costs, as well as product flexibility and relaunch cost were considered, as shown in the yellow highlighted column in table 7-2.

6- ***Capacity HR Management:***

Fact: HR management and shift design, which are more tactical/operational concepts, have received limited attention.

Achievement: As explained in chapter 4, in this model only strategic work force-related decisions have been applied in the model's framework, rather than tactical labour planning and scheduling. These strategic decisions are: full lay-off due to plant shutdown, partial or complete redundancy due to capacity mothball and recruitments in case of new plant establishment or plant expansion.

7- ***Supply Chain Network (SCN) Design:***

Fact: Not many of these recent models (26%) have managed to bring SCN design to their models. Those which could, however, have mainly failed to consider many other terms. In other words, the models with SCN management ability are designed more for this purpose than capacity, location, technology or product management purposes, which is mainly because of the cumbersome size of such a model with all these capabilities.

Achievement: To avoid unmanageable complexity in capacity design modelling, the supply chain selection decision has been ignored in the model development, as shown in table 7-2. However, to avoid the unrealistic simplification of ignoring the supply chain design decision on capacity management, the effect of capacity location on the supply/transportation cost as well as the inflation effect on the supply/transportation cost are all put into the modelling logic, according to chapter 4.

Table 7-3 provides more details on the models' features and parameters, including cost parameters and financial parameters. Following the same discussion pattern as the one used for table 7-1 and 7-2, listed below, the highlights and achievements of this table are discussed.

1- ***Cost Parameters:***

Fact: Production cost, transportation cost, overhead/operations cost and unmet demand penalty have received the greatest attention by the current studies, while other cost parameters such as labour cost, capacity maintenance cost, depreciation cost and material/supply cost are dramatically neglected by many of these works.

Achievement: To make a more inclusive and pragmatic model, all of these cost parameters were employed in the model development practice in chapter 4.

2- ***Financial Parameters:***

Fact: Among all financial parameters only the discount rate received enough attention in these recent models, while, as explained in chapter 2, most of these rates are extremely important in a global capacity management model. Tax, exchange rate, custom duty, VAT and inflation rate have been manipulated in only 6, 3, 2, 2 and 1 of these papers, respectively. It indicates a very high need for more attempts to apply these terms in global capacity management models.

Achievement: To make a more pragmatic model in terms of globally managing the capacity, all of these financial parameters but exchange rate, were employed in the logic formulations and model framework in chapter 4. As explained in chapter 2, on the one hand, the exchange rate without uncertainty is nothing but a fixed rate and therefore useless to be considered in modelling; on the other hand, no universally accepted and long-term approach has been proposed yet to formulate the exchange rate under uncertainty. This is why this rate is neglected in this model development.

3- ***Economies of scale, Capacity lumpiness and budget constraint:***

Fact: Although all three terms have received more attention from modellers (as shown in table 7-3), not all modellers have managed to implement them in their models.

Achievement: The yellow highlighted column of table 7-3 shows that the model developed in this research has addressed all of these three terms in its modelling practice, according to chapter 4.

Comparing table 7-1, 7-2 and 7-3, one can conclude that deterministic models have succeeded in applying more factors and terms in their formulation. Therefore, although these models fail to consider uncertainty and the dynamic nature of the real business, they are more realistic in terms of considering more pragmatic features (Kauder et al. 2009, Hammami et al. 2009, Fleischmann et al. 2006, Melo et al. 2006). Apart from the fact that using stochastic programming in capacity design and planning models in the manufacturing industries is relatively novel (Snyder 2006), the reason behind less applied factors in stochastic models is limitations in the solution algorithms and solution time (Baron et al. 2008), as well as the much simpler structure of the deterministic modelling approach (Hammami et al. 2008),which makes it easier for modellers and developers.

To summarise this comparative study and link it to the gaps, aims, objectives and the scope of this study from chapter 1, we should state that many of the recent studies have tackled the gaps mentioned in chapter 1. However, as revealed from the comparison above, many of those gaps still remained open. More applications of the models in the manufacturing industries have been reported recently, to address gap number 3 in section 1-2 (pragmatic approach) but many of them are deterministic models and not all strategic terms are applied in those models. Stochastic capacity management models in the manufacturing industries, on the other hand, are still basic and novel. However, in the model development in chapter 4, almost all strategic terms which are mentioned for a comprehensive capacity management model have been implemented in a multi-stage scenario-based stochastic framework to maximise the NPV of the whole business in a long-term horizon. This approach addresses gaps number 1, 2, 4 and 5 in chapter 1, section 1-2, which are respectively uncertainty implementation, multi-factor capability, integrated approach and profit-related objective.

Since the final customers of such models are the industries, these models should be more industry-oriented, to address gap number 3 in section 1-2, which is asking for more pragmatic approaches. Therefore, the model has been applied using the case of an actual industry, testing parts of the capacity management factors and as a whole to a real-scale case (chapter 6). This demonstrates that the model is pragmatic and applicable in real cases. Moreover, the following major factors were applied **simultaneously** in an integrated capacity management framework under uncertainty, which, again, makes the model inclusive for a pragmatic decision making practice:

- Capacity increase: In 3 empirical strategies of 1- Overutilisation (utilising flexibility reserved) of current capacities; 2- Current capacity expansion (addition of auxiliary tool or bottleneck analysis); or 3- New capacity establishment, depending on demand scenarios
- Capacity Decrease: In 3 practical strategies of 1- Underutilisation of available capacities; 2- Temporary capacity mothballing for a period of time; or 3- Permanent capacity shutdown in some plants, depending on demand scenarios
- Process technology/flexibility selection: With ability to select the flexibility level of the process (when applicable)

- Product-related features: New product development cost, product launch cost, product flexibility level, product development and launch lead time etc.
- Financial terms and factors: Custom duty (tariff), VAT, profit tax, exchange rate and inflation

Finally, the last gap identified in this PhD in section 2-1 (gap number 6), was about making capacity management models more user-friendly for non-OR specialists. To address this gap, a user-friendly application/software was developed in the Visual Basic environment to create a very simple set of forms for input data, which are also connected to a Microsoft Access file, so that the users can easily create an input database. This application/software also eases running the solver (CPLEX), followed by generating a Microsoft Excel file for the result, which makes the model application extremely easy for all users with any/no OR knowledge.

Table 7-1: General information on selected papers for analytical and thematic analysis

No.	Ref.	Journal / Article / Conference Paper	Application in Practice		Objective(s)	Uncertainty & Risk								Optimisation Software
			Designed for Industry	Validation in Industry / Empirical study		Deterministic or Stochastic			Uncertainty Sources	Uncertainty implementation	Linear / Non-Linear	Risk		
						Deter.	Two-Stage Stoch.	Multi-Stage Stoch.				Risk Avert	Risk factor	
1	(Syam 2000)	Decision Science	-	-	Total Cost	√	-	-	-	-	-	-	-	Their own code
2	(Inman et al. 2001)	Computers & Industrial Engineering	Automotive Industry (GM)	-	Minimise unmet demand & Maximise Utilisation	√	-	-	-	-	Linear	-	-	Their own code
3	(Papageorgiou et al. 2001)	Ind. Eng. Chem. Res.	Pharmaceutical Production	Modified actual database	Net present value	√	-	-	-	-	Linear	-	-	CPLEX
4	(Verter et al. 2002)	European Journal of Operational Research	-	-	Total Cost	√	-	-	-	-	Non-Linear	-	-	CPLEX
5	(Chen et al. 2002)	Computers & Operations Research	-	-	Total Cost	-	-	√	Demand and producing lead time	Scenario tree	Linear	-	-	CPLEX
6	(Hood et al. 2003)	IEEE Transaction on Semiconductor Manufacturing	Electronic Industry / Semiconductors	-	Minimise unmet demand	-	√	-	Demand	Enumerated Scenario	Linear	-	-	OSL (IBM product)
7	(Bhutta et al. 2003)	Int. J. Production Economics	-		Profit maximisation	√	-	-	-	-	Linear	-	-	CPLEX
8	(Gatica et al. 2003)	Chemical Engineering Research and Design	Pharmaceutical Production	-	Net present value	-	√	-	Success of New Products	Scenario tree	Linear	√	Financial Risk	CPLEX
9	(Goel et al. 2004)	Computers & Chemical Engineering	Oil and Gas Industry	-	Net present value	-	-	√	Uncertainty in gas reserves	Scenario tree	Linear	-	-	CPLEX
10	(Chauhan et al. 2004)	International Journal of production research	-	-	Total Cost	√	-	-	-	-	Linear	-	-	OSL (IBM product)
11	(Barahona et al. 2005)	Naval Research Logistics	Electronic Industry / Semiconductors	-	Minimise unmet demand	-	√	-	Demand	Enumerated Scenario	Linear	-	-	CPLEX
12	(Chakravarty 2005)	European Journal of Operational Research	-	-	Profit maximisation, Unit cost estimation	√	-	-	-	-	Linear	-	-	CPLEX
13	(Chandra et al. 2005)	Omega	Automotive Industry (Ford Motor)	Modified actual database	Net present value	-	-	√	Demand	Known Distribution/Mont Carlo	Linear	-	-	RISK Optimizer / LINGO
14	(Stray et al. 2006)	IEEE Transaction on Semiconductor Manufacturing	Electronic Industry / Semiconductors	-	Profit maximisation	√	-	-	-	-	Linear	-	-	Not Mentioned
15	(Melo et al. 2006)	Computers & Operations Research	-	-	Total Cost	√	-	-	-	-	Linear	-	-	CPLEX
16	(Fleischmann et al. 2006)	InterFaces	Automotive Industry (BMW)	Modified actual database	Net present value	√	-	-	-	-	Linear	-	-	CPLEX
17	(Silva Filho et al. 2007)	19th International Conference on Production Research	-	-	Total Cost	-	-	√	Demand	Enumerated Scenario	Linear	-	-	CPLEX
18	(Snyder et al. 2007)	European Journal of Operational Research	-	-	Total Cost, Service Level	-	-	√	Demand and Freight Rate	Scenario tree	Non-Linear	√	Service Level	Their own code
19	(Zhang 2007)	Systems Engineering - Theory & Practice	-	-	Total Cost	-	√	-	Demand, consumption of stochastic capacity	Chance Cons. Prog.	Non-Linear	-	-	CPLEX
20	(KATAYAMA et al. 2007)	19th International Conference on Production Research	Automotive Industry/ A Japanese Tire Company	Modified actual database	Total Cost	√	-	-	-	-	Linear	-	-	Their own code
21	(Ahmed et al. 2008)	European Journal of Operational Research	-	-	Minimise Investment Cost	-	-	√	Demand and capacity cost	Known Distribution/Mont Carlo	Linear	-	-	CPLEX
22	(Nagar et al. 2008)	Supply Chain Management: An International Journal	-	-	Total Cost	-	-	√	Demand	Enumerated Scenario	Linear	-	-	LINGO
23	(Azaron et al. 2008)	Int. J. Production Economics	-	-	Total Cost, Financial Risk	-	√	-	Demand, Supply, Processing, Transp., Capacity	Enumerated Scenario	Non-Linear	√	Financial Risk	LINGO

No.	Ref.	Journal / Article / Conference Paper	Application in Practice		Objective(s)	Uncertainty & Risk								Optimisation Software
			Designed for Industry	Validation in Industry / Empirical study		Deterministic or Stochastic			Uncertainty Sources	Uncertainty implementation	Linear / Non-Linear	Risk		
						Deter.	Two-Stage Stoch.	Multi-Stage Stoch.				Risk Avert	Risk factor	
24	(Hamad et al. 2008)	Networks and Spatial Economics	Chemical-Agribusiness	From General Published Data	Total Cost, Service level	√	-	-	-	-	Linear	-	-	Premium Solver Platform
25	(Dehayem Nodem et al. 2008)	Applied Mathematical Science	Electronic Industry / Semiconductors	-	Total Cost	-	√	-	Maintenance and repair time	Known Distribution	Linear	-	-	Not Mentioned
26	(Naraharisetti et al. 2008)	Computers & Chemical Engineering	Chemical Production	-	Net present value	√	-	-	-	-	Linear	-	-	CPLEX
27	(Tarhan et al. 2008)	Computers & Chemical Engineering	Chemical Production	-	Net present value	-	-	√	Process Yield	Scenario tree	Linear	-	-	LINGO
28	(Francas et al. 2009)	Int. J. Production Economics	Automotive Industry (Daimler-Chrysler)	-	Minimise unmet demand	-	√	-	Demand	Known Distribution	Linear	-	-	Their own code
29	(Karnik et al. 2009)	IEEE annual Conference	-	-	Total Cost	-		√	Demand	Enumerated Scenario	Linear	√	Financial Risk	CPLEX
30	(Wagner et al. 2009)	Computers & Operations Research	-	-	Total Cost, Financial Risk	-	Uncertainty applied by Simulation		Demand	Known Distribution	Non-Linear	√	Financial Risk	Matlab
31	(Hammami et al. 2009)	Int. J. Production Economics	Automotive Industry	Modified actual database	Maximise Profit	√	-	-	-	-	Linear	-	-	CPLEX
32	(You et al. 2009)	AIChE Journal	Chemical Production	-	Total Cost, Financial Risk	-	√	-	Demand and Freight Rate	Enumerated Scenario	Linear	√	Financial Risk	CPLEX
33	(Geng et al. 2009b)	European Journal of Operational Research	Electronic Industry / Semiconductors	From General Published Data	Net Present Value, Flexibility	-	-	√	Demand and Capacity	Scenario tree	Linear	-	-	CPLEX
34	(Kauder et al. 2009)	OR Spectrum	Automotive Industry (BMW)	-	Net present value	√	-	-	-	-	Linear	-	-	CPLEX
35	(Colvin et al. 2009)	Computers & Chemical Engineering	Pharmaceutical Production	-	Net present value	-	-	√	Success of New Products	Scenario tree	Linear	-	-	CPLEX
37	(Bihlmaier et al. 2010)	OR Spectrum	Automotive Industry (Daimler-Chrysler)	From General Published Data	Net Present Value, Flexibility	-	-	√	Demand	Scenario tree	Linear	-	-	CPLEX
39	(Aghezzaf et al. 2010)	Computers & Operations Research	X-Ray and graphical film production	-	Total Cost, Financial Risk	-	√	-	Demand	Known Distribution	Linear	√	Financial Risk	CPLEX
36	(Frausto-Hernandez et al. 2010)	Ind. Eng. Chem. Res.	Chemical Production	-	Net present value	-	√	-	Demand and supply	Known Distribution	Linear	-	-	CPLEX
38	(Naraharisetti et al. 2010)	Chemical Engineering Science	Chemical Production	-	Net present value	√	-	-	-	-	Linear	-	-	CPLEX
40	(Wu et al. 2010)	European Journal of Operational Research	-	From General Published Data	Profit maximisation	-	-	√	Demand, Price and Yield	Known Distribution	Linear	-	-	Their own code
41	(Lin et al. 2010)	Computers & Operations Research	Electronic Industry / Semiconductors	Modified actual database	Net present value	-	√	-	Demand	Scenario tree	Linear	-	-	CPLEX
42	(Durksen et al. 2010)	IEEE annual Conference	Railway vehicle industry	-	Total Cost	√	-	-	-	-	Linear	-	-	CPLEX
43	(Lusa et al. 2011)	Computers & Operations Research	-	-	Expected total cost	-	-	√	Capacity	Scenario tree	Linear	-	-	CPLEX
44	(Dal-Mas et al. 2011)	Biomass and Bio energy	Chemical Production	Modified actual database	Net present value	-	-	√	Row material cost and product price	Enumerated Scenario	Linear	√	Financial Risk	CPLEX
45	(Claro et al. 2012)	Computers & Operations Research	-	-	Total Cost, Financial Risk and Flexibility	-	-	√	Demand	Scenario tree	Linear	√	Financial Risk	CPLEX
46	(Chien et al. 2012)	Int. J. Production Economics	Electronic Industry / Semiconductors	Modified actual database	Total Cost	-	-	√	Demand	Known Distribution/ Markov Chain	Linear	-	-	Not Mentioned
-	**The Model in this Research**	NA	Automotive Industry With ability to expand to some other industries	From General Published Data from JLR and TMUK Companies	Net present value	-	-	√	Demand and sales price	Enumerated Scenario	Linear	-	-	CPLEX

Table 7-2: Strategic concepts of the selected papers for analytical and thematic analysis

			(Syam 2000)	(Inman et al. 2001)	(Papageorgiou et al. 2001)	(Verter et al. 2002)	(Chen et al. 2002)	(Hood et al. 2003)	(Bhutta et al. 2003)	(Gatica et al. 2003)	(Goel et al. 2004)	(Chauhan et al. 2004)	(Barahona et al. 2005)	(Chakravarty 2005)	(Chandra et al. 2005)	(Stray et al. 2006)	(Melo et al. 2006)	(Fleischmann et al. 2006)	(Silva Filho et al. 2007)	(Snyder et al. 2007)	(Zhang 2007)	(KATAYAMA et al. 2007)	(Ahmed et al. 2008)	(Nagar et al. 2008)	(Azaron et al. 2008)	(Hamad et al. 2008)	(Dehayem Nodem et al. 2008)	(Naraharisetti et al. 2008)	(Tarhan et al. 2008)	(Francas et al. 2009)	(Karnik et al. 2009)	(Wagner et al. 2009)	(Hammami et al. 2009)	(You et al. 2009)	(Geng et al. 2009b)	(Kauder et al. 2009)	(Colvin et al. 2009)	(Bihlmaier et al. 2010)	(Aghezzaf et al. 2010)	(Frausto-Hernandez et al. 2010)	(Naraharisetti et al. 2010)	(Wu et al. 2010)	(Lin et al. 2010)	(Durksen et al. 2010)	(Lusa et al. 2011)	(Dal-Mas et al. 2011)	Claro et al.)	(Chien et al. 2012)	**The Model in this Research**
Load / Allocation Planning			√	√	√	√	√	-	√	√	√	√	√	√	√	√	√	√	-	-	√	√	-	√	√	√	√	√	√	-	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	-	√	√	-	√
Capacity Level Mangement.	**Capacity Increase**	**Over-utilisation**	-	√	-	-	-	-	-	-	-	√	-	-	√	-	-	√	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	√	-	-	-	-	-	√	-	-	-	√
		Expansion	√	-	-	-	-	√	√	√	√	-	√	√	√	√	√	√	-	-	-	-	√	-	√	-	-	√	√	-	-	-	-	-	√	√	√	√	-	√	√	√	√	√	-	√	√	√	√
		New Capacity	-	-	√	√	-	-	-	√	√	√	-	-	-	√	√	-	-	-	√	-	√	-	-	-	√	√	√	-	-	-	√	-	-	-	-	√	-	-	√	-	-	-	-	-	-	-	√
	Capacity Decrease	**Under-Utilisation**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	√	-	-	-	-	-	-	-	-	-	-	√
		Mothballing	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√
		Capacity Close-down	-	-	-	-	-	-	√	-	-	-	-	-	-	√	√	-	-	-	√	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	√
Facility Location / Relocation		**Location**	√	-	√	√	-	-	√	√	√	-	-	√	-	-	√	-	-	√	√	-	-	-	-	-	-	√	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√ (from limited options)
		Re-location	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√
Technology Selection / Production Flexibility			-	-	-	√	√	√	-	-	-	-	√	-	√	-	-	-	-	-	-	√	√	-	-	-	-	√	-	√	√	-	√	-	-	√	-	√	-	-	-	√	-	√	-	-	√	√	√ (from limited options)
Product Development		**NPD Cost**	-	-	√	-	-	-	-	√	-	-	-	-	-	√	-	-	-	-	-	-	√	-	-	-	-	-	-	-	√	-	-	-	√	√	√	√	-	-	-	√	√	-	-	-	-	-	√
		Product Flexibility	-	-	√	-	-	-	-	-	-	-	-	-	√	√	-	-	-	-	-	-	√	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	√
		Product relaunch	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√
HR Management & Shift Design			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	√	-	-	-	√ (Strategic-not tactical)
Supplier Selection			-	-	-	-	-	-	√	-	-	-	-	-	-	-	√	√	-	√	√	-	-	√	√	√	-	√	-	-	-	-	√	√	-	√	-	-	-	-	-	-	-	-	-	-	-	-	- (Supply Cost is sensitively applied)

Table 7-3: More details about terms and features in the selected papers for analytical and thematic analysis, including cost features, financial terms, capacity lumpiness, investment constraint.

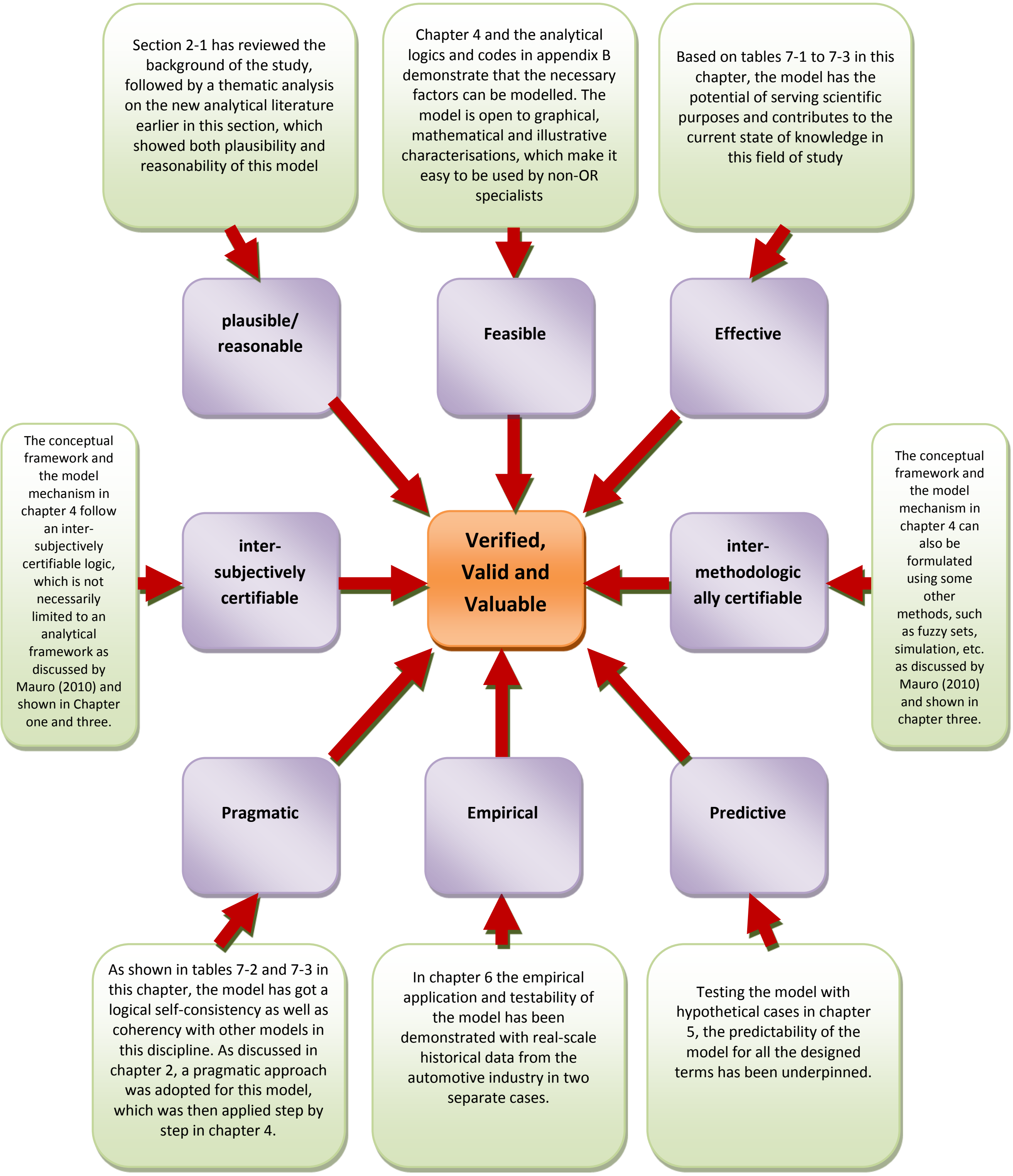
		(Syam 2000)	(Inman et al. 2001)	(Papageorgiou et al. 2001)	(Verter et al. 2002)	(Chen et al. 2002)	(Hood et al. 2003)	(Bhutta et al. 2003)	(Gatica et al. 2003)	(Goel et al. 2004)	(Chauhan et al. 2004)	(Barahona et al. 2005)	(Chakravarty 2005)	(Chandra et al. 2005)	(Stray et al. 2006)	(Melo et al. 2006)	(Fleischmann et al. 2006)	(Silva Filho et al. 2007)	(Snyder et al. 2007)	(Zhang 2007)	(Ahmed et al. 2008)	(KATAYAMA et al. 2007)	(Nagar et al. 2008)	(Azaron et al. 2008)	(Hamad et al. 2008)	(Dehayem Nodem et al. 2008)	(Naraharisetti et al. 2008)	(Tarhan et al. 2008)	(Francas et al. 2009)	(Karnik et al. 2009)	(Wagner et al. 2009)	(Hammami et al. 2009)	(You et al. 2009)	(Geng et al. 2009b)	(Kauder et al. 2009)	(Colvin et al. 2009)	(Bihlmaier et al. 2010)	(Aghezzaf et al. 2010)	(Frausto-Hernandez et al. 2010)	(Naraharisetti et al. 2010)	(Wu et al. 2010)	(Lin et al. 2010)	(Durksen et al. 2010)	(Lusa et al. 2011)	(Dal-Mas et al. 2011)	(Claro et al. 2012)	(Chien et al. 2012)	The Model in this Research
Cost Parameters	Transportation Cost/Management	√	-	-	√	-	-	√	-	√	√	-	√	-	√	√	√	-	√	-	-	√	√	√	√	-	√	-	-	√	√	√	√	√	√	-	√	-	-	√	-	-	√	-	√	-	-	√
	Unmet Demand Penalty / outsourcing	-	√	-	-	-	√	-	√	-	-	√	-	-	√	-	-	√	-	-	-	-	√	√	-	√	-	-	√	√	-	-	-	√	-	√	√	√	√	-	√	-	√	√	√	√	√	√
	Production Cost	√	-	√	√	-	-	√	√	-	√	-	√	√	√	√	√	√	√	√	-	-	√	√	√	√	√	√	-	√	√	√	√	√	√	√	√	√	√	√	√	√	√	-	√	√	-	√
	Labour Cost	√	-	√	-	-	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	√	-	-	-	√
	Material/supply Cost	-	-	√	-	-	-	-	√	-	√	-	-	√	-	-	√	-	-	√	-	√	-	-	-	-	√	√	-	-	-	√	√	√	√	-	-	√	√	√	-	-	√	-	√	-	-	√
	Capacity Maintenance	-	-	-	-	-	-	√	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	√	√	-	-	-	-	-	-	-	-	√	-	-	-	√	-	-	-		-	-	-	√
	Capacity depreciation & Replacement	-	-	√	-	-	-	√	-	-	√	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	√	√	-	-	-	-	-	√	√
	Operation / Overhead fixed Cost	-	-	√	√	-	-	√	√	-	-	-	√	√	√	√	√	-	-	√	-	-	-	-	-	-	√	√	-	-	-	√	-	-	√	√	-	-	-	√	√	-	√	-	√	√	√	√
Financial parameters	Discount/Interest rate	-	-	√	-	-	-	-	√	√	√	-	-	√	-	√	√	-	-	√	-	-	-	-	-	√	√	-	-	√	-	-	-	√	√	√	-	-	-	√	√	-	-	-	√	-	√	√
	Tax	-	-	√	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	√	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	√
	Duty	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√
	VAT	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√
	Inflation rates	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	√
	Exchange rates	-	-	-	-	-	-	√	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	√	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Economies of Scale		-	-	√	√	√	-	√	√	√	-	-	√	-	√	√	√	-	-	-	√	√	-	-	-	-	√	-	-	√	-	-	-	-	-	-	-	-	-	√	-	-	√	-	√	-	√	√
Capacity lumpiness		√	√	√	-	-	√	√	√	√	-	√	-	-	√	√	√	-	-	√	-	√	-	-	-	√	√	√	-	√	-	-	-	-	√	√	-	-	-	√	√	√	√	-	√	-	√	√
Investment Budget Constraint		-	-	√	-	-	√	-	√	-	-	√	-	√	-	√	√	-	-	√	-	√	-	√	-	-	√	-	-	-	√	-	√	-	-	-	-	-	√	√	√	-	-	-	-	-	-	√

Tables 7-1 to 7-3 clearly establish the contributions of this model to the current state of knowledge in comparison with an inclusive set of new optimisation models in this research area. Now, to summarise the discussion section, the eight essential questions of Khazanchi (1996), which were highlighted in the beginning of this section, will be recalled to discuss.

These questions are (Martis 2006, Khazanchi 1996):

1. “Is it plausible/ reasonable? This criterion is useful to assess the apparent reasonableness of an idea and could be demonstrated by deduction from past research or theories”
2. “Is it feasible? A feasible concept would be operational only if it would be open to graphical, mathematical, illustrative characterisation.”
3. “Is it effective? An effective conceptual model should have the potential of serving our scientific purposes.”
4. “Is it pragmatic? This criterion emphasises that concepts and conceptual models should have some degree of logical self-consistency or coherence with other concepts and conceptual models in the discipline.”
5. “Is it empirical? Empirical content implies that a concept or conceptual model must have empirical testability”
6. “Is it predictive? A conceptual model that is predictive would, at least, demonstrate that given certain antecedent conditions, the corresponding phenomenon was somehow expected to occur.”
7. “Is it inter-subjectively certifiable? This criterion states investigators with differing philosophical stance must be able to verify the imputed truth content of these concepts or conceptual structures through observation, logical evaluation, or experimentation.”
8. “Is it inter-methodologically certifiable? This criterion provides that investigators using different research methodologies must be able to test the veracity of the concept or conceptual model and predict the occurrence of the same phenomenon.”

Figure 7-1, with reference to the abovementioned discussion and other chapters of this research, highlights the key answers to these questions. Figure 7-1 consequently underpins the originality and merits of this model and therefore summarises this section.



Section 2-1 has reviewed the background of the study, followed by a thematic analysis on the new analytical literature earlier in this section, which showed both plausibility and reasonability of this model

Chapter 4 and the analytical logics and codes in appendix B demonstrate that the necessary factors can be modelled. The model is open to graphical, mathematical and illustrative characterisations, which make it easy to be used by non-OR specialists

Based on tables 7-1 to 7-3 in this chapter, the model has the potential of serving scientific purposes and contributes to the current state of knowledge in this field of study

The conceptual framework and the model mechanism in chapter 4 follow an inter-subjectively certifiable logic, which is not necessarily limited to an analytical framework as discussed by Mauro (2010) and shown in Chapter one and three.

The conceptual framework and the model mechanism in chapter 4 can also be formulated using some other methods, such as fuzzy sets, simulation, etc. as discussed by Mauro (2010) and shown in chapter three.

As shown in tables 7-2 and 7-3 in this chapter, the model has got a logical self-consistency as well as coherency with other models in this discipline. As discussed in chapter 2, a pragmatic approach was adopted for this model, which was then applied step by step in chapter 4.

In chapter 6 the empirical application and testability of the model has been demonstrated with real-scale historical data from the automotive industry in two separate cases.

Testing the model with hypothetical cases in chapter 5, the predictability of the model for all the designed terms has been underpinned.

Figure 7-1: Merits of the model assessed using the 8 questions by Khazanchi (1996).

7-2- Contributions to Knowledge

The Contributions of this study to the current state of knowledge in this field are:

- To the best of our knowledge, this model is the most comprehensive stochastic strategic capacity design and planning model, which can handle capacity volume, flexibility, product management, capacity location and relocation, capacity merge and decomposition, investment lead time, strategic HR change management, economies of scale and capacity lumpiness.
- The model is able to *simultaneously* handle capacity increase and decrease, with empirical decision solutions of overutilisation, capacity expansion and/or new plant establishment in case of short-term, mid-term and/or long term demand increase respectively, as well as underutilisation, capacity mothballing and/or capacity shutdown in case of short-term, mid-term and/or long term demand decrease.
- As far as we can establish, this is the first strategic capacity planning model that can globally manage the capacity considering all required financial terms of profit tax and inflation rate in the area where production is carried out, as well as custom duty and value added tax in the region where sales happen. Moreover, the model underpins the effects of these parameters on capacity location/relocation decisions.
- Relaunching a current product family in a production line after a reasonably long time, which requires a setup cost, a product design (R&D) cost which is usually invested in head office or research centres and finally a new product launch cost which is the cost of launching the products in a production line for the first time, are also introduced for the first time in a unique framework as the complementary parts of the strategic product management decisions in a capacity planning model.
- This model can simultaneously handle product and process flexibility, with regard to both cost and lead time terms. Meanwhile, early capacity depreciation due to a short product cycle-time is also applied in the model.
- Although many previous models have succeeded in implementing uncertainty in strategic capacity models, applying market uncertainty, in two terms of demand uncertainty and sales price change in such a large-scaled model in this area of research has also happened for the first time.

7-3- Potential Users of the Model

This model is a general capacity design and planning model for a multinational manufacturing company, which may have different plants in different countries as well as different sales regions in the world. Applying VAT in the model makes it flexible to use for manufacturers who sell their products to both end user and/or distributors and retailers. Considering different inflation rates in the manufacturing countries and different custom duties for the sales regions makes the model more sensitive to location/relocation problems.

Having employed a more pragmatic approach, comprehensive strategic terms and also making the model commercial and hassle-free to use by non-OR specialists, makes the model more likely to be used in the industries in which it can significantly reduce the time and risk of strategic decision making in global capacity design and planning.

However, adding all these potentials to the model may make the input structure fairly complex and one may say not all these inputs are not always readily available to the users. Validation cases in chapter 5 and industrial case-studies in chapter 6, however, showed that not all input data is required for any strategic decision and based-on the required level of decision making, users should provide the model with relevant input information. For example, if the demand prospect is promising in all scenarios and logically no plant shutdown will be expected and the model is just exploiting for capacity expansion or planning, no shutdown related input data is required.

Although this model has been developed in a general format, in chapter 5 and 6 the model was adjusted to the automotive industry to be validated and tested. However, this model is capable of extension to many other similar manufacturing industries such as the aerospace, turbine industry, etc. Still, all planning solutions of every kind must be integrated into particular processes which fit the organisation (Kempf et al. 2011a). Therefore, to fit this general model to different manufacturing industries, some slight changes, considerations or redefinitions of the parameters may be needed. For example, in the electronic industry, where the product life cycle is significantly lower than in many other manufacturing industries (Solomon et al. 2000), a time interval of one year and a time horizon of 10 years seem quite long and unrealistic. In such a case, redefinition of the time interval from one year to a quarter or even one month would solve the problem and make the model more applicable.

7-4- Summary and Conclusion

This research developed an inclusive strategic capacity design and planning decision tool, in which market uncertainty can be applied. In this project the author has reviewed the background of the study in chapter 1, which revealed the gaps to be aimed for by the research. Uncertainty in demand and sales price; multi factor, multi-stage, multi echelon and a comprehensive set of strategic terms to be applied in a capacity management mode; an integrated framework; a pragmatic approach with the ability to adjust to an industrial application and time-effectively run the real-scale cases; and finally, a graphical, user-friendly and hassle-free way of using the model for non-OR specialists have all been targeted in this study.

Reviewing the best possible objectives for such a model in chapter 2, the net present value (NPV) under uncertainty was chosen, in which both the 'efficiency principle' and the 'temporary advantages' of an investment have been embedded (Bihlmaier et al. 2010). In the rest of chapter 2, in a search for a set of strategic decisions to apply in such a model, volume, location and timing of investment/disinvestment in capacity (Chakravarty 2005, Matta et al. 2005), type, technology and flexibility of the capacity (Fleischmann et al. 2006), product management and NPD (Papageorgiou et al. 2001) were highlighted and expanded. On top of these strategic terms, several capabilities have been raised for a successful integrated capacity planning model by peer authors, which have all been tackled in the modelling effort in this research. These capabilities are: the ability to consider investment lead time (Van Mieghem 2003, Elkins et al. 2004), the product life cycle (Francas et al. 2009), economies of scale (Claro et al. 2012), the lumpy nature of the capacity (Olhager et al. 2001), the sensitivity to different levels of capacity utilisation (Elmaghraby 2011), capacity depreciation and salvage (Van Mieghem 2003, Julka et al. 2007), the irreversible or partly irreversible nature of capacity investment (Dangl 1999), and finally, the brand image cost and other costs of unfulfilled demand (Eppen et al. 1989).

The methodology, method, technique and programming approach have been discussed and selected in chapter 3. A scenario-based multi-stage stochastic optimisation method was chosen to develop the model in this research. An enumerated scenario technique, which is more pragmatic (Lin et al. 2010), and realistic (Hood et al. 2003) was chosen for the scenario expansion. Visual Basic Compiler was selected as the programming language for the main application/software development, which links Microsoft Access as the input generator, Microsoft Excel as the output generator and GAMS – CPLEX as the optimisation solver.

Recognising the necessary terms and constraints for the model, as well as the desirable outputs of the model in the early chapters, in chapter 4 the conceptual framework in an input-control-output-mechanism (ICOM) frame was developed for this study. The modelling structure and mechanism, then, was established based on this framework, which revealed a road-map for the logic formulation. In the rest of chapter 4, the objective formulation and constraints equations were developed step by step with reference to this road-map. The computer programming approach was also addressed in this chapter, with more details in appendix B and C.

To test the validity of the model in all claimed terms, a black-box validation plan with a series of hypothetical cases was subsequently established in the first section of chapter 5. This validation plan was designed not only to check all individual terms and abilities of the model, but also to validate the link between these terms, including the effect of uncertainty with a series of comparisons between deterministic and stochastic cases, the effect of global design with a comparison between domestic and global choices, etc. Fourteen different hypothetical cases were designed and tested in the rest of that chapter to cover the validation plan. These cases established a high level of confidence in using this model for all embedded terms and decision variables.

After the model validation in chapter 5, the application and ability of this model in two real-scale cases in the automotive industry were illustrated in chapter 6, using publicly released historical data from the Toyota Motors UK (TMUK) and Jaguar Land Rover (JLR) Companies. In the case of TMUK, the application of the model in strategic capacity level management for Toyota's assembly lines in the UK was demonstrated. Affected by the recent global recession, in 2010 TMUK mothballed one of its two assembly lines in Burnaston after a dramatic demand decline. Setting the demand-change history and the plant-related and operations cost of these two assembly lines in the model and running it, the model suggested one of these assembly lines to be mothballed in 2009, which was a year earlier than the actual decision's time. Such an agile decision could have saved more than £10M for the company.

In the second application-study of the model in the automotive industry in chapter 6, JLR's strategic decision of having an assembly line in China was analysed. Responding to the growing Chinese market, JLR has decided to change its strategy from product-to-market to produce-in-market. Having the demand history and demand prospects in the country, gathering data on the required investment figures and using JLR's investment experience in India, this strategic decision was evaluated in this case, using the model's ability on strategic capacity location decisions. Four strategic choices were analysed in this case: 1- No investment in the production facility in the market, but export to the market from the UK; 2- Moderate level of investment in one CKD assembly line; 3- High level of investment in one CKD assembly line; 4- High level of investment in one assembly line, R&D and local suppliers. Different sales prices and demand scenarios were assumed for each of these strategic decisions and the model was run for each individual case. The results showed that, although all but the third strategic decisions can be feasible, the second one is the most profitable one to start with. This result showed a very good match with JLR's decision, which was finally made last year after 2-3 years of analysis and investigations.

Employing an inclusive thematic analysis and a comparison with the most recent analytical models in the field of strategic capacity management for the manufacturing industries, in the first section of this chapter, the novelty of these models in this research area were discussed and contributions of this study to the current state of knowledge were established. Consequently, to summarise the discussion section, eight essential questions of originality and merits of a new conceptual framework, which are proposed by Khazanchi (1996), were asked and discussed for this model. To our knowledge, this capacity management model has managed to apply a more inclusive and pragmatic set of strategic decision variables in a stochastic modelling format and presented a relatively quick and easy-to-use application/software for non-OR specialist applications. Although the model is designed for heavy-duty manufacturing industries such as the automotive, aerospace and turbine manufacturers, with slight adjustments and changes, the model can be used for some other manufacturing industries such as the electronic, semi-conductor and chemical industries.

7-5- Limitation and Future Works

There have been some limitations to this research, which bring the following suggestions for possible future studies:

Future work 1: Capacity investment decisions are not made in a vacuum. These decisions interact with decisions of the competitors, and the general state of the business environment (Van Mieghem 2003). The game theory is a well-established method to deal with such problems (Farahani et al. 2010). Therefore, the author suggests the game theory should be applied in the decision making tool, or the scenario generation procedure.

Future work 2: Optimising the expected NPV under uncertainty is a risk-natural approach. However, risk is an extremely important aspect of long-term strategic decision making, and should be employed in the procedure (Yang 2009). Any risk-avert method can be employed to implement a financial risk indicator in the stochastic programming approach (Verderame et al. 2010, Klibi et al. 2010, Peidro et al. 2009, Wazed et al. 2010). In this research, to avoid the significant complexity of applying risk in the modelling programming, a risk-natural method was employed, which can be addressed in the future works in this field to expand this model into a risk-avert format.

Future work 3: Supply chain network design is one of the most important strategic decisions (Ho et al. 2010), which directly or indirectly affects the capacity topology (Klibi et al. 2010, Melo et al. 2009, Kumar et al. 2010). This part of strategic decision making for manufacturing resource management is neglected in this research to make the size of the model manageable. Although, to avoid unrealistic simplification of ignoring supply chain design in this model, the effect of capacity location on the supply cost has been considered, having supply chain-related decisions-variables directly in the model to design, manage and plan the supply chain network which makes the model more accurate and realistic.

Future work 4: New methods such as simulation techniques and more effective solution algorithms for stochastic optimisation models are highlighted to make the future complex models easier and quicker to solve (Van Mieghem 2003, Klibi et al. 2010, Geoffrion et al. 1995, Vidal et al. 1997, Snyder 2006, Baron et al. 2008, Farahani et al. 2010). The scope of this research was far from developing methods and solution algorithms, which is purely operational research related. However, as a future work in OR, other methods can be employed to expand and formulate the model’s framework presented in this research in order to see the merits and drawbacks of other techniques in comparison with stochastic programming which was employed in this research. Like new methods, new algorithms can also be developed to solve the same stochastic model in a more efficient, robust or quicker practice.

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Appendix A: List of indexes, Definitions and Parameters

Indices:

$i \in I$ Set of Plant

$j \in J$ Set of Products

$r \in R$ Set of sales regions

$t \in T$ Years (time period)

$z \in Z$ Set of Scenarios

Decision Variables (outputs):

X_{ztij}^{A} Number of product (j), produced in plant (i), in year (t) under scenario (z)

X_{ztrij}^{D} Number of products (j), from plant (i), distributed to sales region (r), in year (t), under scenario (z)

X_{ztrj}^{Unmet} Number of unmet demand product (j), in region (r) and year (t), under scenario (z)

Y_{ztij}^{A} Binary decision variable of allocating product (j) in plant (i), in year (t) under scenario (z) It is defined by X_{ijt}^{n}. If $X_{ijt}^{n} \succ 0$ then $Y_{ijt}^{n} = 1$ otherwise $Y_{ijt}^{n} = 0$

Y_{zti}^{On} Binary decision variable for over-normal utilisation of plant (i), in year (t) under scenario (z)

K_{zti}^{Max} Nominal capacity of plant (i) in year (t) under scenario (z)

K_{zti}^{Cl} Shutdown capacity amount of plant (i), in year (t), under scenario (z)

Y_{zti}^{Cl} Binary decision variable for permanently capacity close-down decision for plant (i) in year (t) under scenario (z)

K_{zti}^{Fr} Mothballed capacity amount of plant (i), in year (t), under scenario (z)

Y_{zti}^{Fr} Binary decision variable for temporary capacity mothballing of plant (i) in year (t), under scenario (z)

K_{zti}^{Re} Reopen capacity amount of plant (i), in year (t), under scenario (z), among previously frozen capacities

Y_{zti}^{Re} Binary decision variable for reopen capacity decision for plant (i), in year (t) , under scenario (z), among previously mothballed capacities

K_{zti}^{Exp} Expanded capacity amount of plant (i), in year (t), under scenario (z)

Y_{zti}^{Exp} Binary decision variable for expansion decision on current available plant (i), in year (t), under scenario (z)

$Y_{zti}^{ExpOveral}$ Binary decision variable to show whether any expansion has been happened for plant (i) during or before year (t) and under scenario (z)

K_{zti}^{FrAll} Available amount of mothballed capacity of plant (i) for reopen decision in year (t), under scenario (z)

Y_{zti}^{FrAll} Binary decision variable to show whether any mothballed capacity is available in plant (i) in year (t) and under scenario (z)

Y_{ztij}^{NPL} Binary decision variable for new product launch. If the variable is equal to one, it means that product (j) produces in plant (i), in year (t) , under scenario (z), for the first time

Y_{ztij}^{PL} Binary decision variable for relaunching a product. If the variable is equal to one, it means that product (j) produces in plant (i), in year (t) , under scenario (z), while it has not produced in the plant during the year before (t-1)

$Y_{ztj}^{R\&D}$ Binary decision variable for new product design. If the variable is equal to one, it means that product (j) is producing in at least one plant for the first ever time in year (t) , under scenario (z)

Y_{zti}^{Opr} Binary decision variable shows that whether plant (i) in year (t), under scenario (z) is open, working and subject to yearly operations costs

Z_{zti}^{New} Binary decision variable shows that whether new plant (i) would be established in year (t) , under scenario (z)

$Y_{zti}^{ExpWforce}$ Binary decision variable shows that whether plant (i) in year (t), under scenario (z) is in-use and has ever expanded earlier. In this case this plant will be subject to extra operations cost and work force cost.

Y_{zti}^{Dep} Binary decision variable which shows that whether plant (i) in year (t), under scenario (z) is either in-use or mothballed (subject to depreciation)

Parameters (inputs):

ρ Overall discount rate

σ_i^{Tax} Profit tax rate for the region that plant (i) is operating

σ_r^{VAT} Value Added Tax (VAT) in sales region (r) on the final sales price

σ_{ri}^{Tariff} The rate of custom duty and tariff on the products shipped from plant (i) to sales region (r) on the final sales price

Δ^{oper} The inflation rate on operations costs

Δ^{Inv} The inflation rate on investment costs

Δ^{Sup} The inflation rate on supply costs

Δ^{D} The inflation rate on transportation costs

Δ^{Unmet} The inflation rate on penalty cost of unfulfilled demand

I_i^{New} Required investment to establish the new plant (i)

The current estimation of prices is applied to this parameter, and required investment to establish this plant in the future will be calculated by the model, according to inflation rates. If the plant (i) is not an alternative new plant, there is no need to provide data for this parameter.

I_i^{Exp} Required investment to expand the plant (i)

The current estimation of prices is applied to this parameter, and required investment to expand this plant in the future will be calculated by the model, according to inflation rates on investment costs.

I_i^{Fr} Required investment to mothball the plant (i)

The current estimation of prices is applied to this parameter, and required investment to mothball this plant in the future will be calculated by the model, according to inflation rates on investment costs.

I_i^{Re} Required investment to reopen the plant (i) in case it is already mothballed, or would be mothballed during the planning.
The current estimation of prices is applied to this parameter, and required investment to reopen this plant in the future will be calculated by the model, according to inflation rates on investment costs.

I_i^{On} Required investment to over-utilise the plant (i). The current estimation of prices is applied to this parameter, and required investment to over-utilise this plant in the future will be calculated by the model, according to inflation rates of investment costs.

$I_i^{Workforce}$ Annual cost of work force for normal production in plant (i)
The current estimation of prices is applied to this parameter, and future costs will be calculated by the model, according to inflation rates on operations costs.

I_i^{Opr} Annual operations cost for normal utilisation of plant (i). This cost includes all utility costs, maintenance costs and any other costs which are not considered in other annual costs (for example labour costs, supply cost and transportation costs are considered in other terms). The current estimation of operations costs will be applied to this parameter, and required investment to over-utilise this plant in the future is calculated by the model, according to inflation rates on operations costs.

I_i^{OprExp} Annual extra operations cost of expanded part of plant (i) in case that expansion happens for the plant. The current estimation of operations costs is applied to this parameter, and required investment to over-utilise this plant in the future will be calculated by the model, according to inflation rates on operations cost.

I_i^{OperFr} Annual operations cost for plant (i), in case of mothballing. Any mothballed plant still has some operations costs (for maintenance and so on). The current estimation of operations costs is applied to this parameter, and required investment to over-utilise this plant in the future will be calculated by the model, according to inflation rates on operations cost.

$I_{i,j}^{NPL}$ Investment to launch the product (j) in line (i) for the first time. The current estimation of operations costs is applied to this parameter, and required investment for new launch of the product in the plant for the future will be calculated by the model, according to inflation rates on investment cost.

$I_{i,j}^{PL}$ Investment to relaunch the product (j) in line (i), while it has produced in the plant sometime before for the first time, but there was a production break. relaunching a product in a plant will cost the company to reset the line and machineries. The current estimation of operations costs is applied to this parameter, and required investment for relaunching of the product in the plant for the future will be calculated by the model, according to inflation rates on investment cost.

$I_j^{R\&D}$ Required investment for the design of a new product of (j) in research centre or headquarter. The current estimation of operations costs is applied to this parameter, and required investment for design of the product in the future will be calculated by the model, according to inflation rates on investment cost.

$K_i^{Initial}$ Nominal capacity of plant i, before any volume change

$\mu_{i_i}^{Max}$ normal capacity ratio for plant (i), out of nominal capacity

$\gamma_{ij} \in [0,2]$ Capacity rate for product (j) in plant (i)

C_{ij}^{Sup} Unit supply and material cost of product (j) in plant (i); the current estimation of prices is applied to this parameter, and cost of unit supply in the future is calculated by the model, according to inflation rates on supply costs.

C_{rij}^{D} Distribution costs, product (j), from plant (i), to sales region (r)

The current estimation of prices is applied to this parameter, and cost of transportation in the future is calculated by the model, according to inflation rates on transportation cost.

$C_{rj}^{Penalty}$ Unmet demand penalty for product (j) in region (r)

The current estimation of prices is applied to this parameter, and unmet demand penalty in the future is calculated by the model, according to inflation rates on unmet demand penalty.

C_{ij}^{Unit} Any other unit cost of producing product (j) in plant (i)

The current estimation of the cost is applied to this parameter, and future costs are calculated by the model, according to inflation rates on operations cost.

$C_{z,t,r,j}^{Sale}$ Sales price of product (j) in sales region (r) in the year (t), under scenario (z)

η_i^{New} Investment time table to establish a new plant (i), according to table 4-1

η_i^{Exp} Investment time table to expand the new plant(i), according to table 4-1

η_{ij}^{NPL} Investment time table to launch product (j) in plant (i), according to table 4-1

$\eta_j^{R\&D}$ Investment time table for designing a new product (j), according to table 4-1

E_i Maximum number of possible expansion for plant (i)

$\vartheta_i^{E-\min}$, $\vartheta_i^{E-\max}$ Minimum and maximum rates of capacity expansion for plant (i)

ε_i^{OnA} Increase rate on labour cost, in case of overutilisation for plant (i)

ε_i^{Exp} Increase rate on labour cost, in case of plant expansion for plant (i)

ε_i^{Fr} The rate of labour cost decrease due to redundancy in case of mothballing the plant (i)

l_i	Maximum Number of Plant to produce Product (j)
d_{ztrj}	Demand for Product (j) in sales region (r) and year (t), under scenario (z).
b_t	Maximum investment budget for year (t)
ξ^I_j	Proportion of unit sales price, dedicated for investment in capacity in the year after sale.
$n_i^{\max}$	Maximum number of possible products to be produced in plant (i) at the same time
M	A very large number in the scope of capacities in the model
P_z	Probability of scenario (z)

Appendix B: Visual Basic Programming Codes to Generate the Expanded Formulations from the Database to Solve in GAMS

In this appendix all of the formulations from chapter 4 are recalled and the Visual Basic® codes to generate the extended formulations for GAMS will be explained, in detail.

1- Objective Function

Recall from Obj.2 formula in section 4-1, objective function consists of four main terms: 1- revenue; 2- annual operations costs; 3- annual investment costs; and finally 4- annual R&D costs:

$$Max\sum_{z} P_z \sum_{t=0}^{T} \overbrace{(1+\rho)^{-t}}^{\text{Discount rate}} .[(\sum_{i} \overbrace{Rev_{z,t,i}}^{\text{Total Revenue}} - \overbrace{Oper_{z,t,i}}^{\text{Operational costs}} - \overbrace{Inv_{z,t,i}}^{\text{Investment costs}}) - \overbrace{R\&D_{z,t}}^{\text{R\&D Cost}}]$$

In this section programming codes for each of these four element will be described.

1-1- Revenue

Recall from ‘Formula 05’ (section 4-1), annual revenue for each plant in each year and under each scenario, comes from the total sales of the plant in that year and scenario.

$$\sum_{z} P_z \sum_{t=0}^{T} (1+\rho)^{-t} .\{\sum_{r,i,j} (1-\sigma_i^{Tax}).(C^{Sale}_{z,t,r,j} \cdot X^{D}_{z,t,r,i,j})$$

Following, the Visual Basic code to generate extended formulation in GAMS language in relation with database (the Access file) is recalled.

```
Public Sub Revenue()
    Dim sales As String = "(0"
    z = 0
    t = 0
    r = 0
    i = 0
    j = 0

    If RadioButton1.Checked = True Then

      While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

        While Not Val(year.Rows(t).Cells(0).Value) = 0

          While Not Val(region.Rows(r).Cells(0).Value) = 0

            While Not Val(product.Rows(j).Cells(0).Value) = 0
```

```
                            While Not Val(Demand.Rows(k).Cells(0).Value) = 0

                                If Scenario.Rows(z).Cells(1).Value = Demand.Rows(k).Cells(5).Value And year.Rows(t).Cells(1).Value = Demand.Rows(k).Cells(4).Value And region.Rows(r).Cells(1).Value = Demand.Rows(k).Cells(2).Value And product.Rows(j).Cells(1).Value = Demand.Rows(k).Cells(3).Value Then

                                    While Not Val(Plant.Rows(i).Cells(0).Value) = 0

                                        sales = sales + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "(((1+" + LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*XAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')" + "*1000*" + LTrim(Str(Demand.Rows(k).Cells(6).Value)) + "*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value)) + ")"

                                        GAMSequations.WriteLine(sale)

                                        sales = ""

                                        i = i + 1
                                    End While
                                    i = 0
                                End If
                                k = k + 1
                            End While
                            k = 0
                            j = j + 1
                        End While
                        j = 0
                        r = r + 1
                    End While
                    r = 0
                    t = t + 1
                End While
                t = 0
                z = z + 1
            End While
            z = 0
            sales = "+0)-(("
            GAMSequations.WriteLine(sale)
            sales = ""
        End If

    End Sub
```

1-2- Investment Costs

As explained in section 4-1, annual investment costs can be divided into six different terms of new plant establishment, capacity expansion, capacity mothballing, capacity reopening, plant shutdown, and finally new product launch part of NPD.

$$
\begin{aligned}
Inv = \sum_{z}\sum_{t}\sum_{i}\Big[& \overbrace{\boxed{I^{New}_{ti}\cdot\eta^{New}_{i}\cdot Z^{New}_{i,t}}}^{\text{① New Plant Establishment}} + \overbrace{\boxed{I^{Exp}_{ti}\cdot\eta^{Exp}_{i}\cdot Y^{Exp}_{it}}}^{\text{② Invest to expand capacity}} + \overbrace{\boxed{I^{Fr}_{ti}\cdot Y^{Fr}_{it}}}^{\text{③ Invest to mothball}} \\
& + \underbrace{\boxed{I^{\mathrm{Re}}_{ti}\cdot Y^{\mathrm{Re}}_{it}}}_{\text{④ Invest to reopen a frozen capacity}} + \underbrace{\boxed{I^{Clo}_{ti}\cdot Y^{Clo}_{it}}}_{\text{⑤ Invest to Close down a capacity}} + \underbrace{\boxed{\sum_{j}(I^{NPL}_{tij}\cdot\eta^{NPL}_{i,j}\cdot Y^{NPL}_{ztij}}}_{\text{⑥ Invest to Launch a product in a new line}} + \underbrace{\boxed{I^{PL}_{tij}\cdot(Y^{PL}_{ztij}-Y^{NPL}_{ztij}))}}_{\text{⑦ Re-launch a product in a line}}\Big]
\end{aligned}
$$

η_i is investment time schedule and defines as an input in database by the model users. However, to apply it to the modelling, as explained in section 4-1, some considerations in programming should be taken into account.

In the rest of this section, programming codes of Visual Basic® to generate extended formulas for GAMS, for each term of the investment costs, will be explained.

1-2-1- New Plant Establishment

①

$$\boxed{\sum_{z} \sum_{t} \sum_{i} I_{ti}^{New} \cdot \eta_{i}^{New} \cdot Z_{i,t}^{New}}$$

```
Public Sub NewInv()      ' New plant establishment
        Dim NewInv As String = ""
    Dim TTTest As String = ""
    NewInv = ""
    Dim NI As Integer = 0
    i = 0; j = 0; r = 0; t = 0; z = 0;
    Refresh()
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If Plant.Rows(i).Cells(23).Value = True Then
            While Not Val(New_Plant_time_tableDataGridView.Rows(NI).Cells(0).Value) = 0
              If New_Plant_time_tableDataGridView.Rows(NI).Cells(1).Value = Plant.Rows(i).Cells(1).Value Then

 NewInv = NewInv + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "(((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + LTrim(Str(Plant.Rows(i).Cells(5).Value)) +
"*1000000" + "*((ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 5)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(2).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t + 4)) + "','" + LTrim(Str(i)) + "')*" + Trim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(3).Value)))
+ "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 3)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(4).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t + 2)) + "','" + LTrim(Str(i)) + "')*" + Trim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(4).Value)))
+ "/100)" + "+(ZNewzti('" + "','" + LTrim(Str(z)) + LTrim(Str(t + 1)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(4).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(5).Value))) +
"/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(6).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t - 2)) + "','" + LTrim(Str(i)) + "')*" + Trim(Val(Str(New_Plant_time_tableDataGridView.Rows(NI).Cells(7).Value)))
+ "/100)))*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))
                GAMSequations.WriteLine(NewInv)
                NewInv = ""
                TTTest = "ok"
              End If
              NI = NI + 1
            End While
            NI = 0
            If TTTest = "" Then
              MsgBox("No investment time table is defined in database for one of new plants. It would cause problem in
solving. Run is terminating. Go back to data base in Plant form, and correct the data.", MsgBoxStyle.Critical)
              End
            Else
              TTTest = ""
            End If
          End If
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-2-2- New Plant Establishment

$$\boxed{\sum_{z}\sum_{t}\sum_{i} I_{ti}^{Exp}\cdot\eta_{i}^{Exp}\cdot Y_{it}^{Exp}}$$ ②

```
Public Sub Expansion()
     ' ##############################################################################################
    ' Capacity Expansion:
    ' ##############################################################################################
    Dim Expansion As String
    Dim TTTest As String = ""
    Expansion = ""
    Dim ei As Integer = 0
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If Not Val(Plant.Rows(i).Cells(9).Value) = 0 Then
            While Not Val(Expansion_time_tableDataGridView.Rows(ei).Cells(0).Value) = 0
              If Expansion_time_tableDataGridView.Rows(ei).Cells(1).Value = Plant.Rows(i).Cells(1).Value Then

                Expansion = Expansion + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "(((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + LTrim(Str(Plant.Rows(i).Cells(9).Value)) +
"*1000000" + "*((YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 3)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(2).Value))) + "/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(t + 2)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(3).Value))) +
"/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 1)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(4).Value))) + "/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(5).Value))) +
"/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(6).Value))) + "/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 2)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(7).Value))) +
"/100)))*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))

                GAMSequations.WriteLine(Expansion)
                Expansion = ""
                TTTest = "ok"

              End If
              ei = ei + 1
            End While
            ei = 0
          End If
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-2-3- Capacity Mothball

$$\boxed{\sum_{z}\sum_{t}\sum_{i} I_{ti}^{Fr}\cdot Y_{it}^{Fr}} \quad ③$$

```
Public Sub Mothball()
    ' ##########################################################################################
    ' Capacity Mothball:
    ' ##########################################################################################

    Dim freeze As String = ""
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

      While Not Val(year.Rows(t).Cells(0).Value) = 0

        While Not Val(Plant.Rows(i).Cells(0).Value) = 0

          freeze = freeze + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*(" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + LTrim(Str(Plant.Rows(i).Cells(11).Value)) +
"*1000000)" + "*YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))

          i = i + 1
        End While
        i = 0

        GAMSequations.WriteLine(freeze)
        freeze = ""

        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

1-2-4- Capacity Reopening

$$\boxed{\sum_{z}\sum_{t}\sum_{i} I^{\mathrm{Re}}_{ti}\cdot Y^{\mathrm{Re}}_{it}}$$ ④

```
Public Sub ReopenInv()

    ' ############################################################################################
    ' Capacity Reopen:
    ' ############################################################################################

    Dim Reopen As String = ""
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

      While Not Val(year.Rows(t).Cells(0).Value) = 0

        While Not Val(Plant.Rows(i).Cells(0).Value) = 0

          Reopen = Reopen + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + "(" + LTrim(Str(Plant.Rows(i).Cells(12).Value)) +
"*1000000)" + "*YRezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))

          i = i + 1
        End While
        i = 0

        GAMSequations.WriteLine(Reopen)
        Reopen = ""

        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

1-2-5- Capacity Shutdown

$$\boxed{\sum_z \sum_t \sum_i I_{ti}^{Clo} \cdot Y_{it}^{Clo}} \quad ⑤$$

```
Public Sub CloseDown()

    ' ##########################################################################################
    ' Capacity Closedown:
    ' ##########################################################################################

    Dim CloseDown As String = ""
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

      While Not Val(year.Rows(t).Cells(0).Value) = 0

        While Not Val(Plant.Rows(i).Cells(0).Value) = 0

          CloseDown = CloseDown + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + "(" + LTrim(Str(Plant.Rows(i).Cells(14).Value)) +
"*1000000)" + "*YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))

          i = i + 1
        End While
        i = 0

        GAMSequations.WriteLine(CloseDown)
        CloseDown = ""

        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

1-2-6- New Product Launch (NPL)

$$\boxed{\sum_{z}\sum_{t}\sum_{i}\sum_{j} I_{tij}^{NPL}\cdot\eta_{i,j}^{NPL}\cdot Y_{ztij}^{NPL}}$$ ⑥

```
Public Sub NPL()      ' Product launch costs:
        Dim NPL As String = ""
    Dim ni As Integer = 0
    i = 0 ;     j = 0;      r = 0;      t = 0;      z = 0;
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(k).Cells(0).Value) = 0
              If Not Val(ProductPlant.Rows(k).Cells(3).Value) = 0 Then
                If ProductPlant.Rows(k).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(k).Cells(4).Value = product.Rows(j).Cells(1).Value Then
                  If ProductPlant.Rows(k).Cells(5).Value = NPL_time_tableDataGridView.Rows(ni).Cells(1).Value And
ProductPlant.Rows(k).Cells(4).Value = NPL_time_tableDataGridView.Rows(ni).Cells(2).Value Then
                    While Not Val(NPL_time_tableDataGridView.Rows(ni).Cells(0).Value) = 0
                      NPL = NPL + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "(((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" +
LTrim(Str(ProductPlant.Rows(k).Cells(3).Value)) + "*1000000" + "*((YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 3)) + "','"
+ LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(3).Value))) + "/100)"
+ "+(YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 2)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(4).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t + 1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(5).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(6).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(7).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 2)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(8).Value))) + "/100)))*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))
                      GAMSequations.WriteLine(NPL)
                      NPL = ""
                      ni = ni + 1
                    End While
                    ni = 0
                  End If
                End If
              End If
              k = k + 1
            End While
            k = 0
            j = j + 1
          End While
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-2-7- relaunch a product

$$\boxed{I_{tij}^{PL}\cdot(Y_{ztij}^{PL}-Y_{ztij}^{NPL})}$$ ⑥

```
Public Sub PL()
    Dim PL As String = ""
    Dim ni As Integer = 0
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(k).Cells(0).Value) = 0

              If Not Val(ProductPlant.Rows(k).Cells(7).Value) = 0 Then

                If ProductPlant.Rows(k).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(k).Cells(4).Value = product.Rows(j).Cells(1).Value Then

                  PL = PL + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "(((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" +
LTrim(Str(ProductPlant.Rows(k).Cells(7).Value)) + "*1000000" + "*(YPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')))*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))

                  GAMSequations.WriteLine(PL)
                  PL = ""
                End If
              End If
              k = k + 1
            End While
            k = 0
            j = j + 1
          End While
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-3- Operations costs

Annual operations costs, as explained in section 4-1, consists of different terms, including unit based cost of supply and production, transportation costs, overutilisation costs of production, work force costs (normal, overutilisation, expanded, and redundancy case of mothballed), Tax and VAT, unmet demand penalty, and finally fixed annual costs of operation.

Unit-based Costs of production

Unit-based Costs of Supply

$$
\begin{aligned}
Oper = \sum_{z}\{\sum_{t}\{\sum_{i}\{ & \boxed{[(1+\Delta^{oper})^{t}\cdot C_{i}^{Unit}\, X_{ztij}^{A}]+[\sum_{j}(1+\Delta^{Sup})^{t}\cdot C_{ij}^{Sup}\cdot X_{ztij}^{A}]} \quad ① \\
& \boxed{+[\sum_{rj}(1+\Delta^{D})^{t}\cdot C_{irj}^{D}\cdot X_{ztrij}^{D}]} \quad ② \\
& \boxed{+[(1+\Delta^{oper})^{t}\cdot I_{i}^{Workforce}\cdot(Y_{zti}^{Dep}+\varepsilon_{i}^{OnA}Y_{zti}^{OnA}+\varepsilon_{i}^{Exp}Y_{zti}^{ExpWforce}-\varepsilon_{i}^{Fr}Y_{zti}^{FrAll})]} \quad ③ \\
& \boxed{+[(1+\Delta^{Oper})^{t}\cdot(I_{i}^{Oper}\cdot Y_{zti}^{Oper}+I_{i}^{OperFr}\cdot Y_{zti}^{FrAll}+I_{i}^{OperExp}\cdot Y_{zti}^{ExpWforce})]} \quad ④ \\
& \boxed{+[\sum_{r,j}[\sigma_{r}^{Tariff}+\sigma_{r,i}^{VAT}(1+\sigma_{r}^{Tariff})]\cdot C_{ztrj}^{Sale}\cdot X_{ztrij}^{D}]\ \}} \quad ⑤ \\
& \boxed{+[(1+\Delta^{Unmet})^{t}\sum_{j,r}C_{rj}^{Unmet}\cdot X_{ztij}^{Unmet}]} \quad ⑥
\end{aligned}
$$

Transportation costs

Work force cost

Annual operation and maintenance

VAT and Tariff Costs

Unmet demand Penalty

Formula 06

Now Visual Basic codes for different terms of this formulation will be explained further.

1-3-1- Unit based cost of operation

$$\boxed{\sum_{z}\sum_{t}\sum_{i}[(1+\Delta^{oper})^{t}\cdot C_{i}^{Unit}X_{ztij}^{A}]+[\sum_{j}(1+\Delta^{Sup})^{t}\cdot C_{ij}^{Sup}\cdot X_{ztij}^{A}} \qquad \text{①}$$

```
Public Sub UnitProduction()

    ‘ ####################################################################################
    ' Objective funcion-part1 (operation): Unit based cost of operation and supply
    ' ####################################################################################
    Dim UnitProduction As String
    UnitProduction = ""
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(k).Cells(0).Value) = 0
              UnitProduction = ""
              If ProductPlant.Rows(k).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(k).Cells(4).Value = product.Rows(j).Cells(1).Value Then

                UnitProduction = UnitProduction + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(7).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" +
LTrim(Str(ProductPlant.Rows(k).Cells(6).Value)) + "*XAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))
                UnitProduction = UnitProduction + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(2).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + LTrim(Str(Plant.Rows(i).Cells(17).Value)) +
"*XAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))

                GAMSequations.WriteLine(UnitProduction)
                UnitProduction = ""
              End If
              k = k + 1
            End While
            k = 0
            j = j + 1
          End While
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-3-2- Transportation Cost from production plant to sales region

$$\boxed{+\sum_{z}\sum_{t}\sum_{i}[\sum_{rj}(1+\Delta^{D})^{t}\cdot C^{D}_{irj}\cdot X^{D}_{ztrij}]}$$ ②

```
Public Sub Distribution()
    ' ################################################################################################
    ' Distribution and Transportation Costs:
    ' ################################################################################################
    Dim Distribution As String
    Distribution = ""
    i = 0
    j = 0
    r = 0
    t = 0
    k = 0
    l = 0
    z = 0
    Refresh()
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(region.Rows(r).Cells(0).Value) = 0
          While Not Val(Plant.Rows(i).Cells(0).Value) = 0
            While Not Val(product.Rows(j).Cells(0).Value) = 0
              While Not Val(Transportation.Rows(k).Cells(0).Value) = 0
                If Val(Transportation.Rows(k).Cells(1).Value) <> 0 Then
                  If Transportation.Rows(k).Cells(4).Value = region.Rows(r).Cells(1).Value And
Transportation.Rows(k).Cells(2).Value = Plant.Rows(i).Cells(1).Value And Transportation.Rows(k).Cells(3).Value =
product.Rows(j).Cells(1).Value Then
                    Distribution = Distribution + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(3).Value)) + ")**" + LTrim(Str(t)) + ")" + "*((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + "(" +
LTrim(Str(Transportation.Rows(k).Cells(1).Value)) + "*XDztrij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(r)) +
"','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))

                    GAMSequations.WriteLine(Distribution)
                    Distribution = ""
                  End If
                End If
                k = k + 1
              End While
              k = 0
              j = j + 1
            End While
            j = 0
            i = i + 1
          End While
          i = 0
          r = r + 1
        End While
        r = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-3-3- Work force costs

$$+\sum_{z}\sum_{t}\sum_{i}\left[\left(1+\Delta^{oper}\right)^{t}\cdot I_{i}^{Workforce}.\left(Y_{zti}^{Opr}+\varepsilon_{i}^{OnA}Y_{zti}^{OnA}+\varepsilon_{i}^{Exp}Y_{zti}^{ExpWforce}-\varepsilon_{i}^{Fr}Y_{zti}^{FrAll}\right)\right] \qquad ③$$

```
Public Sub work force()
    ' ####################################################################################################
    '  OWorkforce costs: Iwage.[Yoperation + (E OnA . Y OnA) + (E Exp . Y ExpWage) - (E Freeze. Y Freeze)]
    ' ####################################################################################################
    Dim Work force As String
    Workforce = ""
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0

          Workforce = Workforce + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(2).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + LTrim(Str(Plant.Rows(i).Cells(25).Value)) +
"*1000000" + "*(YDepzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+" +
LTrim(Str(Plant.Rows(i).Cells(32).Value)) + "*YOnAzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+" +
LTrim(Str(Plant.Rows(i).Cells(33).Value)) + "*YExpWforcezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')-
(" + LTrim(Str(Plant.Rows(i).Cells(34).Value)) + "*YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) +
"'))" + ")*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))

          GAMSequations.WriteLine(Workforce)
          Workforce = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-3-4- Fixed Operation Maintenance Costs

$$\boxed{+\sum_{z}\sum_{t}\sum_{i}[(1+\Delta^{Oper})^{t}.(I_{i}^{Oper}.Y_{zti}^{Oper}+I_{i}^{OperFr}.Y_{zti}^{FrAll}+I_{i}^{OperExp}.Y_{zti}^{ExpWforce})]}$$ ④

```
Public Sub overhead()
    ' ##############################################################################################################################
            ' Annual operations costs + Annual operations cost of expanded capacity + annual maintenance cost of
        mothballed capacity:
    ' ##############################################################################################################################
    Dim AnnuOper As String
    AnnuOper = ""
    i = 0
    j = 0
    r = 0
    t = 0
    k = 0
    l = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If Not Val(Plant.Rows(i).Cells(10).Value) = 0 Then

            AnnuOper = AnnuOper + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(2).Value)) + ")**" + LTrim(Str(t)) + ")*" + "((1+" +
LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*((" + LTrim(Str(Plant.Rows(i).Cells(10).Value)) +
"*1000000" + "*YOperzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'))" + "+(" +
LTrim(Str(Plant.Rows(i).Cells(36).Value)) + "*1000000" + "*YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "'))" + "+(" + LTrim(Str(Plant.Rows(i).Cells(35).Value)) + "*1000000" + "*YExpWforcezti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'))" + ")*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))

            GAMSequations.WriteLine(AnnuOper)
            AnnuOper = ""

          End If
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-3-5- VAT and Custom Duty Costs

$$+\sum_{z}\sum_{t}\sum_{i}[\sum_{r,j}[\sigma_{r}^{Tariff}+\sigma_{r,i}^{VAT}(1+\sigma_{r}^{Tariff})].C_{ztrj}^{Sale}\cdot X_{ztrij}^{D}] \tag{5}$$

```
Public Sub VATandTARIFF()
    Dim VATandTARIFF As String = ""
    Dim d As Integer = 0
    i = 0 ,  j = 0,   r = 0,   t = 0,  k = 0,  l = 0,   z = 0
   Refresh()
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(region.Rows(r).Cells(0).Value) = 0
          While Not Val(Plant.Rows(i).Cells(0).Value) = 0
            While Not Val(product.Rows(j).Cells(0).Value) = 0
              While Not Val(Transportation.Rows(k).Cells(0).Value) = 0
                If Val(Transportation.Rows(k).Cells(1).Value) <> 0 Then

  If Transportation.Rows(k).Cells(4).Value = region.Rows(r).Cells(1).Value And Transportation.Rows(k).Cells(2).Value =
Plant.Rows(i).Cells(1).Value And Transportation.Rows(k).Cells(3).Value = product.Rows(j).Cells(1).Value Then

                    While Not Val(Demand.Rows(d).Cells(0).Value) = 0
                      If Demand.Rows(d).Cells(2).Value = region.Rows(r).Cells(1).Value And
Demand.Rows(d).Cells(3).Value = product.Rows(j).Cells(1).Value And Demand.Rows(d).Cells(4).Value =
year.Rows(t).Cells(1).Value And Demand.Rows(d).Cells(5).Value = Scenario.Rows(z).Cells(1).Value Then

                        VATandTARIFF = VATandTARIFF + "+(1-" + LTrim(Str(Plant.Rows(i).Cells(26).Value)) + ")*" +
"(((1+" + LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*(" +
LTrim(Str(Val(Str(region.Rows(r).Cells(2).Value)))) + "+" + LTrim(Str(Val(Str(Transportation.Rows(k).Cells(5).Value)))) +
"*(1+" + LTrim(Str(Val(Str(region.Rows(r).Cells(2).Value)))) + "))*" + LTrim(Str(Val(Str(Demand.Rows(d).Cells(6).Value)))) +
"*1000*XDztrij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(r)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))"

                        GAMSequations.WriteLine(VATandTARIFF)
                        VATandTARIFF = ""
                      End If
                      d = d + 1
                    End While
                    d = 0
                  End If
                End If
                k = k + 1
              End While
              k = 0
              j = j + 1
            End While
            j = 0
            i = i + 1
          End While
          i = 0
          r = r + 1
        End While
        r = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

1-3-6- Unmet demand penalty

$$\boxed{+\sum_{z}\sum_{t}\sum_{i}\left[\left(1+\Delta^{Unmet}\right)^{t}\sum_{j,r}C_{rj}^{Unmet}\cdot X_{ztij}^{Unmet}\right]} \qquad \textcircled{6}$$

```
    ' ##########################################################################################
    ' Unmet demand penalty:
    ' ##########################################################################################
    Dim UnmetPenalty As String
    UnmetPenalty = ""
    i = 0
    j = 0
    r = 0
    t = 0
    k = 0
    l = 0
    z = 0
    Refresh()

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(region.Rows(r).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(Demand.Rows(k).Cells(0).Value) = 0

              If Val(Str(Demand.Rows(k).Cells(7).Value)) <> 0 Then

                If Demand.Rows(k).Cells(2).Value = region.Rows(r).Cells(1).Value And Demand.Rows(k).Cells(3).Value =
product.Rows(j).Cells(1).Value And Demand.Rows(k).Cells(5).Value = Scenario.Rows(z).Cells(1).Value Then

                  UnmetPenalty = UnmetPenalty + "+" + "((1+" + LTrim(Str(Interests.Rows(0).Cells(4).Value)) + ")**" +
LTrim(Str(t)) + ")*" + "((1+" + LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" + "(" +
LTrim(Str(Demand.Rows(k).Cells(7).Value)) + "*1000*XUnmetztrj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(r))
+ "','" + LTrim(Str(j)) + "'))*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))

                  GAMSequations.WriteLine(UnmetPenalty)

                  UnmetPenalty = ""

                End If
              End If

              k = k + 1
            End While
            k = 0
            j = j + 1
          End While
          j = 0
          r = r + 1
        End While
        r = 0
        t = t + 1

      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

1-4- R&D part of NPD

As explained in section 4-1-4, R&D and design part of NPD is not a plant-based activity, and would be done in the research centre or head/engineering quarter of the company.

$$R\&D = \sum_{z} \sum_{t} \sum_{j} I_{tj}^{R\&D} \cdot \eta_{j}^{R\&D} \cdot Y_{ztj}^{R\&D}$$

```
Public Sub R7D()
    ' ##############################################################################################
    ' R&D part of New Product Development (NPD) costs:
    ' ##############################################################################################
    Dim NPD As String
    Dim ni As Integer = 0
    NPD = ""
    i = 0
    j = 0
    r = 0
    t = 0
    z = 0
    Refresh()
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(product.Rows(j).Cells(0).Value) = 0
          If product.Rows(j).Cells(3).Value = True And Val(Str(product.Rows(j).Cells(4).Value)) <> 0 Then
            While Not Val(NPD_time_tableDataGridView.Rows(ni).Cells(0).Value) = 0

              NPD = NPD + "+" + "(((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" +
"((1+" + LTrim(Str(Interests.Rows(0).Cells(6).Value)) + ")**(-" + LTrim(Str(t)) + "))*" +
LTrim(Str(product.Rows(j).Cells(4).Value)) + "*1000000*((YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 3)) + "','" +
LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(2).Value))) + "/100)" + "+(YNPDztj('" +
LTrim(Str(z)) + "','" + LTrim(Str(t + 2)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(3).Value))) + "/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" +
LTrim(Str(t + 1)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(4).Value))) +
"/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(5).Value))) + "/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 1)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(6).Value))) +
"/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 2)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(7).Value))) + "/100)))*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))
              GAMSequations.WriteLine(NPD)
              NPD = ""

              ni = ni + 1
            End While
            ni = 0
          End If
          j = j + 1
        End While
        j = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

2- Constraints

In this section every constraint from 1 to 51 (according to section 4-2 of chapter 4) will be recalled and its Visual Basic® codes will be described, subsequently.

Cons.01: Total Capacity Constraints

$$K^{Max}_{z,t+1,i} = \overbrace{K^{Max}_{z,t,i}}^{\text{Maximum Available capacity in plant (i) in the last year}} + \underbrace{Z^{New}_{z,t,i}}_{\text{Whether it is a new created capacity in this year}} \cdot K^{Initial}_{i} + \overbrace{K^{Exp}_{z,t,i}}^{\text{Capacity Expansion amount of this plant in this year}} - \underbrace{K^{Fr}_{z,t,i}}_{\text{Whether this capacity would be temporary mothballed in this year}} - \overbrace{K^{Cl}_{z,t,i}}^{\text{Whether this capacity would be permanently closed-down mothballed in this year}} + \underbrace{K^{Re}_{z,t,i}}_{\text{Reopened capacity amount of this plant in this year (from frozen capacity)}}$$

Cons.01

```
Public Sub KMaxzti()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim KMax As String = ""
    Dim print As String = ""
    Dim KK As Integer = 0
    Dim E As Integer = 0
    Dim Y As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        t = t + 1
      End While
      E = t - 2   ' now E is equal to a year before the last year

      For Y = 0 To E
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          print = ""
          print = "KMaxztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(Y)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""

          If Y = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then

              'KMax(0,i)=LTrim(Str(plant.Rows(i).Cells(2).Value)) + "*100000"
              KMax = "KMaxztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(Y)) + "T" + LTrim(Str(i)) + ".. KMaxzti('" + LTrim(Str(z))
+ "','" + LTrim(Str(Y + 1)) + "','" + LTrim(Str(i)) + "')=E=(" + LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000)+KExpzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')-KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" +
LTrim(Str(i)) + "')-KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "') ;"
```

```
                        End If


                        If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
                            'KMax(0,i)=0
                            'KMax = "KMaxztiDEF" + LTrim(Str(Y)) + "T" + LTrim(Str(i)) + ".. KMaxzti('" + LTrim(Str(Y + 1)) + "','" +
LTrim(Str(i)) + "')=E=(ZNewzti('" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(plant.Rows(i).Cells(2).Value)) +
"*100000" + ") ;"
                            KMax = "KMaxztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(Y)) + "T" + LTrim(Str(i)) + ".. KMaxzti('" + LTrim(Str(z))
+ "','" + LTrim(Str(Y + 1)) + "','" + LTrim(Str(i)) + "')=E=0;"
                        End If

                        If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
                            'KMax(0,i)=0
                            KMax = "KMaxztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(Y)) + "T" + LTrim(Str(i)) + ".. KMaxzti('" + LTrim(Str(z))
+ "','" + LTrim(Str(Y + 1)) + "','" + LTrim(Str(i)) + "')=E= KRezti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')
;"

                        End If

                    End If



                    If Y <> 0 Then
                        If Str(Plant.Rows(i).Cells(23).Value) = True Then
                            KMax = "KMaxztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(Y)) + "T" + LTrim(Str(i)) + ".. KMaxzti('" + LTrim(Str(z))
+ "','" + LTrim(Str(Y + 1)) + "','" + LTrim(Str(i)) + "')=E= KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) +
"')+(ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(Plant.Rows(i).Cells(2).Value)) +
"*100000" + ")+KExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')-KFreezezti('" + LTrim(Str(z)) + "','" +
LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')-KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')+KRezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "') ;"
                        Else
                            KMax = "KMaxztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(Y)) + "T" + LTrim(Str(i)) + ".. KMaxzti('" + LTrim(Str(z))
+ "','" + LTrim(Str(Y + 1)) + "','" + LTrim(Str(i)) + "')=E= KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) +
"')+KExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')-KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y))
+ "','" + LTrim(Str(i)) + "')-KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "')+KRezti('" + LTrim(Str(z)) +
"','" + LTrim(Str(Y)) + "','" + LTrim(Str(i)) + "');"
                        End If
                    End If

                    GAMSequations.WriteLine(KMax)
                    KMax = ""

                    i = i + 1
                End While
                i = 0

            Next Y

            t = 0
            z = z + 1
        End While
        z = 0
    End Sub
```

Y_{zti}^{Exp} vs K_{zti}^{Exp}

$$Y_{zti}^{Exp} \leq K_{zti}^{Exp} \leq Y_{zti}^{Exp}.M$$

```
Public Sub YExpDEF()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim YExpDEFA, YExpDEFB As String
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    M = 1000000000
    Dim print As String = ""
    YExpDEFA = ""
    YExpDEFB = ""

    While Not Val(year.Rows(t).Cells(0).Value) = 0
      While Not Val(Plant.Rows(i).Cells(0).Value) = 0

        YExpDEFA = "YExpDEFAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') =L= KExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"

        print = ""
        print = "YExpDEFAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
        GAMSEquationDef.WriteLine(print)
        GAMSEquationDef.WriteLine("*")
        print = ""

        YExpDEFB = "YExpDEFBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(M)) + "=G= KExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"


        print = ""
        print = "YExpDEFBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
        GAMSEquationDef.WriteLine(print)
        GAMSEquationDef.WriteLine("*")
        print = ""

        GAMSequations.WriteLine(YExpDEFA)
        YExpDEFA = ""
        GAMSequations.WriteLine(YExpDEFB)
        YExpDEFB = ""

        i = i + 1
      End While
      i = 0
      t = t + 1
    End While
    t = 0

  End Sub
```

Y_{zti}^{Fr} vs K_{zti}^{Fr}

$$Y_{zti}^{Fr} \le K_{zti}^{Fr} \le Y_{zti}^{Fr}.M$$

The first part of this equation ($Y_{zti}^{Fr} \le K_{zti}^{Fr}$) is reflected in Cons.16, and will be coded there; but, the second part ($K_{zti}^{Fr} \le Y_{zti}^{Fr}.M$) is coded below:

```
Refresh()
    GAMSequations.WriteLine(" ")
    Dim YCloseDEFA, YCloseDEFB As String
    Dim KK As Integer = 0
    Dim CapFreezeLowerCon, CapFreezeUpperCon, CapFreezeCapMax As String
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    YCloseDEFA = ""
    YCloseDEFB = ""
    CapFreezeLowerCon = ""
    CapFreezeUpperCon = ""
    CapFreezeCapMax = ""
    Dim YClosebound As String = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          '#########################################################
          ' KFreezezti - M.YFreezezti <=0
          '#########################################################
          CapFreezeLowerCon = "CapFreezeLowerConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')-(" + LTrim(Str(M)) + "*YFreezezti('" + LTrim(Str(z))
+ "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'))=L=0 ;"
          '#########################################################
          print = ""
          print = "CapFreezeLowerConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(CapFreezeLowerCon)
          CapFreezeLowerCon = ""

          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Y_{zti}^{Cl} vs K_{zti}^{Cl}

$$Y_{zti}^{Cl} \le K_{zti}^{Cl} \le Y_{zti}^{Cl}.M$$

The first part of this equation ($Y_{zti}^{Cl} \le K_{zti}^{Cl}$) is reflected in Cons.23, and will be coded there; but, the second part ($K_{zti}^{Cl} \le Y_{zti}^{Cl}.M$) is coded below:

```
Public Sub FreezeCons()
    GAMSequations.WriteLine(" ")
    Dim YCloseDEFA, YCloseDEFB As String
    Dim KK As Integer = 0
    Dim CapFreezeLowerCon, CapFreezeUpperCon, CapFreezeCapMax As String
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    YCloseDEFA = ""
    YCloseDEFB = ""
    CapFreezeLowerCon = ""
    CapFreezeUpperCon = ""
    CapFreezeCapMax = ""
    Dim YClosebound As String = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          '########################################################
          ' KFreezezti - M.YFreezezti <=0
          '########################################################
          CapFreezeLowerCon = "CapFreezeLowerConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')-(" + LTrim(Str(M)) + "*YFreezezti('" + LTrim(Str(z))
+ "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'))=L=0 ;"
          '########################################################

          print = ""
          print = "CapFreezeLowerConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""

          GAMSequations.WriteLine(CapFreezeLowerCon)
          CapFreezeLowerCon = ""


          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

Y_{zti}^{Re} vs K_{zti}^{Re}

$$Y_{zti}^{\mathrm{Re}} \leq K_{zti}^{\mathrm{Re}} \leq Y_{zti}^{\mathrm{Re}}.M$$

The first part of this equation ($Y_{zti}^{\mathrm{Re}} \leq K_{zti}^{\mathrm{Re}}$) is reflected in Cons.20, and will be coded there; but, the second part ($K_{zti}^{\mathrm{Re}} \leq Y_{zti}^{\mathrm{Re}}.M$) is coded below:

```
Public Sub FreezeCons()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim YCloseDEFA, YCloseDEFB As String
    Dim KK As Integer = 0
    Dim CapFreezeLowerCon, CapFreezeUpperCon, CapFreezeCapMax As String
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    YCloseDEFA = ""
    YCloseDEFB = ""
    CapFreezeLowerCon = ""
    CapFreezeUpperCon = ""
    CapFreezeCapMax = ""
    Dim YClosebound As String = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          '##########################################################
          ' KFreezezti - M.YFreezezti <=0
          '##########################################################
          CapFreezeLowerCon = "CapFreezeLowerConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')-(" + LTrim(Str(M)) + "*YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'))=L=0 ;"
          '##########################################################

          print = ""
          print = "CapFreezeLowerConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""

          GAMSequations.WriteLine(CapFreezeLowerCon)
          CapFreezeLowerCon = ""


          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.02: Possibility Matrix and normal production 01

$$\sum_{j} \gamma_{ij} \cdot X^{A}_{ztij} \leq K^{Max}_{zti}$$

Cons.02

```
Public Sub NormConsA()
    GAMSequations.WriteLine(" ")
    Dim KK As Integer
    t = 0;     i = 0;       j = 0;      KK = 0;       M = 1000000000;       z = 0;
    Dim NormConsA As String = "";       Dim Print As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          NormConsA = "NormConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. 0"
          Print = "NormConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(Print)
          GAMSEquationDef.WriteLine("*")
          Print = ""
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(KK).Cells(0).Value) = 0
              If ProductPlant.Rows(KK).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(KK).Cells(4).Value = product.Rows(j).Cells(1).Value And Str(ProductPlant.Rows(KK).Cells(2).Value) <> "0"
And Str(ProductPlant.Rows(KK).Cells(2).Value) <> "" Then
                NormConsA = NormConsA + "+" + LTrim(Str(ProductPlant.Rows(KK).Cells(2).Value)) + "* XAztij('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')"
              End If
              KK = KK + 1
            End While
            KK = 0
            j = j + 1
          End While
          GAMSequations.WriteLine(NormConsA)
          NormConsA = ""
          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              NormConsA = "+0 =L=" + LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000" + " ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
              NormConsA = "+0 =L=0" + " ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
              NormConsA = "+0 =L=0" + " ;"
            End If
          End If
          If t <> 0 Then
            NormConsA = "+0 =L= KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"
          End If
          GAMSequations.WriteLine(NormConsA)
          NormConsA = ""
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.03: Possibility Matrix and normal production 02

If γ_{ij}=0, then $\sum_{t} X^{A}_{ztij}$=0 $\quad \forall z, i,\ j$ **Cons.03**

```
Public Sub NormConsC()
    GAMSequations.WriteLine(" ")
    Dim KK As Integer= 0
    Dim GAMAij As String = ""
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim NormConsC As String
    NormConsC = ""
    Dim Print As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(Plant.Rows(i).Cells(0).Value) = 0
        While Not Val(product.Rows(j).Cells(0).Value) = 0
          While Not Val(ProductPlant.Rows(KK).Cells(0).Value) = 0
            If ProductPlant.Rows(KK).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(KK).Cells(4).Value = product.Rows(j).Cells(1).Value And Str(ProductPlant.Rows(KK).Cells(2).Value) <> "0"
And Str(ProductPlant.Rows(KK).Cells(2).Value) <> "" Then
              GAMAij = "Yes"
            End If
            KK = KK + 1
          End While
          KK = 0
          If GAMAij <> "Yes" Then
            NormConsC = "NormConsCzij" + LTrim(Str(z)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + " .. 0"
            Print = ""
            Print = "NormConsCzij" + LTrim(Str(z)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
            GAMSEquationDef.WriteLine(Print)
            GAMSEquationDef.WriteLine("*")
            Print = ""
            While Not Val(year.Rows(t).Cells(0).Value) = 0
              NormConsC = NormConsC + "+XAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')"
              t = t + 1
            End While
            t = 0
            NormConsC = NormConsC + "=E=0 ;"
            GAMSequations.WriteLine(NormConsC)
            NormConsC = ""
            GAMAij = ""
          End If
          GAMAij = ""
          NormConsC = ""
          j = j + 1
        End While
        j = 0
        GAMAij = ""
        NormConsC = ""
        i = i + 1
      End While
      i = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.04 and Cons.05 : Possibility Matrix and overutilisation production

$$\sum_{j}(\gamma_{ij}\cdot X^{A}_{ztij})-M.Y^{OnA}_{zti}\le(\mu^{Max}_{i_i}\cdot K^{Max}_{zti})$$

Cons.04

$$\sum_{j}(\gamma_{ij}\cdot X^{A}_{ztij})+M.(1-Y^{OnA}_{zti})\ge(1.00001\,\mu^{Max}_{i_i}\cdot K^{Max}_{zti})$$

Cons.05

```
Public Sub OvNormalCons()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim KK As Integer
    t = 0
    i = 0
    j = 0
    z = 0
    KK = 0
    M = 1000000000
    Dim print As String = ""

    ' ############################################################################
    '     sum [gama (i,j).XA(t,i,j)]-[M.YOnA] <= KMaxNormal (t,i)
    ' ############################################################################

    Dim OverNormConsA As String = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0

          OverNormConsA = "OverNormConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. 0"
          print = ""
          print = "OverNormConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""

          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(KK).Cells(0).Value) = 0

              If ProductPlant.Rows(KK).Cells(5).Value = Plant.Rows(i).Cells(1).Value And ProductPlant.Rows(KK).Cells(4).Value = product.Rows(j).Cells(1).Value Then

                OverNormConsA = OverNormConsA + "+" + LTrim(Str(ProductPlant.Rows(KK).Cells(2).Value)) + "* XAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')"

              End If
              KK = KK + 1
            End While
            KK = 0
            j = j + 1
          End While
          OverNormConsA = OverNormConsA + "-(" + LTrim(Str(M)) + "*YOnAzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'))"
          GAMSequations.WriteLine(OverNormConsA)
          OverNormConsA = ""
```

```
          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              'KMax(0,i)=LTrim(Str(plant.Rows(i).Cells(2).Value)) + "*100000"
              OverNormConsA = "+0 =L=" + LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000*" +
LTrim(Str(Plant.Rows(i).Cells(3).Value)) + " ;"
            End If

            If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
              'KMax(0,i)=0
              OverNormConsA = "+0 =E=0" + " ;"
            End If

            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
              'KMax(0,i)=0
              OverNormConsA = "+0 =E=0" + " ;"
            End If

          End If

          If t <> 0 Then
            OverNormConsA = "+0 =L= KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Str(Plant.Rows(i).Cells(3).Value)) + " ;"
          End If

          GAMSequations.WriteLine(OverNormConsA)
          OverNormConsA = ""
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0


    ' ################################################################################
    '     sum [gama (i,j).XA(t,i,j)]+[M.(1-YOnA)] >= 1.00001.KMaxNormal (t,i)
    ' ################################################################################
    Dim OverNormConsB As String = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          OverNormConsB = "OverNormConsBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. 0"
          print = ""
          print = "OverNormConsBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""

          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(KK).Cells(0).Value) = 0
              If ProductPlant.Rows(KK).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(KK).Cells(4).Value = product.Rows(j).Cells(1).Value Then

                OverNormConsB = OverNormConsB + "+" + LTrim(Str(ProductPlant.Rows(KK).Cells(2).Value)) + "* XAztij('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')"
```

```
              End If

              KK = KK + 1
            End While
            KK = 0
            j = j + 1
          End While
          OverNormConsB = OverNormConsB + "+(" + LTrim(Str(M)) + "*(1-YOnAzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t))
+ "','" + LTrim(Str(i)) + "')))"
          GAMSequations.WriteLine(OverNormConsB)
          OverNormConsB = ""

          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              'KMax(0,i)=LTrim(Str(plant.Rows(i).Cells(2).Value)) + "*100000"
              OverNormConsB = "+0 =G=" + LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000*1.00001*" +
LTrim(Str(Plant.Rows(i).Cells(3).Value)) + " ;"
            End If

            If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
              'KMax(0,i)=0
              OverNormConsB = "+0 =G=0" + " ;"
            End If

            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
              'KMax(0,i)=0
              OverNormConsB = "+0 =G=0" + " ;"
            End If

          End If

          If t <> 0 Then
            OverNormConsB = "+0 =G= 1.00001*KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*"
+ LTrim(Str(Plant.Rows(i).Cells(3).Value)) + " ;"
          End If

          GAMSequations.WriteLine(OverNormConsB)
          OverNormConsB = ""
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Y^{Ope}_{zti} vs K^{Opr}_{zti}

$$Y^{Opr}_{zti} \leq K^{Max}_{zti} \leq M.Y^{Opr}_{zti} \qquad Y^{Opr}_{zti} \in [0,1] \qquad \forall i,t$$

```
Public Sub YOper()
    GAMSequations.WriteLine(" ")
    Dim YOperA As String = ""
    Dim YOperB As String = ""
    Dim print As String = ""
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              YOperA = "YOperztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YOperzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=1 ;"
            Else
              YOperA = "YOperztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YOperzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=0 ;"
            End If
          End If
          If t >= 1 Then
            YOperA = "YOperztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YOperzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L=KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') ;"

            YOperB = "YOperztiDEFB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YOperzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(M)) + "=G=KMaxzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"
            GAMSequations.WriteLine(YOperB)
            YOperB = ""
            print = ""
            print = "YOperztiDEFB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""
          End If
          GAMSequations.WriteLine(YOperA)
          YOperA = ""
          print = ""
          print = "YOperztiDEF" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.06: New capacity constraint

$$\sum_{t=0}^{T} Z_{zit}^{New} \leq 1$$

Cons.06

```
Public Sub NewCapCon()  '   SUMt ZNew (t,i) <=1         For all i
    t = 0
    i = 0
    z = 0
    Dim NewCapCon As String
    Dim print As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(Plant.Rows(i).Cells(0).Value) = 0
        If Plant.Rows(i).Cells(23).Value = True Then
          NewCapCon = "NewCapConzi" + LTrim(Str(z)) + "T" + LTrim(Str(i)) + " .. +0"
          print = "NewCapConzi" + LTrim(Str(z)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          While Not Val(year.Rows(t).Cells(0).Value) = 0
            NewCapCon = NewCapCon + "+" + "ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')"
            t = t + 1
          End While
          t = 0
          NewCapCon = NewCapCon + "=L=1 ;"
          GAMSequations.WriteLine(NewCapCon)
          NewCapCon = ""
        End If
        i = i + 1
      End While
      i = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.07: Capacity Expansion 01

$$\sum_{t} Y_{zti}^{Exp} \leq E_i$$

Cons.07

```
Public Sub ExpansionTimes()
    GAMSequations.WriteLine(" ")
    Dim CapExpConsA As String
    Dim LL As Integer = 0
    t = 0;      i = 0;      j = 0;      z = 0;      M = 1000000000;
    Dim print As String = ""
    CapExpConsA = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(Plant.Rows(i).Cells(0).Value) = 0
        If Str(Plant.Rows(i).Cells(6).Value) <> "" And Plant.Rows(i).Cells(6).Value <> 0 Then
          CapExpConsA = "CapExpConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. 0"
          print = ""
          print = "CapExpConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          While Not Val(year.Rows(t).Cells(0).Value) = 0
```

```
                        CapExpConsA = CapExpConsA + "+YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')"
                        If LL = 3 Then
                            GAMSequations.WriteLine(CapExpConsA)
                            LL = 0
                            CapExpConsA = ""
                        End If
                        LL = LL + 1
                        t = t + 1
                    End While
                    CapExpConsA = CapExpConsA + "+0 =L=" + LTrim(Str(Plant.Rows(i).Cells(6).Value)) + " ;"
                    GAMSequations.WriteLine(CapExpConsA)
                    CapExpConsA = ""
                End If
                t = 0
                i = i + 1
            End While
            i = 0
            z = z + 1
        End While
        z = 0
    End Sub
```

Cons.08: Capacity Expansion 02

$$K_{zti}^{Exp} \leq Y_{zti}^{Exp} \cdot \vartheta_{i}^{E-Max} K_{t=0,i}^{Max}$$

Cons.08

```
Public Sub ExpKmaxRelation()
        GAMSequations.WriteLine(" ")
        Dim ExpKmax As String = ""
        Dim KK As Integer = 0
        Dim LL As Integer = 0
        Dim GG As Integer = 0
        t = 1 ;      i = 0;      j = 0;      z = 0;      M = 1000000000
        Dim print As String = ""
        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    If Str(Plant.Rows(i).Cells(6).Value) <> "" And Plant.Rows(i).Cells(6).Value <> 0 Then

                        ExpKmax = "ExpKMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KExpzti('" + LTrim(Str(z))
+ "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L=KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"

                        print = ""
                        print = "ExpKMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(ExpKmax)
                        ExpKmax = ""
                    End If
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            z = z + 1
        End While
        z = 0
    End Sub
```

Cons.09: Capacity Expansion 03

$$\vartheta_i^{E-\min} K_{i,t=0}^{Max} \cdot Y_{zti}^{Exp} \leq K_{zti}^{Exp}$$

Cons.09

```
Public Sub MinExpanCons()
      Refresh()
      GAMSequations.WriteLine(" ")
      Dim print As String = ""
      Dim CapExpConsC As String= ""
      t = 0
      i = 0
      j = 0
      z = 0
      M = 1000000000
      While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
         While Not Val(year.Rows(t).Cells(0).Value) = 0
            While Not Val(Plant.Rows(i).Cells(0).Value) = 0
               If Str(Plant.Rows(i).Cells(6).Value) <> "" And Plant.Rows(i).Cells(6).Value <> 0 Then

                  CapExpConsC = "CapExpConsCzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KExpzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=G= (" + LTrim(Str(Plant.Rows(i).Cells(7).Value)) + "*" +
LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000" + "* YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i))
+ "')) ;"
                  print = ""
                  print = "CapExpConsCzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                  GAMSEquationDef.WriteLine(print)
                  GAMSEquationDef.WriteLine("*")
                  print = ""
                  GAMSequations.WriteLine(CapExpConsC)
                  CapExpConsC = ""

               End If
               i = i + 1
            End While
            i = 0
            t = t + 1
         End While
         t = 0
         z = z + 1
      End While
      z = 0
   End Sub
```

Cons.10: Capacity Mothball 01

$$K_{zti}^{Fr} + M.(1 - Y_{zti}^{Fr}) \geq K_{zti}^{Max}$$

Cons.10

```
    GAMSequations.WriteLine(" ")
    Dim YCloseDEFA, YCloseDEFB As String
    Dim KK As Integer = 0
    Dim CapFreezeLowerCon, CapFreezeUpperCon, CapFreezeCapMax As String
    t = 0;      i = 0;      j = 0;      z = 0;      M = 1000000000;
    Dim print As String = ""
    YCloseDEFA = "";      YCloseDEFB = "";      CapFreezeLowerCon = "";      CapFreezeUpperCon = "";
    CapFreezeCapMax = "";      Dim YClosebound As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              'KMax(0,i)=LTrim(Str(plant.Rows(i).Cells(2).Value)) + "*100000"
              CapFreezeUpperCon = "CapFreezeUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YFreezezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=(1-" + LTrim(Str(Plant.Rows(i).Cells(21).Value)) + ")*" +
LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000" + " ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
              'KMax(0,i)=0
              CapFreezeUpperCon = "CapFreezeUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YFreezezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=0 ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
              'KMax(0,i)=0
              CapFreezeUpperCon = "CapFreezeUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YFreezezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=0 ;"
            End If
          End If

          If t <> 0 Then
            CapFreezeUpperCon = "CapFreezeUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YFreezezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') ;"
          End If
         print = ""
          print = "CapFreezeUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(CapFreezeUpperCon)
          CapFreezeUpperCon = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.11: Capacity Mothball 02

$$K_{zti}^{Fr} \le K_{zti}^{Max}$$

Cons.11

```
Public Sub KfreezeKMax()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim KFreezrKMaxA As String = ""
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    M = 1000000000
    Dim print As String = ""
    While Not Val(year.Rows(t).Cells(0).Value) = 0
      While Not Val(Plant.Rows(i).Cells(0).Value) = 0
        If t = 0 Then
          If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
            'KMax(0,i)=LTrim(Str(plant.Rows(i).Cells(2).Value)) + "*100000"
            KFreezrKMaxA = "KFreezrKMaxAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KFreezezti('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L= " + LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000*(1-"
+ LTrim(Str(Plant.Rows(i).Cells(21).Value)) + ") ;"
          End If

          If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
            'KMax(0,i)=0
            KFreezrKMaxA = "KFreezrKMaxAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KFreezezti('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=0 ;"
          End If

          If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
            'KMax(0,i)=0
            KFreezrKMaxA = "KFreezrKMaxAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KFreezezti('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=0 ;"
          End If
        End If
        If t <> 0 Then
          KFreezrKMaxA = "KFreezrKMaxAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KFreezezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L= KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "')*(1-" + LTrim(Str(Plant.Rows(i).Cells(21).Value)) + ") ;"
        End If
        print = ""
        print = "KFreezrKMaxAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
        GAMSEquationDef.WriteLine(print)
        GAMSEquationDef.WriteLine("*")
        print = ""
        GAMSequations.WriteLine(KFreezrKMaxA)
        KFreezrKMaxA = ""
        i = i + 1
      End While
      i = 0
      t = t + 1
    End While
    t = 0


  End Sub
```

Cons.12: Capacity Reopen 01

$$K_{z,t+1,i}^{FrAll} = K_{zti}^{FrAll} + (K_{zti}^{Fr} - K_{zti}^{\mathrm{Re}})$$

Cons.12

```
Public Sub KFreezeAll()

    Refresh()
    GAMSequations.WriteLine(" ")
    Dim FrozenReopenA As String
    Dim KK As Integer = 0
    Dim LL As Integer = 0
    Dim GG As Integer = 0
    t = 1
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    FrozenReopenA = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

      While Not Val(year.Rows(t).Cells(0).Value) = 0
        t = t + 1
      End While
      GG = t - 1  ' now GG is equal to the last year

      If GG >= 1 Then
        For KK = 0 To GG - 1
          While Not Val(Plant.Rows(i).Cells(0).Value) = 0

            print = ""
            print = "KfreezeAllDEFzti" + LTrim(Str(z)) + "T" + LTrim(Str(KK)) + "T" + LTrim(Str(i))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""


            FrozenReopenA = "KfreezeAllDEFzti" + LTrim(Str(z)) + "T" + LTrim(Str(KK)) + "T" + LTrim(Str(i)) + " ..
KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(KK + 1)) + "','" + LTrim(Str(i)) + "')=E=KFreezeAllzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(KK)) + "','" + LTrim(Str(i)) + "')+(KFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(KK)) + "','" + LTrim(Str(i)) + "')-
KRezti('" + LTrim(Str(z)) + "','" + LTrim(Str(KK)) + "','" + LTrim(Str(i)) + "')) ;"
            GAMSequations.WriteLine(FrozenReopenA)

            FrozenReopenA = ""

            i = i + 1
          End While
          i = 0
        Next KK
      End If
      t = 0
      z = z + 1
    End While
    z = 0


  End Sub
```

Y_{zti}^{FrAll} vs K_{zti}^{FrAll} and its boundary conditions

$$Y_{zti}^{FrAll} \le K_{zti}^{FrAll} \le Y_{zti}^{FrAll}.M$$

```
Public Sub YFreezeAll()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim YFreezeAllC, YFreezeAllD As String
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    M = 1000000000
    Dim print As String = ""
    YFreezeAllC = ""
    YFreezeAllD = ""

    '############################################################
    ' YFreezeAll <= KFreezeAll <= M.KFreezeAll
    '############################################################
    While Not Val(year.Rows(t).Cells(0).Value) = 0
      While Not Val(Plant.Rows(i).Cells(0).Value) = 0
        If t = 0 Then
          If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then

            YFreezeAllC = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') =L= KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"

            print = ""
            print = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""

            YFreezeAllD = "YFreezeAllD" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(M)) + "=G= KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"

            print = ""
            print = "YFreezeAllD" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""

            GAMSequations.WriteLine(YFreezeAllC)
            YFreezeAllC = ""
            GAMSequations.WriteLine(YFreezeAllD)
            YFreezeAllD = ""
          End If


          If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then

            YFreezeAllC = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') =E=0 ;"
```

```
                        print = ""
                        print = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(YFreezeAllC)
                        YFreezeAllC = ""
                    End If


                    If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
                        YFreezeAllC = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') =E=0 ;"
                        print = ""
                        print = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(YFreezeAllC)
                        YFreezeAllC = ""
                    End If

                End If

                If t <> 0 Then
                    YFreezeAllC = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') =L= KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"
                    print = ""
                    print = "YFreezeAllC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    YFreezeAllD = "YFreezeAllD" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(M)) + "=G= KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"
                    print = ""
                    print = "YFreezeAllD" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(YFreezeAllC)
                    YFreezeAllC = ""
                    GAMSequations.WriteLine(YFreezeAllD)
                    YFreezeAllD = ""
                End If

                i = i + 1
            End While
            i = 0
            t = t + 1
        End While
        t = 0

    End Sub
```

Cons.13 and Cons.14: Reopen capacity 02

$$K_{zti}^{\text{Re}} + M.(1 - Y_{zti}^{\text{Re}}) \geq K_{zti}^{FrAll} \qquad \textbf{Cons. 13}$$

$$K_{zti}^{\text{Re}} \leq K_{zti}^{FrAll} \qquad \textbf{Cons.14}$$

```
Public Sub ReopenCons()
        Refresh()
        GAMSequations.WriteLine(" ")
        Dim KK As Integer = 0
        Dim LL As Integer = 0
        Dim print As String = ""
        Dim FrozenReopenB As String
        t = 0
        i = 0
        j = 0
        z = 0
        M = 1000000000
        FrozenReopenB = ""
        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    '############################################################
                    ' KRe(t,i)<=KFreezeALL(t,i)
                    '############################################################
                    FrozenReopenB = "FrozenReopenBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KRezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L= KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') ;"
                    '############################################################
                    print = ""
                    print = "FrozenReopenBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(FrozenReopenB)
                    FrozenReopenB = ""
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            z = z + 1
        End While
        z = 0
        '---------------------------------------------------------------------------------------------

        Dim ReopenConsD As String = ""

        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    '########################################################
                    ' KRe + M.(1-YRe) >= KFreezeAll (Min)
                    '########################################################
                    ReopenConsD = "ReopenConsDzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KRezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YRezti('" + LTrim(Str(z)) + "','" +
```

```
LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=" + "KFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')
;"    '+ LTrim(Str(plant.Rows(i).Cells(13).Value))
          '###########################################################
          print = ""
          print = "ReopenConsDzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(ReopenConsD)
          ReopenConsD = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.16: Capacity Shutdown 02

$$K^{Cl}_{z,i,t} + (1 - Y^{Cl}_{zti}).M \geq K^{Max}_{z,i,t+1}$$

Cons.16

```
Public Sub YCloseDEF2()
    GAMSequations.WriteLine(" ")
    Dim YCloseDEFA, YCloseDEFB As String
    Dim KK As Integer = 0
    Dim CapCloseUpperCon As String = ""
    t = 0;      i = 0;      j = 0;      z = 0;      M = 1000000000
    Dim print As String = ""
    YCloseDEFA = ""
    YCloseDEFB = ""
    Dim YClosebound As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              CapCloseUpperCon = "CapCloseUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YClosezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=(1-" + LTrim(Str(Plant.Rows(i).Cells(21).Value)) + ")*" +
LTrim(Str(Plant.Rows(i).Cells(2).Value)) + "*100000" + " ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
              CapCloseUpperCon = "CapCloseUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YClosezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=0 ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
              CapCloseUpperCon = "CapCloseUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YClosezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=0 ;"
            End If
          End If

          If t <> 0 Then
            CapCloseUpperCon = "CapCloseUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')+(" + LTrim(Str(M)) + "*(1-YClosezti('" +
```

```
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')))=G=KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "');"
          End If
          '############################################################
          print = ""
          print = "CapCloseUpperConzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(CapCloseUpperCon)
          CapCloseUpperCon = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

Cons.18: Capacity Shutdown 03

$$K_{zti}^{Cl} \le K_{zti}^{Max}$$

Cons.18

```
Public Sub YCloseDEF3()
    GAMSequations.WriteLine(" ")
    Dim YCloseDEFA, YCloseDEFB As String
    Dim KK As Integer = 0
    Dim CapCloseCapMax As String = ""
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    YCloseDEFA = ""
    YCloseDEFB = ""
    Dim YClosebound As String = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If t = 0 Then
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = False Then
              CapCloseCapMax = "CapCloseCapMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L=" + LTrim(Str(Plant.Rows(i).Cells(2).Value)) +
"*100000" + " ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = True And Str(Plant.Rows(i).Cells(24).Value) = False Then
              CapCloseCapMax = "CapCloseCapMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=0 ;"
            End If
            If Str(Plant.Rows(i).Cells(23).Value) = False And Str(Plant.Rows(i).Cells(24).Value) = True Then
              CapCloseCapMax = "CapCloseCapMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=0 ;"
            End If
          End If
```

```
                    If t <> 0 Then
                        CapCloseCapMax = "CapCloseCapMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. KClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L=KMaxzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') ;"
                    End If
                    '############################################################
                    print = ""
                    print = "CapCloseCapMaxzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(CapCloseCapMax)
                    CapCloseCapMax = ""
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            z = z + 1
        End While
        z = 0
    End Sub
```

Cons.20, 21 and 22: Merge / Relocation Constraints

$$Z_{zti}^{New} \cdot n_i^{merge} \le \sum_{\tau=0}^{\tau=t} p_i^{merge}$$

Cons.20

$$p_i^{merge} = Y_{zt,R_1}^{Close} + Y_{zt,R_2}^{Close} + Y_{zt,R_3}^{Close} + Y_{zt,R_4}^{Close}$$

Cons.21

If $n_i^{merge} \ge 0 \quad \Rightarrow \quad Z_{zti}^{New} = 0$ for t=0 and $\forall z, i$

Cons.22

```
Public Sub MergeRelocation()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim MergeRelocationA As String = ""
    Dim MergeRelocationB As String = ""
    Dim ZNewMergeRelocationA As String = ""
    Dim r As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    Dim print As String = ""
    While Not Val(Plant.Rows(i).Cells(0).Value) = 0
      If Val(Str(Plant.Rows(i).Cells(27).Value)) >= 1 Then
        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
          ZNewMergeRelocationA = "ZNewMergeRelocationA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "..
ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=0;"
          print = ""
          print = "ZNewMergeRelocationA" + LTrim(Str(z)) + "T" + LTrim(Str(0)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(ZNewMergeRelocationA)
          ZNewMergeRelocationA = ""
          While Not Val(year.Rows(t).Cells(0).Value) = 0
            MergeRelocationA = ".. (0"
            For x = 0 To t
              While Not Val(Plant.Rows(r).Cells(0).Value) = 0
                If Val(Str(Plant.Rows(i).Cells(27).Value)) = 4 Then
                  If Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(28).Value Or Plant.Rows(r).Cells(1).Value =
Plant.Rows(i).Cells(29).Value Or Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(30).Value Or Plant.Rows(r).Cells(1).Value
= Plant.Rows(i).Cells(31).Value Then
                    MergeRelocationA = MergeRelocationA + "+YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(x)) + "','" +
LTrim(Str(r)) + "')"
                  End If
                End If

                If Val(Str(Plant.Rows(i).Cells(27).Value)) = 3 Then
                  If Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(28).Value Or Plant.Rows(r).Cells(1).Value =
Plant.Rows(i).Cells(29).Value Or Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(30).Value Then
                    MergeRelocationA = MergeRelocationA + "+YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(x)) + "','" +
LTrim(Str(r)) + "')"
                  End If
                End If

                If Val(Str(Plant.Rows(i).Cells(27).Value)) = 2 Then
```

```
                                    If Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(28).Value Or Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(29).Value Then
                                        MergeRelocationA = MergeRelocationA + "+YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(x)) + "','" + LTrim(Str(r)) + "')"
                                    End If
                                End If

                                If Val(Str(Plant.Rows(i).Cells(27).Value)) = 1 Then
                                    If Plant.Rows(r).Cells(1).Value = Plant.Rows(i).Cells(28).Value Then
                                        MergeRelocationA = MergeRelocationA + "+YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(x)) + "','" + LTrim(Str(r)) + "')"
                                    End If
                                End If

                                r = r + 1
                            End While
                            r = 0
                        Next x
                        If MergeRelocationA <> ".. (0" Then
                            MergeRelocationA = MergeRelocationA + ")=G=(" + Str(Val(Plant.Rows(i).Cells(27).Value)) + "*ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "'));"
                            print = ""
                            print = "MergeRelocationBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                            GAMSEquationDef.WriteLine(print)
                            GAMSEquationDef.WriteLine("*")
                            MergeRelocationB = print + MergeRelocationA
                            print = ""
                            GAMSequations.WriteLine(MergeRelocationB)
                            MergeRelocationB = ""
                        End If
                        t = t + 1
                    End While
                    t = 0
                    z = z + 1
                End While
                z = 0
            End If
            i = i + 1
        End While
        i = 0
    End Sub
```

Cons.32: New Product Launch

$$[(Y^{A}_{ztij} - Y^{A}_{z,t-1,i,j}) - 1] + M.(1 - Y^{NPL}_{ztij}) \geq 0$$

$$(Y^{A}_{ztij} - Y^{A}_{z,t-1,i,j}) \leq Y^{NPL}_{ztij}$$

Cons.23

```
  Public Sub YNPLDEF()

    Refresh()
    GAMSequations.WriteLine(" ")
    Dim YNPLDEFA As String = ""
    Dim YNPLDEFB As String = ""
    Dim print As String = ""
    Dim SUMY As String = ""
    Dim KK As Integer = 1
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(KK).Cells(0).Value) = 0
              If ProductPlant.Rows(KK).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(KK).Cells(4).Value = product.Rows(j).Cells(1).Value Then
                If Val(ProductPlant.Rows(KK).Cells(3).Value) > 0 Then
                  If t = 0 Then
                    YNPLDEFA = "YNPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" +
LTrim(Str(j)) + " .. (1-YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))*" +
LTrim(Str(M)) + "+((YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-YAztij('" +
LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))-1)=G=0 ;"
                    '**********************************************
                    print = ""
                    print = "YNPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(YNPLDEFA)
                    YNPLDEFA = ""
                    '**********************************************
                    YNPLDEFB = "YNPLDEFBztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" +
LTrim(Str(j)) + " .. YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=G=(YAztij('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t -
1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')) ;"
                    print = ""
                    print = "YNPLDEFBztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(YNPLDEFB)
                    YNPLDEFB = ""
                    '**********************************************
                  ElseIf Val(ProductPlant.Rows(KK).Cells(3).Value) = 0 Then
                    YNPLDEFA = "YNPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" +
LTrim(Str(j)) + " .. YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=E=0 ;"
                    '**********************************************
                    print = ""
```

```
                    print = "YNPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(YNPLDEFA)
                    YNPLDEFA = ""
                    '*********************************************
                  End If
                End If
                If t > 0 Then
                  SUMY = "(0"
                  For tt = 0 To t - 1
                    SUMY = SUMY + "+YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(tt)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')"
                  Next tt
                  SUMY = SUMY + ")"
                  YNPLDEFA = "YNPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
+ " .. (1-YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))*" + LTrim(Str(M)) +
"+((YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-" + SUMY + ")-1)=G=0 ;"
                  '*********************************************
                  print = ""
                  print = "YNPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                  GAMSEquationDef.WriteLine(print)
                  GAMSEquationDef.WriteLine("*")
                  print = ""
                  GAMSequations.WriteLine(YNPLDEFA)
                  YNPLDEFA = ""
                  '*********************************************
                  YNPLDEFB = "YNPLDEFBztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
+ " .. YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=G=(YAztij('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t -
1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')) ;"
                  print = ""
                  print = "YNPLDEFBztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                  GAMSEquationDef.WriteLine(print)
                  GAMSEquationDef.WriteLine("*")
                  print = ""
                  GAMSequations.WriteLine(YNPLDEFB)
                  YNPLDEFB = ""
                  SUMY = ""
                End If

              End If
              SUMY = ""
              KK = KK + 1
            End While
            KK = 0
            j = j + 1
          End While
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      i = 0
      j = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Y^{A}_{zti} vs X^{A}_{zti} and its boundary conditions

$$Y^{A}_{ztij} \le X^{A}_{ztij} \le Y^{A}_{ztij}.M$$

```
Public Sub YAztijDEF()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim YAztijDEFA, YAztijDEFB As String
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    YAztijDEFA = ""
    YAztijDEFB = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            YAztijDEFA = "YAztijDEFA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + " ..
YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "') =L= XAztij('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "') ;"
            print = ""
            print = "YAztijDEFA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""

            YAztijDEFB = "YAztijDEFB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + " ..
YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Str(M)) + "=G= XAztij('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "') ;"
            print = ""
            print = "YAztijDEFB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""

            GAMSequations.WriteLine(YAztijDEFA)
            YAztijDEFA = ""
            GAMSequations.WriteLine(YAztijDEFB)
            YAztijDEFB = ""

            j = j + 1
          End While
          j = 0
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

Cons.34: Product relaunch

$$[(Y^{A}_{ztij} - Y^{A}_{z,t-1,i,j}) - 1] + M.(1 - Y^{PL}_{ztij}) \geq 0$$

$$(Y^{A}_{ztij} - Y^{A}_{z,t-1,i,j}) \leq Y^{PL}_{ztij}$$

Cons.24

```
Public Sub YPLDEF()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim YPLDEFA As String = ""
    Dim YPLDEFB As String = ""
    Dim print As String = ""
    Dim KK As Integer = 1
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000


    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(ProductPlant.Rows(KK).Cells(0).Value) = 0

              If ProductPlant.Rows(KK).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(KK).Cells(4).Value = product.Rows(j).Cells(1).Value Then

                If Val(ProductPlant.Rows(KK).Cells(7).Value) > 0 Then

                  YPLDEFA = "YPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + "
.. (1-YPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))*" + LTrim(Str(M)) +
"+((YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-YAztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "'))-1)=G=0 ;"

                  '**********************************************
                  print = ""
                  print = "YPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                  GAMSEquationDef.WriteLine(print)
                  GAMSEquationDef.WriteLine("*")
                  print = ""

                  GAMSequations.WriteLine(YPLDEFA)
                  YPLDEFA = ""
                  '**********************************************

                  YPLDEFB = "YPLDEFBztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + "
.. YPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=G=(YAztij('" + LTrim(Str(z)) +
"','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')-YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" +
LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')) ;"


                  print = ""
                  print = "YPLDEFBztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                  GAMSEquationDef.WriteLine(print)
                  GAMSEquationDef.WriteLine("*")
                  print = ""

                  GAMSequations.WriteLine(YPLDEFB)
```

```
                                    YPLDEFB = ""
                                   '***********************************************
                                ElseIf Val(ProductPlant.Rows(KK).Cells(3).Value) = 0 Then

                                    YPLDEFA = "YPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + "
.. YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=E=0 ;"
                                '***********************************************
                                    print = ""
                                    print = "YPLDEFAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                                    GAMSEquationDef.WriteLine(print)
                                    GAMSEquationDef.WriteLine("*")
                                    print = ""

                                    GAMSequations.WriteLine(YPLDEFA)
                                    YPLDEFA = ""
                                    '***********************************************
                                End If
                            End If
                            KK = KK + 1
                        End While
                        KK = 0
                        j = j + 1
                    End While
                    j = 0
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            i = 0
            j = 0
            z = z + 1
        End While
        z = 0

    End Sub
```

Cons.25: Y^{h}_{zti} VS Y^{NPL}_{zti} and its boundary conditions

$$Y^{h}_{ztj} \le \sum_{i} Y^{NPL}_{ztij} \le M.Y^{h}_{ztj}$$

Cons.25

```
Public Sub YhztjDEF()
      Refresh()
      GAMSequations.WriteLine(" ")
      Dim YhztjDEFA As String = ""
      Dim YhztjDEFB As String = ""
      Dim print As String = ""
      Dim KK As Integer = 0
      Dim E As Integer = 0
      Dim Y As Integer = 0
      t = 0
      i = 0
      j = 0
      z = 0
      M = 1000000000

      While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
         While Not Val(year.Rows(t).Cells(0).Value) = 0
            While Not Val(product.Rows(j).Cells(0).Value) = 0
               print = ""
               print = "YhztjDEFA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j))
               GAMSEquationDef.WriteLine(print)
               GAMSEquationDef.WriteLine("*")
               print = ""
               print = "YhztjDEFB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j))
               GAMSEquationDef.WriteLine(print)
               GAMSEquationDef.WriteLine("*")
               print = ""
               While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                  YhztjDEFA = YhztjDEFA + "+YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')"
                  i = i + 1
               End While
               YhztjDEFB = "YhztjDEFA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j)) + "..(" + YhztjDEFA +
")=G=Yhztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "') ;"
               GAMSequations.WriteLine(YhztjDEFB)
               YhztjDEFB = ""

               YhztjDEFB = "YhztjDEFB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j)) + "..(" + YhztjDEFA +
")=L=Yhztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Str(M)) + " ;"
               GAMSequations.WriteLine(YhztjDEFB)
               YhztjDEFB = ""
               YhztjDEFA = ""
               i = 0
               j = j + 1
            End While
            j = 0
            t = t + 1
         End While
         t = 0
         z = z + 1
      End While
      z = 0

   End Sub
```

Cons.26 and Cons.26: $Y^{R\&D}_{ztj}$ definition

$$[(Y^{h}_{ztj} - Y^{h}_{z,t-1,j}) - 1] + M.(1 - Y^{R\&D}_{ztj}) \geq 0$$

Cons.26

$$(Y^{h}_{ztj} - Y^{h}_{z,t-1,j}) \leq Y^{R\&D}_{ztj}$$

Cons.27

```
Public Sub YR7D()
        GAMSequations.WriteLine(" ")
        Dim YNPDDEFA As String = ""
        Dim YNPDDEFB As String = ""
        Dim print As String = ""
        Dim KK As Integer = 1
        t = 0
        i = 0
        j = 0
        z = 0
        M = 1000000000

        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(product.Rows(j).Cells(0).Value) = 0
                    YNPDDEFA = "YNPDDEFAztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j)) + " .. (1-YNPDztj('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "'))*" + LTrim(Str(M)) + "+((Yhztj('" + LTrim(Str(z)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(j)) + "')-Yhztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" + LTrim(Str(j)) + "'))-1)=G=0 ;"
                    ' [(Yh (z,t,i) - Yh (z,t-1,i)] + M.[1-YR&D (z,t,j)] >= 0
                    '**********************************************
                    print = ""
                    print = "YNPDDEFAztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(YNPDDEFA)
                    YNPDDEFA = ""
                    '**********************************************


                    YNPDDEFB = "YNPDDEFBztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j)) + " .. YNPDztj('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "')=G=(Yhztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(j)) + "')-Yhztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" + LTrim(Str(j)) + "')) ;"
                    ' [(Yh (z,t,i) - Yh (z,t-1,i)] <= YR&D (z,t,j)]
                    print = ""
                    print = "YNPDDEFBztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(YNPDDEFB)
                    YNPDDEFB = ""
                    '**********************************************

                    j = j + 1
                End While
                j = 0
                t = t + 1
            End While
            t = 0
            i = 0
            j = 0
            z = z + 1
        End While
        z = 0
End Sub
```

Cons.28: Simultaneous Constraints

$$
\begin{array}{lll}
(Y^{Re}_{zti} + Y^{Fr}_{zti}) \le 1 & & \\
(Y^{Re}_{zti} + Y^{Cl}_{zti}) \le 1 & (Y^{Exp}_{zti} + Y^{Fr}_{zti}) \le 1 & \\
(Y^{Exp}_{zti} + Y^{Cl}_{zti}) \le 1 & (Y^{Cl}_{zti} + Y^{Fr}_{zti}) \le 1 & \forall z,t,i
\end{array}
$$

Cons.28

```
Public Sub SimulYReYFreeze()
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim SimulConsA As String
    t = 0
    i = 0
    j = 0
    z = 0
    Dim print As String = ""
    SimulConsA = ""
    '###############################################
    ' YRe(t,i)+ YFreeze(t,i) <=1
    '###############################################
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
           SimulConsA = "SimulConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YRezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') + YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') =L=1  ;"
            print = ""
            print = "SimulConsAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
            GAMSEquationDef.WriteLine(print)
            GAMSEquationDef.WriteLine("*")
            print = ""
            GAMSequations.WriteLine(SimulConsA)
            SimulConsA = ""
            i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
  '-----------------------------------------------------------------------------------------------
  Public Sub SimulYExpYFreeze()
    '###############################################
    ' YExp(t,i)+ YFreeze(t,i) <=1
    '###############################################
    GAMSequations.WriteLine(" ")
    t = 0
    i = 0
    j = 0
    z = 0
    Dim print As String = ""
    Dim SimulConsB As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
```

```
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    SimulConsB = "SimulConsBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YExpzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') + YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') =L=1  ;"
                    print = ""
                    print = "SimulConsBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(SimulConsB)
                    SimulConsB = ""
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            z = z + 1
        End While
        z = 0
    End Sub

    Public Sub SimulYReYClose()
        Refresh()
        GAMSequations.WriteLine(" ")
        Dim SimulYReYClose As String = ""
        t = 0
        i = 0
        j = 0
        z = 0
        Dim print As String = ""
        '################################################
        ' YRe(t,i)+ YClose(t,i) <=1
        '################################################
        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    SimulYReYClose = "SimulYReYClosezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YRezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') + YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') =L=1  ;"
                    print = ""
                    print = "SimulYReYClosezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(SimulYReYClose)
                    SimulYReYClose = ""
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            z = z + 1
        End While
        z = 0
    End Sub


    Public Sub SimulYFreezeYClose()
        GAMSequations.WriteLine(" ")
        Dim SimulYReYClose As String = ""
```

```
    t = 0
    i = 0
    j = 0
    z = 0
    Dim print As String = ""
    '################################################
    ' YFreeze(t,i)+ YClose(t,i) <=1
    '################################################
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          SimulYReYClose = "SimulYFreezeYClosezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " ..
YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') + YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t))
+ "','" + LTrim(Str(i)) + "') =L=1  ;"
          print = ""
          print = "SimulYFreezeYClosezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(SimulYReYClose)
          SimulYReYClose = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub

  Public Sub SimulYExpYClose()
    '################################################
    ' YExp(t,i)+ YFreeze(t,i) <=1
    '################################################
    GAMSequations.WriteLine(" ")
    t = 0
    i = 0
    j = 0
    z = 0
    Dim print As String = ""
    Dim SimulYExpYClose As String = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          SimulYExpYClose = "SimulYExpYClosezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. YExpzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "') + YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "') =L=1  ;"
          print = ""
          print = "SimulYExpYClosezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(SimulYExpYClose)
          SimulYExpYClose = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
```

```
            z = z + 1
        End While
        z = 0
    End Sub

    Public Sub SimulYNLPYFreeze()
        '################################################
        ' YNLP(t,i,j)+ YFreeze(t,i) <=1
        '################################################
        Refresh()
        GAMSequations.WriteLine(" ")
        t = 0
        i = 0
        j = 0
        z = 0
        Dim print As String = ""
        Dim SimulConsC As String = ""
        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    While Not Val(product.Rows(j).Cells(0).Value) = 0
                        SimulConsC = "SimulConsCztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + "
.. YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=L= (1-YFreezezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')) ;"
                        print = ""
                        print = "SimulConsCztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(SimulConsC)
                        SimulConsC = ""
                        j = j + 1
                    End While
                    j = 0
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
            z = z + 1
        End While
        z = 0
    End Sub

    Public Sub SimulYNLPYClose()
        '################################################
        ' YNLP(t+1,i,j)+ YFClose(t,i) <=1
        '################################################
        GAMSequations.WriteLine(" ")
        t = 0
        i = 0
        j = 0
        Dim print As String = ""
        Dim SimulConsD As String = ""
        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    While Not Val(product.Rows(j).Cells(0).Value) = 0
                        SimulConsD = "SimulConsDztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + "
.. YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=L= (1-YClosezti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')) ;"
```

```
                    print = ""
                    print = "SimulConsDztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    GAMSequations.WriteLine(SimulConsD)
                    SimulConsD = ""
                    j = j + 1
                End While
                j = 0
                i = i + 1
            End While
            i = 0
            t = t + 1
        End While
        t = 0
        z = z + 1
    End While
    z = 0
End Sub
```

Cons.29: Non-Anticipative Constraints

$$
\begin{array}{ll}
K^{Exp}_{t,\,i,\,z_q} = K^{Exp}_{t,\,i,\,z_l} & l \neq q, \forall t, i, z_q, z_l \\
Y^{Cl}_{t,\,i,\,z_q} = Y^{Cl}_{t,\,i,\,z_l} & l \neq q, \forall t, i, z_q, z_l \\
Z^{New}_{t,\,i,\,z_q} = Z^{New}_{t,\,i,\,z_l} & l \neq q, \forall t, i, z_q, z_l \\
Y^{NPL}_{t,\,i,\,j,\,z_q} = Y^{NPL}_{t,\,i,\,j,\,z_l} & l \neq q, \forall t, i, j, z_q, z_l \\
Y^{R\&D}_{t,\,j,\,z_q} = Y^{R\&D}_{t,\,j,\,z_l} & l \neq q, \forall t, j, z_q, z_l \\
Y^{Fr}_{t,\,j,\,z_q} = Y^{Fr}_{t,\,j,\,z_l} & l \neq q, \forall t, j, z_q, z_l \\
Y^{\mathrm{Re}}_{t,\,j,\,z_q} = Y^{\mathrm{Re}}_{t,\,j,\,z_l} & l \neq q, \forall t, j, z_q, z_l
\end{array}
$$

Cons.29

```
Public Sub YExpNonAnticipative() '    YExp(z,t,i) = YExp(z',t,i)
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim PrameterTrans As String = ""
    t = 0
    i = 0
    j = 0
    r = 0
    z = 0
    Dim print As String = ""
    z = 0
```

```
    If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
        While Not Val(year.Rows(t).Cells(0).Value) = 0
            While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
                    If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
                        PrameterTrans = "YExpNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "..YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=YExpzti('" + LTrim(Str(z + 1)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"
                        print = ""
                        print = "YExpNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(PrameterTrans)
                        PrameterTrans = ""
                    End If
                    z = z + 1
                End While
                z = 0
                i = i + 1
            End While
            i = 0
            t = t + 1
        End While
        t = 0
    End If
End Sub



Public Sub YCloseNonAnticipative()  '   YClose(z,t,i) = YClose(z',t,i)
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim PrameterTrans As String = ""
    t = 0
    i = 0
    j = 0
    r = 0
    z = 0
    Dim print As String = ""
    z = 0
    If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
        While Not Val(year.Rows(t).Cells(0).Value) = 0
            While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
                    If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
                        PrameterTrans = "YCloseNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "..YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=YClosezti('" + LTrim(Str(z + 1)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"
                        print = ""
                        print = "YCloseNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(PrameterTrans)
                        PrameterTrans = ""
                    End If
                    z = z + 1
                End While
                z = 0
                i = i + 1
```

```
            End While
            i = 0
            t = t + 1
        End While
        t = 0
    End If
End Sub




Public Sub ZNewNonAnticipative() '   ZNew(z,t,i) = ZNew(z',t,i)
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim PrameterTrans As String = ""
    t = 0
    i = 0
    j = 0
    r = 0
    z = 0
    Dim print As String = ""
    z = 0
    If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
        While Not Val(year.Rows(t).Cells(0).Value) = 0
            While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
                    If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
                        PrameterTrans = "ZNewNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) +
"..ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=ZNewzti('" + LTrim(Str(z + 1)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"
                        print = ""
                        print = "ZNewNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                        GAMSEquationDef.WriteLine(print)
                        GAMSEquationDef.WriteLine("*")
                        print = ""
                        GAMSequations.WriteLine(PrameterTrans)
                        PrameterTrans = ""
                    End If
                    z = z + 1
                End While
                z = 0
                i = i + 1
            End While
            i = 0
            t = t + 1
        End While
        t = 0
    End If
End Sub


Public Sub YR7DNonAnticipative()  '   YNPD(z,t,j) = YNPD(z',t,j)
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim PrameterTrans As String = ""
    t = 0
    i = 0
    j = 0
    r = 0
    z = 0
    Dim print As String = ""
```

```
        z = 0
        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(product.Rows(j).Cells(0).Value) = 0
                    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
                        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then

                            PrameterTrans = "YNPDNonAnticipativeztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j)) +
"..YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "')=E=YNPDztj('" + LTrim(Str(z + 1)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(j)) + "');"
                            print = ""
                            print = "YNPDNonAnticipativeztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j))
                            GAMSEquationDef.WriteLine(print)
                            GAMSEquationDef.WriteLine("*")
                            print = ""
                            GAMSequations.WriteLine(PrameterTrans)
                            PrameterTrans = ""
                        End If
                        z = z + 1
                    End While
                    z = 0
                    j = j + 1
                End While
                j = 0
                t = t + 1
            End While
            t = 0
        End If
    End Sub


    Public Sub YNPLNonAnticipative()  '   YNPL(z,t,i,j) = YNPL(z',t,i,j)
        Refresh()
        GAMSequations.WriteLine(" ")
        Dim PrameterTrans As String = ""
        t = 0
        i = 0
        j = 0
        r = 0
        z = 0
        Dim print As String = ""
        z = 0
        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    While Not Val(product.Rows(j).Cells(0).Value) = 0
                        While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
                            If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then
                                PrameterTrans = "YNPLNonAnticipativeztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" +
LTrim(Str(j)) + "..YNPlztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=E=YNPlztij('" +
LTrim(Str(z + 1)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "');"
                                print = ""
                                print = "YNPLNonAnticipativeztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" +
LTrim(Str(j))
                                GAMSEquationDef.WriteLine(print)
                                GAMSEquationDef.WriteLine("*")
                                print = ""
                                GAMSequations.WriteLine(PrameterTrans)
                                PrameterTrans = ""
                            End If
                            z = z + 1
                        End While
```

```
                        z = 0
                        j = j + 1
                    End While
                    j = 0
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
        End If
    End Sub

Public Sub YFreezeNonAnticipative()  '      YFreeze(z,t,i) = YFreeze(z',t,i)
        Refresh()
        GAMSequations.WriteLine(" ")
        Dim PrameterTrans As String = ""

        t = 0
        i = 0
        j = 0
        r = 0
        z = 0
        M = 1000000000
        Dim print As String = ""

        z = 0
        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then


            While Not Val(year.Rows(t).Cells(0).Value) = 0

                While Not Val(Plant.Rows(i).Cells(0).Value) = 0

                    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

                        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then

                            PrameterTrans = "YFreezeNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "..YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=Yfreezezti('" + LTrim(Str(z + 1)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"

                            print = ""
                            print = "YFreezeNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                            GAMSEquationDef.WriteLine(print)
                            GAMSEquationDef.WriteLine("*")
                            print = ""

                            GAMSequations.WriteLine(PrameterTrans)
                            PrameterTrans = ""
                        End If
                        z = z + 1
                    End While
                    z = 0
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
```

```
        End If


    End Sub

    Public Sub YReNonAnticipative()  '     YRe(z,t,i) = YRe(z',t,i)
        Refresh()
        GAMSequations.WriteLine(" ")
        Dim PrameterTrans As String = ""

        t = 0
        i = 0
        j = 0
        r = 0
        z = 0
        M = 1000000000
        Dim print As String = ""

        z = 0
        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then


            While Not Val(year.Rows(t).Cells(0).Value) = 0

                While Not Val(Plant.Rows(i).Cells(0).Value) = 0

                    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

                        If Val(Scenario.Rows(z + 1).Cells(0).Value) <> 0 Then

                            PrameterTrans = "YReNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) +
"..YRezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=E=YRezti('" + LTrim(Str(z + 1)) + "','" + LTrim(Str(t))
+ "','" + LTrim(Str(i)) + "');"

                            print = ""
                            print = "YReNonAnticipativezti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                            GAMSEquationDef.WriteLine(print)
                            GAMSEquationDef.WriteLine("*")
                            print = ""

                            GAMSequations.WriteLine(PrameterTrans)
                            PrameterTrans = ""
                        End If
                        z = z + 1
                    End While
                    z = 0
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0

        End If


    End Sub
```

Workforce Constraints:

$$Y^{ExpOveral}_{zti} \text{ vs } K^{ExpOveral}_{zti}$$

$$Y^{ExpOveral}_{zti} \le \sum_{\tau=0}^{t} K^{Exp}_{z\tau i} \le M.Y^{ExpOveral}_{zti} \qquad Y^{Opr}_{zti} \in [0,1]$$

```
Public Sub YExpOvr()   'To find out whether capacity has ever expanded before (t):
    GAMSequations.WriteLine(" ")
    Dim YExpOverAti As String = ""
    Dim YExpOvrBti As String = ""
    Dim Sigma1 As String = ""
    Dim sigma2 As String = ""
    Dim print As String = ""
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          Sigma1 = "(0"
          For w = 0 To t
            Sigma1 = Sigma1 + "+YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(w)) + "','" + LTrim(Str(i)) + "')"
          Next w
          Sigma1 = Sigma1 + ")"
          print = ""
          print = "YExpOverAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          YExpOverAti = "YExpOverAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + ".. YExpOvrzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=L=" + Sigma1 + " ;"
          GAMSequations.WriteLine(YExpOverAti)
          YExpOverAti = ""

          print = ""
          print = "YExpOvrBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          YExpOvrBti = "YExpOvrBzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + ".. YExpOvrzti('" +
LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Str(M)) + "=G=" + Sigma1 + " ;"

          GAMSequations.WriteLine(YExpOvrBti)
          YExpOvrBti = ""
          Sigma1 = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.30 and 31: Workforce constraint 01

$$Y_{zti}^{FrAll} + \sum_{\tau=0}^{\tau=t} Y_{z,\tau,i}^{Close} \le 1 - Y_{zti}^{ExpWforce} \qquad \forall z,t,i \tag{Cons.30}$$

$$Y_{zti}^{ExpOveral} - Y_{zti}^{FrAll} - \sum_{\tau=0}^{\tau=t} Y_{z,\tau,i}^{Close} \le Y_{zti}^{ExpWforce} \qquad \forall z,t,i \tag{Cons.31}$$

```
Public Sub YExpWforceA()        ' |  YFreezeAll(z,t,i) + Sum t (t=0 , t=t) YClose(z,t,i)<=1-YExpWforce(z,t,i)
    '                '      ' |  YExpOveral(z,t,i) - YFreezeAll(z,t,i) - Sum t (t=0 , t=t) YClose(z,t,i)<=YExpWforce(z,t,i)
    Refresh()
    GAMSequations.WriteLine(" ")
    Dim Inter As String = ""
    Dim InterA As String = ""
    Dim InterB As String = ""
    Dim InterC As String = ""
    Dim print As String = ""

    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0

      While Not Val(year.Rows(t).Cells(0).Value) = 0

        While Not Val(Plant.Rows(i).Cells(0).Value) = 0

          InterA = "YExpWforceA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + ".."
          InterB = "YExpWforceB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + ".."
          Inter = "(0"
          For aa = 0 To t
            Inter = Inter + "+YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(aa)) + "','" + LTrim(Str(i)) + "')"
          Next aa

          InterA = InterA + Inter + ")+YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')" + "=L=1-YExpWforcezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"
          InterB = InterB + Inter + ")+YFreezeAllzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')" + "-" + "YExpOvrzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')" + "=G=YExpWforcezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"

          print = ""
          print = "YExpWforceA" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(InterA)
          InterA = ""

          print = ""
          print = "YExpWforceB" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(InterB)
          InterA = ""

          i = i + 1
```

```
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0

  End Sub
```

Cons.32: Workforce constraint 03

$$Y_{zti}^{ExpOveral} \geq Y_{zti}^{ExpWforce}$$

Cons.32

```
Public Sub YExpWforceC()   ' |  YExpOveral(z,t,i)>=YExpWforce(z,t,i)
    GAMSequations.WriteLine(" ")
    Dim InterC As String = ""
    Dim print As String = ""
    t = 0;        i = 0;       j = 0;       z = 0;
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          InterC = "YExpWforceC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + ".."
          InterC = InterC + "YExpOvrzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')=G=YExpWforcezti('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "');"
          print = ""
          print = "YExpWforceC" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          GAMSequations.WriteLine(InterC)
          InterC = ""
          i = i + 1
        End While
        i = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.33: Maximum Number of Plant for each Product

$$\sum_i Y^A_{ztij} \le l_j$$

Cons.33

```
Public Sub MaxPlant()
    GAMSequations.WriteLine(" ")
    Dim MaxPlantA As String
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    Dim print As String = ""
    MaxPlantA = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(product.Rows(j).Cells(0).Value) = 0
          MaxPlantA = "MaxPlantAztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j)) + " .. 0"

          print = ""
          print = "MaxPlantAztj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(j))
          GAMSEquationDef.WriteLine(print)
          GAMSEquationDef.WriteLine("*")
          print = ""
          While Not Val(Plant.Rows(i).Cells(0).Value) = 0
            MaxPlantA = MaxPlantA + "+YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')"
            If KK = 4 Then
              GAMSequations.WriteLine(MaxPlantA)
              MaxPlantA = ""
              KK = 0
            End If
            KK = KK + 1
            i = i + 1
          End While
          MaxPlantA = MaxPlantA + "+0 =L=" + LTrim(Str(product.Rows(j).Cells(2).Value)) + " ;"
          GAMSequations.WriteLine(MaxPlantA)
          MaxPlantA = ""
          KK = 0
          i = 0
          j = j + 1
        End While
        j = 0
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.34: Maximum Number of Product in each Plant

$$\sum_j Y^A_{ztij} \le n_i^{\max}$$

Cons.34

```
Public Sub MaxProduct()
    GAMSequations.WriteLine(" ")
```

```
    Dim MaxProductA As String
    Dim KK As Integer = 0
    t = 0
    z = 0
    i = 0
    j = 0
    Dim print As String = ""
    MaxProductA = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
        If Not Str(Plant.Rows(i).Cells(20).Value) = "" Then
            While Not Val(year.Rows(t).Cells(0).Value) = 0
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                    MaxProductA = "MaxProductAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + " .. 0"
                    print = ""
                    print = "MaxProductAzti" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i))
                    GAMSEquationDef.WriteLine(print)
                    GAMSEquationDef.WriteLine("*")
                    print = ""
                    While Not Val(product.Rows(j).Cells(0).Value) = 0

                        MaxProductA = MaxProductA + "+YAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" +
LTrim(Str(j)) + "')"
                        If KK = 4 Then
                            GAMSequations.WriteLine(MaxProductA)
                            MaxProductA = ""
                            KK = 0
                        End If
                        KK = KK + 1
                        j = j + 1
                    End While
                    MaxProductA = MaxProductA + "+0 =L=" + LTrim(Str(Plant.Rows(i).Cells(20).Value)) + " ;"
                    GAMSequations.WriteLine(MaxProductA)
                    MaxProductA = ""
                    KK = 0
                    j = 0
                    i = i + 1
                End While
                i = 0
                t = t + 1
            End While
            t = 0
        End If
        z = z + 1
    End While
    z = 0
End Sub
```

Cons.35: Maximum Investment Constraint

$$\sum_{z} \sum_{t} [\sum_{i} Inv_{zti} + \sum R\&D_{ztj}] \leq b_t \qquad \boxed{Cons.35}$$

```
Public Sub InvCons()

    Refresh()
    GAMSequations.WriteLine(" ")
    Dim NewInv As String
    NewInv = ""
    Dim Expansion As String
    Expansion = ""
```

```
    Dim freeze As String
    freeze = ""
    Dim Reopen As String
    Reopen = ""
    Dim CloseDown As String
    CloseDown = ""
    Dim OverNormal As String
    OverNormal = ""
    Dim UnderNormal As String
    UnderNormal = ""
    Dim NPL As String
    NPL = ""
    Dim NPD As String
    NPD = ""
    Dim InvConsA As String
    Dim KK As Integer = 0
    Dim ni As Integer = 0
    Dim ei As Integer = 0
    t = 0
    i = 0
    z = 0
    j = 0
    M = 1000000000
    Dim print As String = ""
    InvConsA = ""

    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        InvConsA = "InvConsAzt" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + " .. 0"
        print = ""
        print = "InvConsAzt" + LTrim(Str(z)) + "T" + LTrim(Str(t))
        GAMSEquationDef.WriteLine(print)
        GAMSEquationDef.WriteLine("*")
        print = ""
        GAMSequations.WriteLine(InvConsA)
        InvConsA = ""

        ni = 0
        While Not Val(Plant.Rows(i).Cells(0).Value) = 0
          If Plant.Rows(i).Cells(23).Value = True Then
            While Not Val(New_Plant_time_tableDataGridView.Rows(ni).Cells(0).Value) = 0
              If New_Plant_time_tableDataGridView.Rows(ni).Cells(1).Value = Plant.Rows(i).Cells(1).Value Then
                NewInv = NewInv + "+" + "(((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) +
")*" + LTrim(Str(Plant.Rows(i).Cells(5).Value)) + "*1000000" + "*((ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 5)) + "','" +
LTrim(Str(i)) + "')*" + LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(2).Value))) + "/100)" + "+(ZNewzti('"
+ LTrim(Str(z)) + "','" + LTrim(Str(t + 4)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(3).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t + 3)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(4).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t + 2)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(4).Value))) + "/100)" + "+(ZNewzti('" + "','" + LTrim(Str(z))
+ LTrim(Str(t + 1)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(4).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(5).Value))) +
"/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(6).Value))) + "/100)" + "+(ZNewzti('" + LTrim(Str(z)) + "','"
+ LTrim(Str(t - 2)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(New_Plant_time_tableDataGridView.Rows(ni).Cells(7).Value)))
+ "/100)))*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))
                GAMSequations.WriteLine(NewInv)
                NewInv = ""
              End If
              ni = ni + 1
```

```
               End While
               ni = 0
            End If

            ei = 0
            If Not Val(Plant.Rows(i).Cells(9).Value) = 0 Then
               If Not Val(Plant.Rows(i).Cells(9).Value) = 0 Then
                  While Not Val(Expansion_time_tableDataGridView.Rows(ei).Cells(0).Value) = 0
                     If Expansion_time_tableDataGridView.Rows(ei).Cells(1).Value = Plant.Rows(i).Cells(1).Value Then

                        Expansion = Expansion + "+" + "(((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" +
LTrim(Str(t)) + ")*" + LTrim(Str(Plant.Rows(i).Cells(9).Value)) + "*1000000" + "*((YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t
+ 3)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(2).Value))) + "/100)" +
"+(YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 2)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(3).Value))) + "/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(t + 1)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(4).Value))) +
"/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(5).Value))) + "/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "')*" + LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(6).Value))) +
"/100)" + "+(YExpzti('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 2)) + "','" + LTrim(Str(i)) + "')*" +
LTrim(Val(Str(Expansion_time_tableDataGridView.Rows(ei).Cells(7).Value))) + "/100)))*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))

                        GAMSequations.WriteLine(Expansion)
                        Expansion = ""
                     End If
                     ei = ei + 1
                  End While
                  ei = 0
               End If
            End If

            freeze = freeze + "+" + "((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*(" +
LTrim(Str(Plant.Rows(i).Cells(11).Value)) + "*1000000)" + "*YFreezezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "')*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))
            GAMSequations.WriteLine(freeze)
            freeze = ""

            Reopen = Reopen + "+" + "((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*(" +
LTrim(Str(Plant.Rows(i).Cells(12).Value)) + "*1000000)" + "*YRezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "')*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))
            GAMSequations.WriteLine(Reopen)
            Reopen = ""

            CloseDown = CloseDown + "+" + "((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) +
")*(" + LTrim(Str(Plant.Rows(i).Cells(14).Value)) + "*1000000)" + "*YClosezti('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(i)) + "')*" + LTrim(Str(Scenario.Rows(z).Cells(2).Value))
            GAMSequations.WriteLine(CloseDown)
            CloseDown = ""

            ni = 0
            While Not Val(product.Rows(j).Cells(0).Value) = 0
               While Not Val(ProductPlant.Rows(k).Cells(0).Value) = 0
                  If Not Val(ProductPlant.Rows(k).Cells(3).Value) = 0 Then
                     If ProductPlant.Rows(k).Cells(5).Value = Plant.Rows(i).Cells(1).Value And
ProductPlant.Rows(k).Cells(4).Value = product.Rows(j).Cells(1).Value Then
                        If ProductPlant.Rows(k).Cells(5).Value = NPL_time_tableDataGridView.Rows(ni).Cells(1).Value And
ProductPlant.Rows(k).Cells(4).Value = NPL_time_tableDataGridView.Rows(ni).Cells(2).Value Then
                           While Not Val(NPL_time_tableDataGridView.Rows(ni).Cells(0).Value) = 0

                              NPL = NPL + "+" + "(((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*"
+ LTrim(Str(ProductPlant.Rows(k).Cells(3).Value)) + "*1000000" + "*((YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 3)) +
```

```
"','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(3).Value))) +
"/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 2)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(4).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t + 1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(5).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(6).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 1)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(7).Value))) + "/100)" + "+(YNPLztij('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 2)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPL_time_tableDataGridView.Rows(ni).Cells(8).Value))) + "/100)))*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))
                      GAMSequations.WriteLine(NPL)
                      NPL = ""
                      ni = ni + 1
                    End While
                    ni = 0
                  End If
                End If
              End If
              k = k + 1
            End While
            k = 0
            j = j + 1
          End While
          j = 0
          i = i + 1
        End While
        i = 0
        ni = 0
        While Not Val(product.Rows(j).Cells(0).Value) = 0
          If product.Rows(j).Cells(3).Value = True And Val(Str(product.Rows(j).Cells(4).Value)) <> 0 Then
            While Not Val(NPD_time_tableDataGridView.Rows(ni).Cells(0).Value) = 0

              NPD = NPD + "+" + "(((1+" + LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ")*" +
LTrim(Str(product.Rows(j).Cells(4).Value)) + "*1000000*((YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t + 3)) + "','" +
LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(2).Value))) + "/100)" + "+(YNPDztj('" +
LTrim(Str(z)) + "','" + LTrim(Str(t + 2)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(3).Value))) + "/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" +
LTrim(Str(t + 1)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(4).Value))) +
"/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(5).Value))) + "/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" +
LTrim(Str(t - 1)) + "','" + LTrim(Str(j)) + "')*" + LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(6).Value))) +
"/100)" + "+(YNPDztj('" + LTrim(Str(z)) + "','" + LTrim(Str(t - 2)) + "','" + LTrim(Str(j)) + "')*" +
LTrim(Val(Str(NPD_time_tableDataGridView.Rows(ni).Cells(7).Value))) + "/100)))*" +
LTrim(Str(Scenario.Rows(z).Cells(2).Value))

              GAMSequations.WriteLine(NPD)
              NPD = ""
              ni = ni + 1
            End While
            ni = 0
          End If
          j = j + 1
        End While
        j = 0

        InvConsA = ""
        InvConsA = InvConsA + "+0 =L=" + LTrim(Str(year.Rows(t).Cells(2).Value)) + "*1000000*((1+" +
LTrim(Str(Interests.Rows(0).Cells(1).Value)) + ")**" + LTrim(Str(t)) + ");"
        GAMSequations.WriteLine(InvConsA)
        InvConsA = ""
```

```
        t = t + 1
      End While
      t = 0
      z = z + 1
    End While
    z = 0
  End Sub
```

Cons.36: Demand Constraint

$$[\sum_{i}(X^{D}_{ztrij}) + X^{Unmet}_{ztrj}] = d_{ztrj}$$

Cons.36

```
Public Sub DemandConsA()
    GAMSequations.WriteLine(" ")
    Dim DemandConsA As String
    Dim demandA As Integer = 0
    Dim D As Integer = 0
    Dim r As Integer = 0
    Dim KK As Integer = 0
    t = 0
    i = 0
    j = 0
    z = 0
    M = 1000000000
    Dim print As String = ""
    DemandConsA = ""
    While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
      While Not Val(year.Rows(t).Cells(0).Value) = 0
        While Not Val(region.Rows(r).Cells(0).Value) = 0
          While Not Val(product.Rows(j).Cells(0).Value) = 0
            While Not Val(Demand.Rows(D).Cells(0).Value) = 0
              If Demand.Rows(D).Cells(5).Value = Scenario.Rows(z).Cells(1).Value And Demand.Rows(D).Cells(2).Value = region.Rows(r).Cells(1).Value And Demand.Rows(D).Cells(3).Value = product.Rows(j).Cells(1).Value And Val(Demand.Rows(D).Cells(4).Value) = Val(year.Rows(t).Cells(1).Value) And Str(Demand.Rows(D).Cells(1).Value) <> "" And Demand.Rows(D).Cells(1).Value <> 0 Then
                DemandConsA = "DemandConsAztrj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(r)) + "T" + LTrim(Str(j)) + " .. 0"
                print = ""
                print = "DemandConsAztrj" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(r)) + "T" + LTrim(Str(j))
                GAMSEquationDef.WriteLine(print)
                GAMSEquationDef.WriteLine("*")
                print = ""
                While Not Val(Plant.Rows(i).Cells(0).Value) = 0
                  DemandConsA = DemandConsA + "+XDztrij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(r)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')"
                  If KK = 4 Then
                    GAMSequations.WriteLine(DemandConsA)
                    DemandConsA = ""
                    KK = 0
                  End If
                  KK = KK + 1
                  i = i + 1
                End While
                KK = 0
```

```
                        DemandConsA = DemandConsA + "+XUnmetztrj('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" +
LTrim(Str(r)) + "','" + LTrim(Str(j)) + "')=E=1000*" + LTrim(Str(Demand.Rows(D).Cells(1).Value)) + " ;"
                        GAMSequations.WriteLine(DemandConsA)
                        DemandConsA = ""
                        demandA = 0
                     End If
                     i = 0
                     DemandConsA = ""
                     D = D + 1
                  End While
                  D = 0
                  j = j + 1
               End While
               j = 0
               r = r + 1
            End While
            r = 0
            t = t + 1
         End While
         t = 0
         z = z + 1
      End While
      z = 0
   End Sub
```

Cons.37: Transportation Constraint (No inventory)

$$\sum_{r} X^{D}_{ztrij} = X^{A}_{ztij}$$

Cons.37

```
Public Sub TransCon()
      Refresh()
      GAMSequations.WriteLine(" ")
      Dim TransConA As String = ""
      Dim part2 As String = ""
      Dim JJ As Integer = 0
      Dim rr As Integer = 0
      Dim KK As Integer = 0
      Dim print As String = ""
      t = 0
      i = 0
      j = 0
      r = 0
      z = 0
      M = 1000000000

      While Not Val(Scenario.Rows(z).Cells(0).Value) = 0
         While Not Val(year.Rows(t).Cells(0).Value) = 0
            While Not Val(Plant.Rows(i).Cells(0).Value) = 0
               While Not Val(product.Rows(j).Cells(0).Value) = 0
                  TransConA = ""
                  TransConA = "TransConAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j)) + " ..
XAztij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')=E="
                  GAMSequations.WriteLine(TransConA)
                  TransConA = ""
                  print = ""
                  print = "TransConAztij" + LTrim(Str(z)) + "T" + LTrim(Str(t)) + "T" + LTrim(Str(i)) + "T" + LTrim(Str(j))
                  GAMSEquationDef.WriteLine(print)
                  GAMSEquationDef.WriteLine("*")
                  print = ""
```

```
                    While Not Val(region.Rows(r).Cells(0).Value) = 0
                        TransConA = TransConA + "+XDztrij('" + LTrim(Str(z)) + "','" + LTrim(Str(t)) + "','" + LTrim(Str(r)) + "','" + LTrim(Str(i)) + "','" + LTrim(Str(j)) + "')"
                        If KK = 4 Then
                            GAMSequations.WriteLine(TransConA)
                            TransConA = ""
                            KK = 0
                        End If
                        KK = KK + 1
                        r = r + 1
                    End While
                    r = 0
                    TransConA = TransConA + "+0 ;"
                    GAMSequations.WriteLine(TransConA)
                    TransConA = ""
                    j = j + 1
                End While
                j = 0
                i = i + 1
            End While
            i = 0
            t = t + 1
        End While
        t = 0
        z = z + 1
    End While
    z = 0
End Sub
```