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AN ADVANCED DECISION PROCESS FOR CAPACITY  
EXPANSION IN MANUFACTURING NETWORKS

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## **ABSTRACT**

Manufacturing companies develop multiple production sites for various reasons from cheaper labour to access to local markets. Expansion of capacity in such a manufacturing network is a complex decision and requires consideration of multiple factors. Traditionally, industrial decision makers attempt to minimise the cost of expansion and, usually as an afterthought, consider soft factors like manpower availability and logistics connectivity. This approach has gained acceptance as the research community has focused on developing better mathematical representations of the problem rather than investigate the larger decision process. A review of the literature revealed that all existing processes for multi-site capacity expansion decision fail in this way. Therefore, this research sets out to fulfil the needs of practitioners by developing a more complete process for the capacity expansion decision in multi-site manufacturing networks.

The research programme consists of five parts. In the first part an extensive literature review is conducted to identify the state-of-the-art in capacity expansion decision processes. Then, in the second part, a representative process is formed and industrially tested. This generates the specifications for an advanced decision process which addresses the shortcomings of the present body of knowledge and is developed in the third part of the research. In the fourth part the advanced decision process is applied in an industrial setting to validate its effectiveness. Finally, in the fifth part the advanced decision process is refined and illustrated.

The outcome of this research is an improved decision making capability. The advanced decision process has been both validated and appreciated by industrial practitioners. Specifically the contribution to knowledge is an advanced decision process for capacity expansion in multi-site manufacturing network.

## **ACKNOWLEDGEMENTS**

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## NOTATION

A*STAR	Agency for Science, Technology and Research (Singapore)
AFTA	ASEAN Free Trade Area
AHP	Analytical Hierarchy Process
ASEAN	Association of South East Asian Nations
CAGR	Compound Annual Growth Rate
EDB	Economic Development Board (Singapore)
EFTA	European Free Trade Association
FDI	Foreign Direct Investment
FTA	Free Trade Agreement
GDP	Gross Domestic Product
HQ	Head Quarters
IP	Integer Program
IPR	Intellectual Property Rights
IT	Information Technology
ISGP	Interactive Sequential Goal Programming
KBE	Knowledge Based Economy
MILP	Mixed Integer Linear Program
MIP	Mixed Integer Program
LP	Linear Program
MNC	Multi-National Companies
OPL	Optimisation Programming Language
OR	Operations Research
SEA	South East Asia

SIMTech	Singapore Institute Of Manufacturing Technology
SWOT	Strengths, Weaknesses, Opportunities and Threats
TCF	Textiles, Clothing and Footwear

## **PUBLICATIONS**

Julka, N., T. Baines, B. Tjahjono, P. Lendermann and V. Vitanov (2007). "A Review of Multi-factor Capacity Expansion Models for Manufacturing Plants: Searching for a Holistic Decision Aid." International Journal of Production Economics **106**: 607-621. ISSN 0925 5273.

Julka, N., T. Baines, B. Tjahjono and P. Lendermann (2007). "An Evaluation of Leading Capacity Expansion Models for Multi Site Manufacturing" Under preparation.

Julka, N., T. Baines, B. Tjahjono and P. Lendermann (2007). "An Integrated, Comprehensive and Coherent Decision Process Capacity Expansion in Multi Site Manufacturing" Under preparation.

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## **Chapter 1. Introduction**

This chapter introduces the research work described in this thesis. In Section 1.1 an overview of the research challenge is provided and in Section 1.2 the aim and objectives of the research and the research programme are introduced. Then, in Section 1.3, the research findings and the contribution to knowledge of this research work are outlined. Finally, the thesis structure is presented in Section 1.4 with a short description of each chapter.

### **1.1 Overview of the Research Challenge**

Manufacturing companies establish multiple production sites for various reasons such as access to cheaper labour and access to local markets, along with other market and economic factors. With increase in market demand for their products, such companies regularly add more capacity to their production sites which are part of their global manufacturing network. This decision to add capacity is very complex in nature. Companies need to decide upon the timing of expansion, the size of expansion, the product type and the production location. They need to figure out if the capacity expansion is conducted as a one off activity or a series of smaller expansions spread over a finite or infinite time horizon. Their decisions are based on a number of factors including global manufacturing strategy of the firm, the prevailing and future forecasted market conditions and the competitive strengths of the various factories and locations. The combination of the considerations mentioned above make each

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capacity expansion decision in a manufacturing network different, hence no single solution exists for decision makers.

The industrial challenge addressed by this research, stems from the discussions with the manufacturing companies in Singapore who have multiple plants across the region (Chapter 2). Singapore economy's increasing focus on the manufacturing expansion (Section 2.1) coupled with an increasing demand for products is driving most factories to produce close to their maximum capacities. There is thus a need to decide upon investment for capacity expansion. This expansion however needs to take place in a wider context of international competition (Section 2.2). These capacity expansion decisions are normally made by considering the discounted costs associated with the expansion for which a number of decision processes are available in the literature (e.g. Reeves et al. (1988), Li and Tirupati (1994), Syam (2000), Perrone et al. (2002), Ryan (2004), Chakravarty (1999; 2005) and Bish and Hong (2006)). It is however suggested (by company managements that were involved in this study) that soft factors like human resources (availability and skill levels), logistics connectivity and socio-economic factors of the country should also be considered in the decision.

The research conducted for this thesis was sponsored by Singapore Institute of Manufacturing Technology (SIMTech), the employer of the lead researcher. SIMTech is one of the thirteen research institutes under the Agency for Science, Technology and Research (A\*STAR), a Singapore government body supporting the local industry through science and technology research. The industrial partners for the study were

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Singapore-based companies with multi-site production facilities. For the purpose of safeguarding their identity they are addressed as Machine-Co and Glass-Co.

Machine-Co is a world leader in the production of compressors for household refrigerators and commercial cold storage appliances. It has four production facilities in four Asian countries. Glass-Co, on the other hand, produced high quality ophthalmic lenses through its three production facilities in three Asian countries. The managements of both these companies continuously face the decision to expand capacity in their production networks. Traditionally, industrial decision makers minimise the cost of expansion and follow it with the qualitative considerations but this is not considered the best approach by company managements at Machine-Co and Glass-Co. They argue that the accuracy of a decision process based on cost considerations alone is not as much desired by the practitioners as the ability of the decision process to consider all relevant factors and help the practitioner take his/her decision. The discussions with company managements at Machine-Co and Glass-Co hence suggested that there was a deficiency in the body of knowledge dealing with decision processes for capacity expansion in multi-site manufacturing. This forms the central premise of the work presented in this thesis (Section 2.3).

The limitations of existing capacity expansion decision processes are also apparent through a review of literature (Chapter 3). The literature reveals how the plant configurations in a multi-site network depend upon a number of market and business conditions (Section 3.1.1). It also establishes that the need and manner of capacity expansion is influenced by internationalisation and location specific advantages

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(Section 3.2.1). Further, a review of the literature establishes that a number of studies of the capacity expansion problem have been conducted (Section 3.3). There is hence a need to identify decision processes that can be used to effectively solve the capacity expansion problem. In case such processes fall short to their promised potential, there is a further need to develop an advanced decision process which also needs to be tested to establish scientific and industrial validity. This work is structured into a research programme which is discussed in the following section.

## 1.2 Overview of the Research Aim, Objectives and Programme

As developed in Section 4.2, the aim of this study is:

*“to develop an advanced decision process for capacity expansion in global manufacturing networks.”*

This programme investigates decisions leading to capacity expansion within a manufacturing network. In terms of scope, the work focuses on flexing the capacity of the network by expansion of specific facilities, including establishing new facilities, and by contraction of specific facilities, including shutting down facilities. To fulfil the research aim, 5 research objectives have been defined in Section 4.2 namely, to;

1. Establish the state-of-the-art in multi-factor decision processes for capacity expansion in manufacturing networks
2. Test a representative process in a real industrial context
3. Apply the results of the test to formulate an advanced decision process
4. Test the advanced decision process in practice
5. Refine the advanced decision process and prepare for dissemination



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The research programme has been divided into 5 parts in order to deliver the research aim and objectives (Section 4.3). In Part I, a theoretical evaluation of decision processes is conducted by drawing together previous contributions in the literature. To achieve this, an extensive literature review is conducted to identify state-of-the-art in capacity expansion decision processes in multi-site manufacturing. This review selects eleven processes as relevant to the capacity expansion problem in multi-site manufacturing (Section 5.1). An analysis of these processes is carried out (Section 5.3) by looking at their comparative Strengths, Weaknesses, Opportunities and Threats (SWOT) (Section 5.4).

In Part II a representative decision process is chosen from the literature (Section 6.2) and an industrial evaluation is conducted using a case study based approach. Four cases are conducted with Machine-Co and Glass-Co (Section 6.3) and the effectiveness of the representative decision process is evaluated (Section 6.3.5).

In Part III the results of the testing form the starting point of the development of an advanced decision process which addresses the shortcomings of the present body of knowledge in multi-site manufacturing capacity expansion (Section 7.1.2). The advanced decision process includes a data filter to enhance the quality of input data and enable consideration of additional factors into the data (Section 7.2.1), takes into account more constraints (Section 7.2.2), and is enriched by a post-processing module to generate reports for the practitioner (Section 7.2.3).

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This advanced decision process is then tested in an industrial environment in Part IV (Chapter 8). Four more industrial case studies are performed with more complex questions asked by the practitioner (Section 8.2.2). The case reports are then analysed, the strengths and weaknesses of the new decision process are identified, and the opportunities for future development are presented.

Finally refinements to the decision process are suggested in Part V based on results from industrial testing of the new process (Chapter 9). The advanced decision process is presented (Section 9.1) and its implementation is illustrated in detail through a case study (Section 9.2).

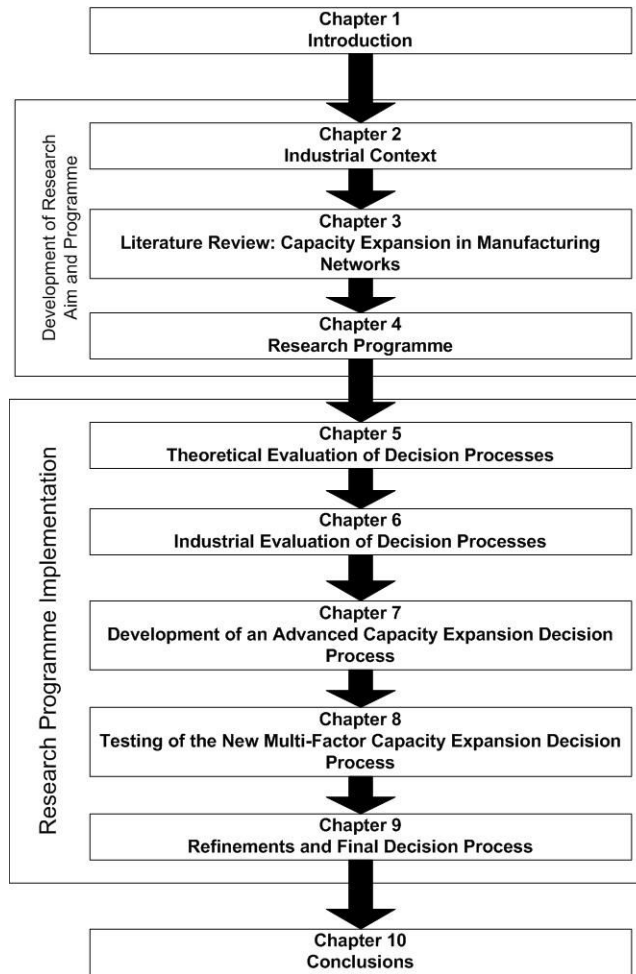
### 1.3 Overview of Research Contribution

The research conducted has enhanced the ability to make decisions regarding capacity expansion in a multi-site manufacturing network. A new integrated, comprehensive and coherent decision process is developed (Section 7.2) and industrially tested (Chapter 8) to fill the gap between practitioners' requirements and available literature. The research also contributes to knowledge through a rigorous analysis of multi-factor decision processes (Section 5.4). It is revealed that none of the available decision processes comprehensively cover all factors identified as important in the capacity expansion decision (Section 5.4.2). Finally this research contributes to the overall understanding of the field of capacity expansion in manufacturing networks. The research findings and contributions are discussed in detail in the Chapter 10.

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## 1.4 Thesis Structure

This thesis consists of 10 chapters (Figure 1.1). This structure is presented at the start of each chapter as a guide to the reader. Given below is a short description of each of the thesis chapters.



**Figure 1.1 Thesis Structure**

Chapter 2 The capacity expansion problem is presented in context to Singapore manufacturing industry and the opportunities and challenges faced by it. The chapter ends with a summary of the industrial problem addressed by this research.

- 
- Chapter 3 This chapter defines the key terms, outlines the decision making techniques used in the literature, and presents the past literature on the research problem. This chapter puts the industrial problem into the scientific research perspective.
- Chapter 4 In this chapter the aim of this research along with the objectives and scope is established. Based on an analysis of the industrial problem, the previous research on capacity expansion, and the aims and objectives of this research, a research programme consisting of five parts is formally developed.
- Chapter 5 A theoretical evaluation of decision processes is conducted in this chapter. The research method includes identification and analysis of capacity expansion decision processes representing the state-of-the-art.
- Chapter 6 In this chapter, a representative process is identified and industrially tested using a case study approach. A structured analysis of the cases identifies the strengths and weaknesses of the representative process and opportunities for development of a new decision process.
- Chapter 7 In this chapter an advanced capacity expansion decision process is developed based on the lessons from the industrial testing of the representative process. A filtering matrix is developed to enhance the quality of data, enhancements are made in the decision process and a

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post-processing module is developed to generate reports for the practitioner.

Chapter 8 This chapter describes the testing of the advanced decision process through four industrial case studies. This is complemented with more case studies based on industrial data to highlight features of the advanced decision process. The advanced decision process is then analysed in a structured manner and the strengths and weaknesses as well as future opportunities are identified.

Chapter 9 This chapter illustrates the advanced decision process and identifies refinements. It also describes the implementation details through an illustration of a case study using the advanced decision process.

Chapter 10 This chapter summarises the key findings of the research and formally presents the research's contribution to knowledge. Limitations of the research methodology are identified and concerns are highlighted. The chapter finally ends with recommendation for future work in the area.

This chapter has provided an overview of the research background, the research aim, objectives and programme, a summary of the research findings and contribution, and the thesis structure. In the next chapter, the industrial context for research in the area of capacity expansion decision processes for multi-site manufacturing is presented.

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## **Chapter 2. Industrial Context**

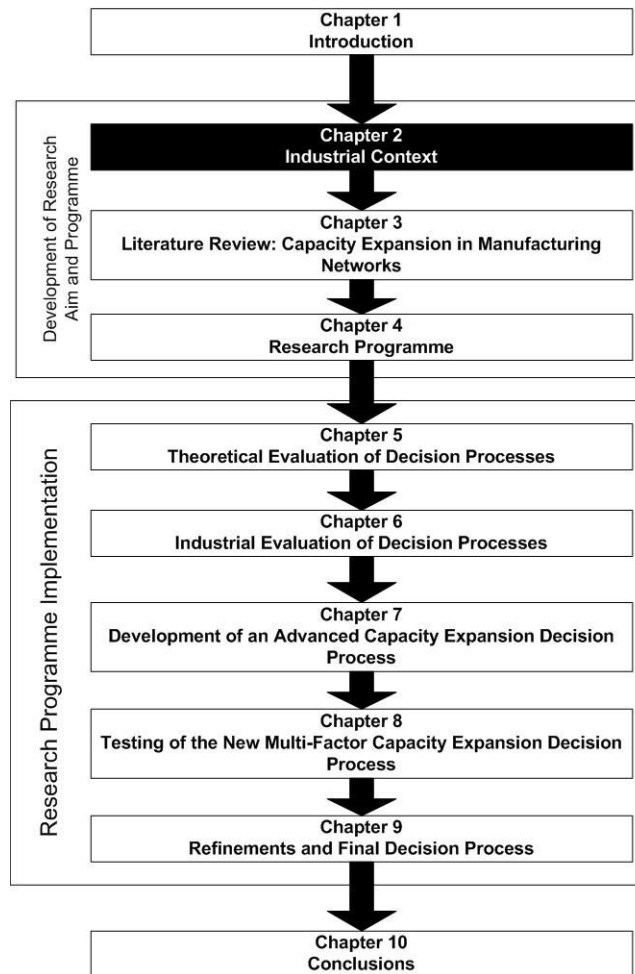
Chapter 1 has set the background to the research, an overview of the research aim, objectives and programme, and a summary of research findings and contribution. This chapter introduces Singapore's manufacturing industry, its competitiveness, and the role it plays in the Singapore economy (Section 2.1). In Section 2.2 the challenges to Singapore's manufacturing position are discussed in view of the rise of China as a global manufacturing competitor and the growing competition from other ASEAN economies. Section 2.3 discusses how this increase in competition is being addressed by Singapore manufacturers by establishing off shore manufacturing facilities. The capacity expansion dilemma faced by these Singapore manufacturers with multiple manufacturing sites is presented. The chapter is then summarised in Section 2.4. Figure 2.1 places this chapter in perspective of the overall research.

### **2.1 Role of Manufacturing within Singapore Economy**

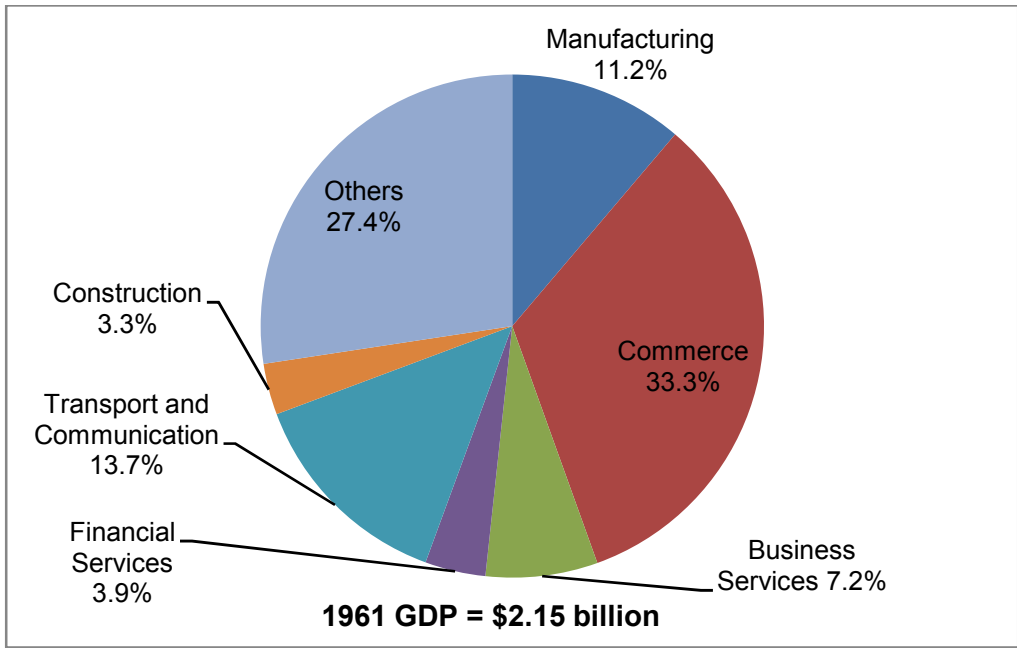
Manufacturing traditionally has played a very important role in Singapore's economy. In the last ten years it has contributed between 22% and 26% of Gross Domestic Product (GDP), more than 50% of its exports, and its total output grew by 7.7% per annum from 1991 to 2005 (Ling, 2006). Figure 2.2 and Figure 2.3 shows the increase in GDP from 1960 to 2004 and the role played by manufacturing (EDB, 2006b). The contribution of manufacturing has significantly increased from 11.2% to 27.7% of GDP. This translates to an increase from S\$ 240M in 1960 to S\$ 50.1B in 2004 at a Compound Annual Growth Rate (CAGR) of 13%. The service industry supporting the

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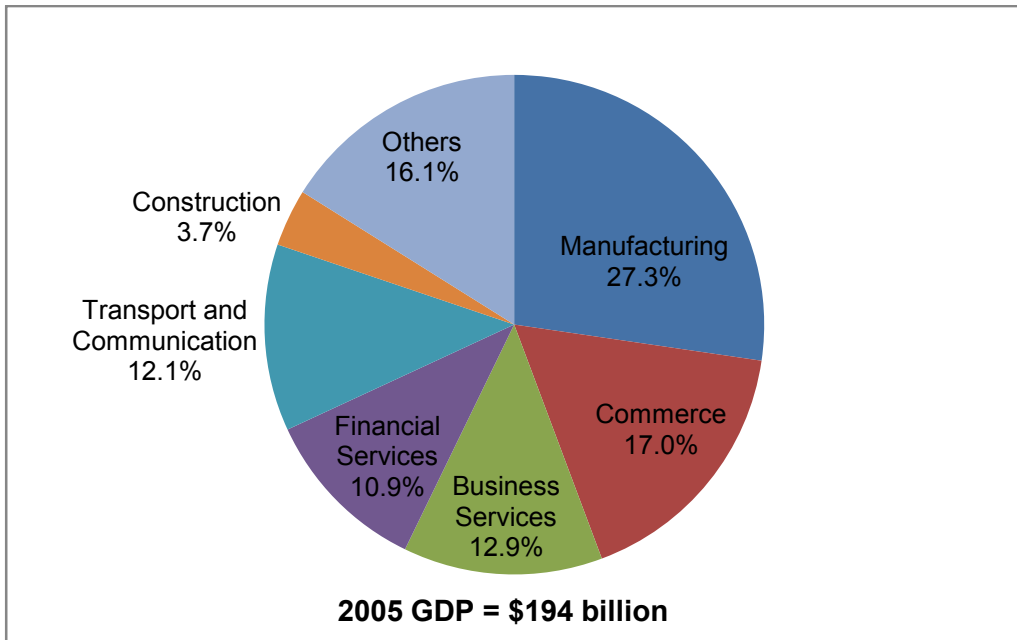
manufacturing operations is also of equal importance to the well being of the economy as there are considerable spin-offs to the growth in manufacturing in form of services needed (EDB, 2006a).



**Figure 2.1 Chapter 2 - Industrial Context**



**Figure 2.2 Role of Manufacturing in Singapore Economy in 1960 (Ling, 2006)**



**Figure 2.3 Role of Manufacturing in Singapore Economy in 2006 (Ling, 2006)**



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Hwa (2003) argues that Singapore will maintain a strong manufacturing base, because:

1. Singapore has built up world class manufacturing capabilities and competitiveness
2. Manufacturing know-how is essential for Singapore's R&D promotion
3. Manufacturing has significant economic spin-offs to other sectors
4. Manufacturing and services diversify risk and moderates impact of business cycles
5. Manufacturing provides employment for those not suitable for services

Manufacturing is hence likely to be retained in Singapore and remain one of the primary drivers to the economy. However, Hwa (2003) and Koh (2003), amongst other authors, present strategies to gain competitive advantage over other nations in the region. These authors suggest possible manufacturing initiatives that have contributed to Singapore's economic competitiveness. These initiatives fall under the following primary categories.

*Value Manufacturing:* The value chain comprises of activities including research and development, production, supply chain management, and regional management. The combination of the national vision of a Knowledge Based Economy (KBE) and established state-of-the-art logistics facilities provide the unique advantage of Singapore to host the entire value chain of an industry. The strengthening of R&D efforts in the various research institutes, universities and industry are also initiatives taken up to build up this advantage (Koh, 2003).

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*Supply Chain Edge:* Singapore manufacturing strategy has included leveraging the synergy of clusters. A cluster is defined (Carrie, 2000) to be a network of companies, their customers and suppliers of all the relevant factors, including materials and components, equipment, training and finance. The 3 major manufacturing clusters have been electronics, chemical and transport engineering. Since June 2000, the Singapore Government has embarked on an integrated strategy to develop a Biomedical Science cluster. Singapore aimed to grow the output of this cluster to S\$12bn by 2005 however by 2005 the output exceeded S\$17.6bn (EDB, 2007). In 2006 the biomedical manufacturing output grew strongly to S\$23 billion, an unprecedented 30.2% increase over 2005. Within a short span of six years, the manufacturing output has grown almost fourfold from the year 2000 (EDB, 2007).

*Trust, Reliability, IPR:* The Singapore brand has developed over the years into representing quality and reliability. Singapore is part of major Intellectual Property Rights (IPR) conventions and treaties and has one of the most protective intellectual property regimes in Asia. The manner of IPR governance has been attributed as a very important factor in determining alliances between US and non-US firms (Oxley, 1999) and also has an effect on decisions regarding Foreign Direct Investment (FDI) (Maskus, 1998).

*Network of Free Trade Agreements (FTAs):* Industries in Singapore have a greater global market access due to the FTAs with US, Japan, European Free Trade Association (EFTA), Australia, New Zealand, and Jordan. There is also an ASEAN Free Trade Area (AFTA) creating an ASEAN market of 550 million (EDB, 2004). As

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of 1 January 2003, nearly 92 per cent of all tariff lines in AFTA have been reduced to between 0 to 5 per cent, from an average of 12 per cent in 1992. Singapore has the highest proportion of tariff-free items under the AFTA (EDB, 2004). There are a number of agreements under discussion (see Figure 2.4) however the most crucial one is the ASEAN-China FTA which needs to be managed properly and relies on even greater integration between ASEAN nations (Mahani, 2002).

*Cost/Capabilities Competitiveness:* Singapore is still attracting manufacturing investments and managed to beat most of the Asian countries barring China in 2002 (Santiago, 2003). However, recent studies have shown that the cost of doing business in Singapore is ever increasing and thus the focus is now shifting towards high value added manufacturing rather than labour intensive manufacturing. Singapore aims to keep moving up the value chain. The manufacturing sector employed only 19% of the workforce in 2002 compared to 28% in 1992 but showed a CAGR of 5.9%. The nature of manufacturing industry has thus been shifting from labour intensive to high value IT enabled one (Singapore Economic Sub-Committee, 2002).

Based on these components of Singapore competitiveness, EDB (2006b) has set bold targets for the future of manufacturing. From 2006 to 2018 the aim is to create 15,000 new manufacturing jobs per year. Such a growth in manufacturing are also projected to result in 6,500 spin-off jobs in the services sector every year. By 2018, EDB envisages Singapore's manufacturing output to double to S\$300 billion and for the manufacturing value-added to double to S\$ 80 billion. This expansion has however got to take place in a wider context of international competition.



**Figure 2.4 Singapore's Free Trade Agreement (FTA) network (Source: EDB, 2004)**

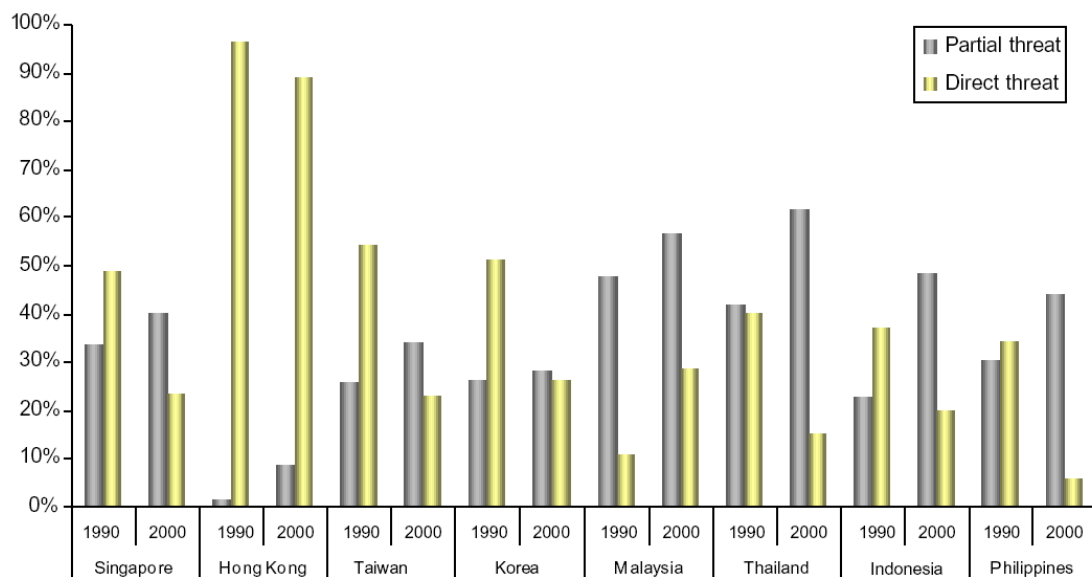
## 2.2 International Challenges and Strategic Manufacturing Initiatives

This section first reviews the principal competitors to Singapore manufacturing, particularly in the South-East Asian region. It also discusses the role China is playing in the world economy as a manufacturing centre (Section 2.2.1). Later in Section 2.2.2, the strategic initiatives that the Singapore government is preparing to counter this competition are outlined.

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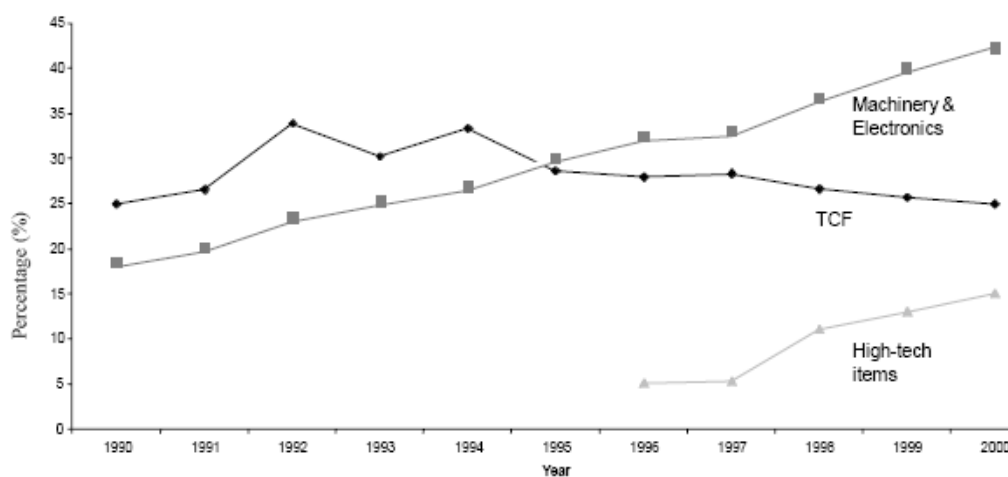
### 2.2.1 Challenges to Manufacturing in Singapore

International competition for Singapore manufacturing industry is intense. China, in particular, is seen as the single biggest source of both competitive challenge and business opportunity by East Asian economies including Singapore (Wong and Chan, 2002). Figure 2.5 shows the share of exports of East Asian countries under direct or partial threat by China. Further to this, Wong and Chan (2002) provide evidence of China's manufacturing sector transformation Textiles, Clothing and Footwear (TCF) to machinery and electronics and hi-tech items (Figure 2.6). This transition of China into high technology industry is causing further competitive pressures on Singapore amongst other East Asian nations. However, in Figure 2.5 it can be seen that direct threat from China has shown a reduction between 1990 and 2000 whereas there has been an increase in partial threat (Lall and Albaladejo, 2004).



**Figure 2.5 Shares of exports under direct or partial threat by China, 1999–2000**  
(Source: Lall and Albaladejo, 2004)

The increase in partial threat and subsequent decrease in direct threat of China on share exports of East Asian countries is explained in Lall and Albaladejo (2004) . Table 2.1 shows an analysis conducted by them on China’s potential competitive threat to Singapore. Apart from the change in direct and partial threat levels, it can be noted that more of Singapore’s production is coming under a category where there is no threat from China. A reason given is that China’s export threat in low-technology activities benefits the more industrially advanced neighbours that are losing their wage advantage but damages less industrialised ones that cannot move into design, marketing or intermediate manufacturing while re-locating facilities in China. Similarly, China’s movement into hi-tech industries is being leveraged by industrialized nations through joint ventures or direct investment (Walsh et al., 1999).



**Figure 2.6 Composition of manufactured exports from China from 1990 to 2000**  
(Source: Wong and Chan, 2002)

**Table 2.1 China's potential competitive threat to Singapore (Source: Lall and Albaladejo, 2004)**

Category	Value (US\$ Million)		Distribution (%)	
	1990	2000	1990	2000
Partial threat	17,366.6	54,779.9	33.6	40.4
No threat	6,630.3	43,416.1	12.8	32.0
Direct threat	25,340.1	31,821.5	49	23.5
China under threat	1,192.2	4,605.2	2.3	3.4
Mutual withdrawal	1,175.3	948.5	2.3	0.7
	51,704.4	135,571.1		

Categories: Partial threat - Both parties gain World Market Share (WMS) but China gains more than Singapore; No threat - Both parties gain WMS but China gains less than Singapore; Direct threat - China gains WMS and Singapore loses; China under threat - China loses WMS and Singapore gains; Mutual withdrawal - Both China and Singapore lose WMS.

### 2.2.2 Strategic Manufacturing Initiatives

In response to the rising regional and international manufacturing competition, a number of initiatives in Singapore are underway (Singapore Economic Sub-Committee, 2002). Those needing cutting edge Information Technology (IT) and Operations Research (OR) solutions include the following.

1. Development of new supply chain models including 'forward hubbing/floating warehouse' facilities
2. Development of a 'Plug and Play' environment for both manufacturing and R&D, including the support services that span the entire industry
3. Improvement of manufacturing infrastructure through development of shared facilities including training

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The common element, in all the above initiatives, is collaboration. Collaboration can take place amongst supply chain partners through use of high technology solutions and leveraging on connectivity to conduct seamless business. EDB aims to develop Singapore into ‘a compelling global hub for business and investment’ (EDB, 2006a). It provides a number of services and incentives for establishing and developing businesses in Singapore. Its Head Quarters (HQ) programme (EDB, 2004) is targeted at MNCs to locate their regional and international HQ in Singapore. This allows corporations to control production activities with Singapore as its ‘nerve centre’. The advantages that the companies gain apart from the generous tax incentives packaged with the HQ award include good business infrastructure, access to ASEAN market through an excellent logistics infrastructure, a simple and business friendly tax system and a large pool of high grade human resources for both management and research and development (Yeo, 2007).

The initiatives led by EDB in Singapore, globalisation and the increasing demands for manufactured goods worldwide has caused an increase in manufacturing facilities being developed in ASEAN and China. Companies headquartered in locations like Singapore and Hong Kong are constructing factories all across the region and developing their manufacturing networks. This is also reflected in the data for Singapore’s investment abroad (Table 2.2). These companies regularly face the issue of where to place capacity within their international manufacturing networks.



**Table 2.2 Distribution of Singapore's Direct Investment Abroad by Activity**  
 (Source: Singapore Department of Statistics, 2007)<sup>1</sup>

	2004 (S\$ mil)	2005 (S\$ mil)	Share in 2005 (%)
<b>Total</b>	<b>175,225</b>	<b>185,101</b>	<b>100.0</b>
Manufacturing	37,713	43,067	23.3
Wholesale & Retail Trade, Hotels & Restaurants	12,584	13,546	7.3
Transport & Storage	6,766	9,366	5.1
Information & Communications	9,678	10,494	5.7
Financial Services	93,242	90,330	48.8
Real Estate, Rental and Leasing Services	7,847	8,851	4.8
Professional & Technical, Administrative and Support Services	3,233	4,081	2.2

### 2.3 Capacity Expansion Decisions in Manufacturing Networks

The capacity expansion decision is faced by a number of manufacturing companies in Singapore as established in Section 2.2.2. Machine-Co and Glass-Co are examples of Singapore-based discrete product companies struggling with this decision on a regular basis. Machine-Co has four plants in the region in China, Japan, Malaysia and Singapore. The market for their products is increasing rapidly and, with all factories currently producing close to their maximum capacities, there is a need to decide upon the investment (e.g. on facilities, machines, manpower, etc.) for capacity expansion. Based on pure costs, China typically becomes the prime candidate for expansion.

<sup>1</sup> 1 S\$ = US\$ 0.659 (Source: [www.xe.com](http://www.xe.com), 24<sup>th</sup> March 2007)

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However, the industrial practitioners argue that the effect of higher efficiencies and low wastage in Singapore and Malaysia can mitigate the cost advantage that China presently commands<sup>2</sup>. These concerns of the practitioners are based on operational experiences and knowledge of qualitative factors like low availability and high attrition rate of skilled labour in China. Such considerations however don't enter the decision making process directly as the process presently used is cost based.

Glass-Co on the other hand has production sites in Indonesia, Singapore and Malaysia. Their similar concern is that a purely cost-based decision processes will report that optimal expansion strategy was to add capacity in Indonesia. However, in their case lack of manpower combined with the socio-political climate in the country was a turn off. The practitioners at Glass-Co similarly wanted a decision process that was able to handle their concerns which went beyond simple accounting considerations. The practitioners in both Machine-Co and Glass-Co have been searching for a decision process that takes into account the factors beyond just cost and help them take more well rounded decisions.

Both Machine-Co and Glass-Co are in the position of taking advantage of the competitive changes in the manufacturing landscape as they have manufacturing facilities spread across Asia. They are however struggling with the capacity expansion decision and need a decision process which considered all or nearly all elements (Comprehensive) deemed important by the practitioners. In addition, all parts or aspects of the process should be linked or coordinated (Integrated) and the process

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<sup>2</sup> Japan is a production site for historic reasons and produces specific products for the Japanese market only.

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should be logical and consistent forming a unified whole (Coherent) (Soanes and Stevenson, 2005). This process needs to be an improvement over the present processes available in the literature.

The industrial problem needed to be addressed thus was very clear. The words ‘comprehensive’, ‘integrated’ and ‘coherent’ thus jointly cover all the features that are needed by the practitioners. The industrial problem thus reduced to the question

*Is there a comprehensive, integrated and coherent decision process to make investment decisions involving capacity changes in multi-site manufacturing networks?*

If there is one available, then the industrial problem can be addressed by introducing such a process to the practitioners. If there is none available then the industrial problem will result in a research problem focused on developing such a process based on existing and new knowledge. For purpose of this research, any process which has all the three features of being comprehensive, integrated and coherent is also referred to as a ‘holistic’ process. The most obvious next step was to search the literature on capacity expansion processes and establish how this problem has been tackled from different points of view. Once the literature landscape is established then a holistic process, if present in the literature, will be introduced to the industrial practitioners.

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## 2.4 Chapter Summary

This chapter has set out the role of manufacturing in Singapore's economy and the vision of the policy makers. The challenges faced by Singapore in the region from China and other ASEAN countries are discussed along with outlining the strategic initiatives undertaken by the government to mitigate the threats. Finally, the industrial need for a decision process for multi-site capacity expansion has been defined and the need to conduct a detailed literature review is established. In the next chapter we conduct this review to position the industrial problem from a scientific perspective and determine if there is an underlying research problem which needs to be addressed.

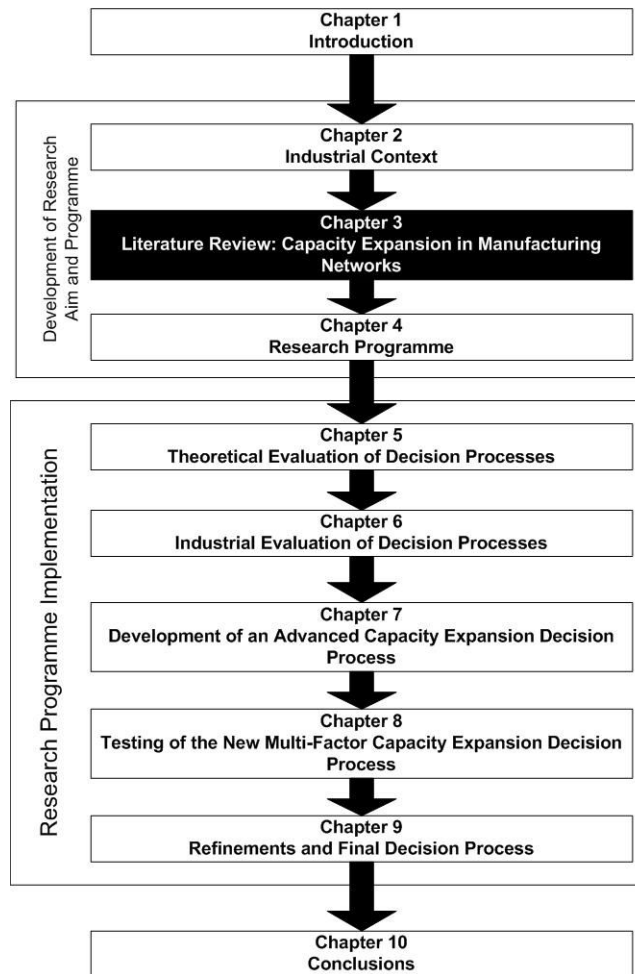
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## **Chapter 3. Literature Review: Capacity Expansion in Manufacturing Networks**

The industrial problem is to determine a holistic decision support process for capacity expansion in manufacturing networks (Chapter 2). This chapter places the industrial problem in context of academic research. The purpose of this chapter is to give an overview of the capacity expansion concepts and to explore the issues related to decision processes in capacity expansion through a literature review. This chapter defines the key terms, mentions importance of the field, outlines previous work in the area, and is structured to answer the following questions.

1. What is a manufacturing network and what does capacity expansion in a manufacturing network imply?
2. What techniques are used for making a capacity expansion decision in a manufacturing network?
3. What are the current research issues associated with the capacity expansion decisions in manufacturing networks?

The terms manufacturing network and capacity expansion within manufacturing networks are defined in Section 3.1. Decision support techniques are discussed in general and with respect to capacity expansion in Section 3.2. Finally, in Section 3.3 a literature review is presented on decision processes for capacity expansion. Figure 3.1 places this chapter in perspective of the overall research.



**Figure 3.1 Chapter 3 – Literature Review: Capacity Expansion in Manufacturing Networks**

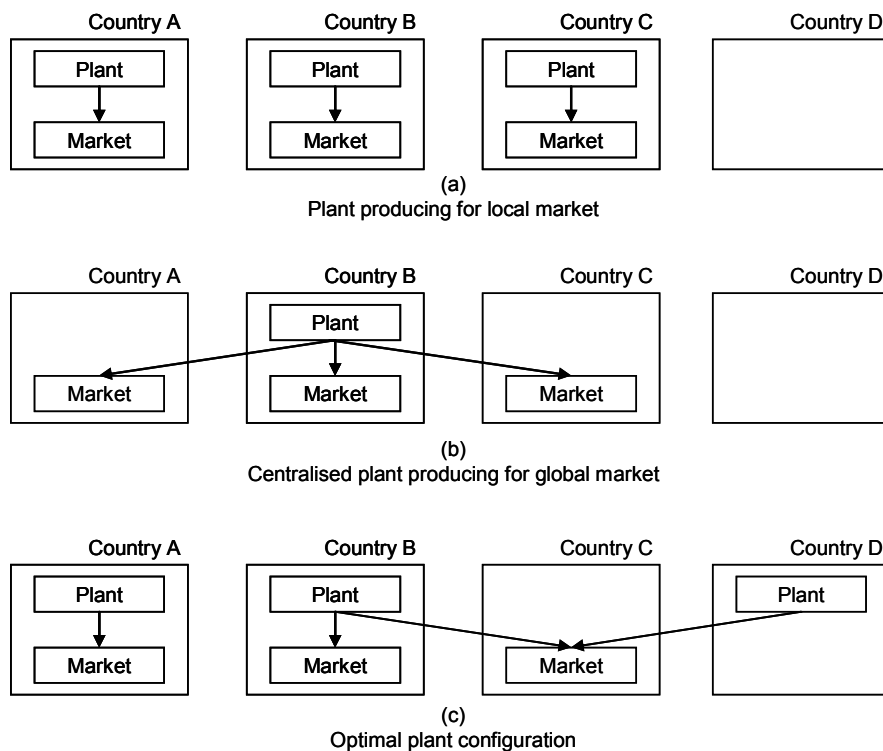
### 3.1 Manufacturing Networks and Capacity Expansion

The purpose of this section is to define the two key terms ‘manufacturing networks’ and ‘capacity expansion’ in context of the research presented in this thesis.

#### 3.1.1 Plant Configuration in Global Manufacturing Networks

Global manufacturing networks can take up a variety of configurations. Chakravarty (2005) suggests two extremes. First, a plant in each country serving its local market

(Figure 3.2a) and second, a single centralised plant which exports to all countries (Figure 3.2b). Most global manufacturing networks operate somewhere between the above two extreme configurations (Figure 3.2c). For example, Kanter (1995) uses this to explain Gillette's operations. She reported that 70% of the \$6 billion annual sales are outside the US through 58 plants in 28 countries serving markets in 200 countries.



**Figure 3.2 Plant configurations for global manufacturing networks (adapted from Chakravarty, 2005)**

Since both the demand for the product in the markets and the host conditions for a plant vary across different countries, each of the links in Figure 3.2 is also different in nature (Chakravarty, 2005). The choice of foreign plant to supply products to a local market is also dependent on the comparative positions of all the plants in the network based on factors like production costs, transport costs, tariffs and economic and social

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conditions e.g. increase in competency of manpower in a country, change in local living conditions and change in the IPR regime (Porter, 1986).

### **3.1.2 Capacity Expansion in Manufacturing Networks**

Investment in capacity expansion remains one of the most critical decisions for a manufacturing organisation with global production facilities. In the late 1970s, Wheelwright (1978) put forward the notion that aggregate capacity was one of the five strategic manufacturing decision areas and thus should be part of a company's operations strategy. As Rudberg and Olhager (2003) report, this view is widely supported (Porter, 1980; Fine and Hax, 1985; Hill, 1989; Samson, 1991; Miltenburg, 1995; Slack et al., 1995; Skinner, 1996). Wheelwright (1978) also identified the remaining four decision areas as facilities (size, focus and location), manufacturing infrastructure, vertical integration and production process choice. The decision of capacity expansion across multiple facilities and multiple focuses (types of capacity) thus spans across three of the above mentioned strategic manufacturing decision areas too.

Capacity is defined in a number of ways by different authors. Slack et al. (1995) define capacity of an operation as the maximum level of value-added activity over a period of time. Alternatively, capacity is often referred to as the throughput or output capacity in terms of the number of units produced by a resource in unit time (Buffa, 1983). The measurement of capacity is thus in itself an immensely complicated task especially when the resources (machines, manpower, logistics) are disparate and non homogeneous in nature as is the case in any manufacturing plant (Elmaghraby, 1991).



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Hence, in context of this study, the term capacity will represent the mean output capacity (or throughput), which is the number of units of a product produced in unit time. This capacity normally depends on the type of product being produced, especially in a multi-product environment. Increasing the number of units of a product produced per unit time by adding more equipment or new facilities is thus categorised as capacity expansion in the context of this study.

Capacity expansion in manufacturing networks is hence defined in this study as “increasing the number of units of product produced per unit time by adding more equipment in a single or multiple facilities, or adding new facilities to a group of facilities, serving local or foreign markets, owned by a single company”.

## 3.2 Techniques for Capacity Expansion Decision Making

The purpose of this section is to outline different decision making techniques followed for capacity expansion in manufacturing networks. In the following sections, decision making techniques are first discussed in general (Section 3.2.1). Following this, qualitative techniques for capacity expansion, based on site competence and proximity to market are presented (Section 3.2.2), in contrast with quantitative techniques (Section 3.2.3) based on production parameters, various costs and economic considerations.

### 3.2.1 Techniques for decision making

Bazeley (2004) classifies decision support techniques as qualitative and quantitative, defines both and discusses each of them. Qualitative techniques are based on

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structured or unstructured textual information, with the type of investigation being exploratory, and using an interpretive method of analysis. Quantitative techniques, on the other hand are based on numerical data with the type of investigation being confirmatory and using statistical analysis. Borland Jr. (2001) suggest a synergistic approach is the most powerful however every decision support scenario cannot be approached with it. Borland Jr. (2001) also provides a comprehensive comparison of the two approaches. Important from the context of this research is the difference in the setting, naturalistic for qualitative and controlled for quantitative and difference in evaluation and data being narrative and words for the former and numerical and statistics for the latter. Pidd (2003) discusses the different techniques by categorising them as ‘hard’ and ‘soft’ approaches Table 3.1. This comparison is presented through four categories, problem definition, the organisation, the model and outcome. The ‘hard’ approach is best when the problem definition is straightforward. ‘Soft’ approaches on the other hand debate the definition of the problem and aim to understand how different stakeholders may frame the issues differently. There are a number of techniques belonging to each of these approaches. These techniques are discussed in the following section with respect to capacity expansion.

**Table 3.1 ‘Hard’ versus ‘soft’ approaches (Pidd, 2003)**

	<b>Hard approaches</b>	<b>Soft approaches</b>
Problem definition	Seen as straightforward, unitary	Seen as problematic, pluralistic
The organisation	Taken for granted	Has to be negotiated
The model	A representation of the real world	A way of generating debate and insight about the real world
Outcome	Product or recommendation	Progress through learning

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### 3.2.2 Qualitative techniques

Qualitative techniques for capacity expansion are discussed in this section. As established in Section 2.3, MNCs establish factories in multiple geographical locations. This internationalisation has been deemed to be critical for their continuance and needs to be included in their strategy formation process (Porter, 1986). Labour cost is one of the reasons for establishment of such foreign factories but equally important are reduced overhead costs (logistics, taxes, etc.), access to suppliers and customers, access to skilled labour and trade concessions. There are two different theories, both of which are equally important in explaining reasons for ‘foreign’ factories. Firm-level theories like that of Ferdows (1997) view internal motives for location decisions whereas industry-level theories like that proposed by Dunning (1993) take into fact the environment that the firm operates in.

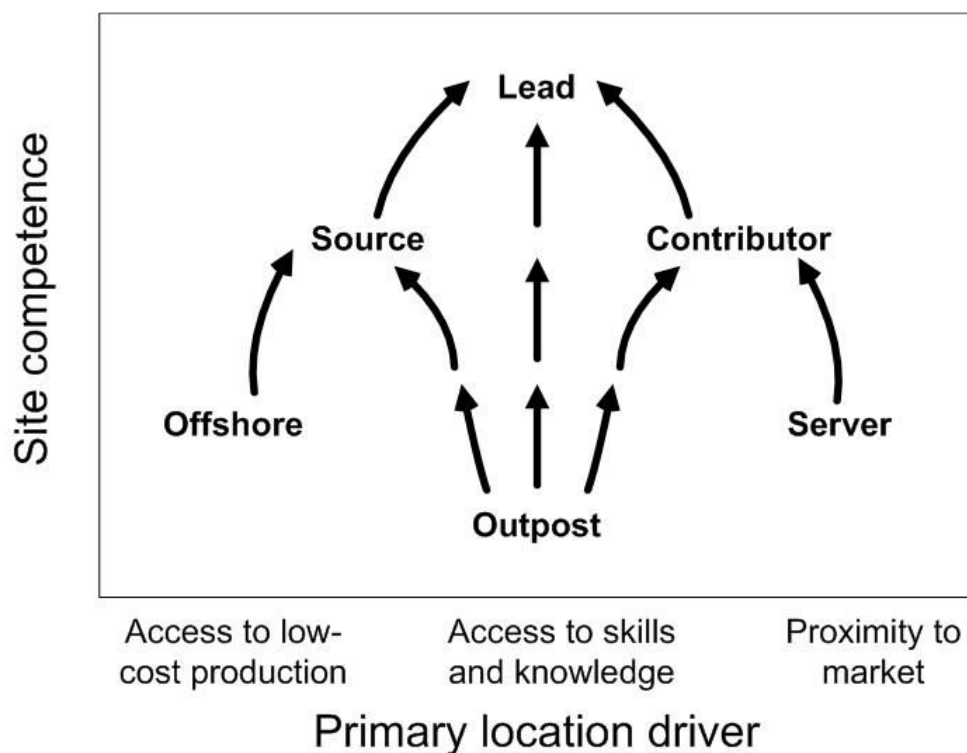


Figure 3.3 Strategic role of factories (Source: Ferdows, 1997)

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Ferdows (1997) provides the first framework to classify factories based on their strategic roles. He suggests six roles generated from the combination of two variables-

1. Site Competence – low or high
2. Strategic Reason for the site –
  - Access to low cost production
  - Access to skills and knowledge
  - Proximity to market

Ferdows (1997) explains the six roles to be *offshore*, *source*, *contributor*, *server*, *outpost* and *lead* (see Figure 3.3). An *offshore* factory is established to leverage factors which permit low-cost production e.g. low wages and cheap raw material. It has only production capabilities and is dependent on other sites for their technological needs. A *source* factory also aims to leverage the low-cost production base (for which it is primarily established), however it also has resources to develop products or processes for the company's global market. A *server* factory is created to supply regional markets while as a contributor assumes product and process modification responsibilities apart from serving the local market. An *outpost* aims to gain access to skills and knowledge whereas a *lead* factory has the responsibilities to create more products for the company and is normally the nerve centre of the organisation. In many cases factories have two or more roles. Ferdows tracks the changes in strategic roles of factories and describes a natural path of increasing site competence.

A second technique supporting industry-level theory is proposed by Dunning (1993). Dunning (1993) argues that decisions to establish 'foreign' factories are based on

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advantages that a firm gets through certain intangible assets it owns (ownership-specific), through the synergy between different sites that can be exploited and the overall business environment (internationalisation-incentive) and competitive advantages attributed to the particular location (location-specific). Though all the above provide mechanisms to formulate internationalisation strategy, they are based on the constituents and the corresponding construction of the underlying information and comparison data. For example, the comparison of the cost of production between facilities (locations) is done solely on the base of the tangible direct inputs like labour and raw material. Intangible costs due to infrastructure differences and differences in labour quality are not considered. Also not considered is the future rise in cost in present low cost centres due to high incoming investment and industrial growth. Such a transformation based on limited data can effectively erode any cost advantages.

There are also a number of soft factors which may outweigh the cost advantages from establishment of 'foreign' factories. Work by Meijboom and Voordijk (2003) provides a study on why a number of production and distribution facilities remained in Western Europe regardless of the globalisation. The findings suggested that facilities with high strategic importance within the MNC gave high importance to the political/legal and macro-economic environment. This was also in line with Ferdows (1997) comments on the managerial approach to upgrading strategic roles of factories. Analytical hierarchy Process (AHP) was another technique used in the academia to study the capacity expansion process. Korpela et al. (2002) combine AHP and integer programming to include risks associated with customer-supplier relationships to production capacity allocation. Datta et al. (1992) introduce a process using AHP to

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evaluate investments for manufacturing systems. These techniques take into account the various qualitative aspects of the decision making process to solve the capacity expansion problem. There is thus a need to examine how the tangible and the intangible factors contributing to the competence of a location are considered in a comparative study.

### **3.2.3 Quantitative techniques**

Quantitative techniques are predominantly used for capacity expansion decision making. Within quantitative techniques, numerical optimisation and simulation are two primary techniques used for decision support in general. Taha (2006) provides a comprehensive analysis of numerical optimisation using linear programming and other advanced techniques. Linear programming (LP) involves optimisation of an objective function using a set of mathematical relationships in the form of equations, equalities, inequalities and logical dependencies. The decision variables in an LP can take any real value. An extension of the LP where decision variables can take integer solutions only is known as an integer program (IP). Finally, a problem which has some decision variables taking any real value, and others being restricted to only integer values, is a mixed integer linear program (MILP). The situation when linear programming should be used includes when there is a linear objective function and the constraints are all linear in nature.

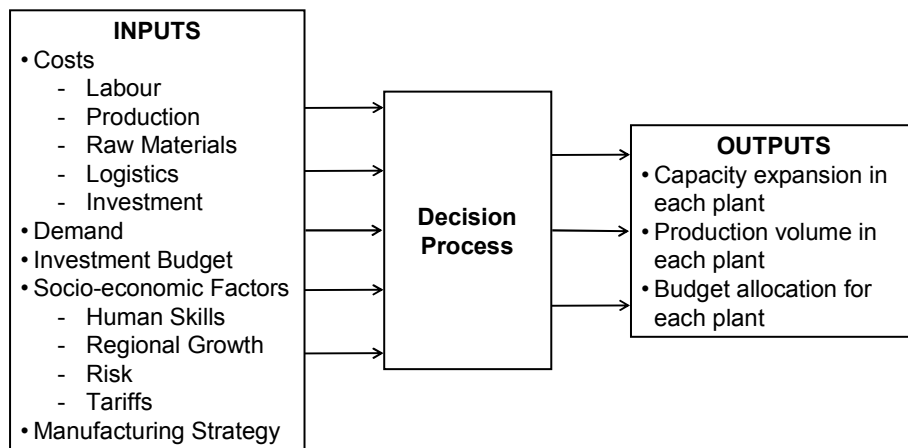
Simulation on the other hand involves imitating the operation of a real-world process or system over time (Banks, 1998). Banks et al. (2000) discuss when to use simulation and when it is not an appropriate tool. They advise not to use simulation if the

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problem can be solved analytically. However, even when simulation is used, there is a situation where the goal is to optimise the system performance which in turn can only be evaluated by running a computer simulation. The technique used in such a scenario is generically referred to as ‘optimisation via simulation’. However, since output of most simulation models is stochastic in nature, the optimised solution is not an exact prediction of performance (Robinson, 2005). Robinson (2004) also argues that such ‘optimisation’ should be more appropriately referred to as ‘searchisation’.

An analysis of the literature in capacity expansion decision techniques reported the most work conducted used numerical optimisation as the technique. One reason for this was that the capacity expansion decision was not looking at the evolution of the system but rather viewing the capacity expansion points deterministically. Most of the techniques used included multiple factors and hence were referred to as multi-factor decision processes.

Luss (1982) provides a comprehensive review of literature on capacity expansion and considers multi-factor decision processes as fundamental aids to strategic capacity planning in a manufacturing network. Illustrated in Figure 3.4 is a typical multi-factor decision process for evaluating capacity expansion in a manufacturing network. The decision process takes in different costs, demands, investment budget, socio-economic factors and the manufacturing strategy of a company as *inputs* and generates the amount of capacity to be expanded in each plant, respective production volumes and investment required as *outputs*.



**Figure 3.4 Example of inputs and outputs for a multi-factor decision process for capacity expansion**

### 3.2.4 Qualitative or quantitative techniques?

The decision to choose the solution technique most suited for the capacity expansion problem can be made based on the frameworks proposed by Pidd (2003), Borland Jr. (2001) and Bazeley (2004). An analysis of the problem defined in Chapter 2 based on the framework by Pidd (2003) suggests ‘hard’ approach to be most useful. This is because the problem definition is straightforward and the work is to be conducted based on the organisation that is present. The model aims to represent how the decision is taken in reality and the result of the process needs to be a recommendation to expand capacity at a time, place of a certain type and amount.

Based on Borland Jr. (2001)’s comparison since the problem at hand is controlled in setting and the data is primarily numerical, a quantitative approach would be best. Finally, based on a classification suggested by Bazeley (2004), since the investigation is confirmatory in nature a quantitative approach would be better suited. However, as suggested by Borland Jr. (2001), a synergistic approach would be the most powerful



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however it needs to be investigated whether the present decision support scenario can be approached with it or not. In the next section previous work using quantitative approaches for addressing the capacity expansion problem are discussed.

### 3.3 Previous Research on Capacity Expansion in Manufacturing Plants

The first methods for evaluating capacity changes focused on optimal utilisation models of capital (Marris, 1964). These had two basic assumptions. First was that the demand was constant over the life of the plant and, second was, that the total capacity existed in a single plant. These processes were then developed to include dynamic capacity, in which the demand increased with time (assumed to be linear in most cases). Manne (1967a) demonstrated such decision processes of capacity expansion in a series of heavy process industries in India.

Manne (1967b) followed his earlier work with a methodology based on integer programming for the evaluation of capacity expansion across two facilities. Erlenkotter (1967) developed a dynamic programming formulation of the same problem with fewer restrictions. This was followed by further improvements in later years by himself (Erlenkotter, 1972; 1974) and Freidenfelds (1981). The work in this field has since expanded to include a number of different issues. Dixit (1980) discussed the effect of capacity expansion decision on entry-deterrence in an industry. Using models based on game theory and this concept has since been extended by various authors in the field (Dixit and Pindyck, 1994). For example, application of these concepts in U.S. firms is discussed by Bulan (2005).

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Luss (1982) provides the latest comprehensive review of capacity expansion literature (Van-Meighem, 2003) and identifies various research issues (Table 3.2). Since then, important work has been carried out by many researchers including Reeves et al. (1988), Li and Tirupati (1994), Syam (2000), Perrone et al. (2002), Ryan (2004), Chakravarty (1999; 2005), Melo et al. (2005) and Bish and Hong (2006). Many of these authors have focused on addressing issues identified by Luss (1982). The need now is to provide an updated review of work in this field and so provide a basis for research to further progress the field of decision processes for capacity expansion in multi-site manufacturing networks.

### 3.4 Chapter Summary

This chapter has defined the concepts of multi-factor decision processes for capacity expansion in manufacturing networks. Plant configurations in manufacturing networks were discussed along with the strategic reasons behind such decisions. The importance of capacity expansion in such manufacturing networks was established using both firm-level well as industry-level theories viewing the environment that the firm operates in. Techniques available to address the capacity expansion issue were discussed and contrasted. It was deduced that quantitative techniques were the most promising to address the capacity expansion problem. Previous research on capacity expansion in manufacturing plants was then reviewed and current research issues were presented. In the next chapter a research programme is developed based on the industrial problem described in Chapter 2 and the research issues describes in Chapter 3.

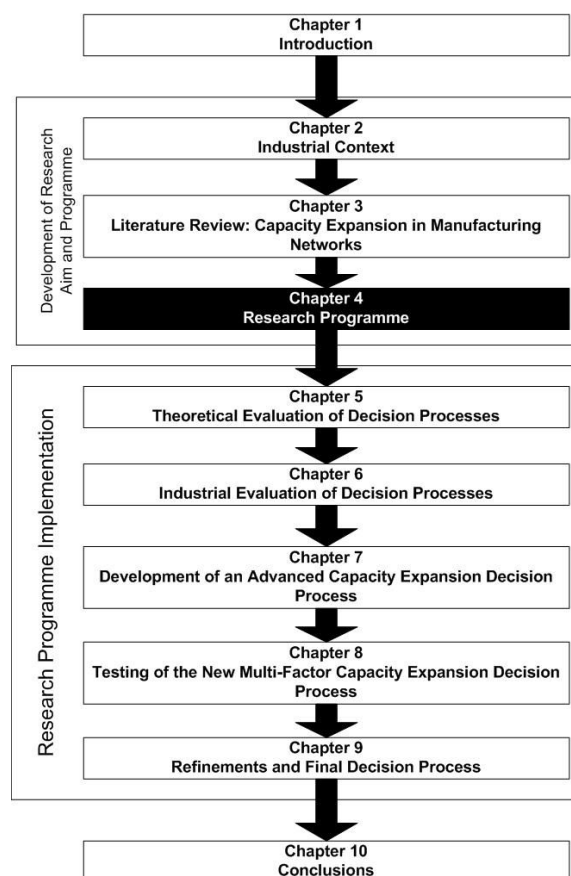
**Table 3.2 Issues in the Capacity Expansion Problem (adapted from Luss, 1982)**

Issue	Features
Size	Continuous (with fixed/ variable/ lumpy expansion sizes)
	Finite (fixed number of expansion sizes and duration)
Time	Dynamic Capacity Expansion (expansion policy)
	Single Period Problem
Location (including Type)	Single Facility
	Two Facility
	Multiple Facility
Cost Functions	Power Cost Function
	Fixed Charge
	Combination
	Piecewise Concave (Technology-based Expansion)
Demand Function	Linear: $\mu + \delta t$
	Exponential: $\mu \exp(\delta t)$
	Decreasing exponential with saturation: $\beta(1-\exp(\delta t))$
Deferring Expansion	Capacity Shortages
	Inventory Build-up
	Temporary "importing" capacity (Outsourcing)
Costs	Congestion cost
	Holding cost
	Operating cost as function of demand
	Operating cost as function of technology and age
Decision Maker Constraints	Budgetary Constraints
	Corporate Policies
	Upper Bounds on Expansion Sizes
	Excess Capacity
Special Issues with Multi-facility	Multi-location - Same Country / Area
	Multi-location – Global
	Multi-type (Multiple Products)
Capacity Modification	Capacity Conversion
	Replacement

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## Chapter 4. Research Programme

The intention of this research is to assist practitioners in the process of capacity expansion in a manufacturing network. A review of the industrial problem in Chapter 2 followed by a literature review in Chapter 3 has established the extent of previous work in the area and identified, qualitatively, the limitations of current work. This chapter summarises the knowledge from those earlier chapters (Section 4.1) to generate the precise aim (Section 4.2) to fulfil the intention of this research. A research programme is then developed to realise this aim (Section 4.3). Figure 4.1 places this chapter in perspective of the overall research.



**Figure 4.1 Chapter 4 – Research Programme**

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## 4.1 Industrial Problem and the Research Context

Manufacturing plays a very important role in the Singapore economy (Section 2.1). The Economic Development Board (EDB) of Singapore (2003) provides compelling reasons why Singapore will keep its focus on manufacturing in future (Section 2.1). The rising competition from China and other ASEAN countries is threatening Singapore's position as a manufacturing hub (Section 2.2.1). The strategic manufacturing initiatives to counter these threats include the initiative to move up the value chain, establish a supply chain edge due to Singapore's location and excellent logistics infrastructure and development of network of FTAs between Singapore and other countries (Section 2.2.2). Singapore based manufacturers are leveraging these initiatives and establishing factories in the region. They face the issue of locating capacity in their international manufacturing networks (Section 2.3). The practitioners have found present techniques inadequate and need an integrated, comprehensive and coherent (holistic) decision process to make such capacity expansion investment decisions (Section 2.3).

A literature review of capacity expansion decision processes carried out in Chapter 3 discusses different aspects of the problem domain. The definitions of manufacturing networks (Section 3.1.1) and capacity expansion (Section 3.1.2) associated with them are established. Different techniques proposed by academia are then discussed (Section 3.2). It was established that qualitative and quantitative techniques were available. Quantitative techniques especially numerical optimisation using linear programming showed the most promise. Finally, previous work in the field was presented through a literature review (Section 3.3). There is now a need to identify

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decision processes for multi-site capacity expansion that can be described as holistic (comprehensive, integrated and coherent) and if such processes do not qualify as relevant to the practitioners then an advanced decision process needs to be developed.

## 4.2 Development of Research Aim and Objectives

Taking into account the description of the research problem given in Section 4.1, a research aim is formulated for this thesis that will, if satisfied, make a worthy contribution to knowledge about decision processes for capacity expansion in manufacturing networks. This aim is:

*“to develop an advanced decision process for capacity expansion in global manufacturing networks.”*

Explicit in the research aim is an intention to form and verify a decision process. Verification of such a process cannot commence until a theoretical evaluation of present decision processes is conducted. Following this, an industrial testing of present processes is conducted to develop the specifications of the new process. Thus, the objectives of this research are to:

1. Establish the state-of-the-art in multi-factor decision processes for capacity expansion in manufacturing networks
2. Test a representative process in a real industrial context
3. Apply the results of the test to formulate an advanced decision process
4. Test the advanced decision process in practice
5. Refine the advanced decision process and prepare for dissemination

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### 4.3 Development of the Research Programme

The research programme is a sequence of activities that are to be carried out to realise the aim and objectives of this research. The objectives defined above naturally lead to a five-part research programme (see Figure 4.4). This section will determine the required parts, the associated objectives and guiding methods necessary to realise each objective. Each Part is presented as a separate chapter in the rest of the thesis in which detailed research activities executed in that part are discussed.

#### **4.3.1 Part I: Theoretical Evaluation of Capacity Expansion Decision Processes**

As outlined above in Section 4.2, the first objective of this research is to establish the state-of-the-art in multi-factor decision models for capacity expansion in manufacturing networks. There are a number of approaches to handle this.

Based on the analysis carried out by Baines (1994) in the field of manufacturing strategy, three methods exist in addressing the development of a holistic decision process for capacity expansion in manufacturing networks. The first approach is to ignore existing knowledge and develop the decision process. This uninfluenced development may lead to a fundamentally new approach and a novel decision process. The major concern here is that the effort spent may yield a decision process strikingly similar to something already existing in the literature. The second approach is to develop the decision process based on the existing knowledge about such decision processes available in the literature. However, weaknesses in the existing decision processes may mislead research effort and deliver a sub-optimal solution. Also,

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decision processes developed using any of the above paths will need to be tested in the industry to gain confidence that the process is suitable to be used for capacity expansion decisions, and to avoid being criticised as an unsupported conceptual solution. A third approach is essentially a combination of the above two. Under this approach the capabilities and effectiveness of the existing processes are assessed and the shortcomings are identified. These shortcomings are then addressed by a new decision process.

The approach combining an incremental change in present processes with addition of concepts based on first principles is considered most appropriate for this part of the research. It builds on the previous literature and so avoids building something strikingly similar to an already developed process. It also avoids biases that may exist in present literature by improvements based on first principles. In Part I of the research, a detailed literature survey conducted along with a comparative analysis of the relevant processes. A structured analysis is performed which summarises the theoretical evaluation of capacity expansion decision process in multi-site networks.

### **4.3.2 Part II: Industrial Evaluation of Capacity Expansion Decision Processes**

Part I performs a theoretical evaluation of capacity expansion decision processes. It is likely that the outcome of Part I of the research will provide a methodology to identify a preferred decision process. Once this decision process is identified the challenge will then be to test this process to know how competent it is. As outlined in Section 4.2, the second objective of this research is to test such a representative process in a



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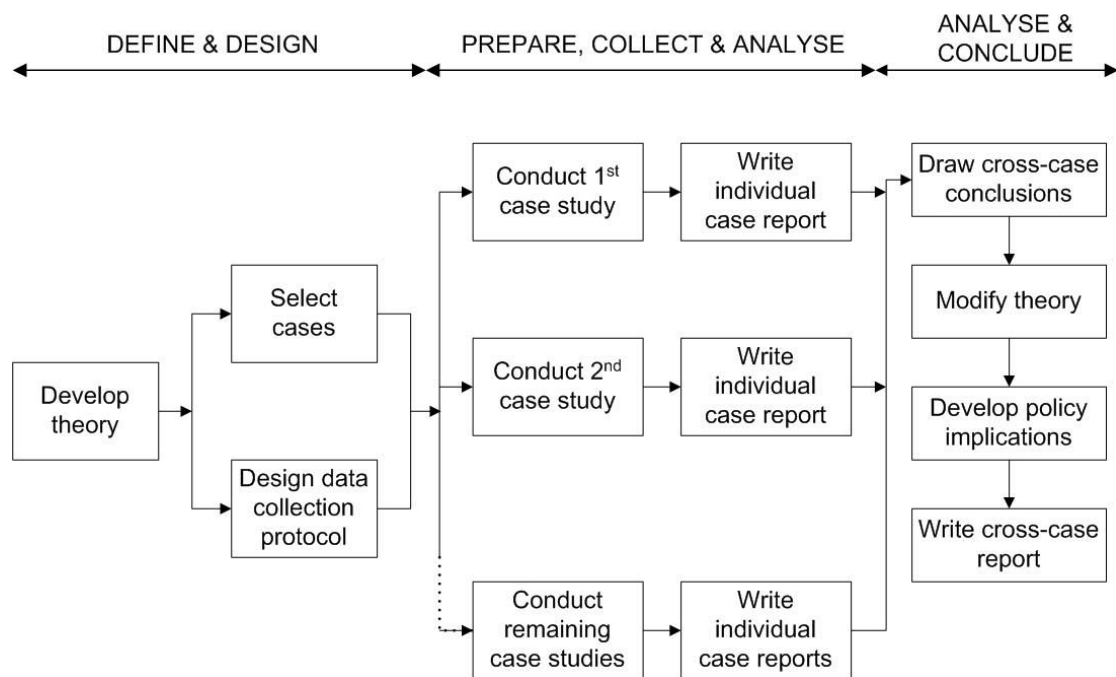
real industrial context. Such a test can be conducted using different methods defined in the literature.

Yin (2003) discusses relevant situations for different research methods (Table 4.1). The purpose to test a representative process is to determine ‘how’ good the process is in practice. The research methods that are appropriate to answer ‘how’ questions are Experiment, History and Case study. Further, the test needs to be conducted in an industrial setting and hence there is no control of behavioural events. Use of Experiment as a research method is eliminated through this reasoning. Further, since the focus of any test needs to be based on contemporary issues, History is also eliminate as an appropriate method. A case study based approach is chosen as the research method to test the representative process in Part II of the research as it addresses ‘how’ questions, do not need a control over behavioural events and focus on contemporary events and developments.

**Table 4.1 Relevant situations for different research methods (Yin, 2003)**

<b>Methods</b>	<b>Form of Research Question</b>	<b>Requires Control of Behavioral Events</b>	<b>Focuses on Contemporary Events?</b>
Experiment	how, why?	Yes	Yes
Survey	who, what, where, how many, how much?	No	Yes
Archival analysis	who, what, where, how many, how much?	No	Yes/No
History	how, why?	No	No
Case study	how, why?	No	Yes

The case study method is described in detail by Yin (2003). The research method described by him is shown in Figure 4.2. In Part II of the research a representative process is selected followed by a selection of cases and development of a data collection protocol. The cases are then executed and the cross case analysis summarises the industrial evaluation of capacity expansion decision process in multi-site networks.



**Figure 4.2 Case study method (Source: Yin, 2003)**

### **4.3.3 Part III: Multi-factor Capacity Expansion Decision Process Development**

In Part II an industrial evaluation of capacity expansion decision processes is planned. A likely outcome of Part II will be shortcomings identified in the representative decision process. As outlined above in Section 4.2, the third objective of this research is to apply the results of the test to formulate a new pilot decision process. There are different ways to achieve this objective.

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Each of the shortcomings determined by the testing process can be mitigated by modifications in the decision process. There is however a risk of making the decision process too specific to the cases that have used in the industrial test. Thus all enhancements need to be made in a fashion that the biases to the cases are low and all identified shortcomings are addressed. These include external enhancements of the decision process, enhancement of the underlying multi-factor model or enhancements of data presentation and interpretation.

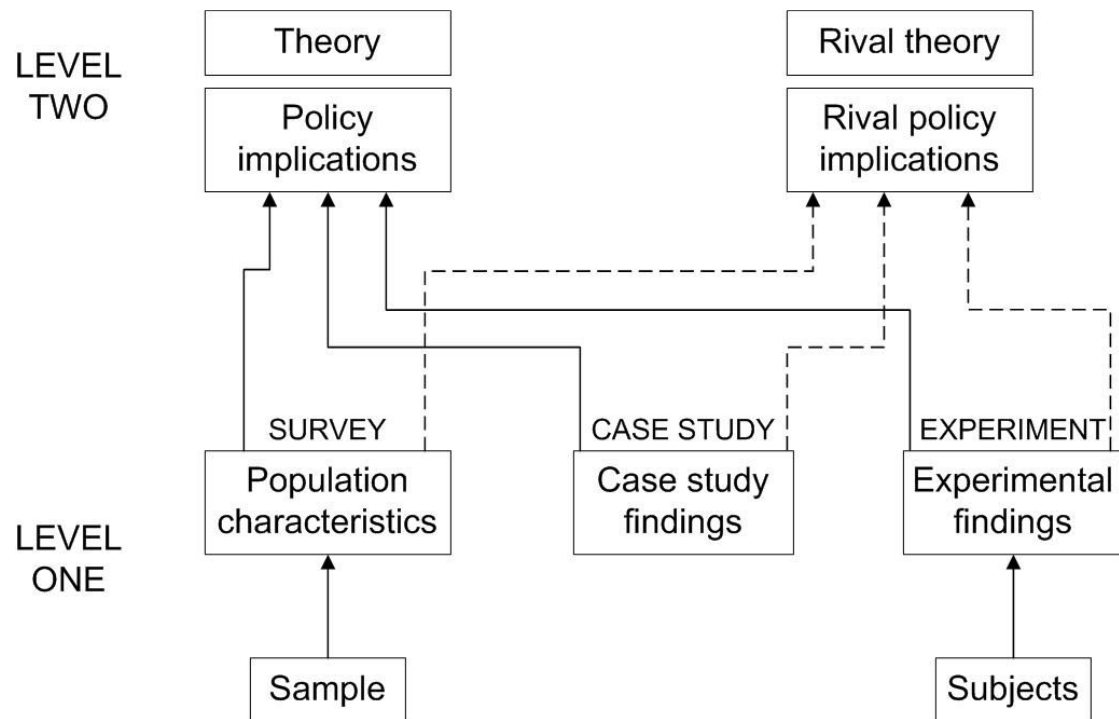
Part III of the research focuses on enhancing the representative decision process. In the end an advanced capacity expansion decision process is developed.

#### **4.3.4 Part IV: Testing of the New Multi-Factor Capacity Expansion Decision Process**

The task in Part IV of the research is to validate the pilot process developed in Part III and to assess if it is an advanced decision process than the representative one. There are however different ways to achieve the same.

Similar to Part II, the underlying factors to justify a case study based approach remain. However, there needs to be designed a process where the results from case studies conducted in Part IV can be compared with those from Part III. There is hence a need to define how inferences are made in case study based approaches and how two different theories (in this case the two different decision processes) can be

compared against each other. Yin (2003) provides a simple framework of how inferences are derived in case study, survey and experiment strategies.



**Figure 4.3 Making inferences: Two levels (Source: Yin, 2003)**

The focus of Part IV is to conduct case studies using the developed process to evaluate the new process compared to the old one as well as to further progress the development of the new process. The selection of case studies plays an important role in this. Yin (2003) points out that case studies should not be used to derive statistical generalisations but rather analytical generalisations. Two or more case studies hence support replication and the empirical results are considered more potent. It is thus needed that the case studies on which the new process is tested are similar in context but differ enough to avoid the argument that the decision process is too specific to the problem in hand and hence analytical generalisation cannot be made.

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A similar method to Part II is used to execute the case studies for Part IV. The same criteria for evaluation of success are used as in Part II. The cross case analysis summarises the effectiveness of the advanced decision process.

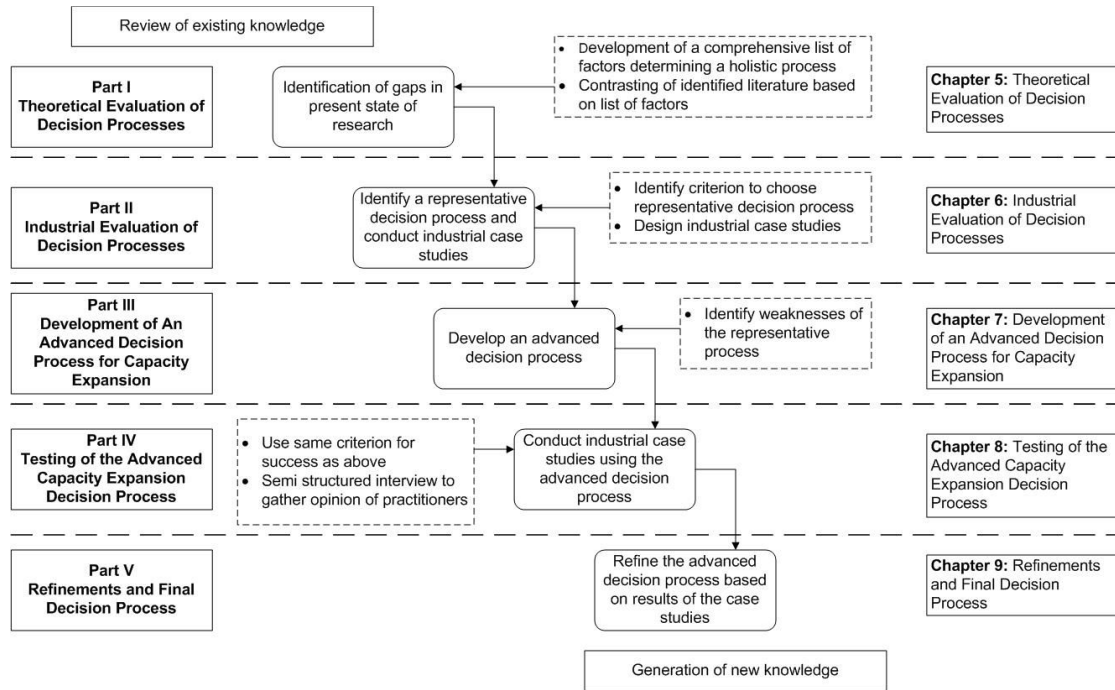
#### **4.3.5 Part V: Refinements and Final Decision Process**

The intention of Part V of the research is to collate the learning from Part I-IV, identify any shortcomings, and suggest refinements which would then be part of potential future work in the field. The final process is illustrated by a walkthrough of one of the industrial case studies. The outcome of the research programme is an advanced decision process for capacity expansion in global manufacturing networks.

### **4.4 Chapter Summary**

This research has set out the research problem and established the research aim and objectives for the thesis. A five Part research programme is proposed based on the five well-defined objectives (Figure 4.4). The research programme is initiated by a review of existing knowledge in literature and industry. Part I then deals with the theoretical evaluation of the capacity expansion processes and identifies gaps in the present state of research. In Part II a representative model is identified and tested in an industrial environment through case studies. A holistic capacity expansion decision process is developed in Part III based on the industrial case studies conducted in the earlier phase. In Part IV the new decision process is tested through industrial case studies, and a structured analysis of the strengths and weaknesses as well as future opportunities is conducted. Part V defines the implementation details through an illustration of a case study using the developed decision support process. These Parts

are described in Chapters 5-9 in this thesis. In the next chapter, Part I of this research programme, namely theoretical evaluation framework, is presented.



**Figure 4.4 Research Programme**

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## Chapter 5. Part I: Theoretical Evaluation of Decision Processes

This chapter describes the Part I of the research – Theoretical Evaluation of Decision Processes. In Chapter 3 it was established that mathematical optimisation of multi-factor models was the most promising approach. The purpose of this chapter is to establish the current state of research in multi-factor models for capacity expansion. The research methodology for Part I is described (Section 5.1) and issues are outlined. Each of the issues is addresses in Section 5.3, Section 5.4 and Section 5.4. Figure 5.1 places this chapter in perspective of the overall research.

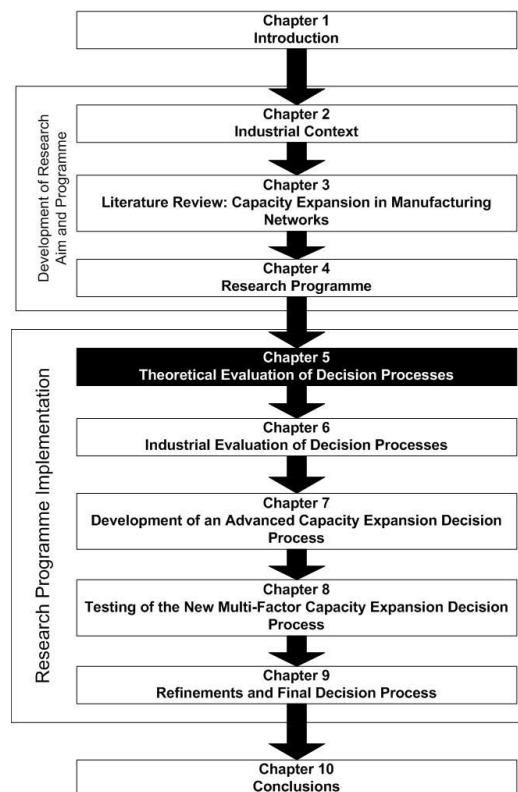


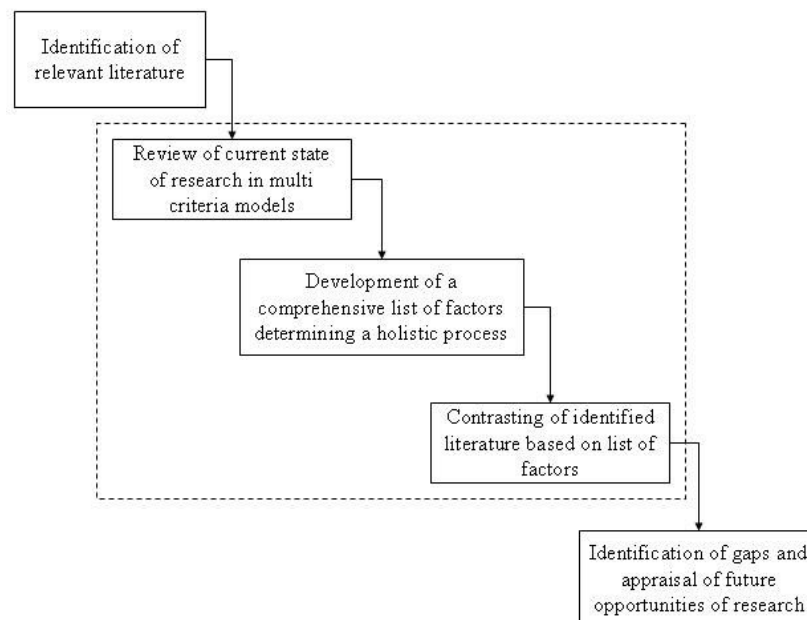
Figure 5.1 Chapter 5 – Theoretical Evaluation of Decision Processes

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## 5.1 Part I: Research Method

This chapter sets out to address Objective 1 of the research (Section 4.2), namely, to establish the state-of-the-art in multi-factor decision models for capacity expansion in manufacturing networks. In Section 4.3.1, the methodology for this has been outlined as a combination of incremental change in present processes with addition of concepts based on first principles. To realise this, the following outstanding issues need to be addressed.

1. What is the established literature that is relevant to the capacity expansion decision?
2. What are the range of factors considered in models along with the associated assumptions and solution techniques?
3. What are the strengths and weaknesses of the research base and the opportunities for further work in the field?



**Figure 5.2 Research Conducted in Part I**



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The approach to address these questions can now be considered. The research method followed to address each of the three issues is described in the following sub-sections.

### **5.1.1 Research method to identify relevant literature**

The method to identify relevant literature in capacity expansion in manufacturing networks included a sequence of four steps. First a set of keywords were identified and used to conduct searches in established research databases. This search was extended by using a combination of the above keywords. This was followed by an elimination of papers not relevant to the manufacturing domain through a qualitative analysis of the abstract. Finally, papers that focused on a specific capacity expansion issue were eliminated. The result of this research was a list of decision processes establishing the state-of-the-art. The execution of the research method is presented in Section 5.2.

### **5.1.2 Research method to establish range of factors, assumptions and solution techniques**

The result of the Section 5.2 was a list of decision processes proposed in the literature. These decision processes were then explored in terms of inputs, outputs, assumptions and techniques. Care was taken to ensure that the capabilities of each model were fully expressed. This was achieved by first capturing, in totality, all the factors presented by the range of models. Then, using this set of factors as a checklist, revisiting each model in turn to search for the existence of factors that were implicit in the model but not immediately apparent in the paper. In this way the confidence in the assessment was improved. The result of this research is a matrix of all factors,

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assumptions and solution techniques in capacity expansion in manufacturing networks. The execution of the research method is presented in Section 5.3.

### **5.1.3 Research method to identify strengths, weaknesses and opportunities with the state-of-the-art**

A structured analysis of the state-of-the-art represented by the set of decision processes representing was to be carried out now. The method followed for this was to structure the analysis based on strengths, weaknesses, opportunities and threats (SWOT). The factors considered by a majority of the decision processes are identified and common solution techniques are highlighted. Factors that have not been addressed by any of the processes but have been considered by other papers which were eliminated through the research method described in Section 5.1.1 are also identified. Finally, opportunities for improvement are compiled based on the above analysis. The result of this research is a structured theoretical analysis of the state-of-the-art. The execution of the research method is presented in Section 5.4.

## **5.2 Identification of Relevant Literature**

This section describes how relevant literature was identified to address the first issue mentioned in Section 5.1. The research method used is described in Section 5.1.1. Searches were initially conducted on research databases including ABI/INFORM (Proquest, 2005) and Web of Knowledge (ISI, 2005). The keywords used were ‘manufacturing’, ‘network’, ‘capacity’, ‘expansion’ and ‘global’ and their combinations (Table 5.1). Searches in ABI/INFORM were focused on scholarly peer-reviewed journals, whereas the Web of Knowledge searches included conference

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proceedings and articles from magazines. The keyword combinations of ‘manufacturing capacity expansion’, ‘capacity global expansion’ and ‘manufacturing global expansion’ yielded the most relevant results. Around 140 papers were identified and included in the first cut search results (Table 5.1).

The papers identified from the first search were further refined by taking into consideration the industrial context. Papers not relevant to manufacturing, for example those from the sectors of telecommunication networks, power networks, utilities and chemical industry, were eliminated from the set. Relevant papers were first identified through their title followed by a more careful consideration of the abstract. Cross checking of citations was also carried out. Hence, important contributions, such as those by Manne (1961; 1967a; 1967b) and Luss (1982), were identified and then a search carried out for all subsequent papers that cited these. Discounted from this search were papers that singularly focused on specific capacity expansion issues. These included, for example, work on investment times (Bean and Smith, 1985; Bean, Higle and Smith, 1992; Higle and Corrado, 1992; Dangl, 1999; Ahmed, King and Parija, 2003), investment in flexible production technology (Fine and Freund, 1990; Van-Meighem, 1998; Netessine, Dobson and Shumsky, 2002; Cochran and Uribe, 2005), machine replacement (Rajagopalan, Singh and Morton, 1998; Chand, McClurg and Ward, 2000) and risk (Callen and Sarath, 1995; Birge, 2000; Borgonovo and Peccati, 2004). Following this process, eleven decision processes were identified as illustrated in Table 5.2.

**Table 5.1 Keywords and the number of search results from the structured literature survey**

	<b>Terms</b>	<b>ABI/Informs</b>	<b>Web of Science</b>
1	Manufacturing	29,966	53,909
2	Network	54,440	113,447
3	Capacity	26,142	111,695
4	Global	39,611	108,216
5	Expansion	16,443	102,137
6	(1)+(2)	1,503	848
7	(3)+(5)	831	1,916
8	(1)+(5)	527	547
9	(1)+(2)+(3)	105	45
10	(1)+(3)+(5)	54	46
11	(3)+(4)+(5)	35	46
12	(1)+(4)+(5)	35	18
13	(1)+(2)+(3)+(4)+(5)	0	0

### 5.3 Factors, Assumptions and Solution Techniques in Capacity Expansion Decision Processes

This section presents the categorisation and summary of the factors, assumptions and solution techniques in the eleven decision processes identified in Section 5.2. The research method used is described in Section 5.1.2. Each of the decision processes are analysed below and Table 5.2 is filled up accordingly.

Reeves et al. (1988) considers capacity expansion of an industrial firm producing multiple products in several economic regions over a multiple period horizon. They consider market demand, capital costs, labour costs and transportation costs and some products manufactured by some plants are consumed internally by other plants in the

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manufacturing network. There are maximum limits on transportation capacity, investment in regional facilities, total capital expenditure and intra regional shipments. They also assume that expected net present values of a unit of capital for each combination of region, time period and capacity expansion in existing or new facilities for production of each product, and are available. The decision process, aims to maximise return on capital invested and maximise total output of a given product and the total output of existing facilities in a particular region, whilst minimising capital invested in new facilities, along with labour, production and transportation costs. They solve this multi-objective problem using the Interactive Sequential Goal Programming (ISGP) technique proposed by Masud and Hwang (1981).

Li and Tirupati (1994) examine a multi-product dynamic investment model for making technology selections and expansion decisions over a finite planning horizon in a firm with a single production facility. The environment is characterised by a dynamic growth in market demand. The objective is to determine the minimal cost schedule for capacity additions to meet the product demands, which are known over the planning horizon. The problem is formulated a mathematical program and a two-phase approach using heuristics is developed to solve it.

Rajagopalan (1998) developed a model that unifies the equipment replacement literature, which generally ignores scale economies; and the capacity expansion literature, which ignores replacement of equipment. This model can also be extended to address issues, such as quantity discounts in purchases, alternative technology selection and multiple equipment types.

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Syam (2000) looks at capacity expansion in international markets and considers production costs (labour and manufacturing), logistics costs, and present capacity at the different plants. The capacity of the plant can achieve three discrete levels and the demand has an increasing or decreasing trend. Syam (2000) also explores the cost-benefit-risk for various expansion scenarios and argues that even when cost premiums are significant, the managers need to weigh them against the potential political benefits and risk factors when making expansion decisions.

Rajagopalan and Swaminathan (2001) argue that inventory management policies have considerable effects on capacity expansion decisions especially in cases where demand is growing rapidly and the firm periodically needs to add machine capacity. They develop a mathematical programming model as an effective solution approach to determine the optimal capacity expansion, production and inventory decisions over time. They study the trade-off between using excess capacity to build inventory and hence postpone future capacity acquisition to using the excess capacity to increase changeovers and reduce lot sizes. Their work is motivated by their interactions with a large firm in the consumer products industry.

Hsu (2002) addresses a capacity expansion problem allowing incremental demand to remain unsatisfied by in-house capacity and use temporary capacity such as leasing or outsourcing. Such a decision is preferred especially in the case of a speculative motive e.g. a firm may delay acquisition of certain technology, which is expected to be cheaper in the near future. The objective of his model is to minimise the total

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acquisition, holding and operating costs associated with all capacity expansion incurred in a multi-period planning horizon.

Perrone et al. (2002) also examine capacity expansion in the presence of both flexible and dedicated capacity. They model a firm in a market characterised by uncertain demand where product prices are linearly dependent on its demand. The outputs of the model are price and production volume of each product in scenarios where either flexible or dedicated equipment is used. This is an extension to previous works where fully flexible resources are considered (Caulkins and Fine, 1990; Harrison and Mieghem, 1999). They also argue that most of the quantitative models deal with specific and focused problems, neglecting the breadth and complexity of the whole capacity expansion problem. They strengthen the aim of this paper by arguing that the development of an integrated and comprehensive decision-support is a path that should be investigated in depth.

Gaimon and Burgess (2003) describe the primary trade-off in capacity expansion as “the total cost over all expansions is reduced through a small number of large-sized expansions (economies of scale), whereas the costs associated with deviating from demand are reduced through a large number of small-sized expansions”. They study the relationship between the lead time for capacity expansion and the size of the expansion and also investigate the effects of learning from prior design and implementation on this lead time. They show that a lead time reduction generates benefits, which may exceed the cost savings from economies of scale. A firm thus is able to invest optimally in a larger number of smaller-sized expansions.

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Ryan (2004) emphasises the risk of capacity shortages during lead time for adding capacity in environments with demand uncertainty and an obligation to provide a specified level of service. She shows that expansion is needed even in the presence of excess capacity to make up for a growing demand. Also in cases of high uncertainty in demand, larger expansion sizes are necessary, but the main impact is still to provoke earlier installations. Even though the domain of the model is not manufacturing industry, the implications of lead time on capacity expansion in a manufacturing network are obvious. Further, Ryan (2004) develops the model using the financial option pricing concept which has been proven by researchers to provide a more accurate evaluation of investment projects with strategic interactions (Miller and Park, 2002). Bulan (2005) provides substantial evidence of the relationship between investment available with a firm for expansion purposes and the uncertainty in its environment using the real options approach. Similar real option approaches for investment decisions related to capacity expansion have been proposed by Feinstein and Lander (2002), Karsak and Ozogul (2002) and Amico et al. (2003).

Chakravarty (2005) proposes a model to optimise plant investment decisions for capacity expansion while ensuring that the plant investment overhead is optimally absorbed by products produced from that plant. The model considers the effect of labour cost, transportation cost, and demand and import tariff on production quantities, investment and overhead absorption pattern. The concept of productivity differences between countries is modelled and the result is a profile of investment allocation to different plants with a fixed total investment budget.



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Melo et al. (2005) propose a mathematical modelling framework to address many practical aspects of manufacturing network design simultaneously. These include a dynamic planning horizon, distribution, supply of materials, inventory, facility configurations, availability of capital for investments and storage limitations. They address strategic issues of relocation of capacity, capacity additions in present and new facilities and link the issue of capacity expansion to overall supply chain strategy of a firm. Details of their model can be found in Melo et al. (2003).

After analysing each decision process and subsequently developing Table 5.2, another round of analysis is conducted where each of the decision processes were checked against all the factors, assumptions and solutions techniques. This was to identify if any of the decision processes indirectly takes any of the identified factors, assumptions and solutions techniques into consideration. The result of the research conducted here is shown in Table 5.2 at the end of the chapter.

## 5.4 Analysis and Discussion

This section presents a structured analysis of the state-of-the-art using the research method used is described in Section 5.1.3. Using Table 5.2 developed in the previous section, an analysis of the strengths, weaknesses, opportunities and threats is carried out. A summary of this analysis is shown in Figure 5.3.

### 5.4.1 Strengths of current models

There are eleven papers (Table 5.2) which were identified as relevant work that addresses multiple factors. Collectively, they comprehensively consider almost all the

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current issues foreseen in the capacity expansion problem. Four factors appear to be the most important ones as most of the authors considered them as inputs to their models.

First, product demand was a factor considered by all the authors in one form or another. Chakravarty (2005) incorporated demand as a function of price, based on the concept of demand curves. Rajagopalan and Swaminathan (2001), Hsu (2002), and Gaimon and Burgess (2003) consider unsatisfied (residual) demand as an input whereas all other authors considered overall demand as an input. Rajagopalan (1998), Perrone et al. (2002) and Ryan (2004) also consider uncertainty in the product demand.

Second, the factor considered important by nine authors is the cost of investment for the required capacity expansion. Reeves et al. (1988) considered expected net present value as an input whereas Hsu (2002) incorporated the capital requirement per unit of output as an input. Except for Syam (2000) and Ryan (2004), all other authors used a standard investment cost function. Rajagopalan (1998) also considers the cost of replacement of existing resources and exhibits how the capacity expansion model can be extended to include concepts of alternative technologies, multiple demand types and quantity discounts.

Third, all authors considered production costs in their models. These costs are categorised as labour, production and transportation costs. Perrone et al. (2002), Chakravarty (2005) and Melo et al. (2005) explicitly consider variable cost of

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production whereas four other authors consider this variable cost indirectly. Most authors consider operating cost function based on a dedicated technology barring Reeves et al. (1988), Li and Tirupati (1994) and Perrone et al. (2002) who include operating cost functions for both dedicated and flexible technologies.

Finally, initial capacity is a factor identified as important by the analysis of Table 5.2. Nine out of eleven of the authors considered it as an input with Li and Tirupati (1994) considering both dedicated and flexible capacity. With regards to the modelling techniques, seven out of the eleven authors employed some form of mathematical programming. Perrone et al. (2002), Gaimon and Burgess (2003), Ryan (2004) and Chakravarty (2005) used theoretical modelling techniques to solve the capacity expansion problem with Ryan (2004) including the concepts of financial option pricing in her model. Some work also enhanced the quality of decision support provided by integrating the detailed risk analysis (Syam, 2000) and the sensitivity analysis (Chakravarty, 2005).

In summary, four factors are considered important by almost all the authors. These are product demand, cost of investment, production costs and initial capacity. Most of the authors have also developed comprehensive solution techniques. The techniques are primarily mathematical models which provide close to optimal results. Some authors have enhanced the quality of decision by additional techniques of risk diversification and sensitivity analysis.

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## 5.4.2 Weaknesses of current research

The primary shortcoming of the current state of literature is the lack of any comprehensive multi-factor model based on all the inputs identified in Table 5.2. Work by Reeves et al. (1988), Chakravarty (2005) and Melo et al. (2005) are closest to being holistic models as they considered the maximum number of identified relevant factors as input to their multi-factor models. Economic factors like market size in the country, currency exchange rates and local taxes are incorporated primarily by Chakravarty (2005), who also includes the concept of overhead allocation to individual factories based on their share of the investment budget. Syam (2000) incorporates risk diversification in his model whereas Hsu (2002), and Gaimon and Burgess (2003) take into account penalty from capacity shortages. Only Gaimon and Burgess (2003) and Ryan (2004) take into account lead time for capacity expansion and the effect of learning on capacity expansion. There are however a number of papers discussing the effect of each of the above in isolation. These works however did not qualify as multi-factor models. Similarly, factors like production efficiency which can inherently capture effects of worker skills and quality of labour are only considered by Reeves et al. (1988) and Rajagopalan and Swaminathan (2001). Accounting policies, investment budgets and other costs like capacity holding and replacement costs are also not considered by most authors. There is thus no single contribution which incorporates all the identified input factors of the capacity expansion problem.

On further reflection, there appear to be some factors that are not considered by any model. This concern is reinforced by, for example, the work of Gutenberg (1992)

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who provides an industrial view of investment for capacity expansion based on a questionnaire survey of the German industry. He identified, in decreasing order of importance, factors such as expectation of favourable markets, bottleneck elimination in plants, improvement in running costs, market share threatened, tax concessions and fear for increase in capital goods.

An additional weakness is that the solution strategy adopted by most authors is almost exclusively mathematical, the emphasis is on costs and the exercise revolves around minimising the discounted costs or maximising the returns on investment. There is a lack of processes that use a combination of decision techniques to yielding a more expansive analysis of the problem. Similarly, none of the work identified the decision makers who need to be involved, or provided guidance about the time and resources required to carry out the analysis. These are crucial for the implementation of any proposed decision process in the industry.

Finally, there is an absence of industrial case studies which reflect the efficacy of such models in industry. Although Ferdows (1997) provides some industrial examples of capacity expansion based on the concept of strategic roles of factories, and Kim and Lee (2001) discuss capacity expansion strategies based on lessons from Hyundai and Daewoo, their models however are focused more on the strategic level and lack details for implementation. An industrial case of capacity expansion in the wafer fabrication industry is presented by Nazzal, Mollaghasemi and Anderson (2006). They provide a complete decision making process including simulation modelling, design of experiments, statistical analysis and economic justification. However, the

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input to the model is cost of buying equipment and the output is net cash flow derived from change in cycle times.

In summary therefore, there are a number of weaknesses in the current literature. There is no model which is sufficiently holistic to handle all the factors deemed important for capacity expansion. Similarly, there is limited information about how to apply models or, indeed, examples of application in real industrial cases.

### **5.4.3 Opportunities from current research**

The identification of weaknesses of the work provides an important starting point for the opportunities of future work in this area. The first opportunity lies in expanding the set of factors deemed important for capacity expansion. Such ratification should take account, first hand, of the actual questions and concerns held by decision makers in industry. Understanding these factors will be the first step to developing an advanced decision process.

In addition, the knowledge base in this area would benefit from much greater industrial based evaluation of techniques. Ideally, such case studies should be conducted in a variety of situations so that a broad appreciation can be developed of the validity and rigour of models.

### **5.4.4 Threats from/of current research**

It was observed that most of the literature was not embedded in the general framework of decision sciences. The work is well developed but focus on users of the research is lacking. This creates an inherent threat that the various decision processes

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proposed in the literature are not used. The evidence for the above observation lies in the absence of any literature discussing industrial case studies on implementation of such frameworks.

There is also no work based on industrial data, which compares the different factors and develops a reference list based on importance. There are studies carried out in the related field of facility location (MacCarthy and Atthirawong, 2003; Bhutta, 2004) but results cannot be directly applied to capacity expansion. The work seems to be suffering with the limitation of taking into account quantitative factors like costs, and then applying the softer socio-economic factors on the decisions derived from the quantitative analysis (MacCormack, III and Rosenfield, 1994). The threat arises where soft factors supersede the quantitative factors. Taking a stronger stance on this issue, there is no evidence that the entire body of work is still industrially relevant anymore.

#### **5.4.5 Generation of key findings**

This summary of the analysis is shown in Figure 5.3. It can be seen that the current state of literature has its strengths in considering the same factors in most cases. The solution techniques used by them are rigorous in nature and considerable effort has been made to ensure that optimal solutions are generated (Section 5.4.1). However, a number of weaknesses have been identified which provide opportunities for future work in the field. Although substantial work has been carried out in this field, no model yet provides a truly holistic capability by taking into consideration all the factors identified deemed important for capacity expansion (Section 5.4.2). Further,

the list of factors is extensive but not comprehensive. Finally, industrial implementation details of the decision processes are lacking. Guidelines for industrial adoption are missing and there is a lack of case studies that illustrate execution of such decision processes (Section 5.4.2).

<p style="text-align: center;"><b>Strengths</b></p> <ul style="list-style-type: none"> <li>• Four factors considered important - product demand, cost of investment, production costs and initial capacity.</li> <li>• Solution techniques are rigorous. Solution techniques which provide close to optimal results are also developed.</li> <li>• Quality of decision is enhanced by additional techniques of risk diversification and sensitivity analysis.</li> </ul>	<p style="text-align: center;"><b>Weaknesses</b></p> <ul style="list-style-type: none"> <li>• No model holistic enough to handle all the factors deemed important for capacity expansion.</li> <li>• The list of factors is extensive but incomplete.</li> <li>• No description of the sources of data or involvement of company personnel.</li> <li>• Guidelines for industrial adoption absent. No case studies that will enable a decision maker to adopt such models.</li> </ul>
<p style="text-align: center;"><b>Opportunities</b></p> <ul style="list-style-type: none"> <li>• Development of a holistic model for capacity expansion based on the list of factors identified in the study</li> <li>• Development of an implementation path to facilitate adoption of above model to industry</li> <li>• Conduct a case study based on the above process</li> </ul>	<p style="text-align: center;"><b>Threats</b></p> <ul style="list-style-type: none"> <li>• Research moving away from the industry and users</li> <li>• Work not embedded in decision sciences</li> <li>• Industrial relevance needs to be established with case-studies</li> </ul>

**Figure 5.3 A summary of the current condition of literature in decision processes for capacity expansion in manufacturing networks**

The main focus of future research should thus be in the development of an advanced decision processes and the embedding this process in a decision framework with focus on the users (Section 5.4.3). This is a key research opportunity. However, more generally, there is also a significant opportunity to report more widely on the application of the decision processes within industry. One way to achieve this will be to run industrial case studies using the present as well as any future decision processes



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proposed. Industrial case studies will also help strengthen the case for relevance of the work and its utility to the decision-makers in industry (Section 5.4.4). Such experiences will be vital in moving forward work in this area.

## 5.5 Chapter Summary

The purpose of this chapter was to conduct a theoretical evaluation of decision processes for capacity expansion which in turn formed Part I of the research described in this thesis. The issues needed to be addresses were defined (Section 5.1) and each of them were resolved in Section 5.3, Section 5.4 and Section 5.4. A structured summary of the results of the study is presented using strengths, weaknesses, opportunities and threats (SWOT) tool (See Figure 5.3). The next chapter describes Part II of this research in which an industrial evaluation of the decision processes identified in Part I is carried out.

**Table 5.2 Contrasting the work on decision processes for capacity expansion in manufacturing networks**

CLASSIFICATION FACTORS	AUTHORS										
	Reeves et al. (1988)	Li and Tirupati (1994)	Rajagopalan (1998)	Syam (2000)	Rajagopalan and Swaminathan (2001)	Hsu (2002)	Perrone et al. (2002)	Gaimon and Burgess (2003)	Ryan (2004)	Chakravarty (2005)	Melo et al. (2005)
<b>Inputs</b>											
<i>Product demand</i>											
Overall demand	✓	✓	✓	✓	✓	✓	◇		✓		✓
Unsatisfied demand					✓	✓		◇			
Demand uncertainty			✓				✓		✓		
Demand function								✓	✓	✓	
<i>Cost of investment</i>											
Investment cost function	◇	✓	✓		✓		✓	✓		✓	✓
Cost for per unit of capacity		◇	✓		✓			✓		◇	
Capacity replacement cost			✓								
Capital requirement per unit output in new facilities	✓		◇			✓		◇	✓	✓	
<i>Production costs</i>											
Unit costs of producing goods	✓	◇		✓	✓			✓	◇	✓	✓
Annualised per unit labour costs	✓	◇		✓			◇			◇	✓
Annualised per unit production costs	✓	◇		✓			◇			◇	✓
Annualised per unit transportation costs	✓	◇		✓						◇	✓
Variable cost	◇	◇	◇	◇			✓			✓	✓
Operating cost function (dedicated technology)	◇	✓		◇	✓	✓	◇			✓	✓
Operating cost function (flexible technology)	◇	✓					◇				
<i>Initial capacity</i>											
Initial dedicated capacity		✓	✓	✓	✓	✓		✓	✓	✓	✓
Initial flexible capacity		✓									

**Table 5.2 Contrasting the work on decision processes for capacity expansion in manufacturing networks (cont'd)**

CLASSIFICATION FACTORS	AUTHORS										
	Reeves et al. (1988)	Li and Tirupati (1994)	Rajagopalan (1998)	Syam (2000)	Rajagopalan and Swaminathan (2001)	Hsu (2002)	Perrone et al. (2002)	Gaimon and Burgess (2003)	Ryan (2004)	Chakravarty (2005)	Melo et al. (2005)
<i>Market / Economic factors</i>											
Diversification needed				√							
Market size in the country										√	
Local taxes										√	
Currency exchange rates										√	
Capacity shortage penalty (demand unsatisfied)						√		√			
<i>Lead time and learning</i>											
Lead time for capacity expansion								√	√		
Cost reduction due to learning in the organisation								√			
Lead time reduction due to learning								√			
Production efficiency											
Technical coefficient modelling input-output relationship	√										
Unit processing time (production)					√						
<i>Accounting policies</i>											
Expected net present values for per unit of capital	√	◇						√		◇	√
Allocation of plant overheads										√	
<i>Investment budget</i>											
Regional expansion budget	√			◇							
Global expansion budget	√			◇						√	√
<i>Other costs</i>											
Capacity holding costs					√	√					
Capacity relocation costs											√

**Table 5.2 Contrasting the work on decision processes for capacity expansion in manufacturing networks (cont'd)**

CLASSIFICATION FACTORS	AUTHORS										
	Reeves et al. (1988)	Li and Tirupati (1994)	Rajagopalan (1998)	Syam (2000)	Rajagopalan and Swaminathan (2001)	Hsu (2002)	Perrone et al. (2002)	Gaimon and Burgess (2003)	Ryan (2004)	Chakravarty (2005)	Melo et al. (2005)
<b>Outputs</b>											
Production volume (dedicated technology)			√	√	√		√	√		√	√
Production volume (flexible technology)			√				√				
Price of product produced (dedicated technology)							√			√	
Price of product produced (flexible technology)							√				
Timing of capacity expansion			√		√	√		√	√		√
Production quantity in different plants	√	◇	√	√	√	√				√	√
Return on capital invested	√	◇					◇			◇	
Total capital invested in new facilities	√	◇	√					√			√
Total labour, production and transport costs	√	◇		√	√						
Amount of capacity addition (dedicated & flexible)		√	√	√	√	√	◇	√			√
Total discounted costs over planning horizon		√				√					
Inventory carrying costs					√						√
Inventory planning policies					√						
Capacity shifted from old facility to new											√
Capital invested in each plant			√					√		√	
<b>Assumptions</b>											
Multiple plants producing multiple products	√			√					√	√	√
Single plant producing multiple products		√	√		√	√	√	√			
Machine replacement permitted			√								
Quantity discounts			√								

**Table 5.2 Contrasting the work on decision processes for capacity expansion in manufacturing networks (cont'd)**

CLASSIFICATION FACTORS	AUTHORS										
	Reeves et al. (1988)	Li and Tirupati (1994)	Rajagopalan (1998)	Syam (2000)	Rajagopalan and Swaminathan (2001)	Hsu (2002)	Perrone et al. (2002)	Gaimon and Burgess (2003)	Ryan (2004)	Chakravarty (2005)	Melo et al. (2005)
Service level to customer to be maintained								✓			
Risk of capacity shortages considered						✓		✓		✓	
Deferred capacity expansion (leasing/outsourcing)						✓				✓	
Leadtime for capacity to come online								✓			
Input-output relationship between plants	✓										
Limited transport capacity	✓										
Limited regional budget	✓			✓							
Limited global budget	✓			◇					✓		
Limited intra-regional shipment	✓										
Dedicated technology available	✓	✓	✓	✓		✓	✓		✓	✓	
Flexible technology available		✓	✓				✓				
Overhead absorption of products at plant									✓		
Capacity relocation (old to new)										✓	
<b>Techniques</b>											
Multi-objective linear programming	✓										
Interactive sequential goal programming	✓										
Mixed integer linear programming (MILP)			✓	✓	✓						✓
Heuristics		✓	✓	✓	✓	✓			✓		
Lagrangian relaxation (LP)		✓	✓	✓	✓	✓		✓			
Integer programming		✓									
Disaggregate formulation			✓								
Theoretical Modelling							✓	✓	✓	✓	
Financial option pricing								✓			
Dynamic Programming					✓	✓					

**Table 5.2 Contrasting the work on decision processes for capacity expansion in manufacturing networks (cont'd)**

CLASSIFICATION FACTORS	AUTHORS										
	Reeves et al. (1988)	Li and Tirupati (1994)	Rajagopalan (1998)	Syam (2000)	Rajagopalan and Swaminathan (2001)	Hsu (2002)	Perrone et al. (2002)	Gaimon and Burgess (2003)	Ryan (2004)	Chakravarty (2005)	Melo et al. (2005)
Sensitivity analysis										√	
Non-linear optimisation										√	
<b>Legend</b>											
Factors directly included in the process										√	
Factors indirectly included in the process										◇	

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## Chapter 6. Part II: Industrial Evaluation of Decision Processes

This chapter describes the Part II of the research – Industrial Evaluation of Decision Processes. The purpose of this chapter is to test a representative decision process in a real industrial context. The research method for Part II is described (Section 6.1) and issues are outlined. These issues are addressed in Section 6.2, Section 6.3 and Section 6.4. Figure 6.1 places this chapter in perspective of the overall research.

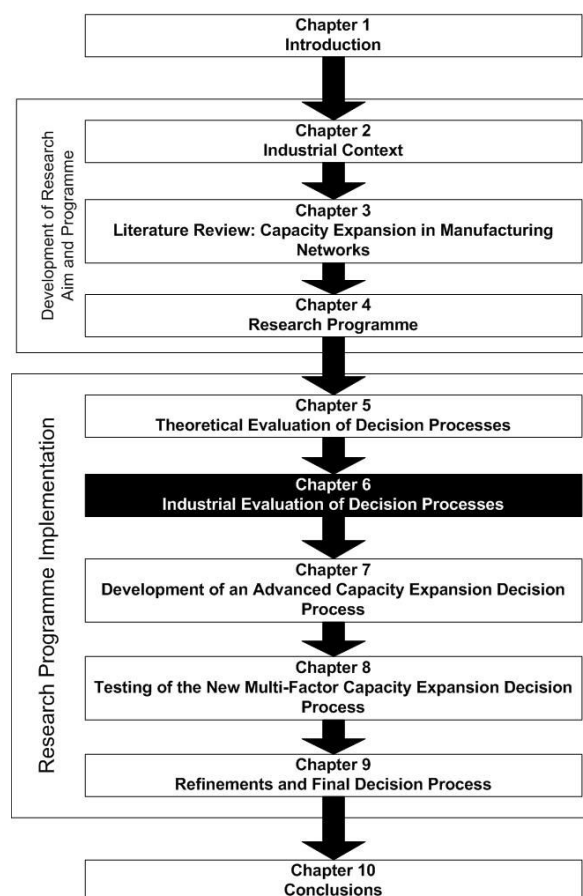


Figure 6.1 Chapter 6 – Industrial Evaluation of Decision Processes

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## 6.1 Part II: Research Method

This chapter sets out to address Objective 2 of the research (Section 4.2), namely, to test a representative process in a real industrial context. In Section 4.3.2 a case study based research strategy was identified as appropriate for this part of the research. To realise this following outstanding issues need to be addressed.

1. How to choose a representative process from the literature?
2. How to select cases for investigation of the problem?
3. What are the criteria for success of the case studies?
4. How good is the representative process in solving the capacity expansion problem in an industrial setting?
5. What are the features that are needed for an advanced decision process?

The approach to address these questions can now be considered. The research method followed to address each of the issues is described in the following sub-sections.

### **6.1.1 Research method to choose a representative process**

In Section 5.4.5 it has been established that there is a lack of a holistic process for capacity expansion in the present literature. Eleven decision processes representative of literature in the field were identified (Section 5.2) and the following set of factors needed to be considered in a decision process to qualify it as a holistic decision process (Section 5.3) for capacity expansion in manufacturing networks.

1. Product demand
2. Cost of investment
3. Production costs
4. Initial capacity



- 
5. Market / economic factors
  6. Production operations
  7. Lead time and learning
  8. Accounting policies
  9. Investment budget
  10. Other costs

The eleven identified processes need to be compared with each other to identify a representative decision process which is the most holistic in nature. Such a comparison will require a rating system which measures how each of the decision processes fare with respect to taking into consideration most factors determined as critical by the literature as well as addressing a variety of problems within the capacity expansion decision. A measurement of number of factors considered can be directly attained from the list of factors mentioned above and Table 5.2 contrasting the various decision processes. For example, if a decision process takes into account product demand, cost of investment, production cost, initial capacity, market factors and other costs it scores a 6 out of a maximum 10.

A second measurement is needed to evaluate how widely the decision process can be used in terms of scenarios. The following five criteria were defined to measure the same – multi-facility, multi-product, multi-period, expansion and contraction, and special cases. A decision process was rated with a score of 2 for each of the above criteria. For example, if a decision process was able to evaluate scenarios with multi-products, multi-period and take into account special cases like flexible capacity it was

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rated a 6 out of the maximum possible score of 10. Finally these scores were multiplied to award a decision process for having above average scores in both criteria and penalise a process which scores good in one and performs poorly on the other. The execution of the research method is presented in Section 6.2.

### **6.1.2 Research method to select cases for investigation**

The selection of cases to be tested was based primarily on the dimensions which were deemed important for the study. It was decided in Section 2.3 to limit the domain to discrete manufacturing as continuous manufacturing (e.g. chemical industry) had significantly different processes and models of capacity expansion. Further, fundamental to this research is the practitioners using the decision process have multiple discrete product manufacturing plants. Therefore, a selection of companies were sought which operated in the discrete product manufacturing environment and a natural variable to be included in the test was the number of sites that are part of their manufacturing network.

The representative process identified by the execution of the research method presented in Section 6.1.1 is selected based on the number of factors it considers and the variety of scenarios it can handle. Therefore, any case study aiming to test the decision process should involve a number of factors. Hence, a high number of factors in the case study were considered desirable for the test. The variety of applicability of a capacity expansion decision process cannot be determined quantitatively however authors do provide examples of various applications and extensions of their models. There is thus a need to test if a variety of scenarios can be handled by the decision

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process. This was achieved by extending the scope of the case study to capacity expansion with and without new facility creation.

An argument against the size of the candidate company (large, medium and small) to be a parameter was made with a justification that the capacity expansion problem does not itself change with the size of the company. However, the data gathering process may change (become easier or problematic), based on the individual characteristics of the company and the support of the management. The size of the company was hence not a variable to be tested in the case study.

In summary, the case studies to be selected need to be based on two variables namely number of manufacturing sites and variety of scenarios. The case studies should also consider a high number of factors. Table 6.1 summarises these variables and the values that they can take. Industrial case studies based on these variables are selected in Section 6.3.1.

**Table 6.1. Variables defining the case studies used for industrial evaluation**

<b>Variables</b>	<b>Values</b>
Number of sites	Low ( $\leq 3$ )
	High ( $\geq 4$ )
Number of factors	High (7 or more of the identified 10 factors)
Variety of scenarios	Capacity Expansion with No New Sites
	Capacity Expansion with New Sites

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### **6.1.3 Research method to identify criteria for case study success**

The result of the execution of the research method described in Section 6.1.2 will be a set of case studies which will be used to test the representative process identified from the execution of the research method defined in Section 6.1.1. The case studies are then executed and result in the evaluation of the representative process. Viseras (2004) uses an evaluation methodology based on Platts' (1990) assessment criteria for testing manufacturing process research. Similar criteria can be used for the evaluation of the representative process too. The evaluation criteria consisted of three categories which translate to the present case as follows.

- 1) Feasibility – Can the decision process be used to conduct industrial cases?
- 2) Usability – How easy is it to use the process?
- 3) Usefulness – How does the decision process help the practitioner make the capacity expansion decision?

Viseras (2004) extends the above by combining the work of Adesola (2002) and includes 'Context' as a fourth assessment criteria. Viseras (2004) argues that a process may mean different things in different organisations and the measurement of contextual factors can help to analyse the outputs of the application of such a process in a specific organisation. For the purpose of this study, context represented the extent that the process is holistic in nature. These criteria were seen a natural fit for evaluation of the capacity expansion representative process identified in Section 6.2. The criteria of success are defined in Section 6.3.2 based on the research method described above.

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#### **6.1.4 Research method to evaluate the performance of the representative process**

The result of the execution of the research method described in Section 6.1.3 will be a list of criteria for success. There is now a need to determine how the representative decision process will be used and how each of those criteria will be measured. The representative process can be embodied in a tool and used to execute the case study. The tool will need some inputs and produce some outputs based on the underlying representative decision process and experiences regarding its working will also be generated. These inputs, outputs and experiences can then be mapped to the criteria for success. The tool is described in Section 6.3.3 and the mapping along with the data collection protocol is presented in Section 6.3.4.

#### **6.1.5 Research method to identify features of an improved decision process**

The result of the execution of the research method described in Section 6.1.4 above will be case study reports comprising of the observations based on the criteria of success. These case study reports are presented in Section 6.3.5. They are then analysed to identify shortcomings, if any, in the representative decision process. This is conducted by a cross case analysis and presents the performance results of the representative process with respect to the criteria of success defined in Section 6.3.2. The cross case analysis is presented in Section 6.4.

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## 6.2 Selection of a Representative Decision Processes

This section describes how a representative decision process is identified from the identified state-of-the-art eleven processes determined in Section 5.2 to address the first issue mentioned in Section 6.1. The research method used is described in Section 6.1.1.

The eleven decision processes are scored based on the strategy described in Section 6.1.1. The scores and the qualitative analysis of each model are shown in Table 6.2. The decision process proposed by Melo et al. (2005) achieved the highest score and hence was identified as the representative decision process used to execute industrial case studies in Part II of the research.

**Table 6.2 Analysis of literature to identify a representative process**

Author	Number of Factors	Qualitative Analysis of Processes (Variety of Application Scenarios)	Applicability Score	Total score
Reeves et al. (1988)	6	Considers a multi-region input output constraint in order to capture product and regional interdependence over time. It also models limited transport between regions to represent economic and trade considerations. The model involves multiple objectives allowing greater modelling realism. Takes into account single-facility, multi-products and multi-period and can handle special cases.	6	36
Li and Tirupati (1994)	5	Model considers dedicated and flexible capacity choices in an environment characterised by dynamic growth in market demand. The model can be extended to multi-plant and include plant closures. Takes into account single-facility, multi-products and multi-period. It can handle special cases as well as capacity contraction and expansion.	10	50

**Table 6.2 Analysis of literature to identify a representative process (cont'd)**

<b>Author</b>	<b>Number of Factors</b>	<b>Qualitative Analysis of Processes (Variety of Application Scenarios)</b>	<b>Applicability Score</b>	<b>Total score</b>
Rajagopalan (1998)	5	Model allows replacement of capacity as well as expansion and disposal to adapt to arbitrary demand changes, and permits economies of scale in capacity purchases. The model also considers deterioration and obsolescence and can be extended to scenarios with alternative technologies and suppliers, multiple demand types satisfied by the same capacity type and quantity discounts when purchasing high volumes of capacity in form of equipment. Takes into account multi-facility, multi-products and multi-period. It can handle special cases as well as capacity contraction and expansion.	10	50
Syam (2000)	5	Incorporates recent changes in global environment by limiting the number of global and regional sites. Allows economies of scale, diseconomies of scale and constant costs in manufacturing. Diversification strategies can be investigated and cost-risk trade-off can be explored. Takes into account multi-facility, single-product and multi-period and can handle special cases.	6	30
Rajagopalan and Swaminathan (2001)	6	Interaction between production-planning decisions and capacity expansion decision is explored in an environment with demand growth. The production-planning perspective of using excess capacity in a period, to do more equipment changeovers and thus reduce inventories, is compared with the capacity acquisition perspective suggesting building additional inventory with the excess capacity to meet demand growth in future periods and thus delaying the purchase of additional capacity in the future. Takes into account single-facility, multi-products and multi-period.	6	36
Hsu (2002)	6	The model studies the option of deferring capacity in a situation where future trends and cost of production technology is know with some uncertainty or in presence of a speculative motive. Takes into account single-facility, single-product and multi-period and can handle some special cases.	4	32
Perrone et al. (2002)	3	The model allows a comparison of the economic advantages achieved by using flexible equipment instead of a dedicated one. Takes into account single-facility, multi-product and single-period and can handle some special cases.	4	12

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**Table 6.2 Analysis of literature to identify a representative process (cont'd)**

<b>Author</b>	<b>Number of Factors</b>	<b>Qualitative Analysis of Processes (Variety of Application Scenarios)</b>	<b>Applicability Score</b>	<b>Total score</b>
Gaimon and Burgess (2003)	8	Model explicitly considers the lead times required to construct and operationalise additions of capacity. The model also takes into account the effects of learning from prior design and implementation activities on the duration of the lead time. Takes into account single-facility, single-product and multi-period and can handle some special cases.	4	32
Ryan (2004)	5	The model determines the timing and sizes of expansions to minimise the expansion cost while controlling the risk of shortage, due to the lead time for adding capacity, in an environment with exponentially increasing but uncertain demand. Takes into account multi-facility, single-product and multi-period and can handle some special cases.	6	30
Chakravarty (2005)	8	Model optimises plant investment decisions, while ensuring that the plant investment overhead is optimally absorbed by products produced from that plant. The model can also be used to study the implications of labour cost, transportation cost, demand, and import tariff on production quantities, investment, and overhead absorption pattern. Takes into account multi-facility, multi-products and single-period and can handle some special cases.	8	64
Melo et al. (2005)	7	Model deals with gradual relocation of existing facilities and capacity expansion and reduction scenarios. Includes dynamic facility location problems as special cases. Takes into account multi-facility, multi-products and multi-period, capacity expansion and contraction and can also handle special cases.	10	70

### 6.3 Industrial Case Study Design and Execution

A case-study based research methodology has been chosen so that an in-depth understanding of the practice could be gained (Section 4.3.2). Based on the case study method (Figure 4.2) the cases to be tested are selected and a data collection protocol is



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developed. The case studies are then executed following which a case study report is presented. These steps are described in the following sub-sections.

### **6.3.1 Selection of cases**

This section describes the cases selected to evaluate the representative decision process by Melo et al. (2005). This section addresses the second issue mentioned in Section 6.1 and the research method is described in Section 6.1.2.

The case studies were executed with two different companies, Glass-Co and Machine-Co who were also the industrial partners for the research (Section 1.1). The capacity expansion decision scenarios faced by both these companies is described below. These scenarios are used for the case studies and are summarised at the end of this sub-section.

#### ***Glass-Co***

Glass-Co produces more than 400 products in its 3 production sites in Singapore, Malaysia and Indonesia. Its products are categorised as P, F and S. Product P is the simplest product with the least amount of variety. Product F has large variety (>600) and demands high quality finish whereas product S has medium variety (<12) and requires quality between the P and F varieties.

The first facility in Singapore was setup around 15 years ago in a country having a good combination of skill, quality consciousness and cheap labour. Over the years the Singapore site has become more expensive as the country's economy has boomed resulting in increase in wages. Singapore now produces the high value products (from

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product F family) where the labour cost is smaller compared to the raw material and workforce skill plays an important task. Singapore does not produce any product from the P family. In the last 10 years Malaysia and Indonesia have been setup as cheaper production locations. Indonesia has the lowest labour cost but due to the lack of skills mainly P family products are produced in Indonesia.

Glass-Co management aims to study the capacity expansion scenario comparing expansion through establishment of a new site in Vietnam to expansion without a new site. These two scenarios are formed as two case studies.

### ***Machine-Co***

Machine-Co is one of the largest manufacturers of refrigerator compressors (17% of the market share) in the world. It is one of the companies under a large conglomerate and has 4 factories located in Japan, Singapore, Malaysia and China. Japan was the first factory established in the home country of the holding conglomerate. Singapore was established in 1972 and after almost 30 years of manufacturing experience and increased core competency, was raised to the status of the Manufacturing Headquarter (MHQ) in 1999 and International Headquarter in 2006. The Malaysia site was established after Singapore and the latest factory site in China represents a low manpower cost site and is ramping up its operations slowly. A fifth facility is being planned however the exact location is still under discussion. Vietnam is one of the candidates and will be used for the case studies. This situation made Machine-Co a good candidate to test the capacity expansion decision process. There are three product families (Q, S, and E). The Japan facility produces only product E, Malaysia

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and China facilities produce only product Q whereas the Singapore facility produces all three product families of Q, S and E. The additional facility planned in Vietnam will produce product S. Machine-Co management aims to study the capacity expansion scenario comparing expansion through establishment of a new site in Vietnam to expansion without a new site. These two scenarios are formed as two case studies.

There were hence 4 case studies that were decided to be used to evaluate the representative decision process by Melo et al. (2005). The Glass-Co case study represented scenarios with less number of sites (3 present sites and 1 new site) and Machine-Co case studies represented larger number of sites (4 present sites and 1 new site). The case studies were numbered from 1 to 4 accordingly. The execution of the case studies is presented in Section 6.3.5.

- 1) Glass-Co: Case Study 1 – Low number of sites (3), no new site
- 2) Glass-Co: Case Study 2 – Low number of sites (3), with new site
- 3) Machine-Co: Case Study 3 – High number of sites (4), no new sites
- 4) Machine-Co: Case study 4 – High number of sites (4), with new site

### **6.3.2 Criteria for industrial evaluation of the representative decision process**

This section describes the criteria to evaluate the representative decision process by Melo et al. (2005). This section addresses the third issue mentioned in Section 6.1 and the research method is described in Section 6.1.3.

It was established that feasibility, usability, usefulness and context were four criteria which can be used to evaluate success of the representative process. These criteria are then broken down into performance indicators which can be observed and measured. Table 6.3 provides the definitions of each of the indicators and the criteria they assess.

**Table 6.3. Performance indicators for evaluation of success of the decision process**

<b>Criteria</b>	<b>Performance Indicators</b>	<b>Definition</b>
Feasibility	Amount of data	The amount of data required by the decision process in terms of the different numbers of sources
	Type of data	The ease or difficulty to collect the type of data needed by the decision process
	Human intervention	Data which is dependent on human perception or data sources being thumb rules, industrial averages, etc.
Usability	Ease of use	Degree of usefulness at all stages of the decision process
	Time required	Time required in different stages of the decision process
	Understanding	Number of problems encountered following the process
	Flexibility	Extent of changes made to the decision process during the application
Usefulness	Efficiency	Degree of resources required to use the decision process including personnel and time
	Learning curve	Reduction in effort undergone for subsequent applications once the decision process was applied for the first time
Context	Limitations	Inability of the solution technique to handle certain special cases including size of the problem in terms of number of facilities, and number of products.

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### **6.3.3 Development of the testing tool based on the representative decision process**

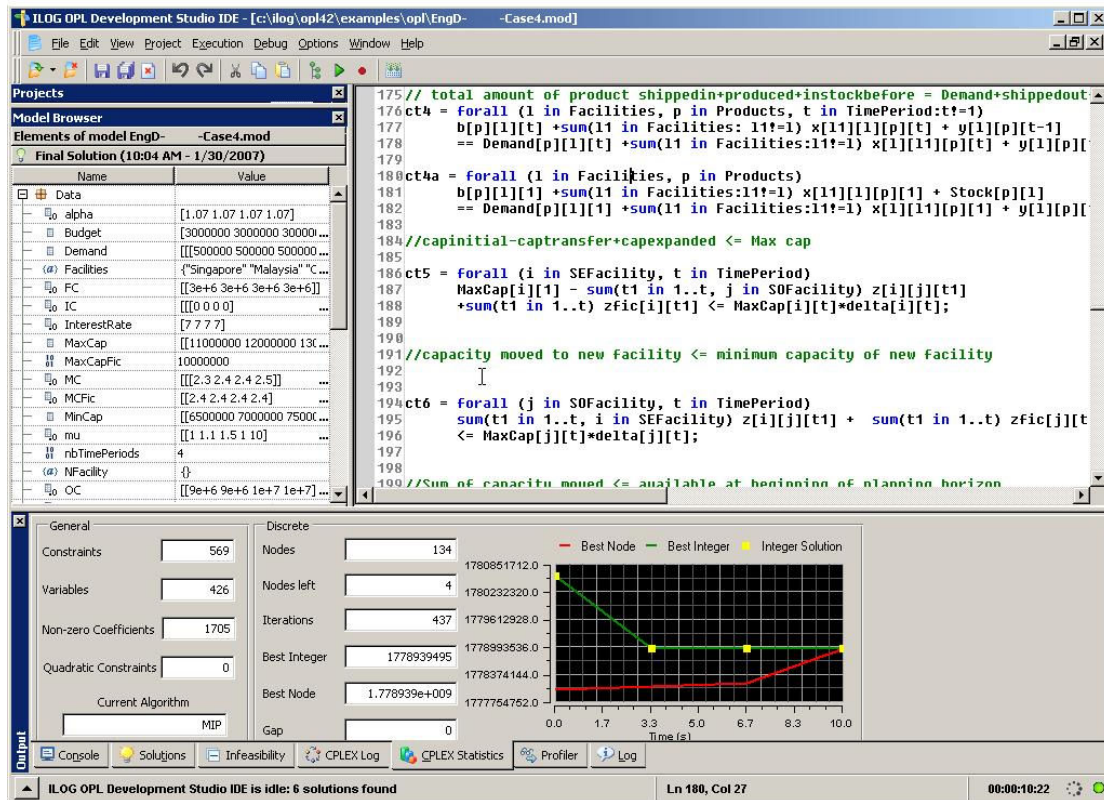
Melo et al.'s (2005) decision process consists of a set of equations which define the capacity expansion problem. These equations model the problem as a Mixed Integer Linear Programming (MILP) problem. Since the decision process is to be used by the practitioners, there was a need to shield them from the complicated mathematics in the MILP. This was considered an important attribute by both Machine-Co and Glass-Co teams. They mentioned that any tool which is to be used for such decision making should have inputs and outputs that can be clearly understood by the practitioner. The details of implementation (MILP in this case) should be verified and validated separately. Hence, to execute the decision process a tool was required which implements this MILP, allows data input, solves the MILP and furnishes the results.

There are a number of commercial solvers available that are able to model MILPs (Fourer, 2007). Over 40 software packages are available each providing the user the option to choose different algorithms to solve the MILP. ILOG is one of the leading companies that develop commercial solvers and provides an Optimisation Programming Language (OPL) to develop optimisation applications (Henternryck, 1999). SIMTech holds a license to ILOG OPL Studio<sup>3</sup>, an integrated environment that allows modelling of various types of optimisation problems and also provides interfaces to link to other office software. Constrained by the cost of acquisition of another commercial software, ILOG OPL Studio was used to develop the tool to implement the decision process by Melo et al. (2005). A sample implementation is

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<sup>3</sup> [www.ilog.com/products/oplstudio/](http://www.ilog.com/products/oplstudio/)

presented in Appendix A and Appendix B. Figure 6.2 shows a screen capture of the tool used to execute the case studies.



**Figure 6.2 Implementation of the representative process in ILOG OPL Studio to execute the industrial case studies**

### 6.3.4 Design of the data collection protocol

This section describes the data collection protocol to evaluate the representative decision process by Melo et al. (2005). This section addresses the fourth issue mentioned in Section 6.1 and the research method is described in Section 6.1.4.

The performance indicators developed in Section 6.3.2 are to be observed and measured in the case studies. The observation can be done before the execution, during the execution and after the execution of the case study. Further the

measurement for each of the performance indicators is determined. This data collection protocol is illustrated in Table 6.4.

**Table 6.4. Data collection framework for evaluation of success**

Category	Performance Indicator	When?	Data Gathered
			How?
Feasibility	Amount of data	B	Number of sources the case study data was collected from
	Type of data	B	User evaluates how difficult the case study data gathering was
	Human intervention	B & D	Number of occasions that human judgment was required
Usability	Ease of use	A	User evaluates how easy/difficult the case study execution was
	Time required	A	Time required for executing the case study
	Understanding	A	List the problems with the process followed by an evaluation by the user
	Flexibility	A	Number of times when the decision process was tweaked to suit a case study
Usefulness	Efficiency	A	Number of man hours required
	Learning curve	A	User evaluates the reduction in effort in executing a case study following a previously similar case study
Context	Limitations	A	User evaluates if the solution technique used was unable to handle special cases of the problem

B: Before the case study, A: After the case study, D: During the case study

### 6.3.5 Execution of the case studies

Using the tool defined in Section 6.3.3 and the data collection protocol defined in Section 6.3.4 the case studies defined in Section 6.3.1 are now executed. The input data for the case studies was obtained from three sources. A large proportion of the data required was available in the annual accounts of the company. Industrial averages available in public databases were used to develop some of the input data

and finally a meeting with the practitioners was arranged to fill up any gaps in the required data.

***Glass-Co: Case 1 & 2***

Data for the case study execution was collected from the practitioners and supplemented with industrial averages and practitioners experience. This data was input into the decision process. The results were then discussed with the practitioner. The data collection framework from Table 6.4 was then used to develop Table 6.5.

**Table 6.5. Data Collection - Case Study 1&2**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
Feasibility	Amount of data	Data from three primary sources – production, accounting and higher management was gathered. The model required quite a large amount of data.
	Type of data	Most data that was used was approximate. Accurate data was tough to gather as the study was not considering all products individually but lumping them in their families.
	Human intervention	An initial dry run was performed by conducting a paper analysis of the data. Since the model assumed all production sites can produce all products, data for some products not being able to be produced at a particular site was estimated.
Usability	Ease of use	The model was developed in ILOG ‘s OPL studio (Figure 6.2). Data was required to be entered in a particular format. For some cases there was manual copying of the data needed for the different case studies.
	Time required	It took 5 man-days to gather the data. 2 man-days were needed to conduct case study 1. Case study 2 required 4 man-days as extra work was required to modify the data to fit the concept of a new facility. The modified data on some occasions was causing the solution to be infeasible which was handled by relaxing the model constraints manually.
	Understanding	The internal workings of the process are complicated to understand for a non-operations research background person. Thus the researcher was playing



**Table 6.5. Data Collection - Case Study 1&2 (cont'd)**

Category	Performance Indicator	Data Gathered
	Flexibility	the partial role of the user and providing a walkthrough to the managers in the company regarding the decision process. The process allowed minor modifications to suit the needs of the case study however a number of concerns the management had could not be handled by the model. Examples of such concerns are – availability of skill on the expansion decision, type of machines that should be used (differ in cost, quality and maintenance).
Usefulness	Efficiency  Learning curve	It took 5 man-days to gather the data. 2 man-days were needed to conduct case study 1. Case study 2 required 4 man-days as extra work was required to modify the data to fit the concept of a new facility. Execution of case study 2 was smoother due to the learning attained by the user. Data collection for case study 2 was also incremental over case study 1.
Context	Limitations	The decision process could not handle all special cases of the problem. For example, the decision process assumed that all products could be produced at all sites. This was not true in case of Glass-Co and quite unlikely in other manufacturing networks too. Another case was the representation of labour (and hence production) costs as a non-linear function of production size. This was not possible in the decision process however seemed to be the reality in Glass-Co.

Apart from the data in Table 6.5, Glass-Co management also provided unstructured feedback about the decision process which was very helpful. The following additional points were raised before and after the case studies were executed and the results presented to Glass-Co management.

- 1) Labour cost – Glass-Co management raised a number of concerns in the way the decision process modelled labour. The process viewed capacity as a single concept and assumed that labour cost is factored into the production cost and

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changes with the scale of production in a linear fashion. In reality, for example, Glass-Co labour force comprised of a combination of full time local and contracted foreign labour. Their labour costs thus changed with the scale of production on a non-linear basis.

- 2) Skill availability and training – The decision process also assumed that skills will be available at all places and the production efficiency of new labour will be same as preset labour. They refuted this assumption by presenting cases of massive trained labour shortages that had effected their decisions to expand in certain cheaper locations in the past.
- 3) Modelling the lack of competition – The management also pointed out that the present decision process seemed to model the industry from a monopoly point of view and assumed that there are no competing elements for skilled labour. In reality they faced a continuous pressure from low cost competitors in neighbouring countries who were trying to poach away skilled labour by offering similar (or slightly lower) remunerations in the home country with lot lower cost of living and hence better value for money.

Overall, the management felt that the decision process reiterated the reality they knew but could not act on because of constraints primarily labour related. There was thus a need for the decision process to expand and take into account the additional issues.

***Machine-Co : Case 3 & 4***

The decision process was executed with a team of two personnel from Machine-Co. Data required for the case study execution was gathered from the annual planning exercise conducted by Machine-Co, which also included data taken into consideration for the decision of the location of a new site in Vietnam. The results from the decision process were then discussed with the practitioner. The data collection framework from Table 6.4 was then used to develop Table 6.6.

**Table 6.6. Data Collection - Case Study 3&4**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
Feasibility	Amount of data	Data from two sources – central planning and production. The company was undergoing their annual planning exercise during which a long term budget for capacity expansion was also being discussed. Some data required was based on estimates of the planning team representative.
	Type of data	Most data that was used was from the annual planning exercise and thus was quite accurate. Data for product families was being constructed by consolidating individual product data.
	Human intervention	The model assumed all production sites can produce all products, data for some products not being able to be produced at a particular site was estimated.
Usability	Ease of use	The model was developed in ILOG ‘s OPL studio (Figure 6.2). Data was required to be entered in a particular format. For some cases there was manual copying of the data needed for the different case studies. This was extremely difficult in the case of Machine-Co as it was larger and more complex organization than Glass-Co.
	Time required	It took 5 mandays to gather the data. 3 mandays were needed to conduct case study 3. Case study 4 required 4 mandays as extra work was required to modify the data to fit the concept of a new facility. Infeasibility was still a concern and relaxation of

**Table 6.6. Data Collection - Case Study 3&4 (cont'd)**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
	Understanding	certain constraints was done manually. The researcher was again playing the partial role of the user and providing a walkthrough to the managers in the company regarding the decision process. The managers and practitioners expected the decision process to be embodied in software that could be used by them as a tool by interfacing with the required data sources. Practitioners were not interested in the internal workings of the model and suggested that a rigorous validation exercise (historical efficacy) will suffice them to use it as a tool for future capacity expansion decisions.
	Flexibility	The model could not handle a number of concerns the management had. Examples of such concerns were – changes in worker efficiencies with time (learning, especially in the new site in Vietnam), effect of tariffs and export duties (again especially for Vietnam site), economic factors like currency exchange rate profiles, constraints regarding transportation of finished goods.
Usefulness	Efficiency	It took 5 mandays to gather the data. 3 mandays were needed to conduct case study 3. Case study 4 required 4 mandays as extra work was required to modify the data to fit the concept of a new facility.
	Learning curve	Execution of case study 3 was smoother due to the learning attained by the user. Data collection for case study 4 was also incremental over case study 3. Further, since case studies 3 and 4 were conducted after case studies 1 and 2 with Glass-Co, some learning on the part of the researcher was also in effect. From that point of view, though case studies 3 and 4 were lot more complex than case studies 1 and 2, they required similar number of mandays to execute (11 for Glass-Co, 12 for Machine-Co).
Context	Limitations	The decision process could not handle all special cases of the problem. For example, the decision process assumed that all products could be produced at all sites. This was not true in case of Machine-Co too. Another case was the representation of labour efficiencies (and hence production) costs as a non-linear function of both production size and time.

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**Table 6.6. Data Collection - Case Study 3&4 (cont'd)**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
		Economic factors like tariffs, export duties, currency exchange rates and transportation constraints could not be represented too.

Apart from the data in Table 6.6, Machine-Co team also provided unstructured feedback about their concerns regarding the capacity expansion decision and how they would like to see a process or a tool to address it. The following additional points were raised before and after the case study were executed.

- 1) Complex sourcing - As a global supplier, although the primary objective for each factory was to serve the domestic market, the trend in supplying goods from different factories to the same customer was more common now. To fulfil the sales demand, sometimes sub assembly parts were imported from sister factories. With the objective of not failing to meet customers' requirement, parts/product were also delivered via airfreight at times. The service level to customers is given highest priority. Since this entire process and transaction costs associated with it are not tracked and summarised, taking them into account in any decision process is a huge challenge.
- 2) Logistics connectivity rising in importance - The overall production planning process has also undergone a change due to the demand pattern switching from 'mass order' to 'batch order'. Delivery lead-time is being increasingly emphasised by customers. The pre-1995 delivery lead-time was around 6

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weeks; the lead-time has since reduced to 4 weeks. Any reduction in delivery lead-time due to better logistics connectivity is treated as a competitive advantage. Taking into account only the logistics cost in the model does not make up for the importance of this factor in any capacity expansion decision.

Machine-Co team considered this as a good exercise but not yet representative of all conditions that they wish to take into account when making a capacity expansion decision. Economic conditions and logistics connectivity were seen as very important factors in their decision making.

This section has presented the case studies conducted along with the data gathered and some preliminary analysis. The next section analyses the decision process based on the case studies and presents it in a structured manner.

## 6.4 Analysis and Discussion of Results

On the basis of the case study results given above this section evaluates the representative decision process based on the criteria of feasibility, usability, usefulness and context.

### 6.4.1 Evaluation of the representative decision process - Feasibility

Based on the criteria of feasibility, some weaknesses of the representative decision process were identified. The first was regarding the quality of data which was needed as an input but was not available. In case studies 3 & 4 with Machine-Co the data was of considerable higher quality than in case studies 1 & 2 with Glass-Co. One reason

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for this was that Machine-Co data was extracted from their annual planning exercise which was quite current. The quality of data caused in some cases the underlying MILP to be infeasible, i.e. no solution existed which took into account all constraints placed on the problem. A considerable problem arose when the data provided by the practitioner had the wrong units e.g. instead of inventory cost per unit of product, total annual inventory cost was provided. Going through the categories of data one by one and checking consistencies took too much effort and time. There were also no guidelines available to the practitioner over the sources of such data. A number of times the researcher had to sit down with the practitioner to discuss the various sources of data that were available and identify the most appropriate source based on the perceived accuracy.

There was also some human intervention required in the case study execution. This was especially needed as the decision process assumed that every product could be produced at every site. The process thus needed production and cost data to support this assumption. The data was hence fabricated in such a manner that producing the particular product at a facility where it cannot be produced is made economically very expensive. The fabricated data required a lot of iterations to force the decision process to model the reality. This shortcoming also affected the usability of the decision process and is explained with an example in the next sub section.

#### **6.4.2 Evaluation of the representative decision process - Usability**

The decision process fared better with regard to usability. The decision process was able to handle a number of factors deemed important by both the practitioners and

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academics. Further the underlying mathematical model is linear in nature (MILP) ensuring that the time to solve it using commercial solvers was within tolerable limits. However, weaknesses of the decision process were also identified with regard to usability.

The decision process did not perform very well in terms of flexibility, one of the performance indicators for usability (Table 6.3). It was also not able to handle some special cases and some factors considered important. One common case was that certain factories did not produce certain products. However, the model used in the decision process assumed all factories can produce all products. Modification (and sometimes construction) of data was required to handle this case. For example, In case of Machine-Co, China only produced product Q and did not produce product S and product E. One modification was to increase the transportation cost of both S & E at the China factory to be very high when transported from China to anywhere else. Such modification made it uneconomic for S & E to be produced at China and shipped to other locations. Another example of construction of data in this case was the unit cost to produce S & E in China was again set at a high level to deter any production of both.

Other cases where the decision process failed on usability included representation of labour efficiencies (and hence production) costs as a non-linear function of both production size and time. Also, the effects of economic factors like tariffs, export duties, currency exchange rates on the decision as well as consideration of logistics



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connectivity and transportation constraints as key for any site being chosen for a future factory.

A final point made by the practitioners was the form the decision process was in. They commented that the process would have been more easily understood and smoothly executed if it was embodied in some form of software. The results of the decision process are available in form of outputs from the ILOG OPL software but lacked any post-processing or report generation. Hence the results were not immediately clear to the practitioner and needed some interpretation and translation by the researcher.

#### **6.4.3 Evaluation of the representative decision process - Usefulness**

The usefulness of the decision process was measured by two performance indicators – efficiency and learning curve. Though 11 mandays were required for cases 1&2 and 12 mandays were required for cases 3&4 the real time was over 8 weeks for each. There were large time gaps in the collection of data as a number of times the researcher had to get back to the practitioners to clarify and refine the data. During consequent case studies i.e. case 2 after case 1 and case 4 after case 3, was smoother. These gains in efficiency were made by going through the learning curve in the initial former study. The practitioner however did not gain much on the learning curve as the researcher was executing the decision process and reporting processed information. In a good decision process the practitioner should have been able to execute the process themselves and in turn gain knowledge about the problem.

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#### **6.4.4 Evaluation of the representative decision process – Context**

In terms of the context only the limitations of the decision process were recorded. The process was not able to take into account a number of factors like tariffs and exchange rates and missed out constraints like transportation capacity and production specificity.

#### **6.4.5 Summary of analysis**

The analysis of the feasibility, usability, usefulness and context identified a number of weaknesses of the representative decision process by Melo et al. (2005). Research opportunities arise from addressing these weaknesses. The first opportunity is to improve the data gathering and filtering process. This can be achieved by developing a tool to assist the practitioner in understanding what data are needed and identifying appropriate corporate sources for each piece of data required. Such a tool can also help modify the available data to represent special cases which cannot be directly handled by the underlying multi-factor model in the decision process. For example, any assumptions that the practitioner has on the economic climate of the future can be represented through modified cost data. Some disadvantages of developing such a tool are the specificity to the underlying multi-factor model and data required by it as well as specificity to the companies with which the case studies were done. Constant improvement of this tool through case studies with other companies will however mitigate this threat.

Another opportunity is available in modification of the underlying MILP to represent more factors and also to be able to handle some special cases. Addition of variables

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and constraints will definitely expand the applicability of the model however they might have an adverse effect on the solution space by further constraining the problem and reducing the chance to find a feasible solution. This needs to be taken into account whenever such a modification is made. Future case studies with an advanced decision process will mitigate this concern.

Finally there is an opportunity to embody the decision process in software or a workbook. Presently, since the decision process is represented and solved using ILOG OPL studio, additional software to handle data input, and post processing can be built to enhance the usability and usefulness of the decision process.

In summary, analysis of the industrial case studies conducted in identification of the following shortcomings of the decision process.

1. Input data that is available is often poor
2. Assumptions built into the model are overly constraining
3. Input data available is not always what is needed
4. Some factors that are key constraints, are missing

Apart from the above shortcomings, the practitioners also recommended that the process of reporting the case study results be improved. These shortcomings are addressed in Part III of the research through development of an advanced decision process.

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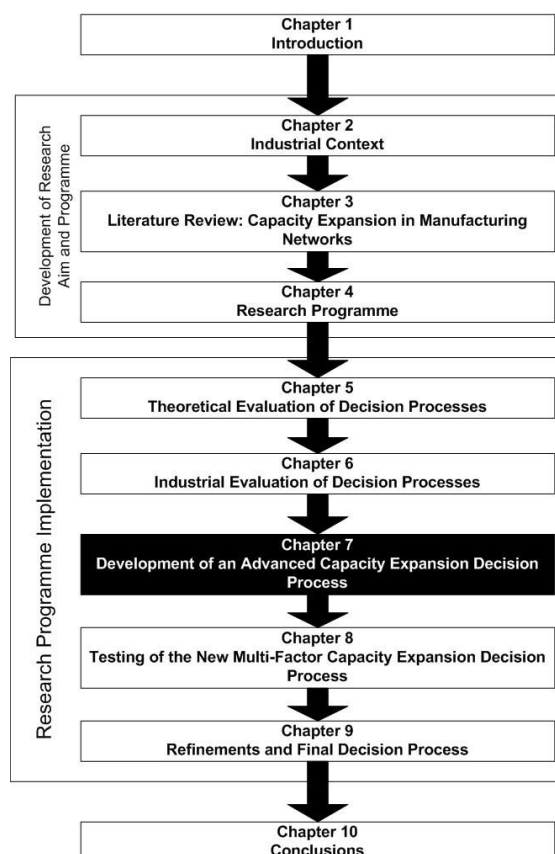
## 6.5 Chapter Summary

Part II of the research had set out to address the research objective to industrially evaluate a representative decision process. In the research conducted, a tool was created based on the representative process (Melo et. al, 2005), and industrial case studies were executed. The case studies revealed that the decision process was useful for the user however some shortcomings were there. These shortcomings include lack of clarity of data types and sources, limited cases that can be analysed by the decision process, and the absence of a framework to embody the decision process.

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## Chapter 7. Part III: Development of an Advanced Decision Process for Capacity Expansion

A theoretical evaluation of present state-of-the-art in capacity expansion decision processes (Chapter 5) constituted Part I of this research. In Part II an industrial evaluation of a representative process was conducted through case studies (Chapter 6). Shortcomings of the representative process were identified in Section 6.4.5. This Chapter deals with the development of a multi-factor capacity expansion process that overcomes limitations of existing processes. Figure 7.1 places this Chapter in perspective of the overall research.



**Figure 7.1 Chapter 7 – Development of an Advanced Capacity Expansion Decision Process**

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## 7.1 Part III – Research Method

This chapter sets out to address Objective 3 of the research (Section 4.2), namely, to apply the results of the test to formulate an advanced decision process. In Section 4.3.3 the research strategy identified is based on external enhancements of the decision process, enhancement of the underlying MILP and enhancements of data presentation and interpretation. To realise this, the following outstanding issues need to be addressed.

1. What is the research progression till now and how can the representative decision process by Melo et al. (2005) be improved?
2. How can the quality of input data be improved?
3. How can impractical assumptions be removed and important constraints considered in the decision process?
4. Can a completely different approach to the decision process be taken?
5. How can the presentation and interpretation of the decision process and its results be enhanced?

The approach to address these questions can now be considered. The research method followed to address each of the issues is described in the following sub-sections.

### 7.1.1 Summary of Research Progression

The research objective addressed in Part III was to apply the results of the theoretical and industrial evaluation to formulate a new pilot decision process. There is a need at this stage to summarise the research executed and to analyse its alignment to the research programme. Figure 7.2 describes the research path followed in Part I - III of the research. The research was initiated with the industrial problem that

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*“the companies undergoing capacity expansion did not find the available tools useful.”*

A review of the literature revealed a number of tools amongst which multi-factor decision processes were most used. Hence there was a gap between the practitioners and the available literature. The research problem now changed to

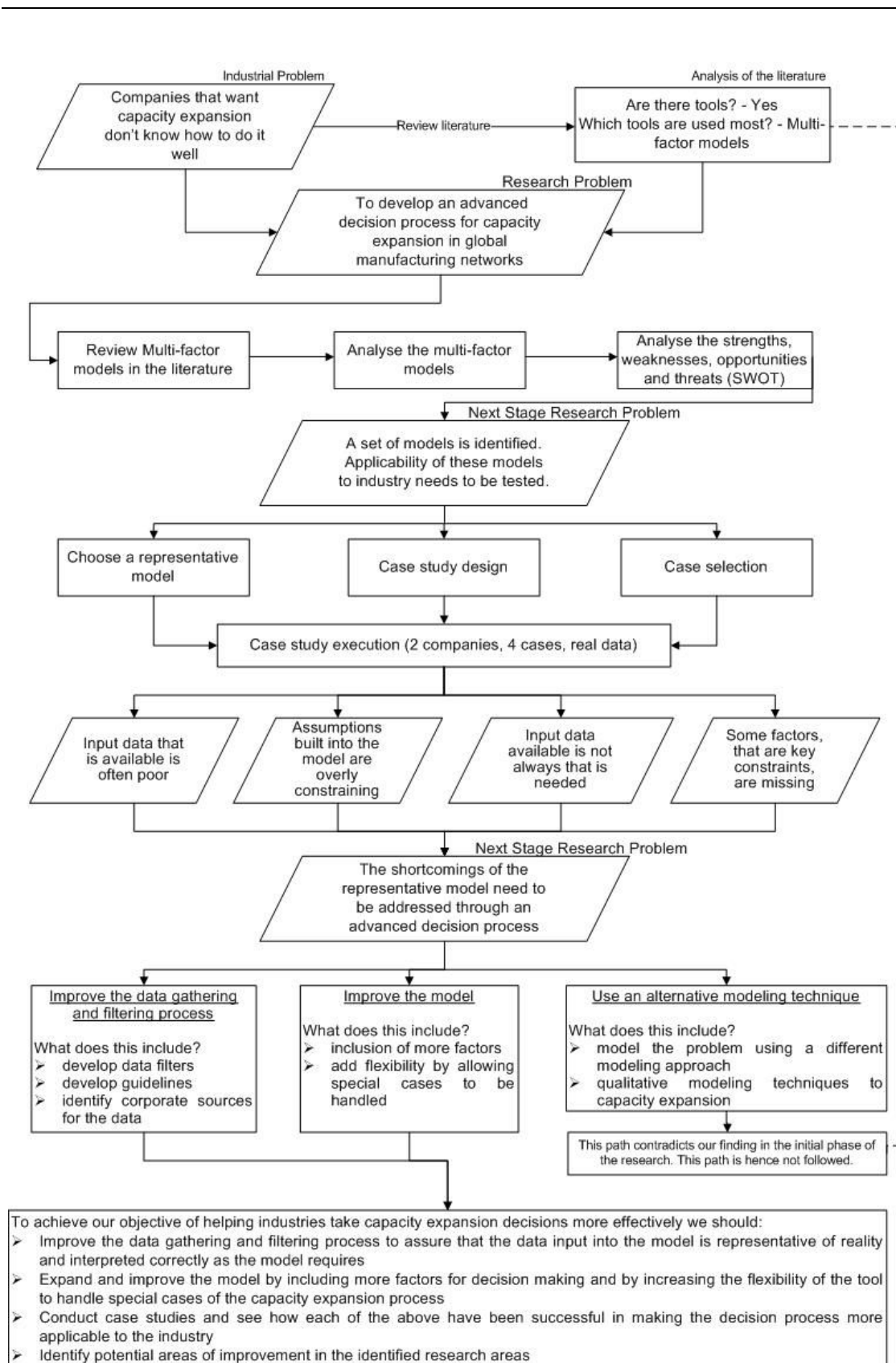
*“to develop an advanced decision process for capacity expansion in global manufacturing networks.”*

In Part I of the research a theoretical evaluation of capacity expansion decision processes was conducted. This evaluation identified eleven decision processes which were then analysed to ascertain the strengths and weaknesses of the body of knowledge and its applications. Hence, the next objective to solve the research problem was

*“to test the applicability of these representative decision processes to industrial needs.”*

Part II of the research addressed the objective mentioned above. Using a structured approach, the model by Melo et al. (2005) was identified and selected as a representative decision process to be tested in industrial context. A case study based approach was taken and industrial case studies were performed. Shortcomings of the representative decision process were identified. The next objective was

*“to address the shortcomings of the representative decision process by developing an advanced decision process.”*



**Figure 7.2 Research path followed for Part I-III**



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The above statement forms the purpose of this part of the research. Four shortcomings of the representative decision process were determined by research conducted in Part II (Section 6.4.5). Each of these shortcomings were further analysed and an advanced decision process was developed. Figure 7.2 illustrates the research path of Part I-III. In the next subsection we discuss the research method to address issues 2-5 mentioned at the beginning of Section 7.1.

### **7.1.2 Approaches taken for the formation of an advanced decision process**

The research method followed to address issues 2-5 (Section 7.1) are discussed below.

#### ***Issue 2: Improvement of the data gathering and filtering process***

Improvement of data gathering and filtering process aims to address shortcoming 1 and 3 identified in Section 6.4.5. It included development of a data filter to guide the user in preparing input data for the decision process using knowledge derived from the case studies conducted. Certain guidelines were also identified and incorporated in the data filter. Corporate sources of data were also identified and documented assist the user in gathering the data.

Certain drawbacks identified in developing this data filter included the inherent specificity to the case studies conducted. Since only two companies were involved in the case studies, there was a threat that any data filter developed might not have wider usability and applicability. The reasoning for development of this data filter was on the pattern of inductive research where the movement would be from the specifics

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(the companies involved) to the general by adding and augmenting it with knowledge from more case studies. The data filter thus becomes a tool that has the potential to keep growing and becoming more useful as more case studies is conducted using it. Section 7.2.1 describes the new data filter and gathering process in detail.

***Issue 3: Overcoming impractical assumptions and including important constraints***

Improvement of the representative decision process was needed to address shortcomings 2 and 4. In a number of cases the decision process was also not able to handle some special cases and some factors considered important were not considered at all. Assumptions like all factories being able to produce all products and unlimited transportation capacity were considered too constraining and unrealistic. Certain improvements were thus needed in the decision process which aimed to enhance the usefulness of the decision process. One of the main considerations was to keep the complexity of the underlying MILP on a linear scale and thus keep the decision process usable. Section 7.2.2 describes in detail the improvements made to the decision process.

***Issue 4: Consideration of an alternative modelling technique***

Another way to address almost all the shortcomings was to take a completely different path, or to supplement the present process with a more qualitative technique for decision making. There were approaches different than the numerical optimisation-based multi-factor decision process available in the literature. Examples include using techniques like Analytical Hierarchy Process (AHP) used by O'Brien and Smith (1993). It was however decided to not take the path of replacing the decision process

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with some qualitative technique as it was in contradiction to the findings that numerical optimisation-based multi-factor decision processes were the most preferred tool by the academia. It was more prudent to include elements of qualitative techniques into the present decision process thereby enhancing the present methodology of addressing the capacity expansion problem.

***Issue 5: Enhancing the presentation and interpretation of the decision process***

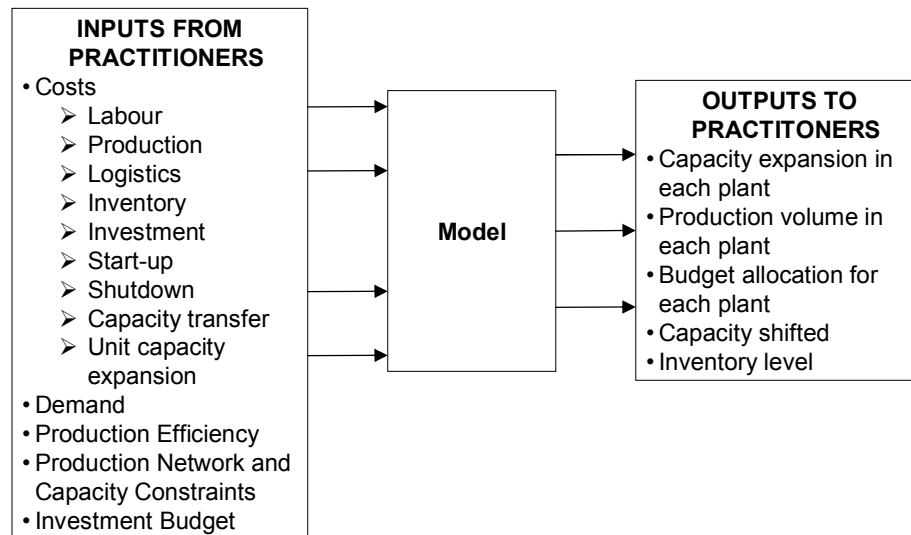
Development of a tool to improve the reporting of results of the decision process was suggested. Essentially this was also a way to embody the entire decision process in a more structured and systematic form which can be documented and can also be used to execute the decision process. The tool is defined in Section 7.2.3 below.

## 7.2 Development of the Advanced Decision Process

With the tasks to develop a comprehensive and coherent decision process defined, the next step was to execute the development tasks based on the research methods outlined in Section 7.1.2. This section defines the advanced decision process and its various components. In Figure 7.3 the representative decision process by Melo et al. (2005) is shown with its inputs directly from the practitioners. The decision process is represented in a MILP, which is solved using ILOG OPL Studio, a commercial solver. Finally the results from the solver are provided to the practitioners. Details of the model and the MILP implementation are available in Appendix A and Appendix B respectively.

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The advanced decision process is developed in Section 7.2.1, Section 7.2.2 and Section 7.2.3. The advanced decision process is then presented in Section 7.2.4.



**Figure 7.3 Representative decision process by Melo et al. (2005)**

### **7.2.1 Development of the data filter**

The development of a data filter addresses issue 2 from Section 7.1.2. There are three sets of data needed as input in the representative decision process by Melo et al. (2005). These data sets are:

1. Index data set – this data set defines the structure of the network that is candidate for expansion. The data set includes information on the facilities part of the manufacturing network, the facilities which are being considered in the expansion decision, potential sites for new facilities, the products being produced at the facilities and the number of time periods for which the capacity expansion decision is to be taken. The data needed is presented in column 1 of Table 7.1.

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2. Cost data – this data set includes all costs related to the manufacturing facility. This includes variable costs of production, inventory, and transportation. The fixed costs of operating a present facility, shutting down a facility and starting up a new facility are also part of this data set. The data needed is presented in column 1 of Table 7.2.
  
  3. Parameter data – this data set includes data on the boundary limits for certain activities as well as information on the external economic factors. The data set includes the maximum allowed capacity at a facility and the minimum throughput required at an operating facility. The efficiency of a facility is defined using a unit capacity consumption factor. The stock of a product at a facility at the beginning of the planning and the external demand of a product at a facility is also defined here. The data needed is presented in column 1 of Table 7.3.

Based on the case studies executed in Part II, a filtering matrix was developed. This matrix defines the data needed, identifies the data sources (when multiple sources are available the choice is based on relevance), any filtering that is needed to make the data relevant for the case study and any other learning from the case studies. This matrix was discussed and refined with the practitioners participating in the case studies. The matrix representing the index set data, the cost data and the parameter data is presented in Table 7.1, Table 7.2, and Table 7.3, respectively. This data filter forms the first enhancement of the advanced decision process over the representative decision process by Melo et al. (2005).

**Table 7.1 Filtering matrix for index set data**

<b>Data Needed</b>	<b>Definition</b>	<b>Data Available</b>	<b>Filtering needed</b>	<b>Remarks</b>
<i>Index set data</i> Set of facilities	All facilities owned by the company which contribute to manufacturing any of the company products and sites for potentially new facilities	Names of the facilities (sites)	None	
Set of selectable facilities	Facilities (and sites) which are part of the decision process	Names of the facilities (sites)	None	
Set of selectable existing facilities	Facilities where production is presently carried out	Names of the facilities	None	
Set of potential sites for establishing new facilities	Sites which are candidates for new production facilities	Names of sites	Since detailed estimates of various costs will be needed to assess the suitability of a site, it is recommended that a preliminary filtering of the potential sites is conducted	To assess suitability of multiple sites it is also needed that the maximum new facilities be decided and each potential combination is assessed separately. The overall objective function is suitable for a cross case analysis in this regard.
Set of product types	Products that need to be part of the study	Products produced by the company, major products (families), products whose production needs to be increased	Lump products into families and consolidate all the data regarding costs and other parameters based on the families. This keeps the number of variables low and speeds up the optimisation process.	Large product numbers will increase the complexity of the model and reduce the feasibility space drastically.
Set of time periods	Duration of time between which the expansion will be carried out	Internal planning horizon (annual, biennial), time taken for expansion, type of industry, amortisation horizon	Time periods should be long enough for the expanded capacity to come online and short enough to avoid the change in demand being unrealistic	Typically large manufacturers plan expansions with a 5-10 year planning horizon for light-medium industries

**Table 7.2 Filtering matrix for costs**

<b>Data Needed</b>	<b>Definition</b>	<b>Data Available</b>	<b>Filtering needed</b>	<b>Remarks</b>
<b>Costs</b>				
Variable cost of production	Cost to produce/purchase one unit of product by a facility during a time period	Variable cost of facility (based on product), units of each product produced, ratio of units of labour required for different products (families), cost of material for each unit of product	If product based variable cost is not available then using the ratio of labour required for different products, a relative variable production cost can be derived which is representative of reality	Typically product based variable cost is available with the sales and accounting people who internally calculate it for pricing/accounting purposes
Variable inventory cost	Inventory cost per unit of product in facility at the end of a time period	Total warehousing cost, handling cost based on units stored, obsolescence cost, average storage in warehouse	Inventory cost is usually estimated at a percent of the variable production cost of the product.	In some cases companies have a policy where the finished good is transferred to a sister organisation which is responsible for sales and delivery. In such a case the inventory cost of finished good can be taken as zero. The effect of the inventory cost will be included in the operations of the sister organisation mentioned above.
Unit variable cost of moving capacity from the existing facility to a new facility at the beginning of a time period	Average cost to increase the capacity of a site by one unit while simultaneously reducing the capacity of another by one unit	Cost to buy new equipment, cost to ship equipment, cost to setup equipment, disposal cost	None	
Fixed cost of operating facility during a time period	Fixed cost incurred per year on a facility	Capital cost of equipment, depreciation costs, management costs, corporate overheads	The fixed cost needs to be decided in conjunction with the variable production cost.	In some cases labour is considered a fixed operating cost and hence can be included in the fixed cost. Cost of raw materials will nevertheless still be part of the variable production cost.

**Table 7.2 Filtering matrix for costs (cont'd)**

<b>Data Needed</b>	<b>Definition</b>	<b>Data Available</b>	<b>Filtering needed</b>	<b>Remarks</b>
Fixed cost for shutdown	Total cost charged in a time period for having shut down an existing facility	Labour severance pay, equipment disposal costs, proceeds from sale of assets	Loss of future sales will not be taken into account. This cost is an estimate of net expenses for providing severance to labour and management and net proceeds from asset sales.	In some cases land may be an asset too.
Fixed setup cost	Total cost charged in a time period when a new facility starts its operations in the beginning of a following time period	Cost to lease/buy land, cost for equipment, cost to hire manpower (labour and management), historical data on cost to setup previous facilities	Data from previous years needs to be adjusted to inflation.	Setup cost does not include working capital for the facility. Fixed costs are traditionally amortised over duration of time. The costs here thus are the fixed costs charged to the present time period only.

**Table 7.3 Filtering matrix for parameters**

<b>Data Needed</b>	<b>Definition</b>	<b>Data Available</b>	<b>Filtering needed</b>	<b>Remarks</b>
<b>Parameters</b>				
Maximum allowed capacity at facility in a time period	Maximum amount of each product that the facility is permitted to produce	Available pool of temporary workers, design capacity of the facility, effective capacity of the facility, labour contracts	A combination of available in house manpower and contract workers provides maximum labour units. The maximum allowed capacity will be the lower of the max labour units and the design capacity.	Maximum allowed production can also be effected by issues like logistics connectivity and taxes.



**Table 7.3 Filtering matrix for parameters (cont'd)**

<b>Data Needed</b>	<b>Definition</b>	<b>Data Available</b>	<b>Filtering needed</b>	<b>Remarks</b>
Minimum required throughput at a selectable facility in a time period	Minimum amount of a product to be produced at a facility	Economically feasible batch size of a product, costs to maintain product specific production teams, product specificity of equipment	The minimum limit assures that practically infeasible numbers are not produced in a facility to achieve the "optimal".	The minimum throughput forces the modelling of a condition where a product is dropped in case less number of units are needed from the particular facility.
Unit capacity consumption factor of a product at a facility	Relative units of capacity used for each unit of product	Total capacity of the facility based on a single product, relative capacity requirement for a specific product, equipment specificity, wasted capacity at different sites (wasted labour)	Productivity of a particular site is factored in this parameter. Estimate of the capacity consumption factors of product produced in same facility are moderated by the relative productivity of the different locations.	All data is relative to a base facility. There is hence a need to carefully balance the relative capacity consumption factors.
Stock of a product at a facility at the beginning of the planning horizon	Units of a product produced in earlier time periods and available to satisfy demand in present time period	Average stock levels in warehouses	None	
External demand of a product at a facility during a time period	Units of a product demanded from a facility during a time period	Demand forecasts, demand allocation to different facilities	None	In companies where sales (forecasts/orders) are consolidated and then allocated, the demand is simply equal to the allocation.

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### **7.2.2 Extensions for additional constraints in the advanced decision process**

There were a few assumptions which needed to be removed and constraints which needed to be added in the advanced decision process (Section 6.4.5). It was established that the assumption of all factories being able to produce all products was most constraining and unrealistic (Section 7.1.2). Further, unlimited transportation capacity did not go well with the practitioners. Limits on labour availability and taking into account exchange rate fluctuations were also considered to be incorporated into the new model. Each of these possible extensions are analysed below.

*All products not at all facilities:* The case studies executed in Part II handled this shortcoming by applying modifications in the input data and making it uneconomical to produce a particular product at a facility. This trial and error of modifying data and ‘hoping’ that the decision process will not allocate any production of the non producible part to a facility needs to be definitely taken into account. Hence, the advanced decision process should be able to explicitly take into consideration the fact that certain products are not produced at some factories.

*Limited transportation capacity:* There was a concern raised by the practitioners on assumption made in the representative decision process of the availability of unlimited transportation capacity. Such an upper cap on transportation capacity will make the advanced decision process more realistic but also further constrain it

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when finding a feasible solution. It can be argued that the transportation costs in the objective function will make sure that only “necessary” transportation is carried out. Hence, explicitly adding it to the decision process it was considered unnecessary.

*Limit on labour availability:* Presently there is a total maximum capacity that can be expanded in the network. Each facility has its capacity efficiency included as an input. And further, the max output of a capacity is capped at a figure. These three parameters jointly represent what is the capacity that can be added at a particular facility. There is thus a clear way of representing labour availability and explicitly including it would again over constrain the problem.

*Exchange rates for prices:* The costs used as inputs need to be converted into a standard currency to take into account their origin from different sources. Adding a factor representing currency exchange fluctuations for capacity expansion decision seems to be an overkill as the decision will not be influenced by short-term changes but rather by long-term trends if indeed.

As a result of the analysis above the modification in the advanced decision process included adding the product specificity to facilities explicitly. This modification is represented in detail in Appendix A. This addition represented a second enhancement in the advanced decision process over the representative decision process by Melo et al. (2005).

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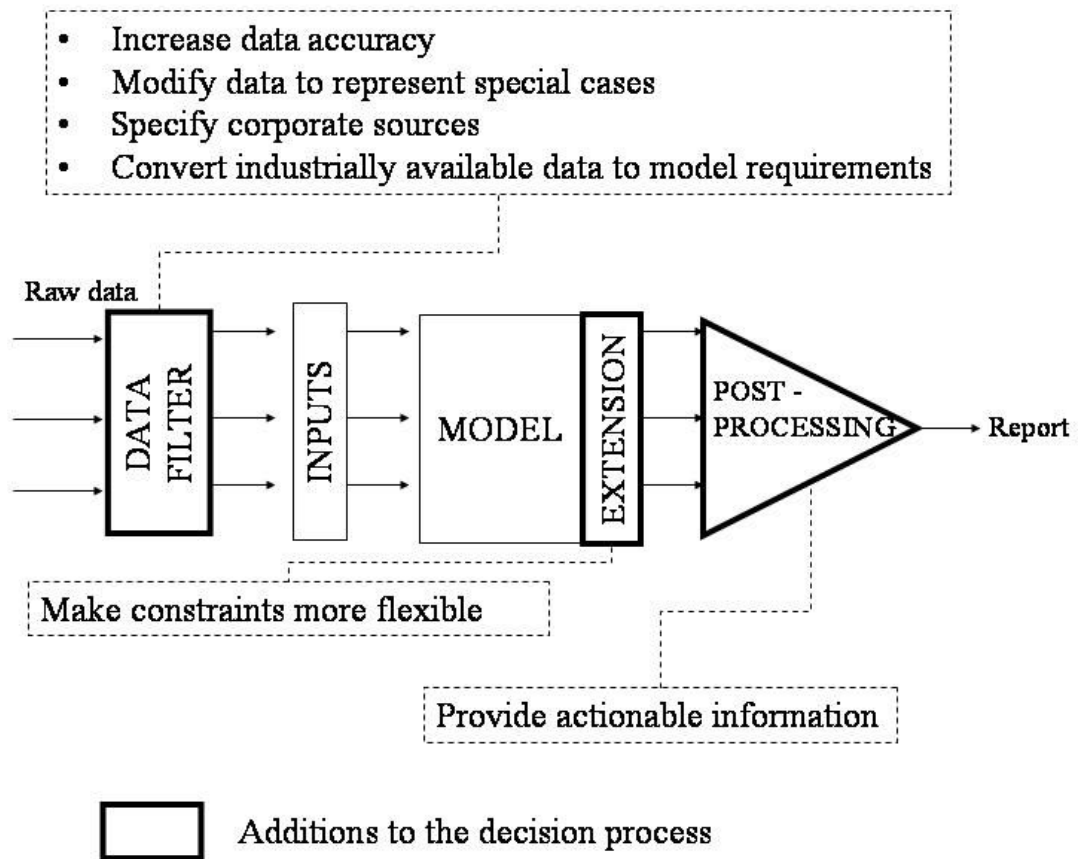
### **7.2.3 Post-processing of results**

Post-processing of results was needed for the practitioners to make sense of the results compared to the scenario being studied (Section 7.1.2). The software used in the case study execution (ILOG OPL Studio) provided the results of the optimisation as the decision variable values. Microsoft Excel was being used to structure the input data and OPL studio provides interfaces to read MS Excel spreadsheets. It was thus decided to use MS Excel to represent the output data too.

A reporting template was created and an interface program was developed in Visual Basic to translate the decision variable data into more presentable and understandable form. The approach thus allowed the practitioners to use a software they were familiar with (MS Excel) to define the scenario by filling up the input data, linking the excel sheet to the OPL model and being able to view the report of the executed scenario in the same excel sheet. A sample report is presented in Appendix C and the Visual Basic code to achieve the same is provided in Appendix D. The development of this post processing module increased the usability of the advanced decision process and represented a third enhancement over the representative decision process by Melo et al. (2005).

### **7.2.4 Advanced capacity expansion decision process**

The advanced capacity expansion decision process is represented in Figure 7.4 and the additions to the representative decision process by Melo et al. (2005) used for industrial case studies in Section 6.3 and illustrated in Figure 7.3 are marked.



**Figure 7.4 Advanced decision process for capacity expansion in manufacturing networks**

The data filter developed in Section 7.2.1 aims to increase data accuracy and enables modification of data to represent special cases. It also specifies corporate sources of data and converts industrially available data to requirements of the decision process. The data filter is designed to be an evolving tool which can be used to capture knowledge from future industrial case studies. The data filter was an extension to the present decision process which was purely based on mathematical optimisation. It took into account qualitative considerations and

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hence enhanced the present methodology embodied as the advanced decision process.

Enhancement in the decision process is also made by addition of the facility specificity to a product (Section 7.2.2). Additional assumptions and constraints that could be incorporated were identified however not included in the model based on the analysis conducted in Section 7.2.2. Future work in the area can focus on how these assumptions and constraints can be considered while ensuring feasibility of the numerical solution.

Finally a post processing module is developed to enhance the usability of the decision process for the practitioners. This module enables the user to interact with the decision process through MS Excel, software they are more familiar with. The input data is defined in Excel and an interface with ILOG OPL Studio parses the data to the required ILOG format. Finally, the decision process results are presented to the practitioner in a understandable and actionable report in the same excel file.

### 7.3 Chapter Summary

The purpose of this chapter was to formulate an advanced decision process based on the shortcomings of the representative decision process which was tested in Part II of the research. The shortcomings were first analysed in detail (Section 7.1) and the features to be added to the decision process identified. A data filter was developed in Section 7.2.1, extensions to include additional constraints were

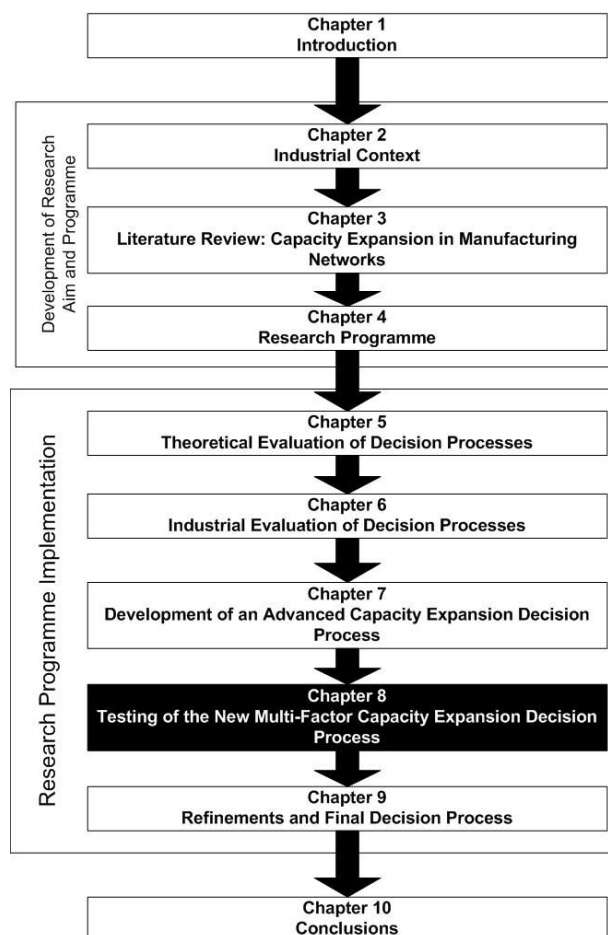
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proposed and implemented in Section 7.2.2 and finally a method of post processing the results for clear actionable information was discussed in Section 7.2.3. The advanced decision process was then presented in Section 7.2.4. The next chapter describes Part IV of this research in which industrial studies are designed and executed based on the advanced decision process.

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## Chapter 8. Part IV: Testing of the Advanced Capacity Expansion Decision Process

This chapter describes Part IV of the research – Testing of the Advanced Capacity Expansion Decision Process. The purpose of this chapter is to test the advanced decision process developed in Part III in an industrial setting. The research methodology for Part IV is described (Section 8.1) and issues are outlined. Each of the issues is addressed in Section 8.2.1, Section 8.2.2 and Section 8.3. Figure 8.1 places this chapter in perspective of the overall research.



**Figure 8.1 Chapter 8 – Testing of the Advanced Capacity Expansion Decision Process**



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## 8.1 Part IV: Research Method

This chapter sets out to address Objective 4 of the research (Section 4.2), namely, to test the advanced decision process in practice. In Section 4.3.2 a case study based research strategy was identified as appropriate for Part II of the research which dealt with testing of the representative process. In Part IV we use the same research strategy of executing case studies to test the validity of the new decision process. To execute this research strategy a number of issues need to be addressed such as:

1. How to select cases for investigation of the problem?
2. What are the criteria for success of the case studies?
3. How good is the advanced decision process in solving the capacity expansion problem in an industrial setting?
4. What are additional features that are needed to improve the advanced decision process?

The approach to address these questions can now be considered. The research method followed to address each of the issues is described in the following sub-sections.

### **8.1.1 Research method to select cases for investigation**

A process of identifying the appropriate industrial cases was developed and executed in Section 6.3.1. As defined in Section 4.3.4, the case studies to be selected for the testing of the advanced process in this chapter need to be similar in context to the case studies in Part II but differ enough to avoid a claim for specificity of the underlying decision process to the case study used to test it. In

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practice this would require case studies with industrial companies similar to Glass-Co and Machine-Co. However, there were some practical challenges to accomplish this.

The nature of the capacity expansion decision process demands involvement of top management and requires data that is highly confidential to the company. It is thus a logistically complicated task to include a number of companies to participate in this case study especially if some of them are similar in nature (e.g. discrete manufacturing). The primary industrial partner for this research was Machine-Co and they eventually agreed to define case studies for Part IV which was different in context than those studied in Part II and based on a subset of facilities to be considered for expansion. Ideally the new pilot process should have been tested with case studies from a different organisation. This was hence a compromise on the scientific process that was made in light of practical hurdles.

To compensate for the compromise made on choosing Machine-Co as the company for case studies in Part IV, the case studies defined were stricter in terms of the decision support capability to be tested. Machine-Co management, having observed the capability of the representative process in Part II defined scenarios each of which had specific questions to be addressed rather than a generic question of where the capacity expansion should take place. The scenarios which were used as industrial case studies are described in Section 8.2.1.

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In addition to the industrial case studies described in Section 8.2.1, a set of hypothetical case studies was also executed. The aim for these case studies was to demonstrate how the advanced decision process could be used for more complicated decision scenarios especially those requiring multiple sub-scenarios. These case studies also demonstrated the ability of the advanced decision process to enable sensitivity analysis on the various parameters of the decision process. These case studies are presented in Section 8.2.4.

### **8.1.2 Research method to identify criteria for case study success**

The criteria for evaluation remained the same as the ones used in Section 6.3.2 i.e. feasibility, usability, usefulness and context (Table 6.3). The data collection protocol was the same too as defined in Table 6.4. However, since the advanced decision process was being tested, apart from the data collection based on the data collection protocol defined in Table 6.4, the application of the data filter from Section 7.2.1 (Table 7.1, Table 7.2, and Table 7.3), and the decision support ability in answering the practitioner's questions is also described.

The criteria for evaluation and data collection protocol were kept unchanged to make sure that the comparison of case studies in Part IV can be done with case studies in Part II. Case study execution for industrial evaluation of the advanced decision process is presented in Section 8.2.2.

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### **8.1.3 Research method to evaluate performance of the advanced decision process**

Similar to the research method described in Section 6.1.4, the performance of the advanced decision process in each of the case studies was recorded based on feasibility, usability, usefulness and context. In addition, the data preparation and data collection steps are also recorded in detail. This evaluation of the advanced decision process based on the case studies is presented in Section 8.2.2.

### **8.1.4 Research method to identify features needed to improve the advanced decision process**

The execution of cases and collection of data based on the research methods described in Section 8.1.1, Section 8.1.2 and Section 8.1.3 above will result in case reports describing how the advanced decision process fared in each of the case studies. Finally, a cross case analysis is presented to evaluate the advanced decision process and compare it with the representative decision process. The execution of this research method is carried out in Section 0.

## **8.2 Industrial Case Study Design and Execution**

This section describes the design and execution of case studies to test the new advanced process. The research method for each of the steps is presented in Section 8.1.

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### 8.2.1 Selection of cases

The industrial cases for Part IV were proposed by practitioners from Machine-Co. The cases originated as specific decision scenarios that Machine-Co management wanted to test. These scenarios are described below. The cases are numbered from 5 to 8, in continuation of Part II, for ease of reference in the later part of the thesis. For the case studies 5 - 8, the manufacturing network is the same as described in Section 6.3.1. Each of the cases is based on Machine-Co's present manufacturing network consisting of Japan, Singapore, Malaysia and China facilities and potential for an additional facility in Vietnam. The Japanese facility is the oldest and the facility in China is the most recently established. Another facility is planned with the location still under consideration; however, for the case study indicative data for the new facility in Vietnam is used. There are three product families (Q, S, and E) similar to the case studies in Section 6.3.1. Also, for all the cases mentioned below, a new maximum capacity limit has been provided by the management.

- Case Study 5 – If there is an increase in demand for one product, with no new site, the capacity of which (present) site or sites should be expanded?
- Case Study 6 - Closing down one specific plant, how should the production be allocated to the present manufacturing facilities (where should the expansions be), assuming no new site is established?
- Case Study 7 - Increasing one product's production limit, with possibility of a new site, which site's capacity should be expanded?
- Case Study 8 - Increasing the demand from the cheapest production cost facility, should the corresponding capacity expansion occur in the same facility?

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Apart from the cases mentioned above, two hypothetical cases were also executed. These cases were based on Machine-Co data and aimed to demonstrate how scenarios which require multiple sub-scenarios to be executed can also be handled by the advanced decision process. The cases also demonstrate how sensitivity analysis can be carried out using the advanced decision process. These cases however were evaluated based on the same criteria as the industrial cases as the motivation behind them was to demonstrate how the advanced decision process can handle more complicated scenarios than the ones represented by the industrial case studies. The two hypothetical case studies are as follows.

- Case Study 9 – Increasing the maximum capacity of low cost facilities by enabling larger sized expansion, when does production hollow out in the more expensive production sites?
- Case Study 10 – How do macro-economic changes affect capacity expansion decision for the cheaper production site?

### **8.2.2 Execution of industrial case studies**

The advanced decision process developed in Part III is used to execute case studies 5-8. Hence, apart from the data collection based on the data collection protocol defined in Table 6.4, the application of the data filter from Section 7.2.1 (Table 7.1, Table 7.2, and Table 7.3), and the decision support ability in answering the practitioner's questions is also described. The case study report below includes the data preparation using the filtering matrix, the data collection to evaluate the decision support tool and the effectiveness of the tool in answering the practitioner's questions.

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***Case study 5 - If there is an increase in demand for one product, with no new site, the capacity of which (present) site or sites should be expanded?***

Data preparation: The data needed for the case study is divided into three sets – index set data, costs data and parameter data, with their filtering matrices shown in Table 7.1, Table 7.2 and Table 7.3, respectively. In case study 5 only the present facilities are covered so the potential new facility at Vietnam is not considered. It is assumed that the demand for product S will be increasing in the next 4 years. The time period in this case is 4 periods as the increase in production of product S is gradual (one-fourth of the total increase additional pieces per year). The additional data on product-facility specificity is also added in the data set.

The cost data remained unchanged from the case studies in Part II. However there was a change in the parameter data for the external demand of a product at facility during a time period. Product S was solely produced in Singapore, hence the extra demand was allocated solely to Singapore.

Data collection: The case study yielded the following result. Due to extra demand for product S at Singapore, there was considerable pressure for Singapore to expand. Singapore had excess capacity to start with and hence most expansion occurred there without it having to give up production of product Q and product E to other sites. The data collection in Table 8.1 is done with respect to the case studies 3&4 in Table 6.6. Only incremental and differentiating information is presented in Table 8.1.

**Table 8.1 Data Collection - Case Study 5**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
Feasibility	Amount of data	Additional data on product-facility specificity was provided by the practitioners.
	Type of data	Product-facility specificity data was available.
	Human intervention	The additional demand of product S was to be allocated to different facilities. However, since only Singapore was capable of producing product S this decision parameter was easily added.
Usability	Ease of use	Most data was available from before. Additional data was easy to find. The modelling of increase demand of particular product was easy due to the coincidence that the product was produced at only one facility. Otherwise different demand allocation scenarios would have to be tested.
	Time required	Since data was available from case study 3&4 and additional data was specified by the practitioners, the additional time needed for this case study was minimal (3 mandays).
	Understanding	The practitioners understood the decision process as it was now embedded into excel with an actionable report being generated in the same software. The need of managers and practitioners to have the decision process to be embodied in software that could be used by them as a tool by interfacing with the required data sources was fulfilled.
	Flexibility	The model could still not handle some concerns, one of which was the allocation of the additional production to a facility in a scenario where two or more facilities were able to produce the product. However, due to the modelling of specificity of product to a facility, the flexibility of the decision process had increased. The filtering matrix also added means to model additional concerns of the practitioners.
Usefulness	Efficiency	The new decision process took into consideration more concerns of the practitioner than before.



**Table 8.1 Data Collection - Case Study 5 (cont'd)**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
	Learning curve	Execution of case study 5 was a lot smoother due to the learning attained by the practitioner and the user (researcher in this case). Data collection for case study 5 was incremental. Further, since case studies 1-4 were dealing with the straight forward question of capacity expansion, case study 5 was addressing a more specific question and hence it can be concluded that the usefulness of the decision process had increased.
Context	Limitations	The decision process could still not handle some special cases of the problem. The allocation of the extra demand in case the product was produced by multiple facilities still remained a limitation.

***Case study 6 - Closing down one specific plant, how should the production be allocated to the present manufacturing facilities (where should the expansions be), assuming no new site is established?***

Data preparation: In case study 6 only the present facilities are covered so the potential new facility in Vietnam is not modelled. In this case study, the effect of closing down the facility in Japan on capacity expansion in the rest of the network needs to be studied. The Japan facility is hence not considered in this scenario. The additional data on product-facility specificity is added in the data set. Time period in this case is 4 periods as the proposed closure of the facility in Japan is done at the start of the first year.

The cost data undergoes a lot of change. All Japan facility specific data is removed from the decision process. The major change in parameter data is the reallocation

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of Japan facility's demand to other facilities. Japan solely produced product E which is also produced by Singapore. Hence, all previous demand of product E from the Japan facility is now allocated to Singapore. To accommodate the extra production to satisfy Japan's allocated demand, the maximum capacity at Singapore, Malaysia and China facilities is increased. Since from the preset the practitioners have decided to study the closure of the Japanese facility in this case study, the cost of shut down is manually added to the objective function as a post processing step.

Data collection: The case study yielded the following result. The absence of one of the facilities (Japan in this case) resulted in a production crunch for product E as Singapore was the only facility producing product E. The excess demand allocation of product E to Singapore resulted in reallocation of some demand of product Q to Malaysia and China. The resulting capacity expansion scenario called for the largest expansion in Singapore, followed by China and finally Malaysia. The capacity expansions were conducted in the beginning of year 2 and year 3 for China beginning of year 2, 3 and 4 for Singapore and Malaysia. The data collection in Table 8.2 is done with respect to the case studies 3&4 in Table 6.6 and case study 5 in Table 8.1. Only incremental and differentiating information is presented in Table 8.2 below.

**Table 8.2 Data Collection - Case Study 6**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
Feasibility	Amount of data	Additional data on product-facility specificity was provided. Data needed to be reduced as Japan was not functioning in this scenario.
	Type of data	Product-facility specificity data was available.
	Human intervention	The additional demand of Japan was to be allocated to different facilities. Japan produced only product-E and since only Singapore was capable of producing product-E this decision parameter was easily added.
Usability	Ease of use	Most data was available from before. Additional data was easy to find. The modelling of reducing a facility and allocating its demand to other facilities was easy due to the coincidence that the product was produced at only one other facility. Otherwise different demand allocation scenarios would have to be tested.
	Time required	Since data was available from case studies 3&4 and case study 5 and additional data was specified by the practitioners, the time needed for this case study was minimal (3 man-days).
	Understanding	Embedding of the decision process input and output in an Excel spreadsheet increased the understanding of the practitioners.
	Flexibility	The model could still not handle some concerns, one of which was the allocation of Japan's production to other facilities in a scenario where two or more facilities were able to produce the product(s).
Usefulness	Efficiency	The new decision process took into consideration more concerns of the practitioner than before.
	Learning curve	Execution of case study 6 was a smooth due to the learning attained by the practitioner and the user (researcher in this case). The question in case study 6 was more complicated than that in case study 5 however the additional effort was again minimal.
Context	Limitations	The decision process could still not handle some special cases of the problem. The allocation of the Japan's demand in case the product(s) was produced by multiple facilities still remained a limitation.

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***Case study 7 - Increasing one product's production limit, with possibility of a new site, which site's capacity should be expanded?***

Data preparation: In case study 7 the present facilities are covered along with the potential new facility in Vietnam. The additional data on product-facility specificity is added in the data set. Product Q's demand is increased over the next 4 years and hence the time period in this case is 4 periods. The Vietnam facility however can produce only product S.

The cost data undergoes a lot of change. Additional data for the Vietnam facility is added for all the categories. To accommodate the extra production to satisfy increased demand of Q, the maximum capacity at Japan, Singapore, Malaysia and China is increased. Data for capacity transfer from present facilities to new facility at Vietnam is added. Since the decision process requires that the additional demand is allocated to a site, demand for S is allocated to Vietnam. Hence, in a situation that the decision process reports against setting up a facility in Vietnam, the product will be shipped from other facilities to Vietnam. For the same reason shipping cost of the various products is added in the input data. This case study was thus a modification of case study 4.

Data collection: The case study yielded the following result. In the filtering matrix it was suggested that to represent a new facility only the setup cost for the first year should be represented and all costs amortised over the life of the factory should be included in the fixed operating cost. The practitioners however wished to test this scenario assuming that the entire setup cost was considered in the first year itself.

The large setup cost ended up overtaking the incremental capacity expansion costs at other facilities especially as the facilities (Singapore, Malaysia and China) could be expanded more. The expansion thus was split across Singapore, Malaysia and China. Extra product S was shipped from Singapore to Vietnam to satisfy the demand allocated to it. The data collection in Table 8.3 is done with respect to the case studies 3&4 in Table 6.6 and case study 5-6 in Table 8.1 and Table 8.3. Only incremental and differentiating information is presented in Table 8.3 below.

**Table 8.3 Data Collection - Case Study 7**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
Feasibility	Amount of data	Additional cost data for Vietnam was added. Additional demand for product S was allocated to Vietnam.
	Type of data	Vietnam cost data was available from estimates made during the annual planning exercise.
	Human intervention	The additional demand of product S was allocated to Vietnam.
Usability	Ease of use	This case was a slightly modified version of case 4.
	Time required	Since data was available from case study 4, and additional data was specified by the practitioners, the time needed for this case study was minimal (3 man-days).
	Understanding	Embedding of the decision process input and output in an Excel spreadsheet increased the understanding of the practitioners.
	Flexibility	The decision process was able to address the practitioners question in a comprehensive way.
Usefulness	Efficiency	The new decision process took into consideration more concerns of the practitioner than before.
	Learning curve	Execution of case study 7 was very smooth as it was a modification of case study 4.
Context	Limitations	The decision process could address the exact problem.

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***Case study 8 - Increasing the demand from the cheapest production cost facility, should the corresponding capacity expansion occur in the same facility?***

Data preparation: In case study 8 only the present facilities are covered so the potential new facility at Vietnam is not considered. The demand for product Q was increased in China, the cheapest per unit production cost facility. The additional data on product-facility specificity is added in the data set. Time period in this case is 4 periods as the proposed ramp up of extra production of product Q is done across 4 years. The cost data does not change from case 5. To accommodate the extra production to satisfy product Q demand from the China facility, the maximum capacity at Singapore, Malaysia and China is increased.

Data collection: The case study yields the following results. The capacity expansion is indeed needed in the cheapest production facility only in spite of its lower production efficiency. The capacity expansion takes places at the beginning of year 2, year 3 and year 4 at the China facility.

**Table 8.4 Data Collection - Case Study 8**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
Feasibility	Amount of data	Data similar to case 5. Instead of product S, product Q was to be produced more. Further the extra demand was allocated to China.
	Type of data	Product-facility specificity data was available.

**Table 8.4 Data Collection - Case Study 8 (cont'd)**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
	Human intervention	The additional demand of product Q was allocated to China. No human intervention was required in this case.
Usability	Ease of use	Most data was available from before. Additional data was easy to find.
	Time required	Since data was available from case study 5, and additional data was specified by the practitioners, the time needed for this case study was minimal (3 mandays).
	Understanding	Embedding of the decision process input and output in an Excel spreadsheet increased the understanding of the practitioners.
	Flexibility	The model could handle the scenario without difficulty.
Usefulness	Efficiency	The new decision process took into consideration more concerns of the practitioner than before.
	Learning curve	Execution of case study 8 was a smooth due to the learning attained by the practitioner and the user (researcher in this case).
Context	Limitations	The decision process could handle one special cases of the problem. The practitioner wanted to know at what efficiency of China (represented in the unit capacity conversion factor), will addition of capacity in China not be the better choice.

### **8.2.3 Feedback from Machine-Co**

The results of the case studies 5-8 were presented and discussed with representatives from Machine-Co. They found the process to be useful in addressing the capacity expansion questions they had. The Excel based input and output interface was appreciated. A major concern was the use of ILOG OPL Studio as the solver for the underlying mathematical optimisation. The case of purchasing expensive software for the capacity expansion issue needed to be based

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on some form of return on investment analysis. This was however an internal issue that they needed to handle and would require assistance of the researcher in establishing such a case in near future. However, they have not yet decided on going ahead and implementing this advanced decision process.

Machine-Co also commented on some assumptions made in the decision process. One such assumption was the effect of exchange rate changes on the final decision. This concern was mitigated by explain to them how the data filter could handle such effects by enabling modification of data to represent exchange rate fluctuations.

#### **8.2.4 Execution of hypothetical case studies**

The advanced decision process developed in Part III is used to execute case studies 9 and 10. These case studies do not originate from the industrial user and hence the data preparation is done solely by the researcher. This data preparation through application of the data filter from Section 7.2.1 (Table 7.1, Table 7.2, and Table 7.3), along with the decision support ability in addressing the hypothetical decision scenario is described below. The evaluation is presented based on the criteria of feasibility, usability, usefulness and context.

*Case study 9 - Increasing the maximum capacity of low cost facilities by enabling larger sized expansion, when does production hollow out in the more expensive production sites?*

Data preparation: Case study 9 is an extension to case study 8. In case study 9 only the present facilities are covered so the potential new facility at Vietnam is not



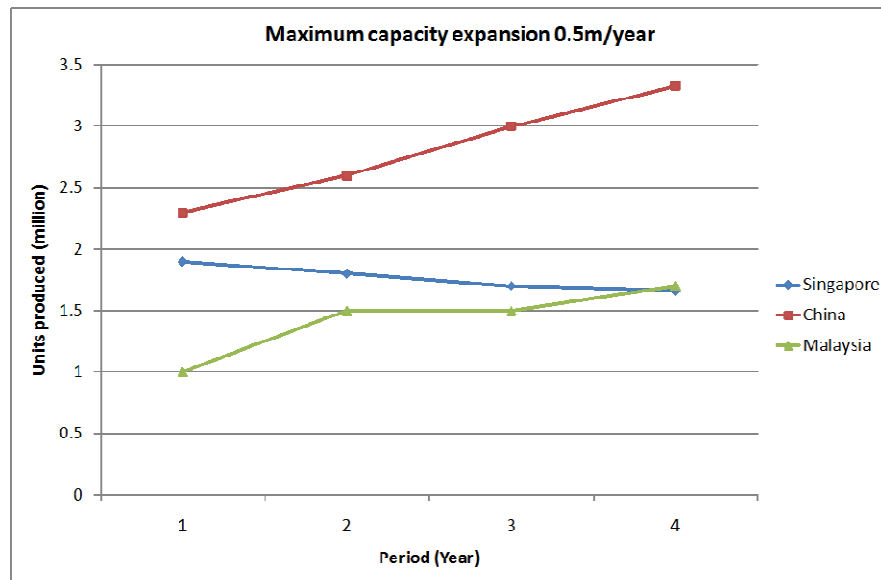
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considered. The demand for product Q was increased in China, the cheapest per unit production cost facility from 1.25m units to 1.5m, 1.75m and 2.5m in period 2, 3 and 4. The capacity expansion decision was to hollow out production of Q from Singapore and hence the question was what rate of expansion will hollow out Singapore as a site for production of Q by the end of the planning period i.e. Period 4. The maximum capacity at China is the main constraint here and increase in capacity could be carried out by addition of production lines each adding 0.5m capacity units.

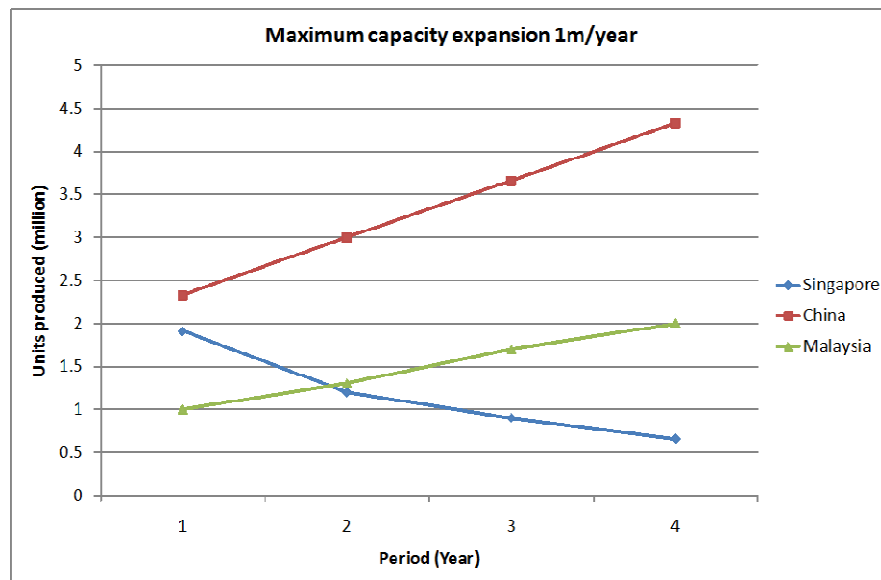
Data collection: The case study yields the following results. Three sub-scenarios were executed by adding one, two or three additional production line in China per year translating to allowable capacity expansion of 0.5m, 1m and 1.5m capacity units per year for period 2, 3 and 4. The decision process suggested capacity expansion in China up to the maximum allowed for all three scenarios and all periods. The decision process also suggested capacity expansion in Malaysia for all the periods in all three scenarios. Singapore had no production for Q in period 4 for the 1.5m/year maximum capacity unit expansion scenario for China. The capacity expansion is indeed needed in the cheapest production facility only in spite of its lower production efficiency (translating to 1 unit produced for each 1.5 unit of capacity for China, 1.1 unit of capacity from Malaysia and 1 unit of capacity for Singapore). The capacity expansion takes places at the beginning of year 2, year 3 and year 4 at the China facility. This is illustrated in Figure 8.2, Figure 8.3, and Figure 8.4. By the end of period 4 for the 1.5m capacity units per year expansion scenario it can be seen that the production of Q in Singapore goes down to nil. The

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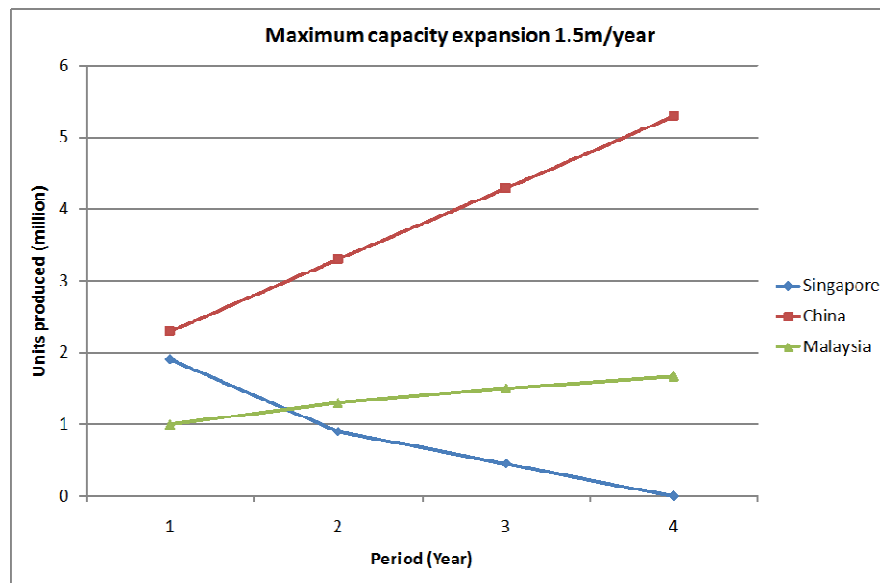
evaluation of the case study based on feasibility, usability, usefulness and context is provided in Table 8.5. This evaluation was entirely conducted by the researcher with no industrial input.



**Figure 8.2 Production profiles for allowable expansion of 0.5m capacity units per year in the China facility**



**Figure 8.3 Production profiles for allowable expansion of 1m capacity units per year in the China facility**



**Figure 8.4 Production profiles for allowable expansion of 1.5m capacity units per year in the China facility**

**Table 8.5 Data Collection - Case Study 9**

Category	Performance Indicator	Data Gathered
Feasibility	Amount of data	Data similar to case 8. Maximum permitted capacity was flexed by 0.5m, 1.0m and 1.5m/year.
	Type of data	Product-facility specificity data was available.
	Human intervention	The maximum capacity values were manually changed. Each sub-scenario was individually executed.
Usability	Ease of use	Most data was available from before.
	Time required	Since data was available from case study 8, the time needed for this case study was minimal (1 manday).
	Understanding	The researcher carried out the case study
	Flexibility	The model could handle the scenario without difficulty. Results from sub-scenarios were used to address the decision.
Usefulness	Efficiency	The new decision process took into consideration more complicated decision scenarios.

**Table 8.5 Data Collection - Case Study 9 (cont'd)**

<b>Category</b>	<b>Performance Indicator</b>	<b>Data Gathered</b>
	Learning curve	Execution of case study 9 was a smooth as it was executed by the researcher.
Context	Limitations	No limitations were identified in the execution of this case study.

***Case study 10 - How do macro-economic changes affect capacity expansion decision for the cheaper production site?***

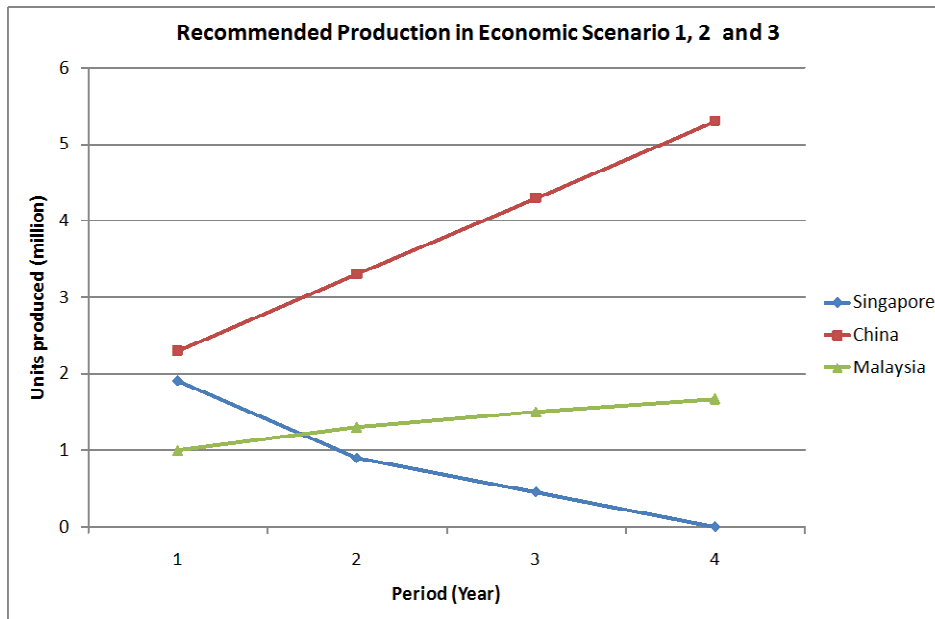
Data preparation: In case study 9 it was deduced that an expansion of 1.5m capacity units per year will allow production of Q to be reduced to zero in Singapore. Case study 10 extends this study to include the question of how this decision will be affected by macro-economic factors. Two macro-economic factors of changing exchange rate and wage conditions are considered in this case study. It is assumed that the Chinese currency appreciates by 5% per year against the base currency of the case study. Beyond that there are multiple values for wage levels that can be studied. The wage increase scenarios studied were the following.

- Economic scenario (ES1): 10% annual increase for all periods
- Economic scenario (ES2): 20% annual increase for first three periods and 7% increase for the last period
- Economic scenario (ES3): 20% annual increase for first three periods and 10% increase for the last period
- Economic scenario (ES4): 20% annual increase for first three periods and 14% increase for the last period
- Economic scenario (ES5): 20% annual increase for all periods

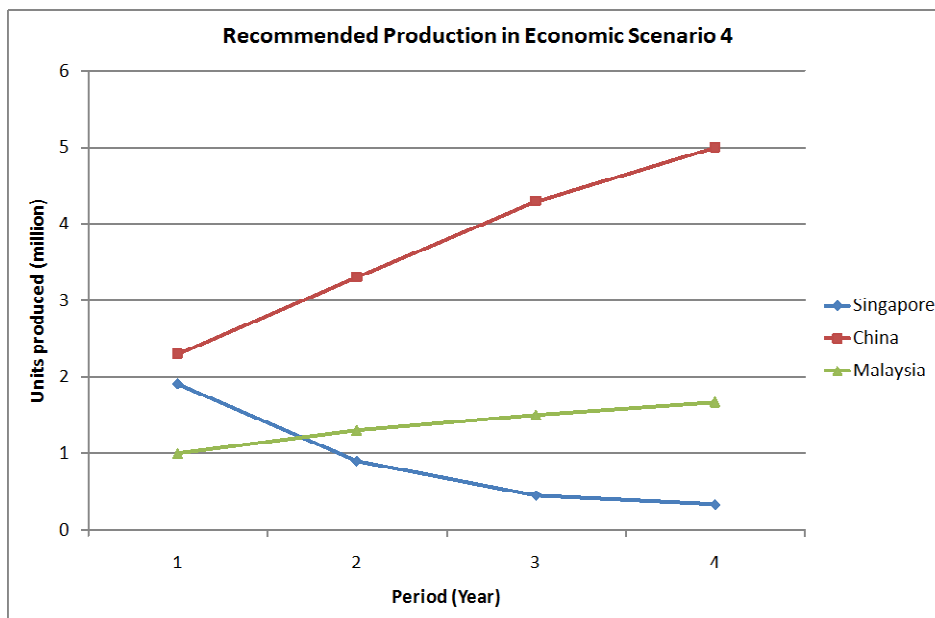
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It is assumed that the wage changes have a direct effect on the production costs and hence the effect is translated into the production cost. The rest of the conditions are same as case study 9. The 1.5m capacity unit per year increase in maximum capacity is considered for this case study. The capacity expansion decision was to study the effect of macro-economic factors and it was observed that if the macro-economic conditions are varied, the decision goes through an inflexion point. This inflexion point represents the scenario where the production in Singapore is not reduced to zero but reduced to gain again in subsequent periods. This takes place as we execute ES1 to ES5.

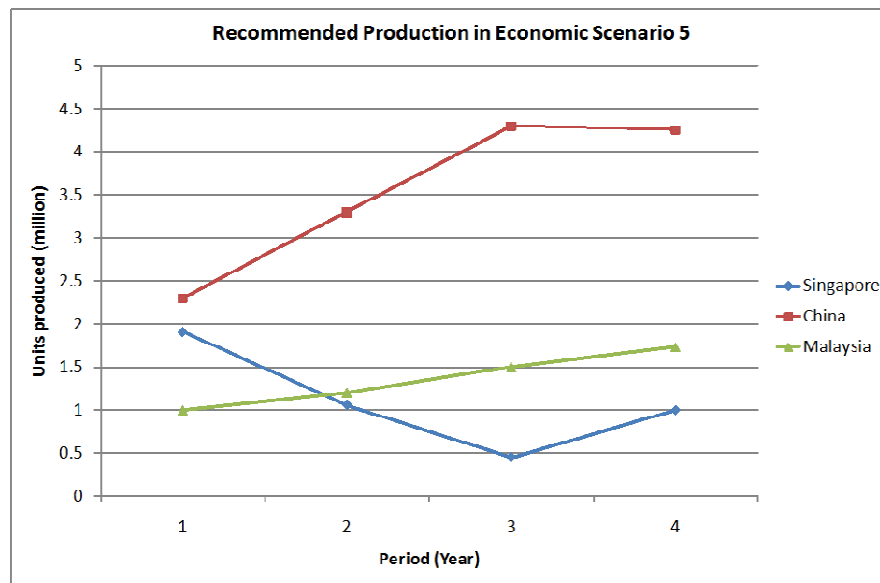
Data collection: The case study yields the following results. ES1, ES2 and ES3 suggest that Singapore production should be reduced to zero by the end of period 4 (Figure 8.5). However, the situation changes in ES4 where some production is allocated to Singapore (Figure 8.6). In ES5 Singapore production reduces to 0.45m units in period 3 but jumps up to 1m units in period 4 (Figure 8.7). The ES4 sub-scenario represents the inflexion point in the decision and shows how the final decision is sensitive to the macro-economic factors like currency changes and wages. The decision remained consistent with the first three sub-scenarios (ES1, ES2 and ES3) however with ES4 a deviation was seen and ES5 represented a situation where there was a need for reduction of production in China (Period 4 in ES5 in Figure 8.7). The evaluation of the case study based on feasibility, usability, usefulness and context is provided in Table 8.6. This evaluation was entirely conducted by the researcher with no industrial input.



**Figure 8.5 Production profiles for economic scenario 1, 2 and 3**



**Figure 8.6 Production profiles for economic scenario 4**



**Figure 8.7 Production profiles for economic scenario 5**

**Table 8.6 Data Collection - Case Study 10**

Category	Performance Indicator	Data Gathered
Feasibility	Amount of data	Data similar to case 9. Production costs were flexed using the data filter.
	Type of data	Same as case 9
	Human intervention	The effects of currency appreciation and wage increase were reflected in the production costs. Each sub-scenario was individually executed and the results were collated for decision making manually.
Usability	Ease of use	Most data was available from before.
	Time required	The case study was completed in 2 mandays
	Understanding	The researcher carried out the case study
	Flexibility	The model could handle the scenario without difficulty. Results from sub-scenarios were used to address the decision with ability to conduct sensitivity analysis over macro-economic factors.
Usefulness	Efficiency	The new decision process took into consideration more complicated decision scenarios.
	Learning curve	Execution of case study 10 was smooth as it was executed by the researcher.
Context	Limitations	No limitations were identified

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## 8.3 Analysis and Discussion

The criteria for success for the case studies 5-10 was feasibility, usability, usefulness and context. This was similar to the evaluation of the representative process in Section 6.3.5. In Section 6.4 a cross case analysis was performed and the representative decision process was evaluated based on the same criteria of feasibility, usability, usefulness and context. The industrial evaluation of the advanced decision process carried out in Part IV is similar to Part II of the research. However, there was a need to conduct a more comparative analysis of the advanced decision process with the representative process by Melo et al (2005). Such a comparative analysis could be better structured through the analysis of the strengths and weaknesses of the advanced decision process and identify further opportunities to improve it. The analysis is still based on the criteria of feasibility, usability, usefulness and context. The summary of the evaluation based on the cross case analysis is presented in Section 8.3.2.

### **8.3.1 Strengths of the advanced decision process**

The strengths of the new decision process can be viewed from two perspectives. Firstly, it can be determined how well the advanced decision process was able to address the shortcomings identified in Section 7.1.2. Secondly, how much better did the advanced decision process perform with respect to the representative decision process evaluated in Part II. The strengths of the advanced decision process are viewed from the two perspectives and presented in sequence of enhancement to the feasibility, usability, usefulness and context with respect to the representative process by Melo et al. (2005).



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In Section 7.1.2, four shortcomings were identified. Each of the shortcomings have been addressed by the advanced decision process and subsequently tested in an industrial setting. The quality of input data has been improved along with a more clear way of communicating what each of those data elements mean. This has been possible through the filtering matrix developed in 7.2.1. The filtering matrix has also been able to relax the constraints and allow the practitioner to add more factors in their decision making. Human intervention has also been reduced as both sources of data are mentioned and the data modifications to represent various constraints are explained in the filtering matrix. The extension of the decision process to include specificity of a facility to produce certain products further reduced human intervention. All of the above enhanced the feasibility of the advanced decision process.

There are areas where the new decision process goes beyond just addressing the shortcomings identified in Section 7.1.2. The entire process from the input data collection, to execution and final report generation is driven through an Excel spreadsheet. There is a minimal need to modify the MILP in the ILOG OPL Studio. This was a considerable boost to ease of use of the decision process. Further, since the practitioner inputs and receives results through Excel, and does not have to bother about the internal working of the MILP, their understanding of the overall decision process increases. The post processing of results into actionable information (report) also increases the usability to the practitioner. Finally, since additional factors and constraints can be considered in the decision

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process, the flexibility of the decision process is also increased. All of the above enhanced the usability of the advanced decision process.

The strengths of the advanced decision process over the representative decision process with respect to usefulness are rather limited. This is a result of using the same company Machine-Co for case studies in Part IV and Part II. Since most of the data was available for the case study, a comment on increased efficiency of the advanced decision process cannot be backed up by evidence. However, a change in the learning curve was apparent. In the advanced decision process, input and output data was structured in a format the practitioner could relate to (spreadsheets). There was hence an increase in the usefulness of the advanced decision process.

Industrial testing with the industrial partner Machine-Co demonstrates the enhanced context using the decision process to answer specific decision-making questions. Even though the underlying problem was that of capacity expansion in a multi site network, different scenarios were configured using the advanced decision process. This ability of the advanced decision process to address a number of different industrial scenarios regarding capacity expansion illustrated the increase in context.

### **8.3.2 Weaknesses of the advanced decision process**

There were no weaknesses of the advanced decision process compared to the representative decision process. This was primarily as the advanced decision

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process was an improvement over the representative decision process and in no way constrained the representative decision process proposed by Melo et al. (2005). The weaknesses of the advanced decision process identified in this section are hence based on an absolute evaluation rather than comparative one.

The first weakness stems from the inability of the decision process to suggest and evaluate alternative scenarios. For example, in cases 5 and 7, when the demand for a product is increased, the demand needs to be allocated to a facility by the practitioner. The decision process does not provide any mechanism to evaluate what the right allocation should be. In both case 5 and case 7 we were fortunate that only one facility was allowed to produce the particular product whereas the case might be different in other future case studies. In scenarios where the facility(ies) to be allocated this extra demand are to be identified, multiple parallel scenarios will need to be studied. This weakness affects both the feasibility and usability of the advanced decision process.

Secondly, as mentioned in Section 6.3.1, the ideal scenario to test the decision process would have been with different companies than Machine-Co or Glass-Co. This has not been possible due to the extremely confidential nature of data needed for the study and the reluctance of company managements to divulge it even under conditions of non-disclosure. Steps were taken to mitigate this weakness including defining case studies 5-8 with more stringent questions from practitioners and conducting more complicated multi-scenario hypothetical case studies 9 and 10. This weakness, however, still affects the overall credibility of the advanced

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decision process to be widely applicable in the industry. This weakness also affects the context of the advanced decision process.

Finally, the tool is based in Excel and ILOG OPL Studio. While the former is a ubiquitous software (in industries), the latter is an expensive specialized software with a commercial license exceeding US\$ 30,000. A tool developed solely in Excel would definitely be welcome by the practitioners. This weakness affects the usefulness of the advanced decision process.

### **8.3.3 Opportunities from evaluation of the advanced decision process**

Based on the weaknesses identified in Section 8.3.2, opportunities for future work can be articulated. The first opportunity is to further improve underlying MILP and allow more flexibility to define constraints and associated data. An immediate improvement could be an allocation function that splits the decision scenario into multiple sub scenarios and provide the practitioner with the best decision. Such an improvement will increase the flexibility of the advanced decision process.

Another opportunity is to conduct more case studies in different companies with manufacturing networks using the advanced decision process. This will have a two-pronged advantage. Firstly, it will improve the data filter by adding knowledge from the case studies and helping future case studies. Secondly, the overall validity of the decision process will be boosted and further improvements in the advanced decision process can be identified and implemented.

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Finally, there is an opportunity to embody the advanced decision process in software like Excel which will bring down the barrier to use it in an industrial environment. Further development in the final reporting of case studies can also be conducted.

#### 8.4 Chapter Summary

The purpose of this chapter was to test the advanced decision process developed in Part III in an industrial setting. The research methodology for Part IV was described in Section 8.1 and issues were outlined. Four industrial and two hypothetical cases were selected in Section 8.2.1. In Section 8.2.2 the industrial case study execution was described. In Section 8.2.4 the hypothetical case study execution is described. Finally, the strengths, weaknesses and opportunities of the advanced decision process are discussed in the cross case analysis in Section 8.3.

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## Chapter 9. Part V: Refinements and Final Decision Process

This chapter describes the Part V of the research – Refinements and Final Decision Process. This chapter sets out to address Objective 5 of the research (Section 4.2), namely, to refine the pilot process and prepare for dissemination. Section 9.1 presents the final decision process with suggested refinements. A step-by-step guide to implement this decision process is presented in Section 9.2 and illustrated through a case study. Figure 9.1 places this chapter in perspective of the overall research.

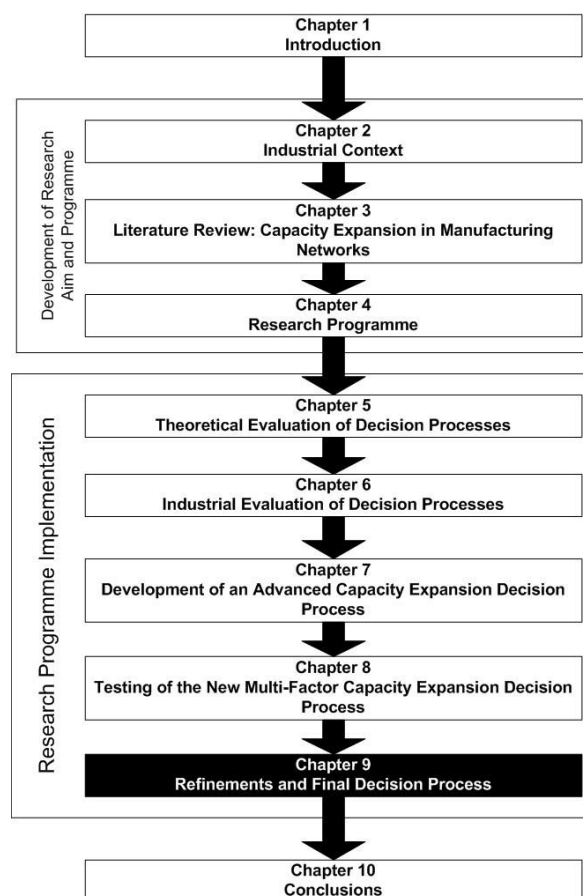
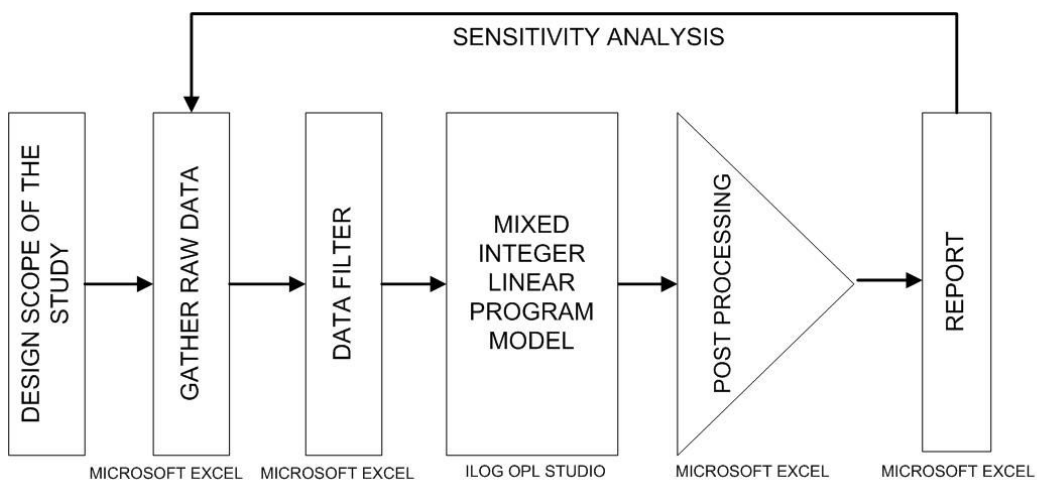


Figure 9.1 Chapter 9 – Refinements and Final Decision Process

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## 9.1 Final Decision Process and Refinements

The final decision process is shown in Figure 9.2 below. A step-by-step guide to implement this decision process is presented in Section 9.2. The first stage of the decision process is to scope the capacity expansion study to be performed. This includes defining the index set of inputs. Gathering of raw data is then to be carried out and entered into the Excel template. This raw data is then refined using the data filter explained in Section 7.2.1 (Table 7.1, Table 7.2 and Table 7.3). The data filter is also used to modify the raw data to represent additional constraints and assumptions. The resulting Excel sheet is then used as an input for the mixed integer linear program (MILP) developed in ILOG OPL Studio. The optimised solution set is then imported into the Excel template. Post-processing of this solution set is done using the reporting function developed in Visual Basic (Appendix C). Finally the generated report can be used to compare alternative expansion scenarios.



**Figure 9.2 Final decision process embodied in Excel and OPL Studio**

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An important refinement that is identified in the decision process is the ability to do sensitivity analysis in a more automated fashion for various parameters in the decision process. Such an analysis will provide the practitioner an insight into the various levers he has and the effect of each one of them. The sensitivity analysis can take in the various values for the parameters and loop across the entire decision process for each of the parameter combinations. The objective function values can be provided to the practitioner then along with detail reports of each capacity expansion scenarios. In case 10 this sensitivity analysis was performed manually by executing various scenarios using different parameters.

## 9.2 Illustration of the Decision Process

A detailed step-by-step guide to conducting a case study is presented in this section. The guide uses case study 5 (Section 8.2.1) to illustrate the advanced decision process. Snapshots of the accompanying Excel template, MILP model in OLP Studio and the post processing function are provided accordingly.

The case study aims to answer the question - Increasing one product's production limit, with no new site, which (present) sites' capacity should be expanded? The demand for product S is to increase from 5.25 million units per annum to 6.6 million units per annum. There are also other demand increases which are based on the long term forecast by Machine-Co. These include an increase in demand from Malaysia and China facilities of product Q by 0.5 million units per annum per site by the beginning of third year. Also the demand for product E from Singapore is



forecasted to be doubled by year 4. No new facility is to be built. The steps followed to execute this case study are presented below.

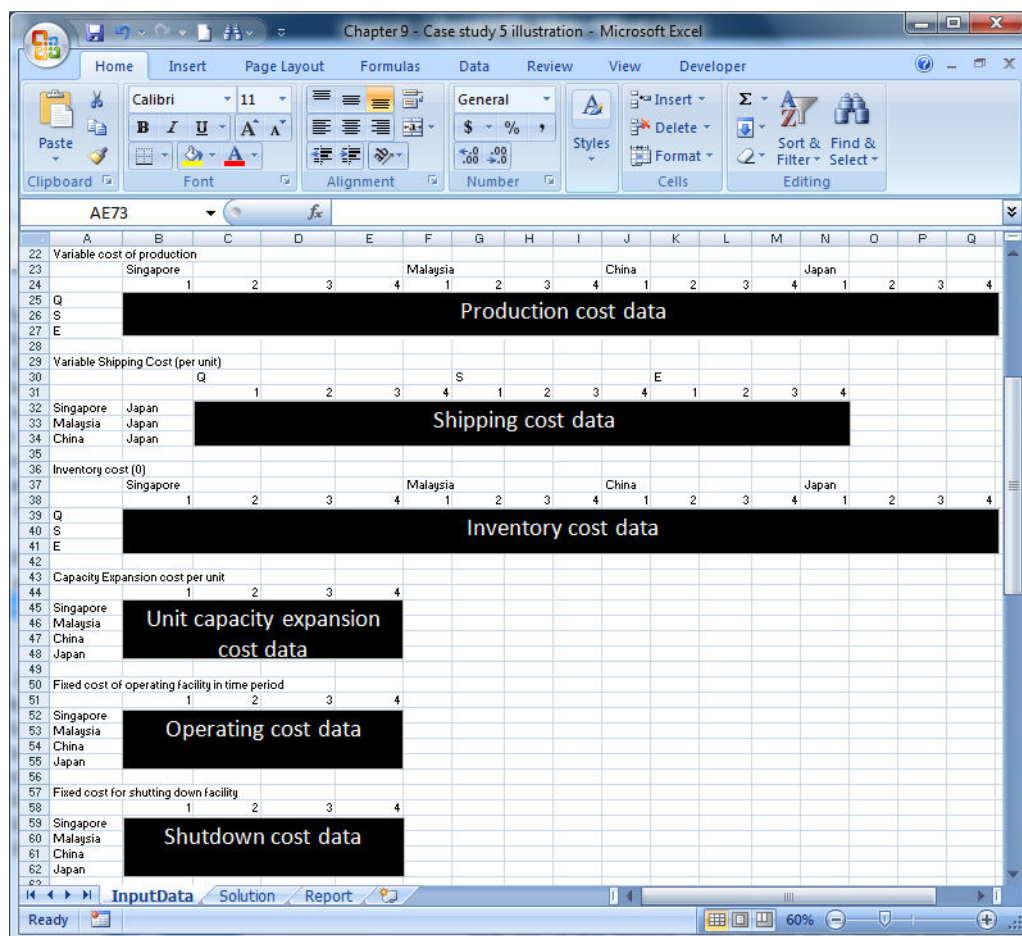
1. The index data is shown in Figure 9.3. The case study is defined with 4 facilities (Singapore, Malaysia, China and Japan). These facilities form the set of facilities, set of existing facilities and set of selectable facilities. There are no new facilities and no non-selectable facilities in this scenario hence the value for both is <null>. There are three types of products (Q, S and E) and the number of time periods is 4.

	A	B	C	D	E
1	Facilities				
2	Singapore	Malaysia	China	Japan	
3					
4	Selectable Facilities				
5	Singapore	Malaysia	China	Japan	
6					
7	Non Selectable Facilities				
8	<null>				
9					
10	Existing Facilities				
11	Singapore	Malaysia	China	Japan	
12					
13	Potential Facilities				
14	<null>				
15					
16	Product Types				
17	Q	S	E		
18					
19	TimePeriods				
20		4			

**Figure 9.3 Case study illustration - Preparation of index data set**

2. The cost data set is prepared next. This data set consists of 6 types of data for case study 5 as shown in Figure 9.4. The cost data was deemed highly confidential by Machine-Co and has been masked in Figure 9.4.

*Production cost data:* The unit variable cost of production was used. The source of the data was the costing information used by the company for pricing policies. For products which are not produced at a particular facility a value of zero was used. This value was of no significance as the product-facility specificity had been included in the advanced decision process (Section 7.2.2).



**Figure 9.4 Case study illustration - Preparation of cost data set**

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*Variable shipping cost:* The unit shipping cost was extracted from the accounting systems where the yearly cost of shipping a particular product from one facility to another was computed and averaged out with respect to each unit of that product. There should be 12 lines of data here representing shipping from each facility to every other facility. However, Machine-Co did not ship between all facilities but only from Singapore, China and Malaysia to Japan. In this scenario, Japan only demands product E which is only produced by Singapore. Hence, from that perspective, the shipping cost data from Malaysia to Japan and China to Japan was redundant too.

*Inventory cost:* Inventory cost here is taken as 0. Machine-Co does not charge the manufacturing units for inventory cost. The inventory cost is charged under the marketing budget and the moment a product is produced and moved to the warehouse it is considered sold from the manufacturing unit's perspective.

*Unit capacity expansion cost:* This is the cost of adding one unit of capacity to a facility. The data is calculated from the cost to add a production line to the facility. The number of extra units that can be produced for the baseline product (product which requires one unit of capacity at Japan to produce one unit of product) are estimated. The ratio of total cost to setup a new production line divided by number of units of product Q that can be produced annually is used to determine the cost for unit capacity expansion.

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*Operating cost:* This is the fixed operating cost incurred at the facility during one time period (1 year). The data was obtained from the annual accounting that was conducted by Machine-Co. This data was also used for their annual planning exercise.

*Shutdown cost:* The shutdown cost was computed by summing up the severance wage costs and subtracting the salvage value of the equipment. Since this data was not directly available, the data from annual planning exercise over the annual wage bill was used and a proportion was defined as severance pay. The salvage value of the equipment was assumed to be equal to the asset value (book value) as in the annual balance sheet.

3. The parameter data set is defined in the end. This data set consists of eight types of data for case study 5 as shown in Figure 9.5. Data elements deemed confidential (in this case entire cost set) have been removed from the example.

*Maximum allowed capacity:* The maximum each facility can produce a particular type of product is defined here. The data was estimated by the past production data and the ability of lines to produce multiple products with different productivity (Figure 9.5).

*Minimum throughput:* This was the minimum amount of the product to be produced to ensure proper utilisation of the resources. Theoretically this number could have been zero however the practitioners felt this constraint to be

practical as no facility would be commissioned to produce less than a particular unit of the products (Figure 9.5).

*Maximum allowed capacity expansion:* This is the maximum units of capacity that can be expanded in the entire network over the entire set of time periods. The number here needs to take into account the unit capacity conversion factor and the demand for products (Figure 9.5).

The screenshot shows an Excel spreadsheet with the following data:

	A	B	C	D	E	F
64	Maximum allowed capacity					
65		1	2	3	4	
66	Singapore	11000000	12000000	13000000	14000000	
67	Malaysia	3600000	3800000	4000000	4200000	
68	China	3500000	4000000	4500000	5000000	
69	Japan	2000000	2000000	2000000	2000000	
70						
71	Minimum allowed capacity					
72		1	2	3	4	
73	Singapore	6500000	7000000	7500000	8000000	
74	Malaysia	2500000	2500000	2700000	2800000	
75	China	2500000	2800000	3000000	3300000	
76	Japan	800000	800000	800000	800000	
77						
78	Maximum allowed capacity expansion					
79	10000000					
80						
81	Unit Capacity conversion factor					
82		Singapore	Malaysia	China	Japan	
83	Q	1	1.1	1.5	1	
84	S	1	10	10	10	
85	E	1	10	1.5	1	
86						

Figure 9.5 Case study illustration - Preparation of parameter data set (1/2)

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*Unit capacity conversion factor:* This data represented efficiencies of the different facilities to manufacturing different products. The baseline was product Q produced by Singapore. The values were estimates of the practitioners based on experience of the quality of goods produced at different facilities and the overall production amount compared to the design capacity of the facility (Figure 9.5).

*Stock at the beginning of time period:* This was 0 in case of Machine-Co because of their special constraint that everything produced was immediately sold at the end of the time period (Figure 9.6).

*External demand for the product:* This data was derived from the 6-monthly forecasting exercise by Machine-Co. The demand data was specific to facilities and products. The data was collated from the different marketing and sales offices of Machine-Co, demand was allocated to the various facilities and finally production targets were provided. Facilities were allowed to produce excess products to help other facilities with their targets. This was in line with the model where products were transported from one facility to another after production (Figure 9.6).

*Budget available for expansion:* The data came from Machine-Co's annual planning exercise. This budget was developed to take into account capacity expansion at present facilities and also setting up one new facility if needed. This information was deemed confidential by Machine-Co and hence is masked

in Figure 9.6. However, in case study 5 the new facility was not considered (Figure 9.6).

*Interest rate:* The market interest rate on unused money suggested by the practitioners (Figure 9.6).

*Product-facility specificity:* The ability of a particular facility to produce a particular product is defined through this data. A value of 1 defines the facility's ability to produce a particular product and 0 defines the opposite (Figure 9.6).

The screenshot shows an Excel spreadsheet with the following data:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
93	External Demand for the product																
94	Singapore				Malaysia				China				Japan				
95		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
96	Q	500000	500000	500000	500000	3500000	3500000	4000000	4000000	1000000	1000000	1500000	1500000	0	0	0	0
97	S	5250000	5700000	6150000	6600000	0	0	0	0	0	0	0	0	0	0	0	0
98	E	1000000	1200000	1500000	2000000	0	0	0	0	0	0	0	0	100000	100000	100000	100000
99																	
100	Budget available for expansion																
101		1	2	3	4												
102																	
103																	
104	Interest Rate in Time period																
105		1	2	3	4												
106		7	7	7	7												
107																	
108	Product-Facility Specificity																
109		Singapore			Malaysia			China			Japan						
110	Q	1			1												0
111	S	1			0												0
112	E	1			0												1

**Figure 9.6 Case study illustration - Preparation of parameter data set (2/2)**

4. The data set defined in the “InputData” worksheet was then linked to the OPL data file (Figure 9.7a). The various sets of data were referenced in the OPL data file (Figure 9.7b). Further, since only 2-dimensional data could be referenced, some data sets were copied and pasted into the data file with the appropriate

delimiters (Figure 9.7c). A consistency check regarding the data model was then performed by loading the data into the OPL model (Figure 9.7d) and creating the required constraints in it (Figure 9.7e).

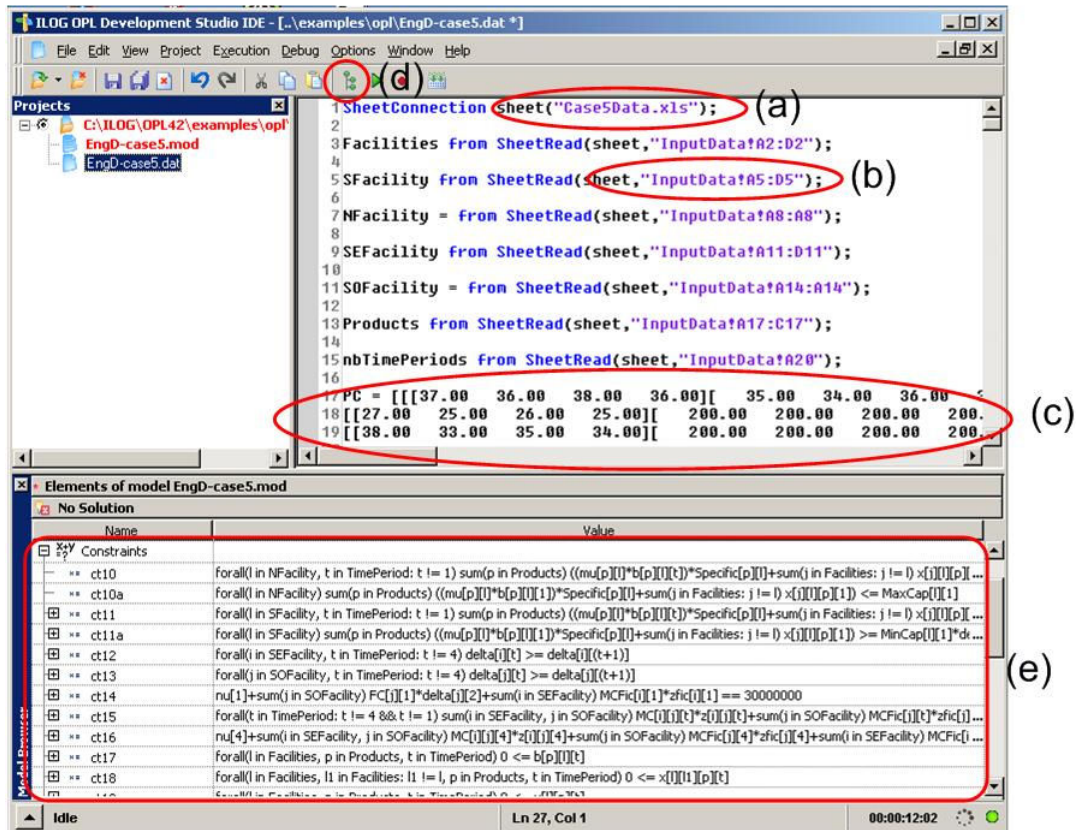


Figure 9.7 Linking the OPL model to the input data

5. Executing the OPL model provided the optimised capacity expansion scenario. However, in some cases, infeasibility errors may occur. These can be weeded out by carefully analysing the input data. The final result is copied and pasted into the “Solution” worksheet which needs to have the post-processing VB code embedded in it. Once this result is processed, a report is generated in the



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“Report” worksheet. Example of the report generated can be found in Appendix C.

6. Finally the capacity expansion scenario report can be compared against other scenario reports to assist the capacity expansion decision.

### 9.3 Chapter Summary

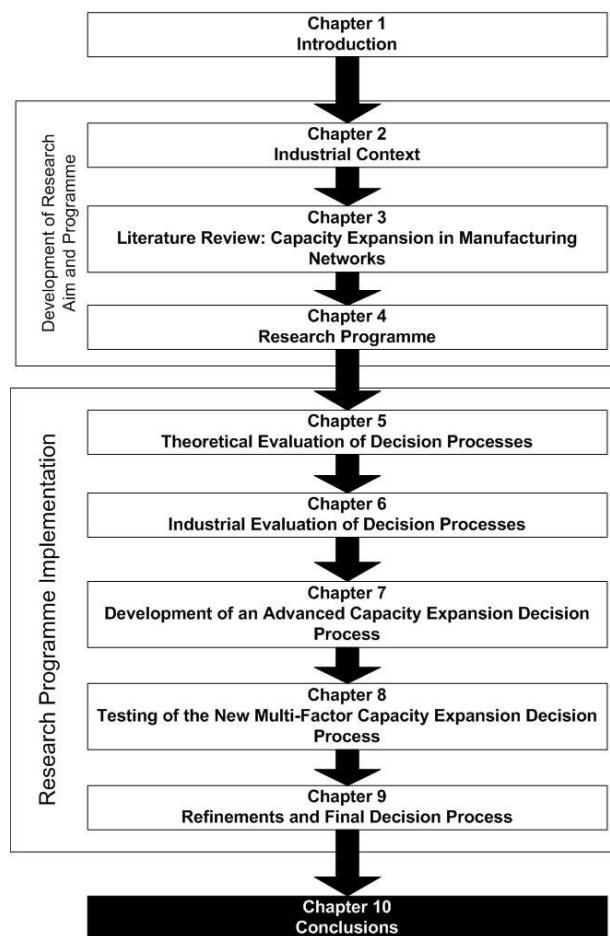
The purpose of this chapter was to present the final version of the advanced decision process and prepare for dissemination. Section 9.1 presented the advanced decision process. A step-by-step guide to implement this advanced decision process using the various decision support tools was presented in Section 9.2 and illustrated through a case study. This will enable practitioners and future researchers to conduct further case studies based on the advanced decision process as well as contribute to its development.

The next chapter describes the conclusions of this research. It discusses the contribution to knowledge made by this research. It also identifies the limitations of the research and provides directions for future research in the area.

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## Chapter 10. Conclusions

This research set out to develop an advanced decision process for industrial practitioners to make capacity expansion decisions in a multi-site manufacturing network (Section 2.3). This chapter summarises the research findings against the research aim and discusses contribution to knowledge. Also, the limitations of the research are presented, directions for future work suggested, and finally, concluding remarks are given. Figure 10.1 places this chapter in perspective of the overall research.



**Figure 10.1 Chapter 10 - Conclusions**

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## 10.1 Overview of Research Aim and Programme

This section provides an overview of the research aim and objectives (Section 4.2) and programme (Section 4.3). It has been established earlier that the research aim for this work was:

*“to develop an advanced decision process for capacity expansion in global manufacturing networks.”*

The research aim was addressed by completing a set of objectives, namely to:

1. Establish the state-of-the-art in multi-factor decision processes for capacity expansion in manufacturing networks
2. Test a representative process in a real industrial context
3. Apply the results of the test to formulate an advanced decision process
4. Test the advanced decision process in practice
5. Refine the advanced decision process and prepare for dissemination

To achieve these objectives a five part research programme was developed. In Part I (Chapter 5) a theoretical evaluation of the state-of-the-art in decision processes for capacity expansion was conducted. In Part II, a representative process was identified (Melo, Nickel and Gama, 2005) out of the relevant decision processes (Section 6.2). Industrial evaluation of the representative decision process was conducted through industrial case studies (Section 6.3). In Part III, the shortcomings of the representative decision process were addressed to develop an advanced decision process for capacity expansion in multi-site manufacturing network (Section 7.2). The advanced decision process was then tested in a real

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industrial context in Part IV (Chapter 8). Finally, the advanced decision process was refined (Section 9.1) and illustrated (Section 9.2) in Part V of the research.

## 10.2 Contribution to Knowledge

The research presented in this thesis contributes to knowledge in a number of ways. Mingers and Brocklesby (1997) provide an excellent framework to categorise and present these contributions in the form of methodology, technique and tools. These contributions to knowledge are presented below.

### 10.2.1 Contributions to Methodology

Numerical optimisation is categorised under hard OR techniques (Mingers and Brocklesby, 1997). There are two contributions that the research makes to the enhancement of this methodology. Firstly, numerical optimisation is combined with an experience gathering technique (the filtering matrix) to enhance the usability, usefulness, and context of the advanced decision process. Secondly, it has been identified that there is a lack of industrial applications of the decision processes and the path to industrial implementation of the decision processes is missing (Section 5.4.4). Industrial case studies performed in this research enhance the industrial applicability and add credibility to using this methodology to address the multi-site capacity expansion problem.

### 10.2.2 Contributions to Technique

There are four contributions that are made to techniques used under the methodology.

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***An advanced process for capacity expansion in multi-site manufacturing networks.*** The advanced decision process has been tested in an industrial context (Chapter 8) and proves to be more effective than the representative decision process (Section 8.3). The advanced decision process increases the decision-making ability of the practitioners regarding capacity expansion in manufacturing networks. *On the basis of the work described in this thesis, the primary contribution to knowledge is an advanced decision process for capacity expansion in multi-site manufacturing networks (Section 7.2).*

***Identification of important decision parameters in the capacity expansion decision process through review of the state-of-the-art.*** The first part of this contribution is a rigorous theoretical analysis of the state-of-the-art in capacity expansion literature for manufacturing networks (Section 5.3). This revealed that a considerable amount of work has been conducted however none of the decision processes covers all factors which are considered important by the body of knowledge collectively (Section 5.4.2). This list of parameters which is deemed important for the capacity expansion decision process is presented in Section 5.3.

***Sensitivity analysis.*** Sensitivity analysis is included in the advanced capacity expansion decision process. This is presented in Section 8.2.4 and illustrated through the hypothetical case studies.

***Technique to test a decision process.*** A technique to test a capacity expansion decision process in an industrial context is another contribution to knowledge

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(Section 6.3). The criterion of usability, usefulness, feasibility and context have been inspired from work by Adesola (2002) and Viseras (2004) and modified to fit the required industrial testing (Section 6.3.2). This technique can be further extended to test other types of decision-making processes.

### **10.2.3 Contributions to Tool**

There are four tools that have been developed in this research.

***Filtering matrix for data preparation.*** As part of the advanced decision process developed, a filtering matrix has been created to assist data preparation for capacity expansion decisions (Section 7.2.1). This matrix can be built upon by both practitioners and researchers and increase both the capability and usefulness of the decision process. This tool has been designed to capture practitioner knowledge which forms an integral part of the data gathering step and make the knowledge available to future practitioners and researchers.

***ILOG OPL implementation of the underlying numerical optimisation model.*** The numerical optimisation model has been implemented in ILOG OPL studio. This tool enables the user to apply the advanced decision process in a decision scenario.

***Integration with MS Excel.*** The integration with MS Excel permits the user to define the input data in a user friendly fashion. It also enables application of the filtering matrix to define any data modification representing additional constraints and/or parameters to be included in the decision process.

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**Reporting module.** This tool completes the link from the output of the OPL studio model to actionable information. The user can use the tool to translate the results of the optimisation into a report which is easy to read and assists in the decision process.

These contributions to methodology, technique and tools illustrate the impact of the research described in this thesis. The aim of the research has been fulfilled and contributions have been made to knowledge. No research work however is complete and perfect. The next section discusses limitations of both the research content produced and the research process followed in this thesis.

### 10.3 Limitations of the Research

The nature of the design and implementation of the research programme gives rise to limitations that could affect the findings of this research. These limitations have been categorised as limitations of the research content ('what was found?') and limitations of the research process ('how was it found?').

#### 10.3.1 Limitations of the Research Content

**Need for large amount of data.** The first limitation of the research content is the inherent need for large amount of data for the decision process. The filtering matrix developed and described in Section 7.2.1 helps the user to prepare data for the required case studies and modify data to represent factors not considered directly in the multi-factor decision process. However, the assumption is that the user has most of the data needed in some form or the other. In reality, the data

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available with the user may be incomplete, and/or inaccurate. The collection of this data also requires considerable resources for the practitioners. Finally, in many cases, the data required for decision making is considered highly confidential which limits case studies by researchers to further refine the decision process.

***Limited to linear models.*** The second limitation identified relates to the mathematical technique used. The advanced decision process is based on a Mixed Integer Linear Program (MILP) (Section 6.2). This choice of solution technique is a combination of utility, usability and feasibility (Section 6.2). An MILP is solvable within a practical time period however it limits incorporating any non-linear parameters into the decision process. An example of non-linearity in this case would be if the labour efficiency was dependent on the production amount. In other words, the higher the production the lower the efficiency gets which is typical from the efficient frontier perpetrated by economic theory. This non-compatibility with non-linear constraints can thus be argued as a limitation of the research content.

***Dependence on expensive commercial software.*** Thirdly, the decision process proposed in this research needs a MILP solver. The software used in the research was ILOG OPL Studio. An academic version was used to conduct the research however the commercial version of this software (>US\$ 30,000) will be needed if practitioners are to use the decision process. There are other software products that are able to solve a MILP but most are in the same price range. This high cost of



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supporting software may reduce the willingness of practitioners to use the decision process and hence is considered another limitation of the research content.

***Failure to take into account tax considerations.*** Finally, the entire study is performed from the point of view of the cost of expansion. However, it has been established that tax structures and tax incentives in a country have a considerable effect on the capacity expansion decision (MacCarthy and Atthirawong, 2003). Tax consideration in turn is seen with respect to the profits of the company which in turn bring in the factors like transfer pricing of the product (Vidal and Goetschalckx, 2001) and product supply-demand characteristics. The scope of the problem thus expands and this might be a reason that academia has not followed this particular decision-making path.

### **10.3.2 Limitations of the Research Process**

***Choice of multi-factor decision processes.*** In Section 3.2 it was deduced from the literature that since multi-factor decision processes based on numerical optimisation techniques are the most used, they are also the most favoured and useful one. There is a chance however that the literature might not be correct. It has been established that a reason for multi-factor decision processes being the tool of choice is the ease of application and thus it may be conceivable that majority of the academia is biased on this issue.

***Variety of case studies.*** Another limitation of research was regarding the industrial testing of decision processes. Due to the fact that the data required for such

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decisions is highly confidential and critical to the competitiveness of a company, the access to such data for case studies is very constrained. This was one of the main reasons why only two companies were ready to share their data for case studies. The advanced decision process thus was tested on different capacity expansion scenarios for one of the two companies. Even though the evaluation of the advanced decision process was enhanced through the execution of two hypothetical multiple sub-scenario case studies, the findings of the research can be argued against from standpoint that the case study selection process was not scientifically robust.

#### 10.4 Directions for Further Research

The directions for further research are defined in this section based on the limitations in Section 10.3.

Firstly, there needs to be work done on integration of corporate sources of data to such decision-making processes. Mapping data required to corporate sources is illustrated in the data filter developed in Section 7.2.1 however a tighter integration is needed.

Secondly, ways to model non-linear behaviour in linear forms can be used to enhance the model further. This transformation can also be part of the data filter proposed or can be incorporated into the underlying MILP model directly.

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There is still the issue of the dependence of the new decision process upon external commercial solver software. One way to mitigate is to use more ubiquitous commercial software like Microsoft Excel. Excel's solver functions can be enhanced (Albright, 2000; Bullen, Bovey and Green, 2005) and its availability in most corporations can be leveraged. An application developed within this spreadsheet software can thus increase the usability and feasibility of the decision process.

Tax considerations have been deemed important for the capacity expansion process (Bhutta, 2001). However, most work on capacity expansion has focused on the cost of expansion and hence tax has not been modelled in it. Future work can include integration of models which focus on cost of expansion with those that consider tax and hence revenue of the firm (Canel and Khumawala, 1996; Hadjinicola and Kumar, 2002) and include economic effects like exchange rate fluctuations (Mohamed, 1999). The literature has also focused more on multi-factor models however qualitative and simulation models have also been discussed (Anglani et al., 2000). Future work on development of qualitative models and their integration with multi-factor models bears potential.

Finally, it has been established in Section 5.4 that the lack of case studies is a weakness of the present state-of-the-art. Reasons for this have been discussed on Section 4.3.4 (confidential data) and Section 8.2.1 (other reasons). Industrial case studies provide an insight into the usability, utility and usefulness of the process. Conducting more industrial case studies in different industry types and different

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manufacturing network configurations is another direction for future research in capacity expansion decision support processes in multi-site global manufacturing networks.

## 10.5 Concluding Remarks

This concluding chapter has given accounts of the principal research findings against the research aim, and discussed major contributions to knowledge. The limitations of the research have been identified and finally recommendations for future work suggested. It is hoped that the main contributions that this thesis has made to the body of knowledge will be relevant in theory and practice.

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## References

- Adesola, M. O. (2002). Development and Assessment of a Methodology for Business Process Improvement. PhD Thesis, School of Industrial and Manufacturing Science, Cranfield University.
- Ahmed, S., A. J. King and G. Parija (2003). "A multi-stage stochastic integer programming approach for capacity expansion under uncertainty." Journal of Global Optimisation **26**: 3-24.
- Albright, S. C. (2000). VBA for Modelers: Developing Decision Support Systems Using Microsoft® Excel, Duxbury Press.
- Amico, M., Z. J. Pasek, F. Asl and G. Perrone (2003). A new methodology to evaluate the real options of an investment using binomial trees and monte carlo simulation. Winter Simulation Conference, pp 351-359. New Orleans, USA
- Anglani, A., P. Caricato, A. Grieco, F. Nucci, A. Matta, Q. Semeraro and T. Tolio (2000). Evaluation of capacity expansion by means of fuzzy-DEVS. Proceedings of 14th European Simulation Multiconference on Simulation and Modelling, pp 129-133
- Baines, T. S. (1994). Modelling in the evaluation of a manufacturing strategy. Ph.D. Thesis, School of Industrial and Manufacturing Science, Cranfield University.
- Banks, J. (1998). Handbook of Simulation New York, John Wiley & Sons, Inc.
- Banks, J., J. S. Carson, B. L. Nelson and D. M. Nicol (2000). Discrete-Event system Simulation (3rd Edition), Prentice Hall.

- 
- Bazeley, P. (2004). Issues in Mixing Qualitative and Quantitative Approaches to Research. Applying qualitative methods to marketing management research. R. Guber, J. Gardner and L. Richards (eds). UK, Palgrave Macmillan: 141-156.
- Bean, J. C., J. L. Hagle and R. L. Smith (1992). "Capacity expansion under stochastic demand." Operations Research **40**(2): 210-216.
- Bean, J. C. and R. L. Smith (1985). "Optimal capacity expansion over an infinite horizon." Management Science **31**(12): 1523-1532.
- Bhutta, K. S. (2001). Global Supply Chains: An Integrated Location, Production Distribution and Investment Model for a Multinational Corporation Operating Under Varying Exchange Rates and Tariff Structures. Ph. D. Thesis, Operations Management. Arlington, University of Texas at Arlington.
- Bhutta, K. S. (2004). "International facility location decisions: a review of the modelling literature." Int. J. of Integrated Supply Management **1**(1): 33-50.
- Birge, J. R. (2000). "Option Methods for Incorporating Risk into Linear Capacity Planning Models." Manufacturing & Service Operations Management **2**(1): 19-31.
- Bish, E. K. and S. J. Hong (2006). "Coordinating the resource investment decision for a two market, price-setting firm." International Journal of Production Economics **101**(2006): 63-88.
- Borgonovo, E. and L. Peccati (2004). "Sensitivity analysis in investment project evaluation." International Journal of Production Economics **90**: 17-25.
- Buffa, E. S. (1983). Modern Production/operations Management New York, Wiley.
- Bulan, L. T. (2005). "Real options, irreversible investment and firm uncertainty: New evidence from U. S. firms." Review of Financial Economics **14**: 255-279.

---

Bullen, S., R. Bovey and J. Green (2005). Professional Excel Development: The Definitive Guide to Developing Applications Using Microsoft(R) Excel and VBA(R) (The Addison-Wesley Microsoft Technology Series), Addison-Wesley Professional.

Callen, J. L. and B. Sarath (1995). "Risk aversion, generalized correlation and investment in manufacturing capacities." Journal of Operations Management **12**(3-4): 225-237.

Canel, C. and B. M. Khumawala (1996). "A mixed integer programming approach for the international facilities location problem." International Journal of Operations and Production Management **16**(4): 49-68.

Carrie, A. S. (2000). "From integrated enterprises to regional clusters: the changing basis of competition." Computers in Industry **42**(2/3): 289.

Caulkins, J. P. and C. H. Fine (1990). "Seasonal inventories and the use of product-flexible manufacturing technology." Annals of Operations Research **26**: 351-375.

Chakravarty, A. K. (1999). "Profit margin, process improvement and capacity decisions in global manufacturing." International Journal of Production Research **37**(18): 4235-4257.

Chakravarty, A. K. (2005). "Global plant capacity and product allocation with pricing decisions." European Journal of Operational Research **165**: 157-181.

Chand, S., T. McClurg and J. Ward (2000). "A model for parallel machine replacement with capacity expansion." European Journal of Operational Research **121**: 519-531.

---

Cochran, J. K. and A. M. Uribe (2005). "A set covering formulation for agile capacity planning within supply chains." International Journal of Production Economics **95**(2): 139-149.

Dangl, T. (1999). "Investment and capacity choice under uncertain demand." European Journal of Operational Research **117**: 415-428.

Datta, V., K. V. Sambasivarao, R. Kodali and S. G. Deshmukh (1992). "Multi-attribute decision model using analytical hierarchy process for the justification of manufacturing systems". International Journal of Production Economics **28**: 227-234.

Dixit, A. (1980). "The role of investment in entry-deterrence." The Economic Journal **90**(March): 95-106.

Dixit, A. and R. Pindyck (1994). Investment under uncertainty Princeton, NJ, Princeton University Press.

Dunning, J. H. (1993). Multinational Enterprises and the Global Economy Wokingham, Addison-Wesley.

EDB (2004). Headquarters Brochure. Available at [http://www.edb.gov.sg/etc/medialib/downloads/industry\\_opportunities.Par.0005.File.tmp/EDB\\_HQ%20Supplement.pdf](http://www.edb.gov.sg/etc/medialib/downloads/industry_opportunities.Par.0005.File.tmp/EDB_HQ%20Supplement.pdf)

EDB (2006a). Annual Report

EDB (2006b). Our Goal for Manufacturing. Available at [http://www.edb.gov.sg/etc/medialib/downloads/downloadable\\_brochure.Par.0014.File.tmp/ManuBookletrevised14032006.pdf](http://www.edb.gov.sg/etc/medialib/downloads/downloadable_brochure.Par.0014.File.tmp/ManuBookletrevised14032006.pdf)



---

EDB (2007). Exceptional growth for Singapore's Biomedical Sciences Industry. Available at [http://www.sedb.com/edb/sg/en\\_uk/index/news\\_room/news/20060/exceptional\\_growth.html](http://www.sedb.com/edb/sg/en_uk/index/news_room/news/20060/exceptional_growth.html)

Elmaghraby, S. E. (1991). "Manufacturing Capacity and its Measurement: A Critical Evaluation." Computers & Operations Research **18**(7): 615-627.

Erlenkotter, D. (1967). Two Producing Areas - Dynamic Programming Solutions. Investments for Capacity Expansion: Size, Location and Time-phasing. A. S. Manne (eds). Cambridge, MA, MIT Press: 210-227.

Erlenkotter, D. (1972). "Economic Integration and Dynamic Location Planning." Swedish Journal of Economics **74**: 8-18.

Erlenkotter, D. (1974). "Dynamic Programming Approach to Capacity Expansion with Specialisation." Management Science **21**: 360-363.

Feinstein, S. P. and D. M. Lander (2002). "A better understanding of why NPV undervalues managerial flexibility." The Engineering Economist **47**: 418-435.

Ferdows, K. (1997). "Making the Most of Foreign Factories." Harvard Business Review **March-April**: 73-88.

Fine, C. H. and R. M. Freund (1990). "Optimal investment in product-flexible manufacturing capacity." Management Science **36**(4): 449-466.

Fine, C. H. and A. C. Hax (1985). "Manufacturing strategy: A methodology and an illustration." Interfaces **15**(6): 28-46.

Fourer, R. (2007). 2007 Linear Programming Software Survey. Available at <http://www.lionhrtpub.com/orms/surveys/LP/LP-survey.html>

---

Freidenfelds, J. (1981). "Near optimal Solution of a Two-Type Capacity Expansion Problem." Computers & Operations Research **8**: 221-239.

Gaimon, C. and R. H. Burgess (2003). "Analysis of the lead time and learning for capacity expansion." Production and Operations Management **12**(1): 128-140.

Gutenberg, E. (1992). "Investment Policy in Industrial Enterprises." Management International Review **32**(1): 17-28.

Hadjinicola, G. C. and K. R. Kumar (2002). "Modeling manufacturing and marketing options in international operations." International Journal of Production Economics **75**: 287-304.

Harrison, J. M. and J. A. V. Mieghem (1999). "Multi-resource investment strategies: operational hedging under demand uncertainty." European Journal of Operational Research **113**: 17-29.

Henternryck, P. V. (1999). The OPL Optimisation Programming Language, The MIT Press.

Higle, J. L. and C. J. Corrado (1992). "Economic investment times for capacity expansion problems." European Journal of Operational Research **59**: 288-293.

Hill, T. (1989). Manufacturing Startegy: Text and CasesHampshire, Palgrave.

Hsu, V. N. (2002). "Dynamic capacity expansion problem with deferred expansion and age-dependent shortage cost." Manufacturing & Service Operations Management **4**(1): 44-54.

Hwa, K. K. (2003). Trends and Challenges in Manufacturing. High Value Manufacturing Forum, Global Entrepolis@Singapore 2003, pp. Singapore

---

ISI (2005). Web of Knowledge: Web of Science. Available at  
<http://wok.mimas.ac.uk/>

Jr., K. W. B. (2001). "Qualitative and Quantitative Research: A Complementary Balance." New Directions for Institutional Research **112**(Winter): 5-13.

Kanter, R. (1995). The new business cosmopolitans. Strategy and Business. **Fall:** 66-77

Karsak, E. E. and C. O. Ozogul (2002). "An options approach to valuing expansion flexibility in flexible manufacturing." The Engineering Economist **47**: 169-193.

Kim, B. and Y. Lee (2001). "Global capacity expansion strategies: Lessons learnt from two Korean carmakers." Long Range Planning **34**: 309-333.

Koh, P. (2003). Singapore: Advancing Up the Value Chain. Singapore, Gartner: 6

Korpela, J., K. KylaKheiko, A. Lehmusvaara and Markku Tuominen (2002). "An analytic approach to production capacity allocation and supply chain design." International Journal of Production Economics **78**:187-195.

Lall, S. and M. Albaladejo (2004). "China's Competitive Performance: A Threat to East Asian Manufactured Exports?" World Development **32**(9): 1441-1466.

Li, S. and D. Tirupati (1994). "Dynamic capacity expansion problem with multiple products: Technology selection and timing of capacity expansion." Operations Research **42**(5): 958-976.

Ling, N. S. (2006). Singapore's Manufacturing Sector 1991-2005. Statistics Singapore Newsletter. **March:** 11

- 
- Luss, H. (1982). "Operations Research and Capacity Expansion Problems: A Survey." Operations Research **30**(5): 907-947.
- MacCarthy, B. L. and W. Atthirawong (2003). "Factors affecting location decisions in international operations - a Delphi study." International Journal of Operations & Production Management **23**(7): 794-818.
- MacCormack, A. D., L. J. N. III and D. B. Rosenfield (1994). "The New Dynamics of Global Manufacturing Site Location." Sloan Management Review **35**(4): 69-80.
- Mahani, Z. A. (2002). "ASEAN Integration: At Risk of Going in Different Directions." The World Economy **25**(9): 1263-1277.
- Manne, A. S. (1961). "Capacity Expansion and Probabilistic Growth." Econometrica **29**: 632-649.
- Manne, A. S., Ed. (1967a). Investments for Capacity Expansion: Size, Location and Time-phasing. Cambridge, MA, MIT Press.
- Manne, A. S. (1967b). Two Producing Areas - Constant Cycle Time Policies. Investments for Capacity Expansion: Size, Location and Time-phasing. A. S. Manne (eds). Cambridge, MA, MIT Press: 193-209.
- Marris, R. (1964). The Economics of Capital Utilisation: A Report on Multiple Shift Work. Cambridge, Cambridge University Press
- Maskus, K. E. (1998). "The Role of Intellectual Property Rights in Encouraging Foreign Direct Investment and Technology Transfer." Duke Journal of Comparative and International Law **9**(1): 109-162.
- Masud, A. S. and C. L. Hwang (1981). "Interactive sequential goal programming." Journal of Operational Research Society **32**: 391-400.

---

Meijboom, B. and H. Voordijk (2003). "International operations and location decisions: a firm level approach." Tijd voor Econ & Soc Geog **94**(4): 463-476.

Melo, M. T., S. Nickel and F. S. d. Gama (2003). Large-scale models for dynamic multi-commodity capacitated facility location, Fraunhofer Institut Techno- und Wirtschaftsmathematik: 40

Melo, M. T., S. Nickel and F. S. d. Gama (2005). "Dynamic multi-commodity capacitated facility location: a mathematical modeling framework for strategic supply chain planning." Computers & Operations Research **33**: 181-208.

Miller, T. L. and C. S. Park (2002). "Decision making under uncertainty- Real options to the rescue?" The Engineering Economist **47**: 105-150.

Miltenburg, J. (1995). Manufacturing strategy: How to formulate and implement a winning plan Portland, OR, Productivity Press.

Mingers, J. and J. Brocklesby (1997). "Multimethodology: Towards a framework for mixing methodologies" International Journal of Management Science **25**(5): 459-501.

Mohamed, Z. (1999). "An integrated production–distribution model for a multinational company operating under varying exchange rates." International Journal of Production Economics **58**: 81–92.

Nazzal, D., M. Mollaghasemi and D. Anderson (2006). "A simulation-based evaluation of the cost of cycle time reduction in Agere Systems wafer fabrication facility - a case study." International Journal of Production Economics **100**: 300-313.

---

Netessine, S., G. Dobson and R. A. Shumsky (2002). "Flexible service capacity: Optimal investment and the impact of demand correlation." Operations Research **50**(2): 375-388.

O'Brien, C. and S. J. E. Smith (1993). "Design of the decision process for strategic investment in advanced manufacturing systems." International Journal of Production Economics **30-31**: 309-322.

Oxley, J. E. (1999). "Institutional environment and the mechanisms of governance: the impact of intellectual property protection on the structure of inter-firm alliances." Journal of Economic Behavior and Organization **38**: 283-309.

Perrone, G., M. Amico, G. L. Nigro and S. N. L. Diega (2002). "Long term capacity decisions in uncertain markets for advanced manufacturing systems incorporating scope economies." European Journal of Operational Research **143**: 125-137.

Pidd, M (2003). Tools for Thinking: Modelling in Management Science (2<sup>nd</sup> Ed.). Chichester, UK, Wiley.

Platts, K. W. (1990). Manufacturing audit in the process of strategy formulation. PhD dissertation, University of Cambridge.

Porter, M. E. (1980). Competitive Strategy New York, NY, Free Press.

Porter, M. E. (1986). Competition in Global Industries Boston, MA, Harvard Business School Press.

Proquest (2005). ABI/INFORM. Available at <http://www.umi.com/products/pt-product-ABI.shtml>

- 
- Rajagopalan, S. (1998). "Capacity expansion and equipment replacement: A unified approach." Operations Research **46**(6): 846-857.
- Rajagopalan, S., M. Singh and T. Morton (1998). "Capacity expansion and replacement in growing markets with uncertain technology breakthroughs." Management Science **44**(12-30).
- Rajagopalan, S. and J. M. Swaminathan (2001). "A coordinated production planning model with capacity expansion and inventory management." Management Science **47**(11): 1562-1580.
- Reeves, G. R., K. D. Lawrence, S. M. Lawrence and J. J. Gonzalez (1988). "A Multiple Criteria Approach to Aggregate Industrial Capacity Expansion." Computers and Operations Research **15**(4): 333-339.
- Robinson, S. (2004). Simulation: The Practice of Model Development and Use, Wiley.
- Robinson, S. (2005). "Discrete-event simulation: from the pioneers to the present, what next?" Journal of the Operational Research Society **56**: 619-629.
- Rudberg, M. and J. Olhager (2003). "Manufacturing networks and supply chains: an operations strategy perspective." Omega **31**: 29-39.
- Ryan, S. M. (2004). "Capacity expansion for random exponential demand growth with lead times." Management Science **50**(6): 740-748.
- Samson, D. (1991). Manufacturing and operations strategy Sydney, Prentice-Hall.
- Santiago, T. (2003). Singapore scores manufacturing investments. Electronic Engineering Times: 24-25

---

Skinner, W. (1996). "Three yards and a cloud of dust: Industrial management at century end." Production and Operations Management **5**(1): 15-24.

Slack, N., S. Chambers, C. Harland, A. Harrison and R. Johnson (1995). Operations Management, Pitman Publishing.

Soanes, C. and A. Stevenson, Eds. (2005). The Oxford Dictionary of English (revised edition), Oxford University Press.

Sub-Committee, Singapore Economic (2002). The Pursuit of Competitive Advantage: Value Manufacturing in Singapore. Singapore, EDB: 51

Syam, S. S. (2000). "Multiperiod Capacity Expansion in Globally Dispersed Regions." Decision Sciences **31**(1): 173-195.

Taha, H. A. (2006). Operations Research: an Introduction (8th Edition), Prentice Hall.

Van-Meighem, J. A. (1998). "Investment strategies for flexible resources." Management Science **44**(8): 1071-1078.

Van-Meighem, J. A. (2003). "Capacity Management, Investment, and Hedging: Review and Recent Developments." Manufacturing & Service Operations Management **5**(4): 269-302.

Vidal, C. J. and M. Goetschalckx (2001). "A global supply chain model with transfer pricing and transportation cost allocation." European Journal of Operational Research **129**: 134-158.

Viseras, E. M. (2004). Development and assesment of a methodology for the implementation of strategic manufacturing initiatives. Engineering Doctorate



---

(EngD) Thesis, School of Industrial and Manufacturing Science, Cranfield University.

Walsh, S. T., R. L. Boylan, D. P. Huzey and R. Burke (1999). "Direct Foreign Manufacturing Investment Decisions for China." Engineering Management Journal **11**(4): 31-39.

Wheelwright, S. C. (1978). "Reflecting Corporate Strategy in Manufacturing Decisions." Business Horizons **21**(February): 57-66.

Wong, J. and S. Chan (2002). "China's Emergence as a Global Manufacturing Centre: Implications for ASEAN." Asia Pacific Business Review **9**(1): 79-94.

Yeo, K. T. (2007). "Restructuring for higher value manufacturing: the case of Singapore." International Journal of Management and Decision Making **8**(2-4): 378-393.

Yin, R. K. (2003). Case Study Research: Design and Methods. Third Edition.

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## Appendices

### Appendix A: Model used in Part II and Part IV to conduct industrial case studies

A multi-factor model proposed by Melo et al. (2005) was used to conduct industrial case studies in Part II of the research programme. The model proposed by them is originally a dynamic relocation problem with an extension to handle capacity expansion. A fictitious facility, denoted by  $i_0$ , was created in the model to cope with increasing demands. All new capacity was concentrated into this fictitious facility. This extended model was used in Part II. The model was further extended to include facility specificity. The final model and its details are provided in this section.

#### **Notation and definition of decision variables**

##### ***Index sets***

$L$  : set of facilities

$S$  : set of selectable facilities,  $S \subset L$

$S^c$  : set of selectable existing facilities,  $S^c \subset S$

$S^o$  : set of potential sites for new facilities,  $S^o \subset S$

$P$  : set of product types

$T$  : set of periods

##### ***Costs***

$PC_{l,p}^t$  : variable cost of producing one unit of product  $p \in P$  by facility  $l \in L$  in period  $t \in T$ .

---

$TC_{ll',p}^t$  : variable cost of shipping one unit of product  $p \in P$  from facility  $l \in L$  to facility  $l' \in L$  ( $l \neq l'$ ) in period  $t \in T$ .

$IC_{l,p}^t$  : variable inventory carrying cost per unit on hand of product  $p \in P$  in facility  $l \in L$  at the end of period  $t \in T$ .

$MC_{i,j}^t$  : unit variable cost of moving capacity from  $i \in S^c$  to  $j \in S^o$  at beginning of  $t \in T \setminus \{1\}$ .

$MC_{i_0,l}^t$  : unit variable capacity acquisition cost in facility  $l \in L$  and period  $t \in T$ .

$OC_l^t$  : fixed cost of operating facility  $l \in L$  in period  $t \in T$ .

$SC_i^t$  : fixed cost charged in period  $t \in T \setminus \{1\}$  for having shutdown an existing facility  $i \in S^c$  at the end of period  $t-1$ .

$FC_j^t$  : fixed setup cost charged in period  $t \in T \setminus \{n\}$  when a new facility established at site  $j \in S^o$  starts its operations at the beginning of period  $t+1$ .

### **Parameters**

$\bar{K}_l^t$  : maximum allowed capacity at facility  $l \in L$  in period  $t \in T$ .

$\underline{K}_l^t$  : minimum required throughput at the selectable facility  $l \in L$  in period  $t \in T$ .

$\bar{K}_{i_0}^{-1}$  : total additional capacity required to cope with increasing demands.

$\mu_{l,p}$  : unit capacity consumption factor of product  $p \in P$  at facility  $l \in L$ .

$H_{l,p}$  : stock of product  $p \in P$  at facility  $l \in L$  at the beginning of the planning horizon ( $H_{l,p} = 0$  for  $l \in S^o$ ).

$D_{l,p}^t$  : external demand of product  $p \in P$  at facility  $l \in L$  in period  $t \in T$ .

$\beta^t$  : interest rate in period  $t \in T$ .

---

$\alpha^t$  : unit return factor on capital not invested in period  $t \in T \setminus \{n\}$ , that is,  $\alpha^t = 1 + \beta^t / 100$ .

$B^t$  : available budget in period  $t \in T$ .

$\Psi_{l,p}$  : 1 - able to product  $p \in P$  at facility  $l \in L$ , 0 - otherwise

**Decision variables**

$b_{l,p}^t$  : amount of product  $p$  produced by facility  $l \in L$  in period  $t \in T$ .

$x_{l,l',p}^t$  : amount of product  $p$  shipped from facility  $l \in L$  to facility  $l' \in L$  ( $l \neq l'$ ) in period  $t \in T$ .

$y_{l,p}^t$  : amount of product  $p$  held in stock in facility  $l \in L$  at the end of period  $t \in T \cup \{0\}$  ( $y_{l,p}^0 = H_{l,p}$ ).

$z_{i,j}^t$  : amount of capacity shifted from existing facility  $i \in S^c$  to a newly established facility at site  $j \in S^o$ , at the beginning of period  $t \in T$ .

$\xi^t$  : capital not invested in period  $t \in T$ .

$\delta_l^t$  : 1 – if the selectable facility  $l \in L$  is operated during period  $t \in T$ , 0 – otherwise.

$z_{i_0,l}^t$  : amount of capacity shifted from fictitious facility  $i_0$  to  $l \in L$  at the beginning of period  $t \in T$ .

$\rho_i$  : 1 – if existing facility  $i \in S^c$  has its capacity extended during the planning horizon, 0 – otherwise.

**Formulation**

Objective,

$$MIN \sum_{t \in T} \sum_{l \in L} \sum_{p \in P} PC_{l,p}^t b_{l,p}^t \Psi_{l,p} + \sum_{t \in T} \sum_{l \in L} \sum_{l' \in L \setminus \{l\}} \sum_{p \in P} TC_{l,l',p}^t x_{l,l',p}^t \Psi_{l,p}$$

---


$$+ \sum_{t \in \mathbb{T}} \sum_{l \in \mathbb{L}} \sum_{p \in \mathbb{P}} IC_{l,p}^t y_{l,p}^t \psi_{l,p} + \sum_{t \in \mathbb{T}} \sum_{l \in \mathbb{L}} OC_l^t \delta_l^t + \sum_{t \in \mathbb{T}} \sum_{l \in \mathbb{L} \setminus \mathbb{S}} OC_l^t, \quad \text{A1}$$

subject to,

$$\psi_{l,p}(b_{l,p}^t + \sum_{l' \in \mathbb{L} \setminus \{l\}} x_{l',l,p}^t + y_{l,p}^{t-1}) = \psi_{l,p}(D_{l,p}^t + \sum_{l' \in \mathbb{L} \setminus \{l\}} x_{l',l',p}^t + y_{l,p}^t), l \in \mathbb{L}, p \in \mathbb{P}, t \in \mathbb{T} \quad \text{A2}$$

$$\bar{K}_i^1 - \sum_{\tau=1}^t \sum_{j \in \mathbb{S}^o} z_{i,j}^\tau + \sum_{\tau=1}^t z_{i_0,i}^\tau \leq \bar{K}_i^t \delta_i^t, i \in \mathbb{S}^c, t \in \mathbb{T}, \quad \text{A3}$$

$$\sum_{\tau=1}^t \sum_{i \in \mathbb{S}^c \cup \{i_0\}} z_{i,j}^\tau \leq \bar{K}_j^t \delta_j^t, j \in \mathbb{S}^o, t \in \mathbb{T}, \quad \text{A4}$$

$$\sum_{\tau=1}^t \sum_{j \in \mathbb{S}^o} z_{i,j}^\tau + \delta_i^t \varepsilon \leq \bar{K}_i^1, i \in \mathbb{S}^c, t \in \mathbb{T}, \quad \text{A5}$$

$$\sum_{p \in \mathbb{P}} \mu_{i,p} \left( b_{i,p}^t + \sum_{l \in \mathbb{L} \setminus \{i\}} x_{l,i,p}^t + y_{i,p}^{t-1} \right) \psi_{i,p} \leq \bar{K}_i^1 - \sum_{\tau=1}^t \sum_{j \in \mathbb{S}^o} z_{i,j}^\tau + \sum_{\tau=1}^t z_{i_0,i}^\tau, i \in \mathbb{S}^c, t \in \mathbb{T}, \quad \text{A6}$$

$$\sum_{p \in \mathbb{P}} \mu_{j,p} \left( b_{j,p}^t + \sum_{l \in \mathbb{L} \setminus \{j\}} x_{l,j,p}^t + y_{j,p}^{t-1} \right) \psi_{j,p} \leq \sum_{\tau=1}^t \sum_{j \in \mathbb{S}^c \cup \{i_0\}} z_{i,j}^\tau, j \in \mathbb{S}^o, t \in \mathbb{T}, \quad \text{A7}$$

$$\sum_{p \in \mathbb{P}} \mu_{l,p} \left( b_{l,p}^t + \sum_{l' \in \mathbb{L} \setminus \{l\}} x_{l',l,p}^t + y_{l,p}^{t-1} \right) \psi_{l,p} \leq \bar{K}_l^t, l \in \mathbb{L} \setminus \mathbb{S}, t \in \mathbb{T}, \quad \text{A8}$$

$$\sum_{p \in \mathbb{P}} \mu_{l,p} \left( b_{l,p}^t + \sum_{l' \in \mathbb{L} \setminus \{l\}} x_{l',l,p}^t + y_{l,p}^{t-1} \right) \psi_{l,p} \geq \underline{K}_l^t \delta_l^t, l \in \mathbb{S}, t \in \mathbb{T}, \quad \text{A9}$$

$$\delta_i^t \geq \delta_i^{t+1}, i \in \mathbb{S}^c, t \in \mathbb{T} \setminus \{n\}, \quad \text{A10}$$

$$\delta_j^t \leq \delta_j^{t+1}, j \in \mathbb{S}^o, t \in \mathbb{T} \setminus \{n\}, \quad \text{A11}$$

$$\sum_{j \in \mathbb{S}^o} FC_j^1 \delta_j^2 + \xi^1 = B^1, \quad \text{A12}$$

---


$$\begin{aligned} & \sum_{i \in \mathbf{S}^c \cup \{i_0\}} \sum_{j \in \mathbf{S}^o} MC_{i,j}^t z_{i,j}^t + \sum_{i \in \mathbf{S}^c} MC_{i_0,i}^t z_{i_0,i}^t + \sum_{i \in \mathbf{S}^c} SC_i^t (\delta_i^{t-1} - \delta_i^t) \\ & + \sum_{j \in \mathbf{S}^o} FC_j^t (\delta_j^{t+1} - \delta_j^t) + \xi^t = B^t + \alpha^{t-1} \xi^{t-1}, t \in \mathbf{T} \setminus \{1, n\}, \end{aligned} \quad \text{A13}$$

$$\begin{aligned} & \sum_{i \in \mathbf{S}^c \cup \{i_0\}} \sum_{j \in \mathbf{S}^o} MC_{i,j}^n z_{i,j}^n + \sum_{i \in \mathbf{S}^c} MC_{i_0,i}^n z_{i_0,i}^n + \sum_{i \in \mathbf{S}^c} SC_i^n (\delta_i^{n-1} - \delta_i^n) + \xi^n \\ & = B^n + \alpha^{n-1} \xi^{n-1}, \end{aligned} \quad \text{A14}$$

$$b_{l,p}^t \geq 0, l \in \mathbf{L}, p \in \mathbf{P}, t \in \mathbf{T}, \quad \text{A15}$$

$$x_{l,p}^t \geq 0, l \in \mathbf{L}, l \in \mathbf{L} \setminus \{l\}, p \in \mathbf{P}, t \in \mathbf{T}, \quad \text{A16}$$

$$y_{l,p}^t \geq 0, l \in \mathbf{L}, p \in \mathbf{P}, t \in \mathbf{T}, \quad \text{A17}$$

$$z_{i,j}^t \geq 0, i \in \mathbf{S}^c, j \in \mathbf{S}^o, t \in \mathbf{T}, \quad \text{A18}$$

$$\xi^t \geq 0, t \in \mathbf{T}, \quad \text{A19}$$

$$\delta_l^t \in \{0, 1\}, l \in \mathbf{L}, t \in \mathbf{T}, \quad \text{A20}$$

$$\rho_i \leq \delta_i^n, i \in \mathbf{S}^c, \quad \text{A21}$$

$$\sum_{t \in \mathbf{T}} z_{i_0,i}^t \leq \bar{K}_{i_0}^{-1} \rho_i, i \in \mathbf{S}^c, \quad \text{A22}$$

$$\sum_{t \in \mathbf{T}} \sum_{j \in \mathbf{S}^o} z_{i,j}^t \leq \bar{K}_i^{-1} (1 - \rho_i), i \in \mathbf{S}^c, \quad \text{A23}$$

$$\sum_{t \in \mathbf{T}} \sum_{i \in \mathbf{S}^c} z_{i_0,i}^t + \sum_{t \in \mathbf{T}} \sum_{j \in \mathbf{S}^o} z_{i_0,j}^t \leq \bar{K}_{i_0}^{-1} \quad \text{A24}$$

---

$$z_{i_0,j}^t \geq 0, l \in L, t \in T, \quad \text{A25}$$

$$\rho_i \in \{0,1\}, i \in S^c, \quad \text{A26}$$

## Appendix B: Implementation of the MILP model used in Part II to conduct industrial case studies

The model was implemented in ILOG OPL Studio. The implementation consisted of three components, the MILP model, the data model and the data file. In each of the industrial cases, some minor modifications were done in the MILP model. These modifications were limited to removing constraints that were redundant. For example, in the case studies where no new facilities were planned, constraint defined by equations A5 was removed. The MILP model shown in Appendix 12.2.1 below is the general model used in the case studies. Similarly, the data model was an access to the excel file in which data was stored. Due to the limitation of OPL Studio to read only two-dimensional arrays from a data file, some data were stored directly into the data model file. This data has been hidden for confidentiality reasons.

### Generic MILP model

```
/*  
* OPL 4.2 Model file  
* Author: nirupamj  
* Creation date: 9/25/2006 1:59 PM  
*/  
  
//Model for Glass-Co
```

---

```

//set of facilities
{string} Facilities = ...;

// set of selectable facilities
{string} SFacility = ...;

// set of nonselectable facilities
{string} NFacility = ...;

// set of existing facilities
{string} SEFacility = ...;

//set of potential facilities
{string} SOFacility = ...;

// set of product types
{string} Products = ...;

// time periods for the study
int nbTimePeriods = ...;
range TimePeriod = 1..nbTimePeriods;

//variable purchasing/production cost for one unit of
Product by Facility
float PC[p in Products][f in Facilities][t in
TimePeriod] = ...;

//variable cost of shipping one unit of product
// from one facility to another
float TC[p in Products][i in Facilities][j in
Facilities][t in TimePeriod]=...;

//inventory cost per unit of product at facility at end
// of time period
float IC[Products][Facilities][TimePeriod] =...;

//unit variable cost of moving capacity from existing
facility
//to potential site at beginning of time period
float MC[SEFacility][SOFacility][TimePeriod] =...;

//unit variable capacity expansion cost
float MCFic[SFacility][TimePeriod] =...;

//fixed cost of operating facility in time period
float OC[Facilities][TimePeriod] =...;

//fixed cost charged in time period for shutting down
an
// existing facility at end of earlier period
float SC[SEFacility][TimePeriod] =...;

//fixed setup cost charged in period when new facility
is

```

---



---

```

//established at potential site and begins ops in next
period
float FC[SOFacility][TimePeriod] =...;

//maximum allowed capacity at facility in time period
int MaxCap[Facilities][TimePeriod] =...;

//maximum allowed capacity expansion
int MaxCapFic =...;

//minimum required throughput at selectable facility
int MinCap[SFacility][TimePeriod] =...;

//unit capacity consumption factor of product at
facility
float mu[Products][Facilities] =...;

//stock of product at facility at beginning of planning
horizon
int Stock[Products][Facilities] =...;

//external demand of product at facility in time period
int Demand[Products][Facilities][TimePeriod] =...;

//Interest in time period
float InterestRate[TimePeriod] =...;

//unit return factor on capital not invested in
timeperiod
float alpha[t in TimePeriod] = 1 + InterestRate[t]/100;

//available budget in timeperiod
int Budget[TimePeriod] =...;

//decision variables
//amount of product produced by facility in timeperiod
dvar int b[Products][Facilities][TimePeriod];

//amount of product shipped from one facility to
another in time period
dvar int x[Facilities][Facilities][Products][TimePeriod];

//amount of product in stock at the end of timeperiod
dvar int y[Facilities][Products][TimePeriod];

//capacity shifted from existing facility to new
facility in time period
dvar int z[SEFacility][SOFacility][TimePeriod];

//capital not invested in Time Period
dvar int nu[TimePeriod];

//is facility operated in Time Period (1 if operated, 0
if not operated)

```

---

---

```

dvar boolean delta[Facilities][TimePeriod];

//capacity expansion - if existing facility has had its
capacity
//expanded during the TimePeriod

//new fictitious facility will be created
dvar int zfic[Facilities][TimePeriod];

//if existing facility has capacity extended during
planning horizon
dvar boolean rho[Facilities];

constraint ct4;
constraint ct4a;
constraint ct5;
constraint ct6;
constraint ct7;
constraint ct7a;
constraint ct8;
constraint ct8a;
constraint ct9;
constraint ct10;
constraint ct11;
constraint ct11a;
constraint ct12;
constraint ct13;
constraint ct14;
constraint ct15;
constraint ct16;
constraint ct17;
constraint ct18;
constraint ct19;
constraint ct20;
constraint ct21;
constraint ct28;
constraint ct29;
constraint ct30;
constraint ct31;
constraint ct32;

//OBJECTIVE FUNCTION

//Variable Production cost + Variable Shipping Cost +
Total Inventory cost
// +Fixed cost for operating facility (selectable) +
Fixed cost of operating
// facility (non-selectable)

minimize
    sum(t in TimePeriod, l in Facilities, p in Products)
    PC[p][l][t]*b[p][l][t]+
    sum(t in TimePeriod, l in Facilities, l1 in
Facilities:l1!=l, p in Products)
    TC[p][l][l1][t]*x[l][l1][p][t]+

```

---

```

sum(t in TimePeriod, l in Facilities, p in Products)
IC[p][l][t]*y[l][p][t]+
sum(t in TimePeriod, l in SFacility)
OC[l][t]*delta[l][t]+
sum(t in TimePeriod, l in NFacility) OC[l][t];

subject to{

// total amount of product shippin + produce +
stockbefore = Demand +shipout //+stockafter
ct4 = forall (l in Facilities, p in Products, t in
TimePeriod:t!=1)
b[p][l][t] +sum(l1 in Facilities: l1!=l)
x[l1][l][p][t] + y[l][p][t-1]
== Demand[p][l][t] +sum(l1 in Facilities:l1!=l)
x[l][l1][p][t] + y[l][p][t];

ct4a = forall (l in Facilities, p in Products)
b[p][l][1] +sum(l1 in Facilities:l1!=l)
x[l1][l][p][1] + Stock[p][l]
== Demand[p][l][1] +sum(l1 in Facilities:l1!=l)
x[l][l1][p][1] + y[l][p][1];

//capinitial-captransfer+capexpanded <= Max cap

ct5 = forall (i in SEFacility, t in TimePeriod)
MaxCap[i][1] - sum(t1 in 1..t, j in SOFacility)
z[i][j][t1]
+sum(t1 in 1..t) zfic[i][t1] <=
MaxCap[i][t]*delta[i][t];

//capacity moved to new facility <= minimum capacity of
new facility

ct6 = forall (j in SOFacility, t in TimePeriod)
sum(t1 in 1..t, i in SEFacility) z[i][j][t1] +
sum(t1 in 1..t) zfic[j][t1]
<= MaxCap[j][t]*delta[j][t];

//Sum of capacity moved <= available at beginning of
planning horizon

ct7 = forall (i in SEFacility, t in TimePeriod)
sum(t1 in 1..t, j in SOFacility) z[i][j][t1] +
delta[i][t] <= MaxCap[i][1];

//extension for expansion
ct7a = forall (t in TimePeriod)
sum(t1 in 1..t, i in SEFacility) zfic[i][t1] <=
MaxCapFic;

```

---

---

```

//capacity/unitprodX(prod-
produced+shipped+instock)<=Initialmaxcap-
captransferred+capexpanded
ct8 = forall (i in SEFacility, t in TimePeriod:t!=1)
    sum(p in Products) mu[p][i]*b[p][i][t]
    <= MaxCap[i][1] - sum(t1 in 1..t, j in
SOFacility) z[i][j][t1] + sum(t1 in 1..t) zfic[i][t1];

ct8a = forall (i in SEFacility)
    sum(p in Products) mu[p][i]*b[p][i][1]
    <= MaxCap[i][1] - sum(j in SOFacility) z[i][j][1]
+ zfic[i][1];

//same as ct8 but for new facilities
ct9 = forall (j in SOFacility, t in TimePeriod)
    sum(p in Products) mu[p][j]*b[p][j][t]
    <= sum (t1 in 1..t, i in SEFacility) z[i][j][t1]
+ sum(t1 in 1..t) zfic[j][t1];

//capacity balance for non-selectable facilities
ct10 = forall (l in NFacility, t in TimePeriod)
    sum(p in Products) mu[p][l]*b[p][l][t]
    <= MaxCap[l][t];

//capacity should be more than minimum
ct11 = forall (l in SFacility, t in TimePeriod:t!=1)
    sum(p in Products) mu[p][l]*b[p][l][t] >=
MinCap[l][t]*delta[l][t];

ct11a = forall (l in SFacility)
    sum(p in Products) mu[p][l]*b[p][l][1] >=
MinCap[l][1]*delta[l][1];

//ensure that present facility if closed cannot be
opened again
ct12 = forall (i in SEFacility, t in TimePeriod: t !=
nbTimePeriods)
    delta[i][t]>=delta[i][t+1];

//ensure that new facility if opened stays open till
end of period
ct13 = forall (j in SOFacility, t in TimePeriod: t !=
nbTimePeriods)
    delta[j][t+1]>=delta[j][t];

//First period only allowed to develop/open new
facility which works in second //period
ct14 = sum(j in SOFacility) FC[j][1] * delta[j][1] +
nu[1]+
    sum(i in SEFacility) MCFic[i][1]*zfic[i][1] ==
Budget[1];

//moving capacity+shutdown cost +setup cost + capital
not used=budget+capital //not used earlier*interst rate

```

---

---

```

ct15 = forall(t in TimePeriod: (t !=
nbTimePeriods)&&(t!=1))
    sum(i in SEFacility, j in SOFacility)
MC[i][j][t]*z[i][j][t] + sum(j in SOFacility)
MCFic[j][t]*zfic[j][t]
    + sum (i in SEFacility) MCFic[i][t]*zfic[i][t]
    + sum (i in SEFacility) SC[i][t]*(delta[i][t-1]-
delta[i][t])
    + sum (j in SOFacility) FC[j][t]*(delta[j][t+1]-
delta[j][t])
    + nu[t] == Budget[t] + alpha[t-1]*nu[t-1];

//No new facilities in last period
ct16 = sum(i in SEFacility, j in SOFacility)
MC[i][j][nbTimePeriods]*z[i][j][nbTimePeriods]
    + sum(j in SOFacility)
MCFic[j][nbTimePeriods]*zfic[j][nbTimePeriods]
    + sum (i in SEFacility)
MCFic[i][nbTimePeriods]*zfic[i][nbTimePeriods]
    + sum(i in SEFacility)
SC[i][nbTimePeriods]*(delta[i][nbTimePeriods-1]-
delta[i][nbTimePeriods])
    + nu[nbTimePeriods] == Budget[nbTimePeriods] +
alpha[nbTimePeriods-1]*nu[nbTimePeriods-1];

ct17 = forall(l in Facilities, p in Products, t in
TimePeriod) b[p][l][t]>=0;

ct18 = forall(l in Facilities, l1 in Facilities: l1!=l,
p in Products, t in TimePeriod) x[l][l1][p][t] >=0;

ct19 = forall(l in Facilities, p in Products, t in
TimePeriod) y[l][p][t]>=0;

ct20 = forall(i in SEFacility, j in SOFacility, t in
TimePeriod) z[i][j][t]>=0;

ct21 = forall(t in TimePeriod) nu[t]>=0;

ct28 = forall(i in SEFacility)
rho[i]<=delta[i][nbTimePeriods];

ct29 = forall(i in SEFacility) sum(t in TimePeriod)
zfic[i][t]<=MaxCapFic*rho[i];

ct30 = forall(j in SOFacility) sum(t in TimePeriod)
zfic[j][t]<=MaxCap[j][1]*(1-rho[j]);

ct31 = sum(i in SEFacility, t in TimePeriod) zfic[i][t]
+ sum(j in SOFacility, t in TimePeriod) zfic[j][t]
<=MaxCapFic;

ct32 = forall(l in Facilities, t in TimePeriod)
zfic[l][t]>=0;

```

---

---

}

### **Generic Data Model**

```
SheetConnection sheet("EngDdata.xls");
Facilities from SheetRead(sheet,"GlassCo!A2:E2");
SFacility from SheetRead(sheet,"GlassCo!A5:E5");
NFacility = {};
SEFacility from SheetRead(sheet,"GlassCo!A11:D11");
SOFacility from SheetRead(sheet,"GlassCo!A14");
Products from SheetRead(sheet,"GlassCo!A17:C17");
nbTimePeriods from SheetRead(sheet,"GlassCo!A20");

PC = <DATA>;

TC = <DATA>;

IC = <DATA>;

MC = <DATA>;

MCFic from SheetRead(sheet,"GlassCo!B50:E54");
OC from SheetRead(sheet,"GlassCo!B58:E62");
SC from SheetRead(sheet,"GlassCo!B66:E69");
FC from SheetRead(sheet,"GlassCo!B126:E126");
MaxCap from SheetRead(sheet,"GlassCo!B73:E77");
MaxCapFic from SheetRead(sheet,"GlassCo!A88");
MinCap from SheetRead(sheet,"GlassCo!B81:E85");
mu from SheetRead(sheet,"GlassCo!B92:F94");
Stock from SheetRead(sheet,"GlassCo!B98:F100");
Demand = <DATA>;
InterestRate from SheetRead(sheet,"GlassCo!A115:D115");
Budget from SheetRead(sheet,"GlassCo!A111:D111");
```

---

## Appendix C: Sample report after post-processing of optimised results

Number of present sites = 4 (M1, M2, M3, M4)

No potential new sites

Number of products = 3 (Product-1, Product-2, Product-3)

The names of sites, products and the data has been modified.

<b>Objective function</b>				
1763110000				
<b>Production Data</b>				
Product Type = Product-1				
	1	2	3	4
M2	1500000	721207	1545454	1254545
M3	2272728	2272731	2454546	2545455
M4	1366667	1866667	2000000	2200000
M1	0	0	0	0
Product Type = Product-2				
	1	2	3	4
M2	5000000	5200000	5380134	5600000
M3	0	0	0	0
M4	0	0	0	0
M1	0	0	19866	0
Product Type = Product-3				
	1	2	3	4
M2	0	1078793	574412	1145455
M3	0	0	0	0
M4	300000	0	0	0
M1	800000	800000	601340	800000
<b>Transportation Data</b>				
Transportation of Product-1 from M2 to				
	1	2	3	4
M3	1227272	221207	1545454	1454545
M4	0	0	0	0
M1	0	0	0	0
Transportation of Product-2 from M2 to				
	1	2	3	4
M3	0	0	0	0
M4	0	0	0	0
M1	0	0	0	0

Transportation of Product-3 from M2 to				
	1	2	3	4
M3	0	0	0	0
M4	0	0	0	0
M1	0	0	0	0
Transportation of Product-1 from M3 to				
	1	2	3	4
M2	0	0	0	0
M4	0	0	0	0
M1	0	0	0	0
Transportation of Product-2 from M3 to				
	1	2	3	4
M2	0	0	0	0
M4	0	0	0	0
M1	0	0	0	0
Transportation of Product-3 from M3 to				
	1	2	3	4
M2	0	121207	0	0
M4	0	0	0	0
M1	0	0	0	0
Transportation of Product-1 from M4 to				
	1	2	3	4
M2	227272	0	500000	700000
M3	0	1006062	0	0
M1	0	0	0	0
Transportation of Product-2 from M4 to				
	1	2	3	4
M2	0	0	0	0
M3	0	0	0	0
M1	0	0	0	0
Transportation of Product-3 from M4 to				
	1	2	3	4
M2	300000	0	0	0
M3	0	0	0	0
M1	0	0	0	0
Transportation of Product-1 from M1 to				
	1	2	3	4
M2	0	0	0	0
M3	0	0	0	0
M4	0	0	0	0



Transportation of Product-2 from M1 to				
	1	2	3	4
M2	0	0	19866	0
M3	0	0	0	0
M4	0	0	0	0
Transportation of Product-3 from M1 to				
	1	2	3	4
M2	700000	0	1080133	700000
M3	0	121207	0	0
M4	0	0	0	0
<b>Stock Data</b>				
Stock at M2 at the end of period				
	1	2	3	4
Product-1	0	0	0	0
Product-2	0	0	0	0
Product-3	0	0	154545	0
Stock at M3 at the end of period				
	1	2	3	4
Product-1	0	0	0	0
Product-2	0	0	0	0
Product-3	0	0	0	0
Stock at M4 at the end of period				
	1	2	3	4
Product-1	139395	0	0	0
Product-2	0	0	0	0
Product-3	0	0	0	0
Stock at M1 at the end of period				
	1	2	3	4
Product-1	0	0	0	0
Product-2	0	0	0	0
Product-3	0	578793	0	0
<b>Operations Data</b>				
Facilities producing at the end of period				
	1	2	3	4
M2	TRUE	TRUE	TRUE	TRUE
M3	TRUE	TRUE	TRUE	TRUE
M4	TRUE	TRUE	TRUE	TRUE
M1	TRUE	TRUE	TRUE	TRUE

---

<b>There are no potential new facilities in this scenario!</b>				
<b>Capacity Expansion Data</b>				
Facilities and respective capacity expansion at the beginning of period				
	1	2	3	4
M2	0	1000000	1000000	0
M3	0	0	0	0
M4	0	0	0	0
M1	0	0	0	0
<b>Expansion Budget Left (\$)</b>				
	1	2	3	4
	30000000	59700000	91479000	127882530

Appendix D: Visual Basic code for post-processing and report generation

```

Private Sub Process_Solution_Click()

Dim timePeriod As Integer
Dim fac(), sfac(), nfac(), efac(), pfac(), product() As String
Dim i, row, rowProc, loc, star, h, j, k, adjust As Integer
Dim production(), trans(), stock(), ops(), tranexp() As Integer
Dim budgetleft(), exp() As Long
Dim object, str As String
Dim objectnum As Long

timePeriod = worksheets("Inputdata").cells(20, 1).value

'Create Reporting Structure
'Import Index Set

i = 1
ReDim fac(1)
Do while i < 10
    If ((worksheets("Inputdata").cells(2, i).value = "") Or (worksheets("Inputdata").cells(2, i).value = "<null>")) Then Exit Do
    fac(i) = worksheets("Inputdata").cells(2, i).value
    i = i + 1

```

---

```

        If ((worksheets("Inputdata").Cells(2, i).Value
= "") Or (worksheets("Inputdata").Cells(2, i).Value =
"<null>")) Then Exit Do
        ReDim Preserve fac(i)
Loop

i = 1
ReDim sfac(1)
Do while i < 10
    If ((worksheets("Inputdata").Cells(5, i).Value
= "") Or (worksheets("Inputdata").Cells(5, i).Value =
"<null>")) Then Exit Do
        sfac(i) = worksheets("Inputdata").Cells(5,
i).value
        i = i + 1
        If ((worksheets("Inputdata").Cells(5, i).Value
= "") Or (worksheets("Inputdata").Cells(5, i).Value =
"<null>")) Then Exit Do
        ReDim Preserve sfac(i)
Loop

i = 1
ReDim nfac(1)
Do while i < 10
    If ((worksheets("Inputdata").Cells(8, i).Value
= "") Or (worksheets("Inputdata").Cells(8, i).Value =
"<null>")) Then Exit Do
        nfac(i) = worksheets("Inputdata").Cells(8,
i).value
        i = i + 1
        If ((worksheets("Inputdata").Cells(8, i).Value
= "") Or (worksheets("Inputdata").Cells(8, i).Value =
"<null>")) Then Exit Do
        ReDim Preserve nfac(i)
Loop

i = 1
ReDim efac(1)
Do while i < 10
    If ((worksheets("Inputdata").Cells(11, i).Value
= "") Or (worksheets("Inputdata").Cells(11, i).Value =
"<null>")) Then Exit Do
        efac(i) = worksheets("Inputdata").Cells(11,
i).value
        i = i + 1
        If ((worksheets("Inputdata").Cells(11, i).Value
= "") Or (worksheets("Inputdata").Cells(11, i).Value =
"<null>")) Then Exit Do
        ReDim Preserve efac(i)
Loop

i = 1
ReDim pfac(1)
Do while i < 10

```

---

---

```

        If ((worksheets("Inputdata").Cells(14, i).Value
= "") Or (worksheets("Inputdata").Cells(14, i).Value =
"<null>")) Then Exit Do
        pfac(i) = worksheets("Inputdata").Cells(14,
i).Value
        i = i + 1
        If ((worksheets("Inputdata").Cells(14, i).Value
= "") Or (worksheets("Inputdata").Cells(14, i).Value =
"<null>")) Then Exit Do
        ReDim Preserve pfac(i)
Loop
i = 1
ReDim product(1)
Do while i < 10
        If ((worksheets("Inputdata").Cells(17, i).Value
= "") Or (worksheets("Inputdata").Cells(17, i).Value =
"<null>")) Then Exit Do
        product(i) = worksheets("Inputdata").Cells(17,
i).Value
        i = i + 1
        If ((worksheets("Inputdata").Cells(17, i).Value
= "") Or (worksheets("Inputdata").Cells(17, i).Value =
"<null>")) Then Exit Do
        ReDim Preserve product(i)
Loop
'Process Objective Function Data
row = 1
object = worksheets("Solution").Cells(1, 1).Value
objectnum = Val(Left(Right(object, 13), 12))
'Process Production Data
ReDim production(1 To UBound(product), 1 To
UBound(sfac), 1 To timePeriod)
i = 1
j = 1
k = 1
row = 3
loc = 1
star = 1
Do while i <= UBound(product)
        Do while j <= UBound(sfac)
                str = worksheets("Solution").Cells(row,
1).Value
                str = Trim(str)
                loc = InStr(1, str, " ")
                star = 1
                Do while k <= timePeriod
                        production(i, j, k) = Mid(str, star, loc -
star)
                        str = Trim(str)

```

---

```

        k = k + 1
        star = loc + 1
        If k = timePeriod Then
            loc = Len(str) + 1
        Else
            loc = InStr(star, str, " ")
        End If
    Loop
    j = j + 1
    k = 1
    row = row + 1
Loop
i = i + 1
j = 1
Loop
'Process Transportation Data

ReDim trans(1 To UBound(sfac), 1 To UBound(sfac), 1 To
UBound(product), 1 To timePeriod)
h = 1
i = 1
j = 1
k = 1
row = row + 1
loc = 1
star = 1
Do while h <= UBound(sfac)
Do while i <= UBound(sfac)
    Do while j <= UBound(product)
        str = worksheets("Solution").cells(row,
1).value
        str = Trim(str)
        loc = InStr(1, str, " ")
        star = 1
        Do while k <= timePeriod
            trans(h, i, j, k) = Mid(str, star, loc -
star)
            str = Trim(str)
            k = k + 1
            star = loc + 1
            If k = timePeriod Then
                loc = Len(str) + 1
            Else
                loc = InStr(star, str, " ")
            End If
        Loop
        j = j + 1
        k = 1
        row = row + 1
    Loop
    i = i + 1
    j = 1
Loop
h = h + 1

```

---

---

```

i = 1
Loop

'Process Stock Data

ReDim stock(1 To UBound(sfac), 1 To UBound(product), 1
To timePeriod)

i = 1
j = 1
k = 1
row = row + 1
loc = 1
star = 1
Do While i <= UBound(sfac)
    Do While j <= UBound(product)
        str = Worksheets("Solution").Cells(row,
1).value
        str = Trim(str)
        loc = InStr(1, str, " ")
        star = 1
        Do While k <= timePeriod
            stock(i, j, k) = Mid(str, star, loc - star)
            str = Trim(str)
            k = k + 1
            star = loc + 1
            If k = timePeriod Then
                loc = Len(str) + 1
            Else
                loc = InStr(star, str, " ")
            End If
        Loop
        j = j + 1
        k = 1
        row = row + 1
    Loop
    i = i + 1
    j = 1
Loop

'Process Operations Data
ReDim ops(1 To UBound(sfac), 1 To timePeriod)

i = 1
k = 1
row = row + 1
loc = 1
star = 1
Do While i <= UBound(sfac)
    str = Worksheets("Solution").Cells(row,
1).value
    str = Trim(str)
    loc = InStr(1, str, " ")
    star = 1
    Do While k <= timePeriod

```

---

```

ops(i, k) = Mid(str, star, loc - star)
str = Trim(str)
k = k + 1
star = loc + 1
If k = timePeriod Then
    loc = Len(str) + 1
Else
    loc = InStr(star, str, " ")
End If
Loop
k = 1
row = row + 1
i = i + 1
Loop
'Process Transfer of Capacity Data
row = row + 1
If (worksheets("Solution").Cells(row, 1).Value = "")
Then
    row = row + UBound(efac)
Else
    'Process the data
    ReDim tranexp(1 To UBound(efac), 1 To UBound(pfac),
1 To timePeriod)
    i = 1
    j = 1
    k = 1
    loc = 1
    star = 1
    Do while i <= UBound(efac)
    Do while j <= UBound(pfac)
        str = worksheets("Solution").Cells(row,
1).value
        str = Trim(str)
        loc = InStr(1, str, " ")
        star = 1
        Do while k <= timePeriod
            tranexp(i, j, k) = Mid(str, star, loc -
star)
            str = Trim(str)
            k = k + 1
            star = loc + 1
            If k = timePeriod Then
                loc = Len(str) + 1
            Else
                loc = InStr(star, str, " ")
            End If
        Loop
        j = j + 1
        k = 1
        row = row + 1
    Loop
    i = i + 1
    j = 1

```

---

---

```

    Loop
End If

'Process Capacity Expansion Data

ReDim exp(1 To UBound(fac), 1 To timePeriod)

i = 1
k = 1
row = row + 1
loc = 1
star = 1
Do While i <= UBound(fac)
    str = Worksheets("Solution").Cells(row,
1).Value
    str = Trim(str)
    loc = InStr(1, str, " ")
    star = 1
    Do While k <= timePeriod
        exp(i, k) = Mid(str, star, loc - star)
        str = Trim(str)
        k = k + 1
        star = loc + 1
        If k = timePeriod Then
            loc = Len(str) + 1
        Else
            loc = InStr(star, str, " ")
        End If
    Loop
    k = 1
    row = row + 1
    i = i + 1
Loop

'Process Budget Data

ReDim budgetleft(1 To timePeriod)
row = row + 1
k = 1
str = Worksheets("Solution").Cells(row, 1).Value
str = Trim(str)
loc = InStr(1, str, " ")
star = 1
Do While k <= timePeriod
    budgetleft(k) = Mid(str, star, loc - star)
    str = Trim(str)
    k = k + 1
    star = loc + 1
    If k = timePeriod Then
        loc = Len(str) + 1
    Else
        loc = InStr(star, str, " ")
    End If
Loop

```



---

```

'Write Processed Data Report

rowProc = 1

'Write Processed Objective Function Data

worksheets("Report").Cells(rowProc, 1).Value =
"Objective function"
worksheets("Report").Cells(rowProc, 1).Font.Bold = True
rowProc = rowProc + 1
worksheets("Report").Cells(rowProc, 1).Value =
objectnum

'Write Processed Production Data

rowProc = rowProc + 2
worksheets("Report").Cells(rowProc, 1).Value =
"Production Data"
worksheets("Report").Cells(rowProc, 1).Font.Bold = True
i = 1
j = 1
k = 1
Do while i <= UBound(product)
    rowProc = rowProc + 1
    worksheets("Report").Cells(rowProc, 1).Value =
"Product Type = " + product(i)
    rowProc = rowProc + 1
    Do while j <= timePeriod
        worksheets("Report").Cells(rowProc, j + 1).Value
= j
        j = j + 1
    Loop
    Do while k <= UBound(sfac)
        worksheets("Report").Cells(rowProc + k, 1).Value
= sfac(k)
        k = k + 1
    Loop
    j = 1
    k = 1
    rowProc = rowProc + 1
    Do while j <= UBound(sfac)
        Do while k <= timePeriod
            worksheets("Report").Cells(rowProc, k +
1).Value = production(i, j, k)
            k = k + 1
        Loop
        k = 1
        j = j + 1
        rowProc = rowProc + 1
    Loop
    i = i + 1
    j = 1
    k = 1

```

---

---

Loop

'write Processed Transportation Data

```
rowProc = rowProc + 2
worksheets("Report").Cells(rowProc, 1).Value =
"Transportation Data"
worksheets("Report").Cells(rowProc, 1).Font.Bold = True
h = 1
i = 1
j = 1
k = 1
Do while h <= UBound(sfac)
Do while i <= UBound(product)
    adjust = 0
    rowProc = rowProc + 1
    worksheets("Report").Cells(rowProc, 1).Value =
"Transportation of " + product(i) + " from " + sfac(h)
+ " to"

    rowProc = rowProc + 1
    Do while k <= timePeriod
        worksheets("Report").Cells(rowProc, k + 1).Value
= k
        k = k + 1
    Loop
    Do while j <= UBound(sfac)
    If j = h Then
        j = j + 1
        adjust = -1
    Else
        worksheets("Report").Cells(rowProc + j + adjust,
1).Value = sfac(j)
        j = j + 1
    End If
    Loop
    j = 1
    k = 1
    rowProc = rowProc + 1
    Do while j <= UBound(sfac)
    If j = h Then
        j = j + 1
    Else
        Do while k <= timePeriod
            worksheets("Report").Cells(rowProc, k +
1).Value = trans(h, j, i, k)
            k = k + 1
        Loop
        k = 1
        j = j + 1
        rowProc = rowProc + 1
    End If
    Loop
    i = i + 1
    j = 1
```

---

```

    k = 1
Loop
i = 1
h = h + 1
Loop

'write Processed Stock Data

rowProc = rowProc + 2
worksheets("Report").Cells(rowProc, 1).Value = "Stock
Data"
worksheets("Report").Cells(rowProc, 1).Font.Bold = True
i = 1
j = 1
k = 1
Do while i <= UBound(sfac)
    rowProc = rowProc + 1
    worksheets("Report").Cells(rowProc, 1).Value =
"Stock at " + sfac(i) + " at the end of period"
    rowProc = rowProc + 1
    Do while j <= timePeriod
        worksheets("Report").Cells(rowProc, j + 1).Value
= j
        j = j + 1
    Loop
    Do while k <= UBound(product)
        worksheets("Report").Cells(rowProc + k, 1).Value
= product(k)
        k = k + 1
    Loop
    j = 1
    k = 1
    rowProc = rowProc + 1
    Do while j <= UBound(product)
        Do while k <= timePeriod
            worksheets("Report").Cells(rowProc, k +
1).Value = stock(i, j, k)
            k = k + 1
        Loop
        k = 1
        j = j + 1
        rowProc = rowProc + 1
    Loop
    i = i + 1
    j = 1
    k = 1
Loop

'write Processes Operations Data

rowProc = rowProc + 2
worksheets("Report").Cells(rowProc, 1).Value =
"Operations Data"
worksheets("Report").Cells(rowProc, 1).Font.Bold = True
j = 1

```

---

```

k = 1
rowProc = rowProc + 1
worksheets("Report").Cells(rowProc, 1).Value =
"Facilities producing at the end of period"
rowProc = rowProc + 1
Do while j <= timePeriod
    worksheets("Report").Cells(rowProc, j + 1).Value
= j
    j = j + 1
Loop
Do while k <= UBound(sfac)
    worksheets("Report").Cells(rowProc + k, 1).Value
= sfac(k)
    k = k + 1
Loop
j = 1
k = 1
rowProc = rowProc + 1
Do while j <= UBound(sfac)
    Do while k <= timePeriod
        worksheets("Report").Cells(rowProc, k +
1).Value = (ops(j, k) = 1)
        k = k + 1
    Loop
    k = 1
    j = j + 1
    rowProc = rowProc + 1
Loop

'write Processed Transfer Capacity Data

rowProc = rowProc + 2
If pfac(UBound(pfac)) = Empty Then
    worksheets("Report").Cells(rowProc, 1).Value =
"there are no potential new facilities in this
scenario!"
    worksheets("Report").Cells(rowProc, 1).Font.Bold =
True
Else
    'write Processes Transfer Capacity Data
    rowProc = rowProc + 2
    worksheets("Report").Cells(rowProc, 1).Value =
"Capacity Transfer Data"
    worksheets("Report").Cells(rowProc, 1).Font.Bold =
True
    i = 1
    j = 1
    k = 1
    Do while i <= UBound(pfac)
        rowProc = rowProc + 1
        worksheets("Report").Cells(rowProc, 1).Value =
"Capacity Transferred to " + pfac(i) + " at the end of
period"
        rowProc = rowProc + 1
        Do while j <= timePeriod

```

---

```

        worksheets("Report").Cells(rowProc, j + 1).Value
= j
        j = j + 1
    Loop
    Do while k <= UBound(efac)
        worksheets("Report").Cells(rowProc + k, 1).Value
= efac(k)
        k = k + 1
    Loop
    j = 1
    k = 1
    rowProc = rowProc + 1
    Do while j <= UBound(efac)
        Do while k <= timePeriod
            worksheets("Report").Cells(rowProc, k +
1).Value = tranexp(j, i, k)
            k = k + 1
        Loop
        k = 1
        j = j + 1
        rowProc = rowProc + 1
    Loop
    i = i + 1
    j = 1
    k = 1
    Loop
End If

'Write Capacity Expansion Data

rowProc = rowProc + 2
worksheets("Report").Cells(rowProc, 1).Value =
"Capacity Expansion Data"
worksheets("Report").Cells(rowProc, 1).Font.Bold = True
j = 1
k = 1
    rowProc = rowProc + 1
        worksheets("Report").Cells(rowProc, 1).Value =
"Facilities and respective capacity expansion at the
begining of period"
        rowProc = rowProc + 1
        Do while j <= timePeriod
            worksheets("Report").Cells(rowProc, j + 1).Value
= j
                j = j + 1
            Loop
            Do while k <= UBound(fac)
                worksheets("Report").Cells(rowProc + k, 1).Value
= fac(k)
                k = k + 1
            Loop
            j = 1
            k = 1
            rowProc = rowProc + 1
            Do while j <= UBound(fac)

```

---

```

        Do while k <= timePeriod
            Worksheets("Report").Cells(rowProc, k +
1).value = exp(j, k)
            k = k + 1
        Loop
        k = 1
        j = j + 1
        rowProc = rowProc + 1
    Loop

'write Budget Data

rowProc = rowProc + 2
Worksheets("Report").Cells(rowProc, 1).value =
"Expansion Budget Left ($)"
Worksheets("Report").Cells(rowProc, 1).Font.Bold = True
j = 1
rowProc = rowProc + 1
Do while j <= timePeriod
    Worksheets("Report").Cells(rowProc, j + 1).value
= j
    j = j + 1
Loop
j = 1
rowProc = rowProc + 1
Do while j <= timePeriod
    Worksheets("Report").Cells(rowProc, j +
1).value = budgetleft(j)
    j = j + 1
Loop

End Sub

```