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A review of multi-factor capacity expansion models for manufacturing plants: Searching for a holistic decision aid

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Abstract

Investment in capacity expansion remains one of the most critical decisions for a manufacturing organisation with global production facilities. Multiple factors need to be considered making the decision process very complex. The purpose of this paper is to establish the state-of-the-art in multi-factor models for capacity expansion of manufacturing plants within a corporation. The research programme consisting of an extensive literature review and a structured assessment of the strengths and weaknesses of the current research is presented. The study found that there is a wealth of mathematical multi-factor models for evaluating capacity expansion decisions however no single contribution captures all the different facets of the problem.

Keywords: Manufacturing network; Capacity expansion; Multiple factor; Holistic models

1. Introduction

Investment in capacity expansion remains one of the most critical decisions for a manufacturing corporation 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 so a key part of a company's operations strategy. As Rudberg and Olhager (2003) reported, this view is widely supported (e.g. by Porter, 1980; Fine and Hax, 1985; Hill, 1989; Samson, 1991; Miltenburg, 1995; Slack et al., 1995; Skinner, 1996). The capacity expansion decision can vary in form, for example, it can be in a policy based on an infinite time horizon or a one-off expansion step based on a single period (Luss, 1982). The decision can specify the timing of expansion, the size of expansion, the product impacted and the production location. Similarly, the various factors affecting this decision can include the 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 these factors makes each capacity expansion decision complex.

Since the early 1960s, many studies of capacity expansion problems have been conducted. Manne (1961) provides the first and simplest models. These assumed deterministic demand, single facilities, and infinite economic life. His book (Manne, 1967a)

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went on to give a description of various capacity problems in which optimal location for each expansion is considered explicitly (Erlenkotter, 1967; Manne, 1967b). By the early 1980s, the capacity expansion literature evolved to include a variety of issues and consider multiple facilities in the decision-making process, though Luss (1982) noted that the typical objective was to minimise the discounted costs associated with the expansion. Porter (1980), however, argued that capacity expansion is a very subtle problem and not as simple as just carrying out analysis based on a few factors. Many subsequent contributors have therefore sought to provide more sophisticated methods. For example, much recent work has focused on exploiting advanced computational techniques (Syam, 2000) or broadening models to incorporate soft factors (O'Brien and Smith, 1993; Meijboom and Voordijk, 2003). In light of these contributions, it would be helpful to know the extent to which the earlier concerns of Porter, and others, have been addressed. Therefore, the purpose of this paper is to report on a review of the literature, which we have carried out, to determine the current state of research in multiple factor models for capacity expansion in manufacturing plants of corporations.

The paper is structured as follows. Section 2 explains the problem of capacity expansion and defines key terminology. Section 3 then provides a summary of our research design that has resulted in a three phase programme of work. The first phase (Section 4) establishes the research relevant to this investigation. This is followed (Section 5) by the identification of a comprehensive set of factors, against which models for capacity expansion can be measured, and the subsequent evaluation of existing models against these. The third phase (Section 6) provides a detailed analysis of our findings and finally leads on to the conclusions and directions for future research.

2. Background

This section discusses the industrial challenge and defines the key terminology associated with multi-factor models for capacity expansion.

2.1. The industrial challenge and multi-factor models for capacity expansion

Fuelled by the Asian economies the global demand for manufactured goods continues to rise. As market demand increases, and if existing manufacturing plants are close to their maximum capacities, corporations face decisions about where and how to expand their production capacities. There are few tools to aid the practitioner. Some techniques do exist and amongst these are 'multi-factor' models. These enable a structured analysis of the potential impact of an investment, usually in terms of financial criteria, during the business planning phase of a project.

Multi-factor models are fundamentally aids to strategic capacity planning in a manufacturing network. Capacity can be defined as the maximum level of value-added activity over a period of time (Slack et al., 1995) or, alternatively, the throughput or output capacity and measured as the number of units produced by a resource in unit time (Buffa, 1983). As a manufacturing network is a set of plants producing similar goods, 'capacity of the manufacturing network' can be considered to be the sum of capacities of the individual plants. Hence, 'capacity expansion in a manufacturing network' implies addition of capacity to the network.

Illustrated in Fig. 1 is a typical multi-factor model 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*.

2.2. Plant configurations 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 (Fig. 2a) and, second, a single centralised plant which exports to all countries (Fig. 2b). Most global manufacturing networks operate somewhere between the above two extreme configurations (Fig. 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. As production in plants in a manufacturing network reach their maximum capacities, the need to decide upon the investment for capacity expansion also arises. The

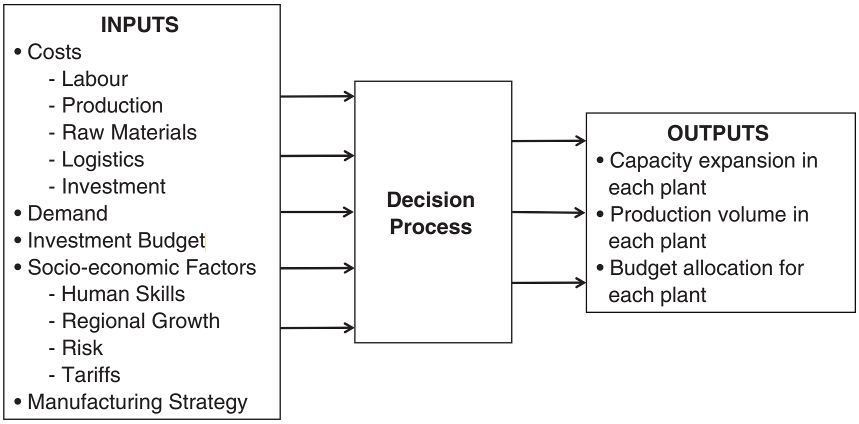

Fig. 1. Example of inputs and outputs for a multi-factor model for capacity expansion.

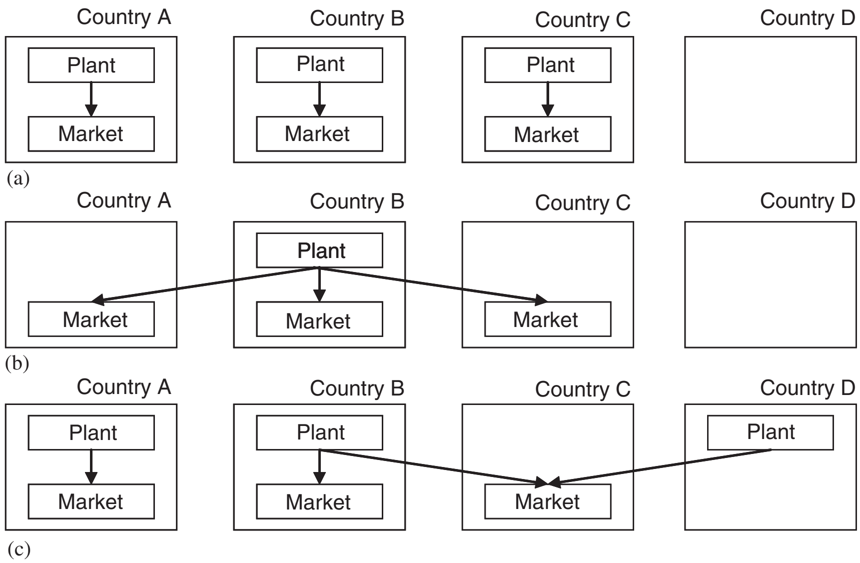

Fig. 2. Plant configurations for global manufacturing networks (adapted from Chakravarty, 2005).

capacity expansion decision then may result in the structure of the network changing.

2.3. *Previous research on capacity expansion in manufacturing networks*

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 models 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 models 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 US firms is discussed by Bulan (2005).

Luss (1982) provides the latest comprehensive review of capacity expansion literature (van Meighem, 2003) and identifies various research issues (Table 1). 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) 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.

Table 1
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: $\beta(1\text{-}\exp(\delta t))$
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 multifacility	Multilocation–same country/area Multilocation–global Multitype (multiple products)
Capacity modification	Capacity conversion Replacement

3. Overview of research programme and methodology

The aim of the research described in this paper is to provide a contemporary review of research in multi-factor models for capacity expansion and so identify opportunities for future work. To achieve this, the following research objectives have been to:

1. Establish literature that is relevant to the capacity expansion decision.
2. Review contributions to identify the range of factors considered in models along with the associated assumptions and solution techniques.
3. Analyse the strengths and weaknesses of the research base and so establish the opportunities for further work.

These objectives naturally lead to a three-phase research programme. Phase 1 consisted of a structured search through databases and filtering to identify relevant literature. Phase 2 generated a comprehensive categorisation of factors based on a detailed review of contributions. Then, in Phase 3, analysis was carried out to identify the strengths, weaknesses, and opportunities in the literature base. Execution of Phases 1, 2 and 3 are described in detail in Sections 4, 5 and 6, respectively.

4. Phase 1: Identification of relevant literature

Initially searches were conducted in 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. Searches in ABI/INFORM were focused on scholarly peer-reviewed journals, whereas the Web of Knowledge searches included conference 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 100 papers were identified and included in the first cut search results.

The set of papers collated from the above search were further refined by taking into consideration the industrial domain. Papers not relevant to manufacturing, for example those from the sectors of telecommunication networks, power networks, utilities and the 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, b) 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 et al., 1992; Higle and Corrado, 1992; Dangl, 1999; Ahmed et al., 2003), investment in flexible production technology (Fine and Freund, 1990; Van Meighem, 1998; Netessine et al., 2002; Cochran and Uribe, 2005), machine replacement (Rajagopalan et al., 1998; Chand et al., 2000) and risk (Callen and Sarath, 1995; Birge, 2000; Borgonovo and Peccati, 2004). Following this process, eleven multi-factor models were identified as illustrated in Table 2.

5. Phase 2: Factor analysis

This section presents the categorisation and summary of the factors put forward in the models shown in Table 2.

5.1. Process of categorising models

The multi-factor models were 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 we improved our confidence in our assessment. A short summary of the models and their associated factors is given in chronological order in the following subsection.

5.2. Description of principal models

Reeves et al. (1988) consider 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 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 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. They formulate the problem as a mathematical programme and develop a two-phase approach using heuristics 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.

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

Table 2
Contrasting the work on holistic models for capacity expansion

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)
Inputs											
Product demand											
Overall demand	√	√	√	√	√	√	◇		√		√
Unsatisfied demand					√	√		◇			
Demand uncertainty			√				√		√		
Demand function									√	√	
Cost of investment											
Investment cost function	◇	√	√		√		√	√		√	√
Cost for per unit of capacity		◇	√		√			√		◇	
Capacity replacement cost			√								
Capital requirement per unit output in new facilities	√		◇			√		◇	√	√	
Production costs											
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)	◇	√					◇				
Initial capacity											
Initial dedicated capacity		√	√	√	√	√		√	√	√	√
Initial flexible capacity		√									
Market/economic factors											

Diversification needed				√							
Market size in the country										√	
Local taxes										√	
Currency exchange rates										√	
Capacity shortage penalty (demand unsatisfied)						√		√			
Lead time and learning											
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)					√						
Accounting policies											
Expected net present values for per unit of capital	√	◇						√		◇	√
Allocation of plant overheads										√	
Investment budget											
Regional expansion budget	√			◇							
Global expansion budget	√			◇						√	√
Other costs											
Capacity holding costs					√	√					
Capacity relocation costs											√
Outputs											
Production volume (dedicated technology)			√	√	√		√	√		√	√
Production volume (flexible technology)			√				√				
Price of product produced (dedicated technology)							√			√	

Table 2 (*continued*)

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)
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 and 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			√					√		√	
Assumptions											
Multiple plants producing multiple products	√			√					√	√	√
Single plant producing multiple products		√	√		√	√	√	√			
Machine replacement permitted			√								
Quantity discounts			√								
Service level to customer to be maintained									√		
Risk of capacity shortages considered						√			√		√

Deferred capacity expansion (leasing/outsourcing)						√					√
Capacity takes certain leadtime 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 permitted (old to new)											√
Techniques											
Multi-objective linear programming model	√										
Interactive sequential goal programming	√										
Mixed integer linear programming model (MIP)			√	√	√						√
Heuristics		√	√	√	√	√				√	
Lagrangian relaxation (LP)		√	√	√	√	√		√			
Integer programming		√									
Disaggregate formulation			√								
Theoretical modelling							√	√	√	√	
Financial option pricing									√		
Dynamic programming					√	√					
Sensitivity analysis										√	
Non-linear optimisation										√	

Factors directly included in the process √.
Factors indirectly included in the process ◇.

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 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 Van 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.

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.

Melo et al. (2005) propose a mathematical modelling framework to address many practical aspects of manufacturing network design simultaneously. These include 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).

6. Phase 3: Analysis and discussion

On the basis of the results given above this section considers the strengths, weaknesses, and opportunities in the literature base. A summary of this analysis is shown in Fig. 3.

6.1. Strengths of current research

There are eleven papers (see Table 2) which were identified as relevant work that addresses multiple factors. Collectively, they comprehensively consider almost all the 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 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

Strengths • Four factors considered important - product demand, cost of investment, production costs and initial capacity. • Solution techniques are rigorous. Solution techniques which provide close to optimal results are also developed. • Quality of decision is enhanced by additional techniques of risk diversification and sensitivity analysis.	Weaknesses • No model holistic enough to handle all the factors deemed important for capacity expansion. • The list of factors is extensive but incomplete. • No description of the sources of data or involvement of company personnel. • Guidelines for industrial adoption absent. No case studies that will enable a decision maker to adopt such models.
Opportunities • Development of a holistic model for capacity expansion based on the list of factors identified in the study • Development of an implementation path to facilitate adoption of above model to industry • Conduct a case study based on the above process	Threats • Research moving away from the industry and users • Work not embedded in decision sciences • Industrial relevance needs to be established with case-studies

Fig. 3. A summary of the current condition of literature in the field of multi-factor capacity expansion models for the manufacturing industry.

operating cost functions for both dedicated and flexible technologies.

Finally, initial capacity is a factor identified as important by the analysis of Table 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.

6.2. 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. Work by Reeves et al. (1988), Chakravarty (2005) and Melo et al. (2005) are closest to being holistic models as they consider the maximum number of identified 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) 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 fearing a further 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 wafer fabrication industry is presented by Nazzal et al. (2006). They provide a complete decision making process including simulation modelling, design of experiments, statistical analysis and economic justification. However, the 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.

6.3. 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 a truly holistic 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.

7. Concluding remarks

The aim of this paper was to establish the current state of research in multi-factor models for capacity expansion. The capacity expansion problem has been described and a three-stage research programme has systematically reviewed and analysed the literature. A structured summary of the results of the study is presented using strengths, weaknesses, opportunities and threats tool (See Fig. 3).

The research leads us to conclude that although substantial work has been carried out in this field, no model yet provides a truly holistic capability. This is a key research opportunity. However, more generally, there is also a significant opportunity to report more widely on the application of all models within industry. One way to achieve this will be to run industrial case studies using the present as well as any future models proposed. Such experiences will be vital in moving forward work in this area.

References

Ahmed, S., King, A.J., Parija, G., 2003. A multi-stage stochastic integer programming approach for capacity expansion under uncertainty. Journal of Global Optimisation 26, 3–24.

Amico, M., Pasek, Z.J., Asl, F., Perrone, G., 2003. A new methodology to evaluate the real options of an investment using binomial trees and Monte Carlo simulation. In: Proceeding of the Winter Simulation Conference, New Orleans, USA, 7–10 December, pp. 351–359.

Bean, J.C., Smith, R.L., 1985. Optimal capacity expansion over an infinite horizon. Management Science 31 (12), 1523–1532.

Bean, J.C., Higle, J.L., Smith, R.L., 1992. Capacity expansion under stochastic demand. Operations Research 40 (2), 210–216.

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., Hong, S.J., 2006. Coordinating the resource investment decision for a two market, price-setting firm. International Journal of Production Economics 101, 63–88.

Borgonovo, E., Peccati, L., 2004. Sensitivity analysis in investment project evaluation. International Journal of Production Economics 90, 17–25.

Buffa, E.S., 1983. Modern Production/Operations Management. Wiley, New York.

Bulan, L.T., 2005. Real options, irreversible investment and firm uncertainty: new evidence from US firms. Review of Financial Economics 14, 255–279.

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

Caulkins, J.P., Fine, C.H., 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., McClurg, T., Ward, J., 2000. A model for parallel machine replacement with capacity expansion. European Journal of Operational Research 121, 519–531.

Cochran, J.K., Uribe, A.M., 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.

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

Dixit, A., Pindyck, R., 1994. Investment Under Uncertainty. Princeton University Press, Prineton, NJ.

Erlenkotter, D., 1967. Two producing areas—dynamic programming solutions. In: Manne, A.S. (Ed.), Investments for Capacity Expansion: Size, Location and Time-Phasing. MIT Press, Cambridge, MA, pp. 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., Lander, D.M., 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., Freund, R.M., 1990. Optimal investment in product-flexible manufacturing capacity. Management Science 36 (4), 449–466.

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

Freidenfelds, J., 1981. Near optimal solution of a two-type capacity expansion problem. Computers & Operations Research 8, 221–239.

Gaimon, C., Burgess, R.H., 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.

Harrison, J.M., Van Mieghem, J.A., 1999. Multi-resource investment strategies: operational hedging under demand uncertainty. European Journal of Operational Research 113, 17–29.

Higle, J.L., Corrado, C.J., 1992. Economic investment times for capacity expansion problems. European Journal of Operational Research 59, 288–293.

Hill, T., 1989. Manufacturing Startegy: Text and Cases. Palgrave, Hampshire.

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

ISI, 2005. Web of Knowledge: Web of Science. http://wok.mimas.ac.uk/.

Kanter, R., 1995. The new business cosmopolitans. Strategy and Business Fall, 66–77.

Karsak, E.E., Ozogul, C.O., 2002. An options approach to valuing expansion flexibility in flexible manufacturing. The Engineering Economist 47, 169–193.

Kim, B., Lee, Y., 2001. Global capacity expansion strategies: lessons learnt from two Korean carmakers. Long Range Planning 34, 309–333.

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

Luss, H., 1982. Operations research and capacity expansion problems: a survey. Operations Research 30 (5), 907–947.

Manne, A.S., 1961. Capacity expansion and probabilistic growth. Econometrica 29, 632–649.

Manne, A.S., 1967a. Investments for Capacity Expansion: Size, Location and Time-Phasing. MIT Press, Cambridge, MA.

Manne, A.S., 1967b. Two producing areas—constant cycle time policies. In: Manne, A.S. (Ed.), Investments for Capacity Expansion: Size, Location and Time-Phasing. MIT Press, Cambridge, MA, pp. 193–209.

Marris, R., 1964. The Economics of Capital Utilisation: A Report on Multiple Shift Work. Cambridge University Press, Cambridge.

Masud, A.S., Hwang, C.L., 1981. Interactive sequential goal programming. Journal of Operational Research Society 32, 391–400.

Meijboom, B., Voordijk, H., 2003. International operations and location decisions: a firm level approach. Tijdschrift voor economische en sociale geografie 94 (4), 463–476.

Melo, M.T., Nickel, S., da Gama, F.S., 2003. Large-scale models for dynamic multi-commodity capacitated facility location. Fraunhofer Institut Techno- und Wirtschaftsmathematik 58 www.itwm.fraunhofer.de.

Melo, M.T., Nickel, S., da Gama, F.S., 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., Park, C.S., 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. Productivity Press, Portland, OR.

Nazzal, D., Mollaghasemi, M., Anderson, D., 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., Dobson, G., Shumsky, R.A., 2002. Flexible service capacity: optimal investment and the impact of demand correlation. Operations Research 50 (2), 375–388.

O'Brien, C., Smith, S.J.E., 1993. Design of the decision process for strategic investment in advanced manufacturing systems. International Journal of Production Economics 30–31, 309–322.

Perrone, G., Amico, M., Lo Nigro, G., La Diega, S.N., 2002. Long term capacity decisions in uncertain markets for advanced manufacturing systems incorporating scope economies. European Journal of Operational Research 143 (1), 125–137.

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

Proquest, 2005. ABI/INFORM. 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., Swaminathan, J.M., 2001. A coordinated production planning model with capacity expansion and inventory management. Management Science 47 (11), 1562–1580.

Rajagopalan, S., Singh, M., Morton, T., 1998. Capacity expansion and replacement in growing markets with uncertain technology breakthroughs. Management Science 44, 12–30.

Reeves, G.R., Lawrence, K.D., Lawrence, S.M., Gonzalez, J.J., 1988. A multiple criteria approach to aggregate industrial capacity expansion. Computers and Operations Research 15 (4), 333–339.

Rudberg, M., Olhager, J., 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. Prentice-Hall, Sydney.

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., Chambers, S., Harland, C., Harrison, A., Johnson, R., 1995. Operations Management. Pitman Publishing, London (Melbourne).

Syam, S.S., 2000. Multiperiod capacity expansion in globally dispersed regions. Decision Sciences 31 (1), 173–195.

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.

Wheelwright, S.C., 1978. Reflecting corporate strategy in manufacturing decisions. Business Horizons 21 (February), 57–66.