Manuscript Details

Manuscript number	OMEGA_2018_533_R1
Title	A strategic and global manufacturing capacity management optimisation model: A Scenario-based multi-stage stochastic programming approach
Article type	Research Paper

Abstract

Large-scale multinational manufacturing firms often require a significant investment in production capacity and extensive management efforts in strategic planning in an uncertain business environment. In this research, we first discuss what decision terms and boundary conditions a holistic capacity management model for the manufacturing industry must contain. To better understand how these decision terms and constraints have been employed by the recent model developers in the area of capacity and resource management modelling for manufacturing, 69 optimisation-based (deterministic and stochastic) models have been carefully selected from 2000 to 2018 for a brief comparative analysis. The results of this comparison show although applying uncertainty into capacity modelling (in stochastic form) has received a greater deal of attention most recently (since 2010), the existing stochastic models are yet very simplistic, and not all the strategic terms have been employed in the current model developments in the field. This lack of a holistic approach although is evident in deterministic models too, the existing stochastic counterparts proved to include much fewer decision terms and inclusive constraints, which limits them to limited applications and may cause sub-optimal solutions. Employing this set of holistic decision terms and boundary conditions, this work develops a scenario-based multi-stage stochastic capacity management model, which is capable of modelling different strategic terms such as capacity level management (slight, medium and large capacity volume adjustment to increase/decrease capacity), location/relocation decisions, merge/decomposition options, and product management (R&D, new product launch, product-to-plant and product-to-market allocation, and product phase-out management). Possibility matrix, production rates, different financial terms and international taxes, inflation rates, machinery depreciation, investment lead-time and product cycle-time are also embedded in the model in order to make it more practical, realistic and sensitive to strategic decisions and scenarios. A step-by-step open-box validation has been followed while designing the model and a holistic black-box validation plan has been designed and employed to widely validate the model. The model then has been verified by deploying a real-scaled case of Toyota Motors UK (TMUK) decision of mothballing one of their production lines in the UK after the global recession in 2010.

Keywords	Stochastic programming; Optimisation modelling; Capacity Management; Manufacturing
Manuscript category	Research Paper- Production Management or Scheduling & Logistics

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Submission Files Included in this PDF

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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
The authors do not have permission to share data

Revision Submission to *Omega*

Dear Editorial Board,

I am pleased to submit the revised version of the attached paper titled "A strategic and global manufacturing capacity management optimisation model: A Scenario-based multi-stage stochastic programming approach" authored by Sabet E., Kian R., Galanakis K. and Yazdani B. to your consideration as a research article for publication in the journal of *Omega,* and after the first round of revision. In this manuscript we develop a scenario-based multi-stage stochastic capacity management model by considering holistic decision terms and constraints. We have verified the model by deploying a real-scaled case of Toyota Motors UK (TMUK) decision of mothballing one of their production lines in the UK after the global recession in 2010.

I hereby declare that this paper is containing original research and has not been published earlier in any journal and is not being considered for publication elsewhere. Besides, none of the authors of this paper has conflict of interest with other people or organizations that could inappropriately influence or bias the content of the paper.

Thank you for your consideration of this revision.

Yours sincerely,

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Response Letter to the Reviewer Comments on the paper titled

A strategic and global manufacturing capacity management optimisation model: A Scenario-based multi-stage stochastic programming approach

by

Sabet, Kian, Galanakis and Yazdani

We sincerely thank the reviewers for their detailed, formative and positive comments that have allowed us to improve our paper.

We explain below how their concerns have been addressed. In order to facilitate reading, all changes are highlighted in blue font in the revised paper.

Associate Editor:

This paper gives a good survey on papers on capacity planning up to 2016. A model is presented illustrated with a case study. As recommended by the reviewers, a revision is recommended. The author should:

1. Update the survey to include papers since 2016,

2. Check and validate the correctness of the model,

3. Check and improve the grammar and writing, and

4. Address the concerns of the reviewers

Response: We highly appreciate your comments and positive feedback and thank you for giving us a chance to revise the paper in line with your and reviewers comments.

1- The survey has been updated and nine most recent papers (2017 and 2018) have been added to the survey. Table 5 and 6, and section 1.2 have been updated accordingly. To take the first reviewer's comment on board, Table 5 and 6 have been moved to the appendix (in the revised paper they are numbered Table 14 and 15).
2- After a few changes suggested by the reviewers, the model was checked two more times to ensure its correctness. We can now confirm its validity.
3- The revised paper received a proofread, and all changes are highlighted in blue within the revised version.
4- All concerns of the reviewers have been very carefully studied, addressed in the revised version, and responded below.
We sincerely believe the thoughts and efforts that the reviewers have put into commenting on our paper have definitely improved our paper.

Reviewer 1:

In this paper, the authors propose a holistic approach for strategic decision-making in manufacturing industry. Different strategic terms, such as capacity level management (slight, medium and large capacity volume adjustment to increase/decrease capacity), location/relocation decisions, merge/decomposition options, and product management (R&D and design, new product launch, product-to-plant and product-to-market allocation, and phase-out management), are considered. The authors also consider demand uncertainty and propose a stochastic programming model to hedge against uncertainty. We believe the paper is well-written and has value for publication. However, the authors need to address the following minor comments and questions.
Response: This is a precise summary of what we aimed to present in this paper and it is great to read that the first reviewer has found merits in our paper for publications.

1. In paper, the authors claim to propose a multi-stage stochastic programming model. However, in the example in section 5, the authors assume that there are only three scenarios with high, medium, low demand, respectively. We believe, the model is actually a two-stage stochastic programming problem. The author can refer to the book of John Birge for the definitions.

Response: The reviewer is right in observing that in our examples and verification cases we have used the common approach of three main scenarios (the best case, the worst case and the most probable scenarios) to simplify the examples. However, the problem formulation is not limited to three scenarios and in fact the model is constructed for multiple scenarios in a scenario-tree format. Besides, the decision variables are open to different stages, meaning that a decision made at one stage can be changed/modified at multiple later stages. For example, a new capacity can be opened in a certain stage and at a certain time step and can be subsequently relocated at later stages and finally get merged/closed/extended at a later stage; similar to the example given for a multi-stage stochastic model at John Birge book that the reviewer kindly recommended (page 65, under the second paragraph of section d). As such, we believe the model is a multi-stage stochastic model. However, in the Toyota UK case (section 5) a two-stage version of the model has been employed as explained in the new paragraph added to the end of the section (see the second sentence of the last paragraph), to respond to the reviewer's comment.

2. Should equation (21) be

$$K_{zti}^{FaAll} \leq \left(1 - Y_{zti}^{Cl}\right)M$$

instead of $\left(1 - Y_{zti}^{Cl}\right)M \leq K_{zti}^{FaAll}$? In other words, the cumulative mothballed capacity is forced to zero is the plant is closed.

Response: We thank the reviewer for the very precise checking. That was a mistake and the correction has been done in the revised version. In the revised version that constraint is now (24).

3. Table 5 takes too much space in the paper while the authors do not analyze the table to great detail. It is preferable to put Table 5 in the appendix.

Response: Thanks for this comment. We acknowledge that this table had not been greatly discussed and analysed in the body of the paper due to the space limitations. We have updated the table 5 and 6 (and section 1.2) to include the most recent studies

(2017 and 2018) and then moved both tables to the Appendix as suggested by the reviewer. In the revised version they are Tables 14 and 15.

4. In page 13, “Traditionally in the real scale optimisation practices, often stochastic parameters have been replaced by their expected values (so called deterministic equivalent of the model)”. This is not called the “deterministic equivalent of the model”. This is called the “expected value problem”. Please refer to John Birge’s book for the definition of deterministic equivalent.

Response: We thank the reviewer for this formative comment. The term has now been corrected in the revised version.

5. It would be desirable to show the size of the optimization problems that are solved, i.e., the number of binary variables, the number of continuous variables, the number of constraints. Solution statistics such as the solution time and the optimality gap should also be reported.

Response: This is a fair and accurate comment by the first reviewer. One paragraph has been added to the end of section 5 in the revised version to address this comment. We appreciate this paragraph may not entirely satisfy all of the first reviewer’s comments, but as the model had been run on one of the major car manufacturers’ central server at the time (2011), we no longer have access to this case for all the inputs, details, and solution statistics. We acknowledge this is a shortcoming in our paper, but we believe the reviewer would appreciate our limitations.

Reviewer 2:

This paper indicates a gap in the current model development practices to design a more holistic and integrated capacity management model in a stochastic form that can handle market uncertainty, while no compromise is needed on decision terms and boundary conditions. The authors have addressed this gap and developed a stochastic model that can simultaneously handle capacity level management, capacity location, relocation merge and decomposition, product development, and technology management. The paper contains some publishable materials. However, it has some major issues to be addressed.

Response: Thanks for the accurate summary of our work and for your positive comment on publication potential of our paper. We appreciate all your comments and below we have attempted to address your concerns.

1. Sec. 1.2, the authors mention "the most recent 60 models in the field" but their table contains the models till 2016 only. The authors should search for 2017 and 2018 papers to enhance it. They may focus recent 10 years' related work while citing other survey/review papers for older papers and findings.

Response: The referee is right. In the revised version we have updated the literature review as well as Table 5 and 6, with 9 more related papers, published between 2017 and 2018. Besides, Figure 2 and section 1.2 have been revised and updated accordingly. To take the first reviewer's comment on board as well, we have moved Table 5 and 6 to the appendix (in the revised version they are Tables 14 and 15).

2. In mathematical formulations like (1), I would suggest the authors to adopt single letters instead of multiple ones for all important variables and parameters. I especially dislike "R&D"as a math symbol in such formulation.

Response: We thank the reviewer for the valuable comment to improve readability of the paper. All the variable and parameters are now in single letter form, including those in the objective function (1) and all "$R\&D_{z,t}$" math symbols have been replaced with $D_{z,t}$.

3. (3) and (4) contain some problems. Do you mean "z,t,i ∈{Exp,Fr,Re,Cl}"?

Response: The reviewer is correct. Constraint (4) was not written formally and correctly in the previous version. It should have been written as four different constraints. They are now reflected as constraints (4),(5),(6),(7). We have kept constraint (3) unchanged.

4. There are too many presentation problems. In Abstract, "this paper develops" => "this work develops". "investment lead-times"=>" investment lead-time".

Response: We thank the reviewer for all editorial and detail comments. We can confirm they have all been corrected in the revised version.

5. In Sec. I, Line 1, "one the most important management tasks"=> "one of the most important management tasks". Page 2, Line 4, add "a" before "quantitative approach".

Lines 6-7, “between available strategic choice” => “among available strategic choices”. Line 9, “which is aimed for this paper” => “which is aimed by this work”.

Response: We thank the reviewer. These have been corrected in the revision.

6. In Sec. 1.1.5, Line 2, “will be”=>”are”. Please make other related changes throughput this paper.

Response: We thank the reviewer. They have been corrected.

7. In Sec. 3.4.1, “Constraints (3) holds” => “Constraint (3) holds”.

Response: Correction has been done.

8. Fig. 3 needs some rework such that b/w printing is clear as well.

Response: The referee is right. A higher quality and B&W print-friendly version has now been replaced.

9. Line 2 above Sec. 6, “a mothball of one the production lines” has bad English.
Response: We thank the reviewer. It is restructured in the revised version.

10. Page 30, Line -3, “This paper was aimed “ => “This work aims”.

Response: Correction has been done.

11. The following references seem related and should be cited:

Hao Liu, Qianchuan Zhao, Ningjian Huang, Xiang Zhao. Production Line Capacity Planning Concerning Uncertain Demands for a Class of Manufacturing Systems with Multiple Products. IEEE/CAA Journal of Automatica Sinica, 2015, 2(2), 217-225
F. J. Yang, K. Z. Gao, I. W. Simon, Y. T. Zhu, and R. Su, “Decomposition methods for manufacturing system scheduling: a survey,” IEEE/CAA J. of Autom. Sinica, vol. 5, no. 2, pp. 389-400, Mar. 2018.

Response: Thanks for introducing two interesting and useful studies. They have been used and cited in the revised version, along with several other references according to comment #1.

A strategic and global manufacturing capacity management optimisation model: A Scenario-based multi-stage stochastic programming approach

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Abstract

Large-scale multinational manufacturing firms often require a significant investment in production capacity and extensive management efforts in strategic planning in an uncertain business environment. In this research we first discuss what decision terms and boundary conditions a holistic capacity management model for the manufacturing industry must contain. To better understand how these decision terms and constraints have been employed by the recent model developers in the area of capacity and resource management modelling for manufacturing, 69 optimisation-based (deterministic and stochastic) models have been carefully selected from 2000 to 2018 for a brief comparative analysis. The results of this comparison show although applying uncertainty into capacity modelling (in stochastic form) has received a greater deal of attention most recently (since 2010), the existing stochastic models are yet very simplistic, and not all the strategic terms have been employed in the current model developments in the field. This lack of a holistic approach although is evident in deterministic models too, the existing stochastic counterparts proved to include much less decision terms and inclusive constraints, which limits them to limited applications and may cause sub-optimal solutions. Employing this set of holistic decision terms and boundary conditions, this work develops a scenario-based multi-stage stochastic capacity management model, which is capable of modelling different strategic terms such as capacity level management (slight, medium and large capacity volume adjustment to increase/decrease capacity), location/relocation decisions, merge/decomposition options, and product management (R&D, new product launch, product-to-plant and product-to-market allocation, and product phase-out management). Possibility matrix, production rates, different financial terms and international taxes, inflation rates, machinery depreciation, investment lead-time and product cycle-time are also embedded in the model in order to make it more practical, realistic and sensitive to strategic decisions and scenarios. A step-by-step open-box validation has been followed while designing the model and a holistic black-box validation plan has been designed and employed to widely validate the model. The model then has been verified by deploying a real-scaled case of Toyota Motors UK (TMUK) decision of mothballing one of their production lines in the UK after the global recession in 2010.

Keywords: Stochastic programming, Optimisation modelling, Capacity Management, Manufacturing

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1 Introduction

Resource management is one of the most important management tasks in manufacturing (Julka et al. 2007), and production capacity is the most strategic internal capability that manufacturing firms must create, sustain and plan for (Chen et al. 2002). Capacity management aims to ensure that a manufacturer has the 'right' capacity to act within a complex structure (Ambrosi 2010); and how best to 'utilise' their internal capabilities (Olhager et al. 2001). Due to the inherently parametric nature of the capacity management decisions, a quantitative approach has been more employed in this field (Julka 2008; Pidd 2003). However, an analytical decision-making model at best will only assist managers to better analyse and understand the trade-offs among available strategic choices (Eppen et al. 1989); and hence implementing a holistic set of important variables and decision terms in such models can improve the understanding of the trade-offs and prevent sub-optimal decisions, which is aimed by this work.

1.1 Decision Terms and Constraints of a Holistic Strategic Capacity Management Model

This section discusses the terms that must be embedded in a strategic capacity management model, which are categorised in four main groups of capacity level management, capacity location management, product and process management, and other terms as financial, political and environmental (Sabet 2012). Using 'input, control, output and mechanism' (ICOM) framework (Matta et al. 2005), the following sub-sections aim to introduce these critical decisions, and step by step configure the overall ICOM framework as summarised in Figure 1, which sets the boundary conditions for the model developed by this paper (Section 3).

1.1.1 Capacity Level Management

Adjusting production level to the long-term changes in demand, with minimum cost and lead-time implications, is the baseline for all capacity management models (Kauder and Meyr 2009). In manufacturing industry production capacities often change in bulk (so called 'lumpy nature' of the production capacity), indicating that the capacity changes in discontinuous and non-linear volumes (Olhager et al. 2001). Besides, manufacturing capacity often can change in 3 ranges of slight, medium and significant (Lin et al. 2010), in sequential form of over-utilization, capacity expansion and new plant/line establishment for capacity increase, and underutilisation, mothball and capacity shut-down for capacity decrease scenarios. See Table 1.

Table 1: ICOM summary for capacity level management- No term for mechanism

	Output	Input	Control
Capacity Level	• Capacity increase (over-utilization, expansion, new plan) • Capacity decrease (over-utilization, mothball, shut-down)	• Maximum annual budget for investment • Current capacities structure: location (in relate to suppliers and customers), operations costs, shut-down costs, expansion costs, over and under-utilisation costs, labour costs, etc. • New plant choices and their cost structure	• Lumpy nature of capacity change • Investment lead-time • Logical Constraints: non-negativity, non-aticipativity, non-simultaneity

1.1.2 Capacity Location Management (Location, Relocation, Merge and Decomposition)

In 1990's and 2000's, more than 75% and 90% of the biggest American companies invested in factories outside their countries respectively (Hamad and Fares Gualda 2008) and more recently an increasing number of EU and US companies are reshoring, which shows a need for the location/relocation decision terms in the capacity management models. Location decisions are functions of the geographical dispersion of the firm's suppliers, their manufacturing facilities, their sales regions and their investment portfolio (Kauder and Meyr 2009), as well as labour cost and energy costs in different locations, tariff and trade concessions, capital subsidies and logistics costs (Ferdows 1997). All these parametric terms can be employed in a holistic model. However, subjective factors, such as the company's policies, organisational learning through closeness to the customers and higher reliability and visibility to customers ought to be taken to the model as possible input options (MacCormack et al. 1994). The lead-time of the location/relocation decisions must also be considered in modelling to make it more realistic and sensitive to investment portfolios (Mula et al. 2006). Sometimes relocation decision is being made to centralise or decentralise the production capacities of a firm (by merging or decomposition), which can be embedded into a location/relocation model, using merge/decomposition possibility matrix. See Table 2 for the ICOM terms of location, relocation, merge and decomposition.

1.1.3 Product and Process Management (product development and technology management)

Product life-cycles are often much less than the capacity management planning horizon, and thus the entire product life-cycle curve, from the new product development to mass-production and final phase-out stage must be included in the time horizon of a capacity management

Table 2: ICOM summary for Capacity location Management - No term for mechanism

	Output	Input	Control
Capacity Location	• Decision on different choices of locations for a new plan. • Decision on whether to close a plant to open a new choice of plant (relocation) • Decision on whether to close two or more current plant to open a new choice of plant (merge) • Decision to close a current plant and open two or more new choice of new plants (decomposition)	• Maximum annual budget for investment • Choices of new plants and current plant structures (as detailed in Table 1) • Taxes, inflations, capital subsidies, labour costs, energy costs • Supply cost/tariff sensitivity to locations • Sales sensitivity to locations (transportation costs and tariffs)	• Merge and decomposition possibility matrix (what set of current plant can be merged for a new choice of plant for merge case, and what plant can be closed down to open a set of new plants for decomposition)Investment lead-time • Investment lead-time • Logical Constraints: non-negativity, non-aticipativity, non-simultaneity

model (Francas et al. 2009). The early phases which often called new product development (NPD) can be divided into two main phases of design or 'research and development' (R&D) and new product launch (NPL). R&D covers innovation, concept development and prototype making, and NPL is about launching a new product into plants, setups, first batch productions, and production ramp-ups. R&D phase is often more centralised and carried out in research centres, while NPL phase requires some product-related investments in the allocated plants (Fleischmann et al. 2006). Besides, both R&D and NPL phases are timely, and their investment lead-time must be considered in the product management models (Papageorgiou et al. 2001). Technology management in capacity and resource management models can be divided into two main domains of manufacturing flexibility, and facility replacement (technology obsolescence). Manufacturing flexibility is about the ability of a system to change its capacity quickly and economically (Ceryan and Koren 2009). It can be categorised into two types of 'product-mix' and 'volume flexibilities' (Kauder and Meyr 2009). Product-mix explains how a production facility can quickly and efficiently switch from one product to another. Volume flexibility explains how quickly and economically a production facility can adjust its production volume to chase the demand. 'Possibility matrix' and 'Production capacity rate' are being commonly used respectively, to model product-mix and volume flexibility in the capacity management models. Luss (1982) studies both physical depreciation and technology obsolescence in technology acquisition models. To formulate technology obsolescence modellers must simultaneously employ product life-cycles, product-plant investment requirements and the overhaul cost of facilities, all in a cost-based objective capacity management model (Wu and Chuang 2010). Table 3 summarises ICOM terms for this section.

Table 3: ICOM summary for product and process management - No term for mechanism

	Output	Input	Control
Product & Process	• Product to plant allocations • Product to market allocation • What choice of new products to develop, when and in which plant • Product re-launch decision (when and in which plant) • Choice of process technology (in form of what choice of new plant or expansion technology is selected, when value increase is needed)	• Choice of process technology and their cost structure and depreciation • Choices of new plants and current plant structures (as detailed in Table 1) • R&D costs for each product family • Product-related investment portfolio in plants (for NPL) • Current and new product life-cycles (in sales forecast scenarios)	• Product/plant possibility matrix and product capacity rate • NPD and re-launch Investment lead-time

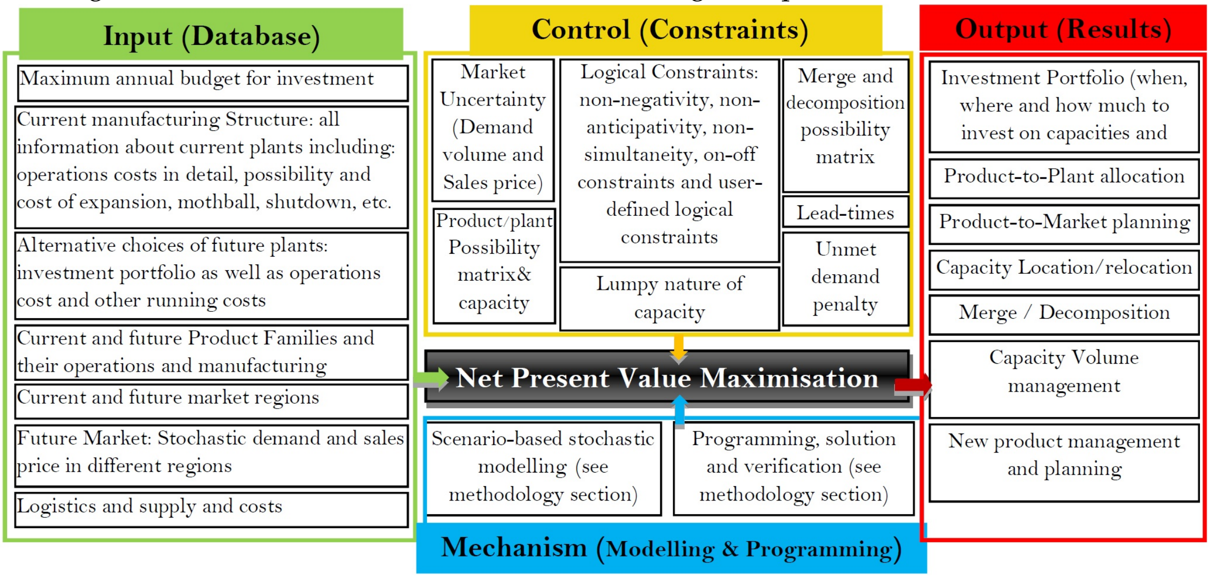
1.1.4 Other Terms (Financial, Political and Environmental)

Factors such as custom duties, inflation rates, tax on profit and value added tax have been mentioned as direct financial terms to be embedded in a strategic capacity management model (Fleischmann et al. 2006) to make a global capacity management model sensitive to location decisions (Verter and Dasci 2002). Although exchange rates directly affect capacity investment choices and relocation decisions (Farahani et al. 2010), there is no universally accepted exchange rate forecasting model (Bhutta et al. 2003). Besides, acquisition of the manufacturing resource is often of high lead-time; and therefore must be planned over a long term horizon (Olhager et al. 2001), for which uncertainty is an inevitable part (Chen et al. 2006). External sources of uncertainty, such as demand changes have been identified as the most disturbing and less controllable ones (Ahmed et al. 2003). However, many capacity planning models assume production should fulfil the entire demand, which may impose significant adjustments to the capacity level, even for a slight demand change. These unrealistic and sub-optimised solutions can be restrained by adapting an acceptable level of unsatisfied demand, which is usually associated with a penalty called 'unmet demand penalty' (Eppen et al. 1989). Although including supply chain selection decisions in capacity management models make them prohibitively complex, strategic capacity models can embed supply chain cost structure as a baseline for the supply chain (SC) related terms to make the models more sensitive to SC locations (Naraharisetti and Karimi 2010). Finally, although human resources and shift design may be considered as operational decisions, they affect some of the strategic ones such as capacity mothball and over/under utilisation; and thus, should not be entirely ignored in capacity management models. See Table 4.

Table 4: ICOM summary for financial and other terms - No term for mechanism

	Output	Input	Control
Financial Terms	• Shift management (in terms of adding or removing a shift to operations to change capacity level)	• Custom duties (on supply and sales, as a dependent of origin and destination countries) • Cost of supply (as a dependent of supplier location vs. manufacturing unit locations) • Inflation rates and tax in countries where R&D centres and manufacturing plants and are located • VAT in sales regions	• Market uncertainty (sales price and demand) • Unmet demand penalties

Figure 1: The Model's Framework in an ICOM logic adapted from Matta et al. (2005)



1.1.5 ICOM Summary for a Holistic Strategic Capacity Management Model

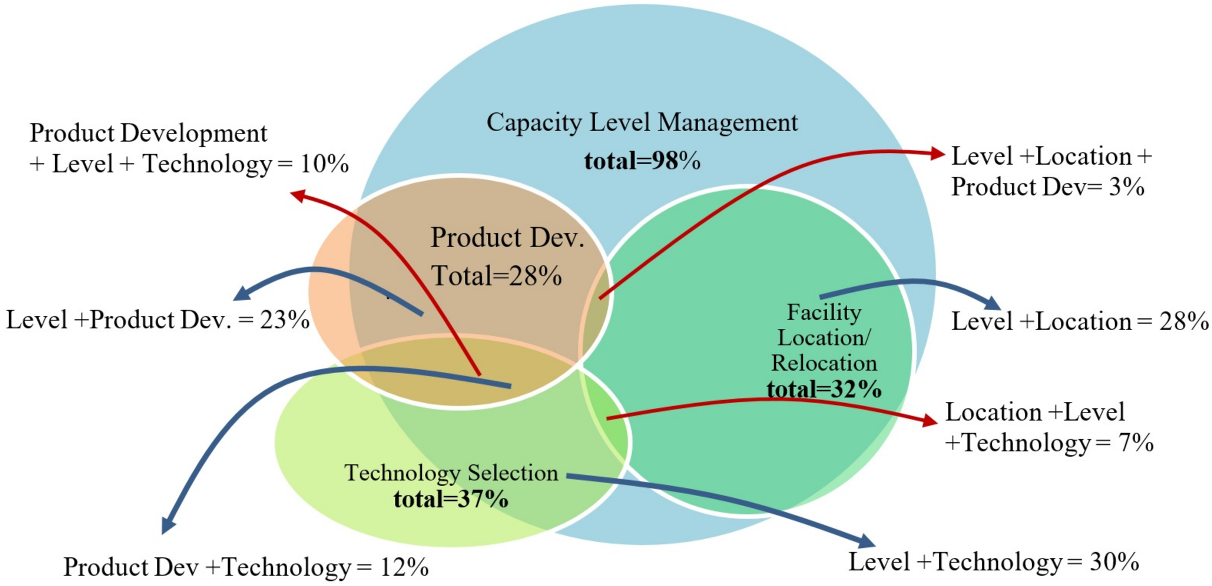
Figure 1 illustrates the boundary conditions of a holistic strategic capacity management model by summarising section 1.1 and Tables 1–4, which are employed in the model development in Section 3.

1.2 Recent Developments and Gaps in Strategic Capacity Optimisation Modelling

To better understand how the recent capacity optimisation models have covered the terms and parameters discussed before as the essential terms for a holistic capacity management model, and to understand how the model proposed in this paper contributes to the knowledge and practices in the field of capacity management modelling, Tables 14 and 15 (see Appendix) compare the terms employed in the most recent 69 models in the field. These models were found and selected in an extensive search for the optimisation-based models from those that embedded at least one of the strategic objective terms that was discussed in the last section. Scholar search engines such as Googlescholar, ScienceDirect, Emarald, IEEE Xplore, JSTOR and Springer were exploited in this search and after initial filtering to most relevant papers to the topic of this research and those published recently (2000 to 2018) these 69 papers were selected for a comparative analysis. To remark academic gaps in alternative topics of manufacturing systems including quantity production, transfer and assembly lines, balancing and, sequencing, etc., the reader may refer to a recent survey in (Yang et al. 2018).

Table 14 shows although embedding uncertainty in the modelling practice has recently received significant attention in capacity modelling, still just under one-third of capacity management models are deterministic. However, comparing Tables 14 and 15, one can see deterministic models tend to embrace more terms and factors into the modelling than their stochastic counterparts, and thus yet remained more multi-angels. Figure 2, summarises the findings from Table 14, and shows how well these recent models manage to simultaneously embed different terms in their formulations and stay multi-purpose.

Figure 2: How recent models in capacity management have embedded strategic terms



Although Table 14 shows capacity decrease modelling has widely left unattempted, Figure 2 illustrates still wide majority of the capacity management models have embedded at least one element of capacity level management in their models. However, only a few of these models have managed to embed at least three of the terms, and no model has yet covered all four strategic terms (Figure 2). Besides, as shown in Table 14, none of these models is capable of simultaneously managing all demand change possibilities (with over-utilisation, expansion and new capacity decisions in case of demand increase and under-utilisation, capacity mothball and capacity shutdown for demand decease scenarios), which limits the application of the models to a sub-set of potential applications. With regards to considering the product life-cycle in capacity management formulations, although the existing models have widely covered the mass production and decline phase, the early stages (concept design and product launch) have mainly left unattempted. Table 15 shows financial terms, detailed cost elements and control factors have been incompletely covered. As the result of this study, the model formulated in this paper (Section 3) aims to address these gaps and offer a more holistic capacity management model.

2 Methodology

Upon reviewing 103 models within the scope of resource planning under uncertainty, Peidro et al. (2009) categorised four quantitative approaches, namely analytical models, artificial intelligence-based models, simulation models and finally hybrid models. They summarise that the analytical approach has been more acknowledged and has had the fastest growth in resource management modelling (Peidro et al. 2009). As a part of analytical modelling, mathematical programming has been widely employed by peer scholars in strategic capacity management modelling (Hvolby and Steger-Jensen 2010; Melo et al. 2009; Mula et al. 2006). Traditionally in the real scale optimisation practices, often stochastic parameters have been replaced by their expected values (so called expected value problem) to make them deterministic and easier to programme and solve (Graves 2011). However, as explained in the last section, long-term capacity planning is subject to a vast uncertainty and thus simple estimations of expected values (or most probable scenarios) are no longer viable, and may lead to unrealistic capacity solutions (Barahona et al. 2005). Besides, statistical data are hardly reliable any more to forecast a long-term demand prospect, and thus a scenario-based stochastic programming has been employed as the most appropriate technique for log-term resource management modelling in Kauder and Meyr (2009), and therefore, is used in this paper, as well. The solution, validation and verification process are detailed later in this paper in Sections 4 and 5.

3 Problem Statement and Model Formulation

Led by ICOM framework in Section 1.1.5 (Figure 1), the rest of this section formulates the model and its constraints. The problem to be modelled is a long term strategic periodic capacity management problem by making decision on opening, closing, mothballing, reopening, expansion or overutilising different manufacturing plant in differently distributed geographical places under a stochastic demand or sales price in different regions by considering the transportation and cost of unmet demand, in such a way to maximise net present value of the firm. First we introduce the parameters and decision variables nomenclature in Table 5 and then describe different costs in the following subsections and subsequently, we present the objective function and mathematical model with the corresponding elaboration of the constraints.

3.1 Fixed Investment Costs

Some of the strategic capacity investments are long term (over one year time interval), and therefore, lead-time (η) should be included in the programming. In this model the lead-time applies to the investments on new plants, expansions, new product developments and research and developments. If any of these investment decision variables ($Z^{\text{New}}_{.t.}, Y^{\text{Exp}}_{.t.}, Y^{\text{NPL}}_{.t.}, Y^{\text{RD}}_{.t.}$) equals 1 at year t, investment starts a few years in advance (depending on the individual lead-time), so that the product or the production capacity is ready at the year t. Although to mothball a capacity the firm must also invest in redundancy and terminating supply contracts, it can often be conducted within the time intervals (one year) and need no lead-time. The same logic applies to shutdown decisions and reopening a mothballed capacity. Over-utilising a capacity requires annual investments for as long as the plant is over-utilised to invest in the extra times and third shifts, etc.. New product launch (NPL) occurs when a product is launched in any of the facilities for the first time. In such cases, a one-off launch cost is required for product-related investments (dedicated lines/machines, tooling, settings, training, first batch productions, system developments) and lead-time apply. However, relaunching an existing product after a long production-break needs a reset/changeover cost, but not as much as the NPL investment and it often needs no lead-time more than the time interval (one year). In a new product launch case, both Y^{PL} and Y^{NPL} equal 1; hence, the term $(Y^{\text{PL}} - Y^{\text{NPL}})$ is applied to the extended objective function (2) for the product relaunch investments.

Table 5: Nomenclatures list for the model formulation

Parameters				**Variables**	
$\vartheta^{\text{E-min}}$	*Min. capacity expansion rate of plant i, out of nominal cap*	Δ^{Opr}	*Inflation rate on operations cost*	X^{Unmet}_{ztrj}	*Amount of unmet product j in region r in year t under scenario z*
$\vartheta^{\text{E-max}}$	*Max. capacity expansion rate of plant i, out of nominal cap*	Δ^{Inv}	*Inflation rate on investment cost*	X^{A}_{ztij}	*Amount of product j in plant i in year t, under scenario z*
σ^{Tax}_{i}	*Profit tax rate in plant i location*	Δ^{Sup}	*Inflation rate on supply cost*	X_{ztrij}	*Amount of product j transported from plant i to region r in year t under scenario z*
$\sigma^{\text{Tariff}}_{ri}$	*Tariff rate of import from plant i to region r*	Δ^{D}	*Inflation rate on transportation cost*	Y^{A}_{ztij}	*Binary variable which equals 1 if product j is produced in plant i in year t under scenario z; and 0, otherwise*
σ^{VAT}_{r}	*Value added tax in region r*	Δ^{Unmet}	*Inflation rate on unmet demand penalty*	Y^{A}_{zti}	*Binary variable which equals 1 if plant i is is subject to depreciation (either open or mothballed) in year t under scenario z; and 0, otherwise*
K^{Initial}_{i}	*Nominal capacity of plant i, before any volume change*	I^{New}_{i}	*Capital investment to establish new plant i*	Z^{New}_{zti}	*Binary variable which equals 1 if plant i is established in year t under scenario z; and 0, otherwise*
μ^{Max}_{i}	*Normal capacity ratio (out of maximum cap.) of plant i*	I^{Exp}_{i}	*Capital investment to expand plant i*	Y^{Exp}_{zti}	*Binary variable which equals 1 if plant i is expanded in year t under scenario z; and 0, otherwise*
$\varepsilon^{\text{Fr}}_{i}$	*Redundancy rate on labour cost, in case of plant i mothball*	I^{Fr}_{i}	*Capital investment to mothball plant i*	Y^{FrAll}_{zti}	*Binary variable which equals 1 if plant i has a mothballed capacity in year t under scenario z; and 0, otherwise*
$\varepsilon^{\text{Exp}}_{i}$	*Increase rate on labour cost, in case of plant i expansion*	I^{OprExp}_{i}	*Extra annual operations cost of plant i, if it has been expanded*	Y^{ExpAll}_{zti}	*Binary variable which equals 1 if plant i has ever been expanded till year t under scenario z; and 0 otherwise*
$\varepsilon^{\text{Ou}}_{i}$	*Increase rate on labour cost, in case of overutilisation in plan i*	I^{Ou}_{i}	*Capital investment to overutilise plant i*	Y^{Ou}_{zti}	*Binary variable which equals 1 if plant i is overutilised in year t under scenario z*
η^{RD}_{j}	*Investment time-table to design the new product j (in form of percentage over a few time intervals)*	I^{RD}_{j}	*Cost of designing product j in research centre/headquarter*	Y^{RD}_{ztj}	*Binary variable which equals 1 if product j is designed in year t under scenario z*
η^{New}_{i}	*Investment timetable to establish plant i (in form of percentage over a few time intervals)*	I^{Re}_{i}	*Capital investment to reopen plant i, if it has been mothballed*	Y^{Re}_{zti}	*Binary variable which equals 1 if any capacity is reopened in plant i in year t under scenario z*
η^{Exp}_{i}	*Investment timetable to expand plant i (in form of percentage over a few time intervals)*	I^{OprFr}_{i}	*Annual maintenance cost of plant i, if it has been mothballed*	Y^{Fr}_{zti}	*Binary variable which equals 1 if plant i is mothballed in year t under scenario z; and 0, otherwise*
η^{NPL}_{ij}	*Timetable of launching product j in plant i for the first time (in form of percentage over a few time intervals)*	I^{NPL}_{i}	*Cost of launching product j in plant i for the first time*	Y^{NPL}_{ztij}	*Binary variable which equals 1 if NPL occurs for product j in plant i in year t under scenario z*
l_j	*Maximum number of plants to produce product j*	I^{PL}_{ij}	*Cost of relaunching product j in plant i, after a production break*	Y^{PL}_{ztij}	*Binary variable which equals 1 if PL occurs for product j in plant i in year t under scenario z*
n^{Max}_{i}	*Maximum possible products to be produced in plant i*	I^{W}_{i}	*Annual work force cost of plant i*	Y^{ExpW}_{zti}	*Binary variable which equals 1 if in-use plant i has ever been expanded until year t under scenario z*
d_{ztrj}	*Demand for product j in region r in year t under scenario z*	I^{Opr}_{i}	*Annual operations cost of plant i*	Y^{ExpW}_{zti}	*Binary variable which takes 1 if plant i is in use in year t under scenario z*
b_t	*Maximum investment budget in year t*	I^{Cl}_{i}	*Fixed cost of shutting down plant i*	Y^{Cl}_{zti}	*Binary decision variable which equals 1 if plant i is closed in year t under scenario z*
n^{Merge}_{i}	*How many plants should be merged together to form plant i*	C^{Sup}_{ij}	*Unit cost of supply for product j in plant i*	K^{Max}_{zti}	*Nominal capacity of plant i in year t under scenario z*
M	*A sufficiently large number*	C^{D}_{rij}	*Unit cost of transp. product j from plant i to region r*	K^{Cl}_{zti}	*Shutdown capacity amount of plant i in year t under scenario z*
P_z	*Probability of scenario z*	C^{Penalty}_{ij}	*Unit unmet demand penalty for product j in region r*	K^{FrAll}_{zti}	*Cumulative amount of mothballed capacity for plant i in year t under scenario z*
P^{Merge}_{i}	*The combination of the plants that should be merged to form plan i*	C^{Unit}_{ij}	*Any other unit cost of producing product j in plant i*	K^{Fr}_{zti}	*Amount of capacity mothballed in plant i in year t under scenario z*
γ_{ij}	*Cap. volume rate of product j in plant i*	C^{Sale}_{ztrj}	*Unit sales price of product j in region r in year t and scenario z*	K^{Exp}_{zti}	*Expanded capacity amount of plant i in year t under scenario z*
E_i	*Maximum number of times for possible expansion for plant i*	ρ	*Discount rate*	K^{Re}_{zti}	*Reopened capacity amount of plant i in year t under scenario z*

3.2 Variable/Operations Costs

Transportation costs and unmet demand penalties are both unit-based costs. Unmet demand penalties should at least cover the net profit margin of the loss of sales, but it can also include the opportunity lost and brand damage (Eppen et al. 1989). However, penalties must have no tax-related implications. Annual workforce cost is a function of the plant location and can be different if a plant is normally utilised or overutilised, and if they are expanded or mothballed (ε is the proportion which adds to or cuts from the normal utilisation situation due to overutilisation and expansion, or mothball). Besides, to make the model sensitive to global capacity decisions and location/relocation decisions VAT and tariff taxes must be directly employed to the model as a function of location of the plants and sales regions. Other annual operations costs, maintenance costs and overheads also apply whenever a plant is functional (utilised or mothballed, but not closed). This model is not aimed to design the supply chain network. However, to avoid unrealistic simplification of ignoring the impact of supply chain network design on capacity location and planning, a location-sensitive supply cost has been applied to the model, as also supported by other researchers (Dal-Mas et al. 2011).

3.3 Objective Function

This model aims to maximise the net present value (NPV) under demand and sales price uncertainty (scenarios). A one-year time interval is set for the model, as cited for the strategic capacity planning by Fleischmann et al. (2006). A minimum of 10 years is suggested for capacity management models in manufacturing (Bhutta et al. 2003) and automotive industry (Kauder and Meyr 2009). Since R&D activities in large and multi-national manufacturing firms often happen in their headquarters and research centres rather than their individual plants, R&D investments do not depend on the sales regions or plant locations. Thus the tax/incentive rates on these investments are not included in the objective function below,

$$\max(NPV) = \max \sum_{z} P_z \sum_{t=1}^{T} \left\{ (1+\rho)^{-t} \left[\sum_{i=1} (1-\sigma_i^{\text{Tax}})(\mathcal{R}_{zti} - \mathcal{I}_{zti} - \mathcal{O}_{zti}) - \mathcal{D}_{z,t} \right] \right\} \quad (1)$$

where $\mathcal{R}_{zti}$, $\mathcal{I}_{zti}$ and $\mathcal{O}_{zti}$ respectively denote revenue, investment cost and operations cost for plant i at year t under scenario z while $\mathcal{D}$ corresponds to R&D cost.

Profit is the sum of sales in different regions over years under different demand and sales price scenarios minus the aforementioned costs. The objective function is extended in (2) to enable the decision-makers to test the impact of different inflation and tax scenarios on the location decisions, or different inflation rates (Δ) on investments, operations, supplies and distributions logistics as,

NPV:	$\max \sum_{z} P_z \sum_{t=1}^{T} (1+\rho)^{-t} \Big\{$
Revenue:	$+\sum_{r,i,j} (1-\sigma_i^{\text{Tax}})(C_{ztrj}^{\text{Sale}} X_{ztrij})$
Investment cost of new plants establishment, expansion or mothball of an existing plant:	$-\left[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Inv}})^t \left(I_i^{\text{New}} \eta_i^{\text{New}} Z_{zti}^{\text{New}} + I_i^{\text{Exp}} \eta_i^{\text{Exp}} Y_{zti}^{\text{Exp}} + I_i^{\text{Fr}} Y_{zti}^{\text{Fr}} \right)\right]$
Annual investment (fixed) cost of overutilization, re-opening a mothballed plant and closing an existing plant:	$-\left[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Inv}})^t \left(I_i^{\text{Ou}} Y_{zti}^{\text{Ou}} + I_i^{\text{Re}} Y_{zti}^{\text{Re}} + I_i^{\text{Cl}} Y_{zti}^{\text{Cl}} \right)\right]$
Investment cost of NPD or fixed cost of product re-launch:	$-\left[\sum_{i,j} (1-\sigma_i^{\text{Tax}}) \left(I_i^{\text{NPL}} \eta_{ij}^{\text{NPL}} Y_{ztij}^{\text{NPL}} + I_i^{\text{PL}} (Y_{ztij}^{\text{PL}} - Y_{ztij}^{\text{NPL}}) \right)\right]$
Unit cost of transportation and Logistics:	$-\left[\sum_{r,i,j} (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{D}})^t C_{rij}^{\text{D}} X_{ztrij}\right]$
Annual workforce cost of the normal-utilised, over-utilised, expanded and mothballed plants:	$-\left[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Opr}})^t I_i^{\text{W}} \left(Y_{zti}^{\text{A}} + \varepsilon_i^{\text{Ou}} Y_{zti}^{\text{Ou}} + \varepsilon_i^{\text{Ou}} Y_{zti}^{\text{ExpW}} - \varepsilon_i^{\text{Fr}} Y_{zti}^{\text{FrAll}} \right)\right]$
Custom duty (tariff) and value added tax on sales:	$-\left[\sum_{r,i,j} (1-\sigma_i^{\text{Tax}}) \left(\sigma_{ri}^{\text{Tariff}} + \sigma_r^{\text{VAT}} (1+\sigma_{ri}^{\text{Tariff}}) \right) C_{zrj}^{\text{Sale}} X_{ztrij}\right]$
Annual operation and overhead costs of operating, expanded or mothballed plants:	$-\left[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Opr}})^t \left(I_i^{\text{Opr}} Y_{zti}^{\text{ExpW}} + I_i^{\text{OprExp}} Y_{zti}^{\text{ExpW}} + I_i^{\text{OprFr}} Y_{zti}^{\text{FrAll}} \right)\right]$
Unit cost of supply:	$-\left[\sum_{i,j} (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Sup}})^t C_{ij}^{\text{Sup}} X_{ztij}^{\text{A}}\right]$
Other unit cost of operations:	$-\left[\sum_{i,j} (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Opr}})^t C_{ij}^{\text{Unit}} X_{ztij}^{\text{A}}\right]$
Unmet unit cost of operations:	$-\left[\sum_{i,r} (1+\Delta^{\text{Unmet}})^t C_{ij}^{\text{Penalty}} X_{ztrj}^{\text{Unmet}}\right]$
R&D cost of designing a product (no tax implementation - not function of plants, is done in headquarters & research centres):	$-\left[\sum_j (1+\Delta^{\text{Inv}})^t I_j^{\text{RD}} \eta_j^{\text{RD}} Y_{ztj}^{\text{RD}}\right]$
	$\Big\}. \qquad (2)$

3.4 Mathematical Model

$$\max \quad NPV$$

s.t.

$$K_{zti}^{\text{Max}} = K_{z,t-1,i}^{\text{Max}} + Z_{z,t-1,i}^{\text{New}} K_i^{\text{Initial}} + K_{z,t-1,i}^{\text{Exp}} - K_{z,t-1,i}^{\text{Fr}} - K_{z,t-1,i}^{\text{Cl}} + K_{z,t-1,i}^{\text{Re}} \quad \forall z,t,i \tag{3}$$

$$Y_{zti}^{\text{Exp}} \leq K_{zti}^{\text{Exp}} \leq M Y_{zti}^{\text{Exp}} \quad \forall i,t,z \tag{4}$$

$$Y_{zti}^{\text{Fr}} \leq K_{zti}^{\text{Fr}} \leq M Y_{zti}^{\text{Fr}} \quad \forall i,t,z \tag{5}$$

$$Y_{zti}^{\text{Re}} \leq K_{zti}^{\text{Re}} \leq M Y_{zti}^{\text{Re}} \quad \forall i,t,z \tag{6}$$

$$Y_{zti}^{\text{Cl}} \leq K_{zti}^{\text{Cl}} \leq M Y_{zti}^{\text{Cl}} \quad \forall i,t,z \tag{7}$$

$$\sum_j X_{ztij}^{\text{A}} / \gamma_{ij} \leq K_{zti}^{\text{Max}} \quad \forall i,t,z \tag{8}$$

$$\sum_j (X_{ztij}^{\text{A}} / \gamma_{ij}) - M Y_{zti}^{\text{Ou}} \leq \mu_i^{\text{Max}} K_{zti}^{\text{Max}} \quad \forall z,t,i \tag{9}$$

$$\sum_j (X_{ztij}^{\text{A}} / \gamma_{ij}) + M(1 - Y_{zti}^{\text{Ou}}) \geq \mu_i^{\text{Max}} K_{zti}^{\text{Max}} \quad \forall z,t,i \tag{10}$$

$$\sum_{t=1}^{T} Z_{zti}^{\text{New}} \leq 1 \qquad \forall i, z \qquad (11)$$

$$\sum_{t=1}^{T} Y_{zti}^{\text{Exp}} \leq E_i \qquad \forall i, z \qquad (12)$$

$$K_{zti}^{\text{Exp}} \leq Y_{zti}^{\text{Exp}} \vartheta^{\text{E-max}} K_i^{\text{Initial}} \qquad \forall z, t, i \qquad (13)$$

$$Y_{zti}^{\text{Exp}} \vartheta^{\text{E-min}} K_i^{\text{Initial}} \leq K_{zti}^{\text{Exp}} \qquad \forall z, t, i \qquad (14)$$

$$K_{zti}^{\text{Fr}} + M(1 - Y_{zti}^{\text{Fr}}) \geq K_{zti}^{\text{Max}} \qquad \forall z, t, i \qquad (15)$$

$$K_{zti}^{\text{Fr}} \leq K_{zti}^{\text{Max}} \qquad \forall z, t, i \qquad (16)$$

$$K_{zti}^{\text{FrAll}} = K_{z,t-1,i}^{\text{FrAll}} + (K_{z,t-1,i}^{\text{Fr}} - K_{z,t-1,i}^{\text{Re}}) \qquad \forall z, t, i \qquad (17)$$

$$K_{zti}^{\text{Re}} + M(1 - Y_{zti}^{\text{Re}}) \geq K_{zti}^{\text{FrAll}} \qquad \forall z, t, i \qquad (18)$$

$$K_{zti}^{\text{Re}} \leq K_{zti}^{\text{FrAll}} \qquad \forall z, t, i \qquad (19)$$

$$\sum_{t=1}^{T} Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \qquad (20)$$

$$K_{zti}^{\text{Cl}} + (1 - Y_{zti}^{\text{Cl}})M \geq K_{zti}^{\text{Max}} \qquad \forall z, t, i \qquad (21)$$

$$K_{zti}^{\text{Cl}} - MY_{zti}^{\text{Cl}} \leq K_{zti}^{\text{Max}} \qquad \forall z, t, i \qquad (22)$$

$$K_{zti}^{\text{Cl}} \leq K_{zti}^{\text{Max}} \qquad \forall z, t, i \qquad (23)$$

$$(1 - Y_{zti}^{\text{Cl}})M \geq K_{zti}^{\text{FrAll}} \qquad \forall z, t, i \qquad (24)$$

$$Z_{zti}^{\text{New}} n_i^{\text{Merge}} \leq \sum_{\hat{i} \in P_i^{\text{Merge}}} Y_{zt\hat{i}}^{\text{Cl}} \qquad R \in I, \forall z, t, i \qquad (25)$$

$$(Y_{ztij}^{\text{A}} - \sum_{\tau=0}^{t-1} Y_{z\tau ij}^{\text{A}}) - 1 + M(1 - Y_{zti}^{\text{NPL}}) \geq 0 \qquad \forall z, t, i, j \qquad (26)$$

$$(Y_{ztij}^{\text{A}} - \sum_{\tau=1}^{t-1} Y_{z\tau ij}^{\text{A}}) \leq Y_{ztij}^{\text{NPL}} \qquad z, t, i, j \qquad (27)$$

$$(Y_{ztij}^{\text{A}} - Y_{z,t-1,ij}^{\text{A}}) - 1 + M(1 - Y_{ztij}^{\text{PL}}) \geq 0 \qquad \forall z, t, i, j \qquad (28)$$

$$Y_{ztij}^{\text{A}} - Y_{ztij}^{\text{A}} - Y_{z,t-1,ij}^{\text{A}} \leq Y_{ztij}^{\text{PL}} \qquad z, t, i, j \qquad (29)$$

$$Y_{zti}^{h} \leq \sum_{i} \sum_{\tau=0}^{t} Y_{ztij}^{\text{A}} \leq M.Y_{ztj}^{h} \qquad \forall z, j \qquad (30)$$

$$(Y_{ztj}^{h} - Y_{z,t-1,j}^{h} - 1) + M(1 - Y_{ztj}^{\text{RD}}) \geq 0 \qquad \forall z, t, j \qquad (31)$$

$$Y_{ztj}^{h} - Y_{z,t-1,j}^{h} \leq Y_{ztj}^{\text{RD}} \qquad \forall z, t, j \qquad (32)$$

$$Y_{zti}^{\text{Exp}} + Y_{zti}^{\text{Fr}} + Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \qquad (33)$$

$$Y_{zti}^{\text{Re}} + Y_{zti}^{\text{Fr}} + Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \qquad (34)$$

$$\sum_{j} Y_{ztij}^{\text{PL}} + Y_{zti}^{\text{Fr}} + Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \qquad (35)$$

$$\sum_j Y^{\text{NPL}}_{ztij} + Y^{\text{Fr}}_{zti} + Y^{\text{Cl}}_{zti} \leq 1 \qquad \forall z,t,i \qquad (36)$$

$$K^{\text{Exp}}_{ti\hat{z}} = K^{\text{Exp}}_{ti\bar{z}} \qquad \forall t,i,\hat{z} \neq \bar{z} \in S_t \qquad (37)$$

$$Z^{\text{New}}_{ti\hat{z}} = Z^{\text{New}}_{ti\bar{z}} \qquad \forall t,i,\hat{z} \neq \bar{z} \in S_t \qquad (38)$$

$$Y^{\text{Cl}}_{ti\hat{z}} = Y^{\text{Cl}}_{ti\bar{z}} \qquad \forall t,i,\hat{z} \neq \bar{z} \in S_t \qquad (39)$$

$$Y^{\text{RD}}_{tj\hat{z}} = Y^{\text{RD}}_{tj\bar{z}} \qquad \forall t,j,\hat{z} \neq \bar{z} \in S_t \qquad (40)$$

$$Y^{\text{Fr}}_{tj\hat{z}} = Y^{\text{Fr}}_{tj\bar{z}} \qquad \forall t,j,\hat{z} \neq \bar{z} \in S_t \qquad (41)$$

$$Y^{\text{Re}}_{tj\hat{z}} = Y^{\text{Re}}_{tj\bar{z}} \qquad \forall t,j,\hat{z} \neq \bar{z} \in S_t \qquad (42)$$

$$Y^{\text{NPL}}_{tij\hat{z}} = Y^{\text{NPL}}_{tij\bar{z}} \qquad \forall t,i,j,\hat{z} \neq \bar{z} \in S_t \qquad (43)$$

$$Y^{\text{FrAll}}_{zti} + \sum_{\tau=0}^{t} Y^{\text{Cl}}_{z\tau i} \leq 1 - Y^{\text{ExpW}}_{zti} \qquad \forall z,t,i \qquad (44)$$

$$Y^{\text{ExpAll}}_{zti} \leq \sum_{\tau=0}^{t} K^{\text{Exp}}_{z\tau i} \leq M Y^{\text{ExpAll}}_{zti} \qquad \forall z,t,i \qquad (45)$$

$$Y^{\text{ExpAll}}_{zti} - Y^{\text{FrAll}}_{zti} - \sum_{\tau=0}^{t} Y^{\text{Cl}}_{z\tau i} \leq Y^{\text{ExpW}}_{zti} \qquad \forall z,t,i \qquad (46)$$

$$Y^{\text{ExpAll}}_{zti} \geq Y^{\text{ExpW}}_{zti} \qquad \forall z,t,i \qquad (47)$$

$$\sum_i Y^{v}_{ztij} \leq l_j \qquad \forall z,t,j \qquad (48)$$

$$\sum_j Y^{\text{A}}_{ztij} \leq n^{\text{Max}}_i \qquad \forall z,t,i \qquad (49)$$

$$\sum_z \Big(\sum_i \mathcal{I}_{zti} + \sum_j \mathcal{D}_{ztj} \Big) \leq b_t \qquad \forall t \qquad (50a)$$

$$\mathcal{I}_{zt} \leq \alpha \sum_{r,i,j} C^{\text{Sale}}_{z,t-1,r,ij} X_{z,t-1,rij} \qquad \forall z,t \qquad (50b)$$

$$\sum_i X_{ztrij} + X^{\text{Unmet}}_{ztrj} = d_{ztrj} \qquad \forall z,t,r,j \qquad (51)$$

$$\sum_r X_{ztrij} = X^{\text{A}}_{ztij} \qquad \forall t,i,j. \qquad (52)$$

$$Y^{\text{Cl}}_{zti}, Y^{\text{Ou}}_{zti}, Y^{\text{Fr}}_{zti}, Y^{\text{Re}}_{zti}, Y^{\text{FrAll}}_{zti}, Y^{\text{ExpAll}}_{zti}, Y^{\text{ExpW}}_{zti}, Y^{\text{A}}_{zti} \in \{0,1\} \qquad \forall z,t,i \qquad (53)$$

$$Z^{\text{New}}_{zti} \in \{0,1\} \qquad \forall z,t,i \qquad (54)$$

$$Y^{\text{Exp}}_{ztj}, Y^{\text{ExpAll}}_{ztj}, Y^{\text{RD}}_{ztj} \in \{0,1\} \qquad \forall z,t,j \qquad (55)$$

$$Y^{\mathcal{P}}_{ztij}, Y^{\text{Cl}}_{ztij}, Y^{\text{NPL}}_{ztij}, Y^{\text{PL}}_{ztij} \in \{0,1\} \qquad \forall z,t,i,j \qquad (56)$$

$$X^{\text{A}}_{ztij}, X_{ztij}, X^{\text{Unmet}}_{ztij} \geq 0 \qquad \forall z,t,i,j \qquad (57)$$

$$K^{\text{Max}}_{zti}, K^{\text{Cl}}_{zti}, K^{\text{Fr}}_{zti}, K^{\text{Re}}_{zti}, K^{\text{Exp}}_{zti}, K^{\text{FrAll}}_{zti} \geq 0 \qquad \forall z,t,i. \qquad (58)$$

As summarised at ICOM framework (Figure 1), the following subsections present the corresponding constraints of the model.

3.4.1 Capacity Volume

Constraint (3) holds the capacity balance equation according to the initial capacity, new plants, expansion, mothballed, reopened and the shutdown capacity. Constraints (4)–(7) detect each of these decisions via their corresponding binary variables.

3.4.2 Possibility matrix and production rate

The fitness of producing product j in plant i is determined via possibility matrix γ_{ij} where $\gamma_{ij} \in [0, 2]$ and,

- $\gamma_{ij} = 1$ indicates that plant j is a normal fit for product i
- $0 < \gamma_{ij} < 1$ product i can be made at plant j, but is not the best fit (the production efficiency is between 0% to 100%)
- $1 < \gamma_{ij} \leq 2$ product i can be made at plant j and with more than normal rates (up to twice faster).
- $\gamma_{ij} = 0$ product i cannot be made in plant j.

Constraint (8) sets the production capacity based on the fitness of the products.

3.4.3 Normal and Overutilisation

A plant i is called overutilised, if it uses more than certain amount of its capacity which is determined by factor μ_i^{Max}. Constraints (9) and (10) force Y_{zti}^{Ou} to get 1 if plant i is overutilised in period t under scenario z and 0, otherwise.

3.4.4 New Capacity Establishment

Constraint (11) guarantees that a new plant can be opened at most once within the entire planning horizon.

3.4.5 Capacity Expansion

Capacity expansion is limited to a certain number as set in constraint (12) while its lumpiness nature is addressed in constraints (13) and (14). That is, every expansion is limited to a certain range of capacity increase, and not less or more ($\vartheta^{\text{E-min}}$ and $\vartheta^{\text{E-max}}$).

3.4.6 Capacity Mothball

If mothballing decision is made for plant i, i.e., $Y^{\text{Fr}}_{zti} = 1$, then its all available capacity are mothballed: Constraints (15) and (16).

3.4.7 Capacity Reopen

Only plants with mothballed capacity can be reopened. The overall mothballed capacity is calculated in (17). Moreover, if reopen decision is made, it opens all the mothballed capacity at once: constraints (18) and (19).

3.4.8 Capacity Shutdown

Shutdown of a plant can only happen once, constraint (20) , and it can never be reopened if closed down. The corresponding capacity and binary variables are set in constraints (21)–(23). In addition, to avoid sub-optimised solutions, no mothballed capacity can be closed at any time. If a plant is not needed in the future at all, it must be closed down and not mothballed which is set by constraint (24).

3.5 Relocation and Merge Constraints

Relocation of a plant means closing a current plant and opening a new one in another location. Similarly, in the case of merging plants, a few plans are closed down to open a new one. Merging portfolios (possible cases) is defined as inputs to the database. It requires investment and lead-time, as well as information on how many (n^{Merge}) plants and which one of them from the possible potential plants (P^{Merge}) could/should be merged to open a new plant as set in (25). For the relocation case (i.e., no merge), $n^{\text{Merge}} = 1$.

3.5.1 Product Development Constraints

Y^{NPL} and Y^{PL} respectively indicate if a product is launched for the first time at all or after a time break. To avoid mixing PL and NPL, the term $Y^{\text{PL}} - Y^{\text{NPL}}$ is applied into the objective function for product relaunch case. Moreover, to formulate whether R&D has performed or not (i.e., Y^{RD}), the auxiliary binary variable Y^{h}_{ztj} is used to identify if product j has ever been produced in any plants before or not. Constraints (26)–(32) define the above relations and logics.

3.5.2 Non-Simultaneous and Non-Anticipative Constraints

Reopening, expansion and product launch (NPL or PL) can simultaneously be done for the same plant, as well as new plant and new product launch. However, mothballing and reopening, mothballing and expansion, reopening and shutdown, expansion and shutdown, NPL/PL and shutdown and finally NPL/PL and capacity mothball cannot be done simultaneously for the same plant: constraints (33)–(36).

Furthermore, non-anticipative constraints are needed for stochastic models (Sterman 2000), indicating that strategic capacity decisions are irreversible and the decision variables corresponding to the scenarios with the same history have the common value. Let S_t denote the set of scenarios with a common history and decisions at time t. These decisions are capacity expansion, shutdown, new plant establishment, new product launch decision, R&D, plant mothball, and finally plant reopening as given in (37)–(43).

3.5.3 Other Constraints

Workforce Constraints

Recalling from the objective function, expanded capacities need extra workforce cost if they are operational (not mothballed or closed). In such situations $Y^{\text{ExpAll}}_{zti} = 1$, and 0 otherwise.

- If capacity has been closed down sometime before year t or mothballed and not reopened, then $Y^{\text{ExpAll}}_{zti} = 0$: constraint (44).
- If the plan has been ever expanded before (i.e., Y^{ExpAll}=1), and is not currently mothballed nor closed down, then $Y^{\text{ExpAll}}_{zti} = 1$: constraints (45) and (46).
- If the plant has never been expanded then $Y^{\text{ExpAll}}_{zti} = 0$: constraint (47).

Maximum Plant and Maximum Product Constraints

The company policy might be not to launch each product j in more than a certain maximum number of plants as shown in (48) . Likewise, a maximum product constrain as (49) can be applied to limit the maximum number of product types launched in certain plants in each period of time.

Budget Constraints

Often companies define a maximum annual budget, b_t, for total investment: (50a). Also, the investment budget can be defined as a proportion of the total annual sales (revenue) as (50b) where $\alpha < 1$ is a constant corresponding to proportion of revenue which is assigned for reinvestment.

Demand and Distribution Constraints

Unmet demand associated with a penalty is considered in this model and (51) formulates the total production with relate to overall demand. Moreover, all products of year t must be transported within the same period: (52). Note that since this model is a strategic planning one, with a time interval of one year, no inventory term and constraint is required if a first-in-first-out stock management applies (Chen et al. 2002).

4 Solution and Validation

This model is a scenario-based stochastic model. After extending the scenarios in the programming (coding in Visual Basic), the model can be reformulated to a mixed integer liner optimisation problem. To validate the model, fourteen hypothetical cases are designed and used, as explained in an ICOM form validation plan in Figure 3. This figure illustrates how all decision outputs of the model and their interactions are validated in this study. Cases 1 to 5 are deterministic cases to validate the model's ability to handle slight, medium and significant capacity changes (increase and decrease). Deterministic cases 6 to 8 are designed to validate model's location decision capability. Case 6 studies the impact of different financial terms (tax, VAT and inflation) on the global decisions, and cases 7 and 8 study the impact of location/relocation capability on capacity volume decisions (relocation versus expansion in demand increase scenarios and relocation versus underutilisation in demand decrease scenarios, respectively). Case 9 and 10 validate stochastic form in capacity volume cases. Although demand is stochastic for the case 9, the expected value of demand is designed to be exactly the same as case 2, in order to study the model's stochastic capability and value of stochastic solutions (VSS) in the increasing demand scenario. Likewise, to study the decreasing demand scenario, case 10 represents a stochastic demand with the same expected value as in the case 5, and calculates VSS in demand decrease scenarios. Similar to Case 7, in case 11 the impacts of global solutions in oppose to local decision (for instance, a new plant in China versus an expansion of a current European plant) is studied in the stochastic form. Cases 12 and 13 validate technology management capability of the model, and respectively volume flexibility and product-mix flexibility. Finally, case 14 validates the model's strategic product development and planning capability. All validation cases are available on request from the corresponding author, but in this paper only cases 5, 9 and 11 are reported to validate the capacity volume and location decision capability of the model in deterministic and stochastic forms. Although the model can be used for a wide range of production industries, to be more specific in this paper, the general rates and figures for the automotive industry is used for the hypothetical cases, and the input data is adjusted to an average car manufacturer.

Cases 5&9: In these cases an existing plant in the UK is operational with a slightly increasing demand forecast. To simplify the case, only one product family and one sales region is considered. Table 6 shows the general information about the plant. The VAT is 20%, and no tariff is applied since the plant and sales regions are located in the EU. Unit cost of operations (transportation, dealership and warehouse cost of the product family) in this sales region has been set at £4,000 per unit.

Running this case in the deterministic form (case 5: deterministic demand similar to the expected value of demand in case 9) and in stochastic form (case 9), the model results in different solutions. The expected demand is more than the normal capacity but just under the maximum capacity of the plant. Table 7 shows two possible solutions (overutilization or expansion) in deterministic case (case 5), overutilization seems to be the best solution. Setting unmet demand penalty as £5K per unit and running the model in the deterministic mode and with expected values, the same solution was suggested by the model as well. However, in stochastic mode and including demand scenarios, the model suggests expansion as the best solution. Table 8 compares two possible solutions in stochastic mode and explains why different solutions are suggested for these cases. The result shows VSS in this example which results in a saving of £347m over 10 years.

Figure 3: Validation plan

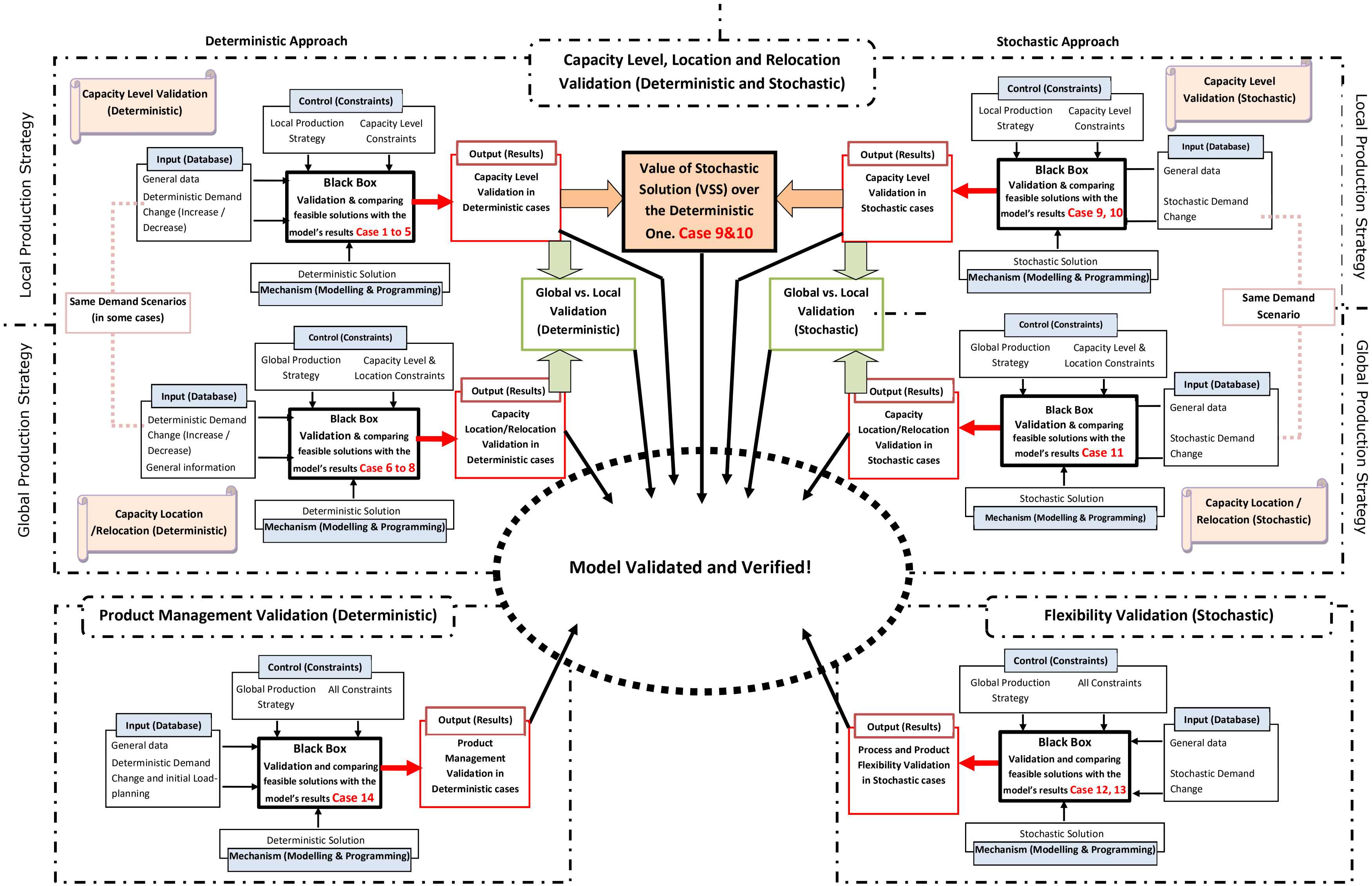


Table 6: General information about the UK plant for the cases 5, 9 and 11

Plant Location	Maximum Capacity (product/ year)	Maximum normal capacity rate	Initial Capital Investment	Annual Operations cost	Annual normal Workforce Cost	Any unit-based cost of production excluding supply	Profit Tax rate
UK	300	0.7	£200m	£150m	£130m	500	0.2

Capacity expansion					**Overutilisation**	
Number of possible Expansions	Maximum Expansion rate	Capital investment - Expansion	Extra operations cost of expansion	Extra workforce cost of expansion	Extra workforce cost of overutilisation	Extra operations cost of overutilisation
1	0.4	£70m	£40m	£39m	£26m	£30m

Table 7: Total cost of different solution in deterministic form (case 5)

Expansion	Expansion Fixed Cost	Extra Operations cost of expansion (in 7 years)	Extra Workforce Cost of expansion (in 7 years)	Overutilisation fixed cost (in 7 years)	Overutilisation Work force cost (in 7 years)	**Sum**
	0.4	£70m	£40m	£39m	£26m	£30m
Overutilisation	Overutilisation fixed cost in 10 years		Overutilisation Workforce cost in 10 years			**Sum**
	£260m		£300m			£560m

Table 8: Total cost of different solutions in stochastic form (case 9) and VSS

Expansion Solution						**Scenario**	Overutilisation and No Expansion Solution Capacity is capped to 3						
Overall gross profit	Total investment (from Table 7)	Expected value	Unmet demand unit	Gross Profit after cost of goods	Total sales number	p=probability GP=Unit Gross Profit (sales price-unit operations and supply cost)	Total sales number	Gross Profit after cost of goods	Unmet demand unit	Total penalty (penalty=£5k/unit)	Expected value	Total investment (from Table 7)	Overall gross profit
£12297m	-£880m	£2306m	0	£7686m	2562k	p=30% GP=£3k £(29-26)k	2562k	£7686m	0	0	£2306m	-£560m	**£11950m**
		£7720m	0	£15440m	3088K	p=50% GP=£5k £(31-26)k	3035k	£15175m	53,000	-£265m	£7455m		
		£3151m	0	£15755m	3151k	p=20% GP=£5k £(31-26)k	2950k	£14750m	201,000	-£1005m	£2749m		
Value of Stochastic solution (VSS) = £12297m - £11950m = £347m over 10 years													

Case11: This case is designed to compare local and global cases and calculates the value of global solutions (VGS). The expected demand volume remains the same as the one in cases 5 and 9, but different sales regions (UK, US and China) are introduced with 3 different demand scenarios for each region given in Table 9. In this case, besides the existing plant in the UK (Table 6), an optional new plant in China can also be opened by the model as an alternative solution to overutilisation and expansion of the UK plant. Investments and financial figures for the plant in China are listed in Table 10. Sales price, transportation costs and tariff rates are shown in Table 11. Running the model in global mode for this simple case, it suggests opening a new plant in China and utilise it at normal level, rather than expanding the plant in the UK. Although as Table 12 shows this option needs £1,780m investment in fixed and variable costs over 9 years (as oppose to £924m for expanding the existing plant in the UK), major savings on tariff and transportation fees justifies this new capacity establishment. Table 12 illustrates that the value of global solution (VGS) in this case is £4,189m over 9 years of planning. This result shows the importance of global location decisions embedded in a capacity management model.

Table 9: Demand scenarios in different sales region (expected demand is similar to case 5 & 9)

	Scenario	UK Demand	US Demand	China Demand	Expected Demand
$t = 0$	S1	133	80	53	
	S2	133	80	53	**265**
	S3	133	80	53	
$t = 1$	S1	130	78	52	
	S2	140	84	56	**275**
	S3	143	86	57	
$t = 2$	S1	128	77	51	
	S2	145	87	58	**285**
	S3	158	95	63	
$t = 3$	S1	125	75	50	
	S2	153	92	61	**293**
	S3	163	98	65.2	
$t = 4$	S1	126	76	50.4	
	S2	154	92	61.6	**295**
	S3	163	98	65	
$t = 5$	S1	125	75	50	
	S2	156	94	62.4	**298**
	S3	168	101	67	
$t = 6$	S1	128	77	51	
	S2	154	92	61.6	**295**
	S3	160	96	64	
$t = 7$	S1	128	77	51	
	S2	155	93	62	**298**
	S3	165	99	66	
$t = 8$	S1	130	78	52	
	S2	153	92	61	**296**
	S3	163	98	65	
$t = 9$	S1	130	78	52	
	S2	153	92	61	**296**
	S3	163	98	65	

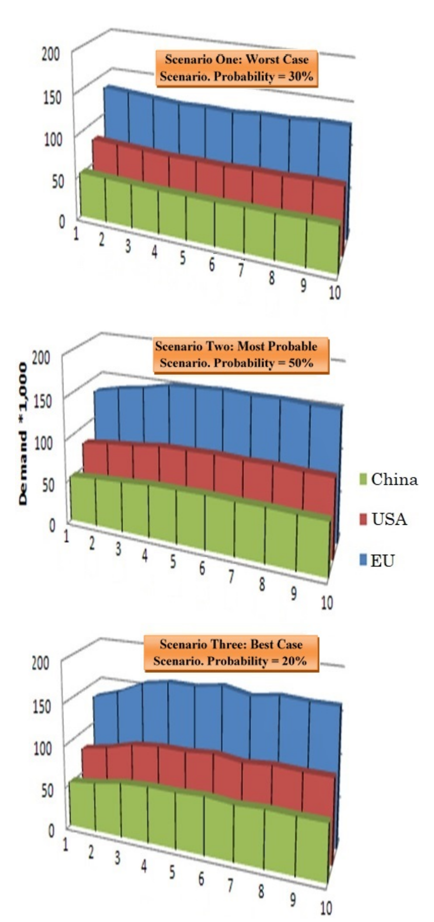


Table 10: Input data for the optional plant in China

Plant Location	Maximum capacity (product/ year)	Maximum normal capacity rate	Initial capital Investment	Annual operations cost	Annual normal workforce Cost	Any unit-based cost of production excluding supply	Profit tax rate
China	200,000	0.8	£200m	£100m	£60m	£500/unit	0
Capacity Expansion					**Overutilisation**		
Number of possible Expansions	Maximum expansion rate	Capital investment for expansion	Extra annual operations cost in case of expansion	Extra annual workforce cost in case of expansion	Capital investment for overutilisation	Extra operations cost in case of overutilisation	Extra workforce cost in case of overutilisation
1	0.4	£50m	£20m	£15m	£5m	£5m	£10m

Table 11: Sales price, transportation costs and tariff rates for different plants in different sales regions

	EU	USA	China
Sales Price in different sales regions	£31,000	£32,000	£33,000
Cost of transportation from the UK plant to dealers within different sales regions	£1,000	£4,000	£8,000
Cost of transportation from China plant to dealers within different sales regions	£4,000	£6,000	£2,000
Tariff rates for products coming from the UK plant to different sales regions	0%	10%	20%
Tariff rates for products coming from China plant to different sales regions	20%	20%	0%

Table 12: Total difference between local capacity options (case 9) and global mode (case 11)

<table>
<tr><td rowspan="4">UK Plant Expansion Solution</td><td>Scenario</td><td>Fixed cost of expansion</td><td colspan="2">Extra operations cost of expanded plant for 8 years</td><td colspan="2">Extra work force cost of expanded plant For 8 years</td><td>Extra Cost of transp., warehouse and dealership for Chinese market in 9 years</td><td>Extra tariff cost for export to China in 9 years (m£)</td><td>Total in scenarios</td><td>Total expected</td><td rowspan="8">Value of global solutions (VGS)= £4,189m</td></tr>
<tr><td>S1</td><td rowspan="3">£80m</td><td colspan="2" rowspan="3">£480m</td><td colspan="2" rowspan="3">£364m</td><td>£2,756m</td><td>£3,032m</td><td>£6,712m</td><td rowspan="3">£7,546m</td></tr>
<tr><td>S2</td><td>£3,268m</td><td>£3,594m</td><td>£7,786m</td></tr>
<tr><td>S3</td><td>£3,463m</td><td>£3,810m</td><td>£8,197m</td></tr>
<tr><td rowspan="4">New Plant in China</td><td>Scenario</td><td>Initial Capital Investment</td><td>Operations cost for 9 years</td><td>Workforce cost for 9 years</td><td>Fixed capital investment for overutilisation</td><td>Extra operation cost of overutilising the plant for 9 years</td><td>Extra workforce cost of overutilising the plant for 9 years</td><td>Extra cost of material supply to the Chinese plant in 9 years</td><td>Total in Scenarios</td><td>Total expected</td></tr>
<tr><td>S1</td><td rowspan="3">£200m</td><td rowspan="3">£900m</td><td rowspan="3">£540m</td><td rowspan="3">£5m</td><td rowspan="3">£45m</td><td rowspan="3">£90m</td><td>£1,378m</td><td>£3,248m</td><td rowspan="3">£3,357m</td></tr>
<tr><td>S2</td><td>£1,634m</td><td>£3,504m</td></tr>
<tr><td>S3</td><td>£1,732m</td><td>£3,602m</td></tr>
</table>

5 Verification of the model: The case of Toyota UK [1]

Having two assembly lines in Burnaston, Toyota UK (TMUK), with a maximum capacity of 285,000 vehicles per year, was one of the top 5 car manufacturers in Britain in 2009 (Bekker 2010). During the last economy recession in 2010, TMUK forced to mothball one of their production lines towards the end of 2010 (Lea 2010). Using publicly available data and simple assumptions, this section employs our model in this real scale case. Financial information of TMUK (FAME Database. 2010) reveals that after the recession in 2008, TMUK lost almost £1 billion in annual sales, from £2.774 billion in 2007 to £1.82 billion in 2009. In the first months of 2010, Toyota faced with another disaster, "safety problems", which forced the company to recall around 8 million passenger cars all over the world, including around 200,000 cars in the UK (Telegraph 2010). To react, TMUK firstly scaled down its second production line in Burnaston to one shift in September 2010, and then mothballed this line by the end of 2010 (Lea 2010). Although no labour layoff happened at the time, TMUK supported their mothballed policy, stating that having one fully utilised production line is more feasible than having two underutilised lines (Bawden and Lewis 2010). Table 13 shows total sales and operations cost of the company.

Table 13: Total annual cost of the company (in £million)

	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
TMUK car production ($\times$1,000)	212	211	245	263	282	275	164	127
Supply costs (Total)	1,004	1,594	1,609	1,823	1,800	1,942	1,419	1,267
Total remuneration	129.2	165.5	175.9	179.2	172.1	162.4	154.6	124.1
Depreciation	135.6	97.4	114.1	103	115.1	115.5	106.1	87.2
Operation expenses	33.3	39.9	37.8	39.2	39.2	33.4	31.4	22
Other costs of operations	198.8	307.6	267.8	358.4	399.7	484.8	476.9	363

Source: (FAME Database. 2010) and (Toyota Motor Annual Report. 2010, Toyota Motor Corporation. 2010)

To generate scenarios only the data and information available prior to mothball decision (end of 2010) was used in this case. The sales estimation for Europe expected a 19.2% decline, to 858,000 units, and Toyota's total production in the EU was expected to decline by 10.2%, to 433,000 units in 2010 (Ruddick 2010). Despite such downtime, what was promising for TMUK sales was the fact that the company was preparing to launch Toyota Auris Hybrid model in the Burnaston facility in 2010, which had been expected to be a game-changer for TMUK. Toyota's first forecast for 2011 fiscal year (ending March 31, 2011) were a vehicle sales of 7.29 million units (Toyota Motor Corporation. 2010). However, due to some evidence of the recession recovery

[1]A verification with the case of Jaguar Land Rover (JLR) investment in China is also available on request from the authors.

signs by early 2010, Toyota revised its sales forecast to 7.41m units for 2011 (Costea 2010). Based on these facts and information, three main scenarios for 2010 and 2011 were defined in this study, comprising demand decrease, stable demand and demand increase. In an interview with TMUK senior management team at the time (2009), demand decrease was found to be the most probable scenario (with 50% probability allocation), in which a 5% and a 10% sales reductions were estimated for 2010 and 2011, respectively. The other 50% probability was divided equally to stable demand scenario (p=25%) and a demand increase scenario with 5% sales increase estimations for 2010 and 2011.

This case consists of 3 products, 2 production lines, 3 scenarios, 3 time periods, and 2 stages. To set the input parameters data from table 13 was used and a two-stage scholastic version of our model was employed for the case. This example contains three binary decision variables of capacity under-utilisation, capacity mothball, and capacity shutdown, as well as two continuous decision variable of production lot allocations to both lines. Unmet demand penalty for each of three cars was set to their gross profit margin plus a fixed penalty as called "trust image penalty". Other decision variables, input parameters and constraints that were not tied to capacity volume module were turned off and The model suggests to mothball the second production line and fully utilise the first production lien in 2010 which verifies the model with the actual decision taken by TMUK at the time. In the second run, the model was given the data available in 2007 and 2008, which shows early signs of global recession, and the model suggested a mothball in 2009, which could have saved the company over £10m of operations cost of running both lines under-utilised for one extra year, before the actual mothball in 2010.

6 Discussion and Conclusion

Although many peers had raised a need to apply external and market uncertainty into capacity management models, as Table 14 shows, the use of stochastic programming in embedding uncertainty into capacity design and planning has only taken off very recently [after 2009] while most of the models in the field were deterministic before that. However, comparing Tables 14 and 15 indicates that the stochastic models are still not as multi-functional and versatile as the deterministic ones, and they can handle less capacity decision terms than what their deterministic counterparts can manage. Thus, it shows although existing stochastic capacity management models may be able to handle market scenarios, they lack taking a global and comprehensive approach into their decision terms, which limits them to limited applications and can cause sub-optimal solutions. It shows a gap for a more holistic and integrated capacity management model in stochastic form that can handle market uncertainty, while not compromising on decision terms and boundary conditions. This work aimed to address this gap and to develop a stochastic model that can simultaneously handle capacity level management (in increase and decrease scenarios and in realistic terms of sight, moderate and significant changes), capacity location, relocation merge and decomposition, product development (R&D, new product introduction and re-launch cases), and technology management (product and process flexibility and technology life-cycles). Cumbersome data requirements of stochastic models and the size of the extended models (which causes long solution times) have been often blamed for limited decision terms in the stochastic practices (Snyder 2006; Tenhiälä 2011). However, this paper showed these limitations can be overcome by the use of enumerated scenarios, detailed constrains, and right programming approach, which all can reduce the size of the final model to a manageable scale. Enumerated scenario approach causes no limitation to the strategic capacity management modelling, as after all, the number of possible scenarios is inherently limited in strategic planning. A systematic model development approach, which is often called open-box validation was adopted, using ICOM logic (Matta et al. 2005), as explained in Section 1 and employed in Section 3. Using the same logic, a holistic validation plan was developed in ICOM format and employed to test and validate the model. As frequently raised by other authors in this area, verification of the resource management models with real-scale and industrial cases has yet been remained widely unattempted (Hammami et al. 2008; Julka et al. 2007), and there is still a widespread need in the field to make managers and industrial decision-makers aware of what operation research (OR) and optimisation-based capacity management models have to offer to the world of practice (Ackermann et al. 2014). This paper briefly applied this model to the case of Toyota-UK (and the case of Jaguar-Land Rover is also available upon request from the corresponding author), in an attempt not only to verify the model in real scales, but also to illustrate the potential contribution such models can offer to strategic decision-making in practice.

Appendix

Table 14: Selected papers for the comparison study, their uncertainty management approach and their capacity management strategic decision terms

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
1	Syam (2000)	✓	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
2	Inman and Gonsalvez (2001)	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	Inman and Gonsalvez (2001)	✓	-	-	-	-	-	✓	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-
4	Verter and Dasci (2002)	✓	-	-	-	-	-	✓	-	-	-	-	✓	-	-	✓	-	-	-	-	-
5	Chen et al. (2002)	-	-	✓	Demand & producing lead-time	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
6	Bhutta et al. (2003)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
7	Bhutta et al. (2003)	✓	-	-	-	-	✓	-	-	-	✓	-	✓	-	-	-	-	-	-	-	✓
8	Gatica et al. (2003)	-	✓	-	Success of New Products	-	✓	✓	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-
9	Goel and Grossmann (2004)	-	-	✓	Uncertainty in gas reserves	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
10	Chauhan et al. (2004)	✓	-	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Barahona et al. (2005)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
12	Chakravarty (2005)	✓	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
13	Chandra et al. (2005)	-	-	✓	Demand	✓	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
14	Snyder (2006)	✓	-	-	-	-	✓	✓	-	-	✓	✓	-	-	-	-	✓	-	-	-	-
15	Melo et al. (2006)	✓	-	-	-	-	✓	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	✓
16	Fleischmann et al. (2006)	✓	-	-	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓
17	Snyder et al. (2007)	-	-	✓	Demand	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
18	Snyder et al. (2007)	-	-	✓	Demand and Freight Rate	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓
19	Zhang (2007)	-	✓	-	Demand, consumption of stochastic capacity	-	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	-	✓
20	Katayama et al. (2007)	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-

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Table 14: continued from previous page

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
21	Ahmed and Sahinidis (2008)	-	-	✓	Demand and capacity cost	-	✓	✓	-	-	-	-	-	-	-	✓	✓	-	-	-	-
22	Nagar and Jain (2008)	-	-	✓	Demand	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
23	Azaron et al. (2008)	-	✓	-	Demand, Supply, Transp., Capacity	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
24	Hamad and Fares Gualda (2008)	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
25	Nodem et al. (2008)	-	✓	-	Maintenance and repair time	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
26	Naraharisetti and Karimi (2010)	✓	-	-	-	-	✓	✓	-	-	✓	✓	✓	✓	-	✓	-	-	-	-	✓
27	Tarhan and Grossmann (2008)	-	-	✓	Process Yield	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
28	Francas et al. (2009)	-	✓	-	Demand	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
29	Kauder and Meyr (2009)	-	-	✓	Demand	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-
30	Wagner et al. (2009)	-	✓	-	Demand	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
31	Hammami et al. (2009)	✓	-	-	-	-	-	✓	-	-	✓	-	-	✓	-	✓	-	-	-	-	✓
32	You et al. (2009)	-	✓	-	Demand and Freight Rate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
33	Geng et al. (2009)	-	-	✓	Demand and Capacity	-	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
34	Kauder and Meyr (2009)	✓	-	-	-	✓	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	✓
35	Colvin and Maravelias (2009)	-	-	✓	Success of New Products	-	✓	-	-	-	-	✓	-	-	-	-	✓	-	-	-	-
36	Bihlmaier et al. (2010)	-	-	✓	Demand	-	✓	✓	✓	-	-	-	-	-	-	✓	✓	-	-	✓	-
37	Aghezzaf et al. (2010)	-	✓	-	Demand	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	Frausto-Hernandez et al. (2010)	-	✓	-	Demand and supply	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
39	Naraharisetti and Karimi (2010)	✓	-	-	-	-	✓	✓	-	-	✓	✓	-	-	-	-	-	-	-	-	-
40	Wu and Chuang (2010)	-	-	✓	Demand, Price and Yield	-	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-

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Table 14: continued from previous page

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
41	Lin et al. (2010)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
42	Durksen and Dangelmaier (2010)	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-	✓	-	-
43	Lusa and Pastor (2011)	-	-	✓	Capacity	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
44	Dal-Mas et al. (2011)	-	-	✓	Row material cost and product price	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
45	Claro and Pinho de Sousa (2012)	-	-	✓	Demand	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
46	Chien et al. (2012)	-	-	✓	Demand	-	✓	-	-	-	-	✓	-	-	-		-	-	-	-	-
47	Chen and Lu (2012)	-	✓	-	Demand	-	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-
48	Nickel et al. (2012)	-	-	✓	Demand & Interest Rates	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	✓
49	Pimentel et al. (2013)	-	-	✓	Demand	✓	✓	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-
50	Erbis et al. (2014)	-	-	✓	Demand, safety regulations, technology	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-
51	Lin et al. (2014)	-	-	✓	Demand	✓	✓	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-
52	Kaya et al. (2014)	-	✓	-	Demand & return	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓
53	Lee and Johnson (2014)	-	✓	-	Demand	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-
54	Chen et al. (2014)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
55	Verma et al. (2014)	-	✓	-	Demand, Sales Price, material Price	✓	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
56	Chen and Fan (2015)	-	✓	-	Demand	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
57	Gupta and Mohanty (2015)	✓	-	-	-	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-
58	Hamta et al. (2015)	-	✓	-	Demand	✓	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓
59	Liu et al. (2015)	-	✓	-	Demand	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	✓	-
60	Garcia-Herreros et al. (2016)	✓	-	-	-	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-

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Table 14: continued from previous page

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
61	Afrouzy et al. (2016)	-	-	✓	Demand, Supply Capacity	-	-	-	-	-	-	-	-	-	-	-	✓	-	✓	-	✓
62	Wang and Nguyen (2017)	-	-	✓	Technology uncertainty	✓	✓	✓	✓	-	-	-	-	-	-	✓	-	-	-	-	-
63	Medina-González et al. (2017)	-	✓	-	Open to a set (example: demand)	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
64	Liu et al. (2018)	-	-	✓	Demand, investment, technology	✓	✓	-	✓	-	✓	-	-	-	-	✓	-	-	-	-	-
65	Chien et al. (2018)	✓	-	-	Demand, Capacity capability, Technology migration	✓	✓	-	✓	-	✓	✓	-	-	-	✓	-	-	-	-	-
66	Wang et al. (2018)	-	✓	-	Demand, technology	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	-	-	✓	-	-
67	Yu and Solvang (2018)	-	✓	-	Material quantity, quality and price	✓	✓	✓	✓	-	-	-	✓	-	-	✓	-	-	-	-	-
68	Zhou and Li (2018)	-	✓	-	Demand	✓	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	✓
69	Shiina et al. (2018)	-	-	✓	Demand	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 15: More detailed terms and constraints in the selected Capacity management models

Paper No. (Table 14)	Cost Parameters								Financial Parameters						Prod./Proc.				
	Transportation	Unmet Demand	Production Cost	Labour Cost	Material / Supply Cost	Maintenance	depreciation / Replacement	Operation / Overhead Cost	Discount / Interest rate	Tax	Duty	VAT	Inflation rates	Exchange rates	Possibility Matrix	Capacity Rate	Economies of Scale	Capacity lumpiness	Budget Constraint
1	✓	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
2	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	✓	-
3	-	-	✓	✓	✓	-	✓	✓	✓	✓	-	-	-	-	✓	✓	✓	✓	✓
4	✓	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
6	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓
7	✓	-	✓	-	-	✓	✓	✓	-	-	✓	-	✓	✓	-	-	✓	✓	-
8	-	✓	✓	-	✓	✓	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓
9	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	✓	-
10	✓	-	✓	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-
11	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	✓	✓
12	✓	-	✓	✓	-	-	-	✓	-	✓	✓	-	-	✓	-	-	✓	-	-
13	-	-	✓	-	✓	✓	-	✓	✓	-	-	-	-	-	✓	-	-	-	✓
14	✓	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	-	✓	✓	-
15	✓	-	✓	-	-	-	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓
16	✓	-	✓	-	✓	-	-	✓	✓	-	-	-	-	-	✓	-	✓	✓	✓
17	-	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	✓	-	✓	-	✓	✓	✓	-	-	-	-	-	-	-	-	✓	✓
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
21	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	✓	✓	✓
22	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
24	✓	-	✓	-	-	-	-	-	-	✓	-	✓	-	✓	-	-	-	-	-
25	-	✓	✓	-	-	✓	-	-	✓	-	-	-	-	-	-	-	-	✓	-
26	✓	-	✓	-	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	✓	✓	✓
27	-	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-
28	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
29	✓	✓	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	✓	-
30	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
31	✓	-	✓	✓	✓	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-
32	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
33	✓	✓	✓	-	✓	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
34	✓	-	✓	-	✓	-	-	✓	✓	✓	-	-	-	-	✓	-	-	✓	-
35	-	✓	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	-	-	✓	-
36	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-
37	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
39	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	-	✓	-	✓	✓	✓	✓	✓
40	-	✓	✓	-	-	-	✓	✓	✓	-	-	-	-	-	-	-	-	✓	✓
41	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	✓	-
42	✓	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-	-	-	✓	✓	-
43	-	✓	-	✓	-		-	-	-	-	-	-	-	-	-	-	-	-	-
44	✓	✓	✓	-	✓	-	-	✓	✓	-	-	-	-	-	-	-	✓	✓	-
45	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-
46	-	✓	-	-	-	-	✓	✓	✓	-	-	-	-	-	✓	✓	✓	✓	-
47	✓	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-	✓	✓	✓	✓	-
48	✓	-	✓	-	✓	-	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓
49	-	-	✓	-	-	-	✓	✓	-	-	-	-	-	-	✓	-	✓	✓	-
50	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	✓

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Table 15: continued from previous page

Paper No. (Table 14)	Cost Parameters								Financial Parameters						Prod./Proc.				
	Transportation	Unmet Demand	Production Cost	Labour Cost	Material / Supply Cost	Maintenance	depreciation / Replacement	Operation / Overhead Cost	Discount / Interest rate	Tax	Duty	VAT	Inflation rates	Exchange rates	Possibility Matrix	Capacity Rate	Economies of Scale	Capacity lumpiness	Budget Constraint
51	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	✓
52	✓	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-
53	-	-	✓	✓	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	-
54	-	-	✓	-	-	-	✓	✓	-	-	-	-	-	-	✓	✓	✓	✓	-
55	✓	✓	✓	-	✓	-	-	✓	-	-	✓	-	-	-	-	-	-	✓	-
56	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	✓
57	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
58	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	-	-
59	-	✓	✓	✓	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	-
60	✓	-	-	-	✓	✓	-	-	✓	-	-	-	✓	-	-	-	✓	✓	✓
61	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
62	-	✓	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
63	✓	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-
64	-	✓	✓	-	-	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	✓
65	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
66	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	✓	-
67	✓	-	✓	-	✓	-	-	✓	-	✓	-	-	-	-	✓	-	-	-	-
68	✓	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-	-	-	✓	-	✓
69	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	✓

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- Decision terms and constraints for a holistic capacity management model
- Review 69 recent (2010-2018) optimisation models in the field to find the gaps
- Design a multi-stage stochastic capacity management model to address the gaps
- Design a holistic black-box validation plan using ICOM framework
- Validation and verification by using a real-scaled case of Toyota Motors UK

A strategic and global manufacturing capacity management optimisation model: A Scenario-based multi-stage stochastic programming approach

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Abstract

Large-scale multinational manufacturing firms often require a significant investment in production capacity and extensive management efforts in strategic planning in an uncertain business environment. In this research we first discuss what decision terms and boundary conditions a holistic capacity management model for the manufacturing industry must contain. To better understand how these decision terms and constraints have been employed by the recent model developers in the area of capacity and resource management modelling for manufacturing, 69 optimisation-based (deterministic and stochastic) models have been carefully selected from 2000 to 2018 for a brief comparative analysis. The results of this comparison shows although applying uncertainty into capacity modelling (in stochastic form) has received a greater deal of attention most recently (since 2010), the existing stochastic models are yet very simplistic, and not all the strategic terms have been employed in the current model developments in the field. This lack of a holistic approach although is evident in deterministic models too, the existing stochastic counterparts proved to include much less decision terms and inclusive constraints, which limits them to a limited applications and may cause sub-optimal solutions. Employing this set of holistic decision terms and boundary conditions, this work develops a scenario-based multi-stage stochastic capacity management model, which is capable of modelling different strategic terms such as capacity level management (slight, medium and large capacity volume adjustment to increase/decrease capacity), location/relocation decisions, merge/decomposition options, and product management (R&D, new product launch, product-to-plant and product-to-market allocation, and product phase-out management). Possibility matrix, production rates, different financial terms and international taxes, inflation rates, machinery depreciation, investment lead-time and product cycle-time are also embedded in the model in order to make it more practical, realistic and sensitive to strategic decisions and scenarios. A step-by-step open-box validation has been followed while designing the model and a holistic black-box validation plan has been designed and employed to widely validate the model. The model then has been verified by deploying a real-scaled case of Toyota Motors UK (TMUK) decision of mothballing one of their production lines in the UK after the global recession in 2010.

Keywords: Stochastic programming, Optimisation modelling, Capacity Management, Manufacturing

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1 Introduction

Resource management is one of the most important management tasks in manufacturing (Julka et al. 2007), and production capacity is the most strategic internal capability that manufacturing firms must create, sustain and plan for (Chen et al. 2002). Capacity management aims to ensure that a manufacturer has the 'right' capacity to act within a complex structure (Ambrosi 2010); and how best to 'utilise' their internal capabilities (Olhager et al. 2001). Due to the inherently parametric nature of the capacity management decisions, a quantitative approach has been more employed in this field (Julka 2008; Pidd 2003). However, an analytical decision-making model at best will only assist managers to better analyse and understand the trade-offs among available strategic choices (Eppen et al. 1989); and hence implementing a holistic set of important variables and decision terms in such models can improve the understanding of the trade-offs and prevent sub-optimal decisions, which is aimed by this work.

1.1 Decision Terms and Constraints of a Holistic Strategic Capacity Management Model

This section discusses the terms that must be embedded in a strategic capacity management model, which are categorised in four main groups of capacity level management, capacity location management, product and process management, and other terms as financial, political and environmental (Sabet 2012). Using 'input, control, output and mechanism' (ICOM) framework (Matta et al. 2005), the following sub-sections aim to introduce these critical decisions, and step by step configure the overall ICOM framework as summarised in Figure 1, which sets the boundary conditions for the model developed by this paper (Section 3).

1.1.1 Capacity Level Management

Adjusting production level to the long-term changes in demand, with minimum cost and lead-time implications, is the baseline for all capacity management models (Kauder and Meyr 2009). In manufacturing industry production capacities often change in bulk (so called 'lumpy nature' of the production capacity), indicating that the capacity changes in discontinuous and non-linear volumes (Olhager et al. 2001). Besides, manufacturing capacity often can change in 3 ranges of slight, medium and significant (Lin et al. 2010), in sequential form of over-utilization, capacity expansion and new plant/line establishment for capacity increase, and underutilisation, mothball and capacity shut-down for capacity decrease scenarios. See Table 1.

Table 1: ICOM summary for capacity level management- No term for mechanism

	Output	Input	Control
Capacity Level	• Capacity increase (over-utilization, expansion, new plan) • Capacity decrease (over-utilization, mothball, shut-down)	• Maximum annual budget for investment • Current capacities structure: location (in relate to suppliers and customers), operations costs, shut-down costs, expansion costs, over and under-utilisation costs, labour costs, etc. • New plant choices and their cost structure	• Lumpy nature of capacity change • Investment lead-time • Logical Constraints: non-negativity, non-aticipativity, non-simultaneity

1.1.2 Capacity Location Management (Location, Relocation, Merge and Decomposition)

In 1990's and 2000's, more than 75% and 90% of the biggest American companies invested in factories outside their countries respectively (Hamad and Fares Gualda 2008) and more recently an increasing number of EU and US companies are reshoring, which shows a need for the location/relocation decision terms in the capacity management models. Location decisions are functions of the geographical dispersion of the firm's suppliers, their manufacturing facilities, their sales regions and their investment portfolio (Kauder and Meyr 2009), as well as labour cost and energy costs in different locations, tariff and trade concessions, capital subsidies and logistics costs (Ferdows 1997). All these parametric terms can be employed in a holistic model. However, subjective factors, such as the company's policies, organisational learning through closeness to the customers and higher reliability and visibility to customers ought to be taken to the model as possible input options (MacCormack et al. 1994). The lead-time of the location/relocation decisions must also be considered in modelling to make it more realistic and sensitive to investment portfolios (Mula et al. 2006). Sometimes relocation decision is being made to centralise or decentralise the production capacities of a firm (by merging or decomposition), which can be embedded into a location/relocation model, using merge/decomposition possibility matrix. See Table 2 for the ICOM terms of location, relocation, merge and decomposition.

1.1.3 Product and Process Management (product development and technology management)

Product life-cycles are often much less than the capacity management planning horizon, and thus the entire product life-cycle curve, from the new product development to mass-production and final phase-out stage must be included in the time horizon of a capacity management

Table 2: ICOM summary for Capacity location Management - No term for mechanism

	Output	Input	Control
Capacity Location	• Decision on different choices of locations for a new plan. • Decision on whether to close a plant to open a new choice of plant (relocation) • Decision on whether to close two or more current plant to open a new choice of plant (merge) • Decision to close a current plant and open two or more new choice of new plants (decomposition)	• Maximum annual budget for investment • Choices of new plants and current plant structures (as detailed in Table 1) • Taxes, inflations, capital subsidies, labour costs, energy costs • Supply cost/tariff sensitivity to locations • Sales sensitivity to locations (transportation costs and tariffs)	• Merge and decomposition possibility matrix (what set of current plant can be merged for a new choice of plant for merge case, and what plant can be closed down to open a set of new plants for decomposition)Investment lead-time • Investment lead-time • Logical Constraints: non-negativity, non-aticipativity, non-simultaneity

model (Francas et al. 2009). The early phases which often called new product development (NPD) can be divided into two main phases of design or 'research and development' (R&D) and new product launch (NPL). R&D covers innovation, concept development and prototype making, and NPL is about launching a new product into plants, setups, first batch productions, and production ramp-ups. R&D phase is often more centralised and carried out in research centres, while NPL phase requires some product-related investments in the allocated plants (Fleischmann et al. 2006). Besides, both R&D and NPL phases are timely, and their investment lead-time must be considered in the product management models (Papageorgiou et al. 2001). Technology management in capacity and resource management models can be divided into two main domains of manufacturing flexibility, and facility replacement (technology obsolescence). Manufacturing flexibility is about the ability of a system to change its capacity quickly and economically (Ceryan and Koren 2009). It can be categorised into two types of 'product-mix' and 'volume flexibilities' (Kauder and Meyr 2009). Product-mix explains how a production facility can quickly and efficiently switch from one product to another. Volume flexibility explains how quickly and economically a production facility can adjust its production volume to chase the demand. 'Possibility matrix' and 'Production capacity rate' are being commonly used respectively, to model product-mix and volume flexibility in the capacity management models. Luss (1982) studies both physical depreciation and technology obsolescence in technology acquisition models. To formulate technology obsolescence modellers must simultaneously employ product life-cycles, product-plant investment requirements and the overhaul cost of facilities, all in a cost-based objective capacity management model (Wu and Chuang 2010). Table 3 summarises ICOM terms for this section.

Table 3: ICOM summary for product and process management - No term for mechanism

	Output	Input	Control
Product & Process	• Product to plant allocations • Product to market allocation • What choice of new products to develop, when and in which plant • Product re-launch decision (when and in which plant) • Choice of process technology (in form of what choice of new plant or expansion technology is selected, when valume increase is needed)	• Choice of process technology and their cost structure and depreciation • Choices of new plants and current plant structures (as detailed in Table 1) • R&D costs for each product family • Product-related investment portfolio in plants (for NPL) • Current and new product life-cycles (in sales forecast scenarios)	• Product/plant possibility matrix and product capacity rate • NPD and re-launch Investment lead-time

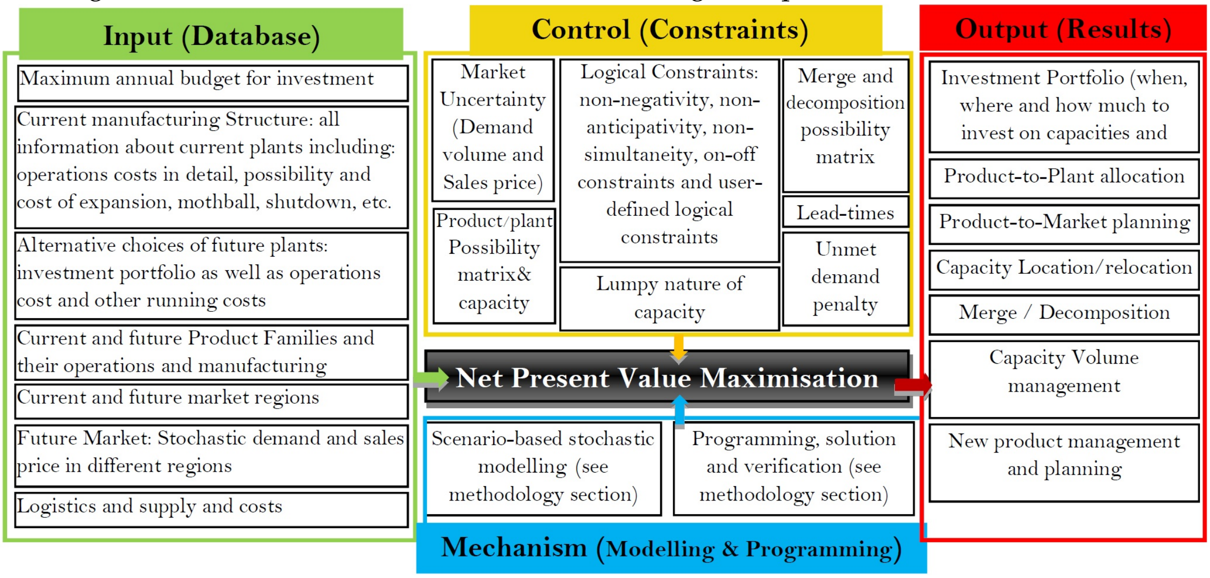
1.1.4 Other Terms (Financial, Political and Environmental)

Factors such as custom duties, inflation rates, tax on profit and value added tax have been mentioned as direct financial terms to be embedded in a strategic capacity management model (Fleischmann et al. 2006) to make a global capacity management model sensitive to location decisions (Verter and Dasci 2002). Although exchange rates directly affect capacity investment choices and relocation decisions (Farahani et al. 2010), there is no universally accepted exchange rate forecasting model (Bhutta et al. 2003). Besides, acquisition of the manufacturing resource is often of high lead-time; and therefore must be planned over a long term horizon (Olhager et al. 2001), for which uncertainty is an inevitable part (Chen et al. 2006). External sources of uncertainty, such as demand changes have been identified as the most disturbing and less controllable ones (Ahmed et al. 2003). However, many capacity planning models assume production should fulfil the entire demand, which may impose significant adjustments to the capacity level, even for a slight demand change. These unrealistic and sub-optimised solutions can be restrained by adapting an acceptable level of unsatisfied demand, which is usually associated with a penalty called 'unmet demand penalty' (Eppen et al. 1989). Although including supply chain selection decisions in capacity management models make them prohibitively complex, strategic capacity models can embed supply chain cost structure as a baseline for the supply chain (SC) related terms to make the models more sensitive to SC locations (Naraharisetti and Karimi 2010). Finally, although human resources and shift design may be considered as operational decisions, they affect some of the strategic ones such as capacity mothball and over/under utilisation; and thus, should not be entirely ignored in capacity management models. See Table 4.

Table 4: ICOM summary for financial and other terms - No term for mechanism

	Output	Input	Control
Financial Terms	• Shift management (in terms of adding or removing a shift to operations to change capacity level)	• Custom duties (on supply and sales, as a dependent of origin and destination countries) • Cost of supply (as a dependent of supplier location vs. manufacturing unit locations) • Inflation rates and tax in countries where R&D centres and manufacturing plants and are located • VAT in sales regions	• Market uncertainty (sales price and demand) • Unmet demand penalties

Figure 1: The Model's Framework in an ICOM logic adapted from Matta et al. (2005)



1.1.5 ICOM Summary for a Holistic Strategic Capacity Management Model

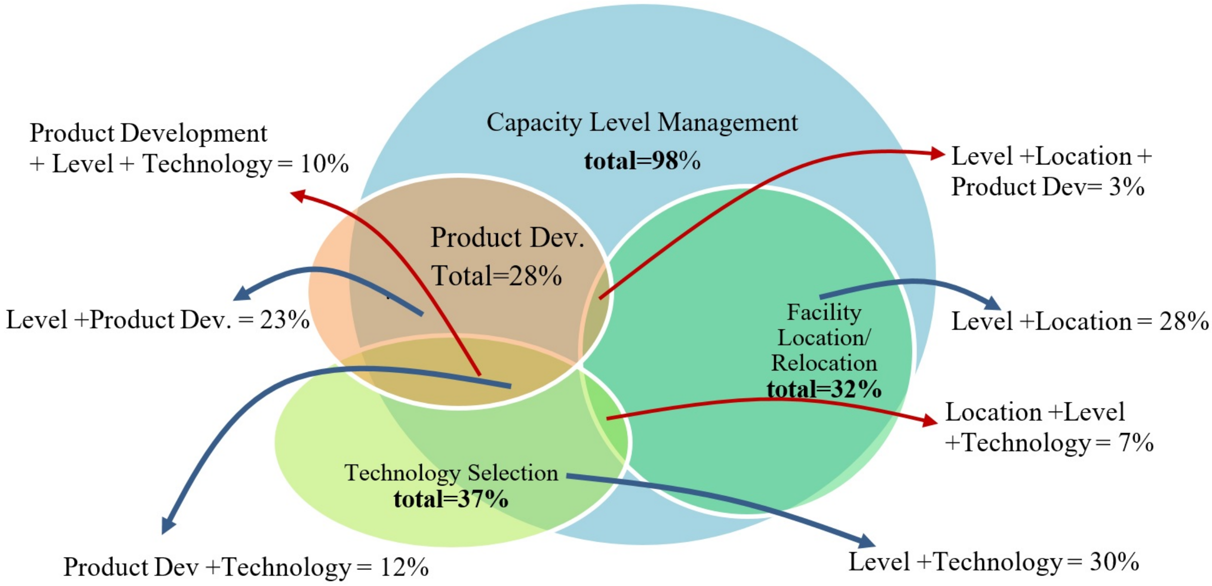
Figure 1 illustrates the boundary conditions of a holistic strategic capacity management model by summarising section 1.1 and Tables 1–4, which are employed in the model development in Section 3.

1.2 Recent Developments and Gaps in Strategic Capacity Optimisation Modelling

To better understand how the recent capacity optimisation models have covered the terms and parameters discussed before as the essential terms for a holistic capacity management model, and to understand how the model proposed in this paper contributes to the knowledge and practices in the field of capacity management modelling, Tables 14 and 15 (see Appendix) compare the terms employed in the most recent 69 models in the field. These models were found and selected in an extensive search for the optimisation-based models from those that embedded at least one of the strategic objective terms that was discussed in the last section. Scholar search engines such as Googlescholar, ScienceDirect, Emarald, IEEE Xplore, JSTOR and Springer were exploited in this search and after initial filtering to most relevant papers to the topic of this research and those published recently (2000 to 2018) these 69 papers were selected for a comparative analysis. To remark academic gaps in alternative topics of manufacturing systems including quantity production, transfer and assembly lines, balancing and, sequencing, etc., the reader may refer to a recent survey in (Yang et al. 2018).

Table 14 shows although embedding uncertainty in the modelling practice has recently received significant attention in capacity modelling, still just under one-third of capacity management models are deterministic. However, comparing Tables 14 and 15, one can see deterministic models tend to embrace more terms and factors into the modelling than their stochastic counterparts, and thus yet remained more multi-angels. Figure 2, summarises the findings from Table 14, and shows how well these recent models manage to simultaneously embed different terms in their formulations and stay multi-purpose.

Figure 2: How recent models in capacity management have embedded strategic terms



Although Table 14 shows capacity decrease modelling has widely left unattempted, Figure 2 illustrates still wide majority of the capacity management models have embedded at least one element of capacity level management in their models. However, only a few of these models have managed to embed at least three of the terms, and no model has yet covered all four strategic terms (Figure 2). Besides, as shown in Table 14, none of these models is capable of simultaneously managing all demand change possibilities (with over-utilisation, expansion and new capacity decisions in case of demand increase and under-utilisation, capacity mothball and capacity shutdown for demand decease scenarios), which limits the application of the models to a sub-set of potential applications. With regards to considering the product life-cycle in capacity management formulations, although the existing models have widely covered the mass production and decline phase, the early stages (concept design and product launch) have mainly left unattempted. Table 15 shows financial terms, detailed cost elements and control factors have been incompletely covered. As the result of this study, the model formulated in this paper (Section 3) aims to address these gaps and offer a more holistic capacity management model.

2 Methodology

Upon reviewing 103 models within the scope of resource planning under uncertainty, Peidro et al. (2009) categorised four quantitative approaches, namely analytical models, artificial intelligence-based models, simulation models and finally hybrid models. They summarise that the analytical approach has been more acknowledged and has had the fastest growth in resource management modelling (Peidro et al. 2009). As a part of analytical modelling, mathematical programming has been widely employed by peer scholars in strategic capacity management modelling (Hvolby and Steger-Jensen 2010; Melo et al. 2009; Mula et al. 2006). Traditionally in the real scale optimisation practices, often stochastic parameters have been replaced by their expected values (so called expected value problem) to make them deterministic and easier to programme and solve (Graves 2011). However, as explained in the last section, long-term capacity planning is subject to a vast uncertainty and thus simple estimations of expected values (or most probable scenarios) are no longer viable, and may lead to unrealistic capacity solutions (Barahona et al. 2005). Besides, statistical data are hardly reliable any more to forecast a long-term demand prospect, and thus a scenario-based stochastic programming has been employed as the most appropriate technique for log-term resource management modelling in Kauder and Meyr (2009), and therefore, is used in this paper, as well. The solution, validation and verification process are detailed later in this paper in Sections 4 and 5.

3 Problem Statement and Model Formulation

Led by ICOM framework in Section 1.1.5 (Figure 1), the rest of this section formulates the model and its constraints. The problem to be modelled is a long term strategic periodic capacity management problem by making decision on opening, closing, mothballing, reopening, expansion or overutilising different manufacturing plant in differently distributed geographical places under a stochastic demand or sales price in different regions by considering the transportation and cost of unmet demand, in such a way to maximise net present value of the firm. First we introduce the parameters and decision variables nomenclature in Table 5 and then describe different costs in the following subsections and subsequently, we present the objective function and mathematical model with the corresponding elaboration of the constraints.

3.1 Fixed Investment Costs

Some of the strategic capacity investments are long term (over one year time interval), and therefore, lead-time (η) should be included in the programming. In this model the lead-time applies to the investments on new plants, expansions, new product developments and research and developments. If any of these investment decision variables ($Z^{\text{New}}_{.t.}, Y^{\text{Exp}}_{.t.}, Y^{\text{NPL}}_{.t.}, Y^{\text{RD}}_{.t.}$) equals 1 at year t, investment starts a few years in advance (depending on the individual lead-time), so that the product or the production capacity is ready at the year t. Although to mothball a capacity the firm must also invest in redundancy and terminating supply contracts, it can often be conducted within the time intervals (one year) and need no lead-time. The same logic applies to shutdown decisions and reopening a mothballed capacity. Over-utilising a capacity requires annual investments for as long as the plant is over-utilised to invest in the extra times and third shifts, etc.. New product launch (NPL) occurs when a product is launched in any of the facilities for the first time. In such cases, a one-off launch cost is required for product-related investments (dedicated lines/machines, tooling, settings, training, first batch productions, system developments) and lead-time apply. However, relaunching an existing product after a long production-break needs a reset/changeover cost, but not as much as the NPL investment and it often needs no lead-time more than the time interval (one year). In a new product launch case, both Y^{PL} and Y^{NPL} equal 1; hence, the term $(Y^{\text{PL}} - Y^{\text{NPL}})$ is applied to the extended objective function (2) for the product relaunch investments.

Table 5: Nomenclatures list for the model formulation

Parameters				**Variables**	
$\vartheta^{\text{E-min}}$	*Min. capacity expansion rate of plant i, out of nominal cap*	Δ^{Opr}	*Inflation rate on operations cost*	X^{Unmet}_{ztrj}	*Amount of unmet product j in region r in year t under scenario z*
$\vartheta^{\text{E-max}}$	*Max. capacity expansion rate of plant i, out of nominal cap*	Δ^{Inv}	*Inflation rate on investment cost*	X^{A}_{ztij}	*Amount of product j in plant i in year t, under scenario z*
σ^{Tax}_{i}	*Profit tax rate in plant i location*	Δ^{Sup}	*Inflation rate on supply cost*	X_{ztrij}	*Amount of product j transported from plant i to region r in year t under scenario z*
$\sigma^{\text{Tariff}}_{ri}$	*Tariff rate of import from plant i to region r*	Δ^{D}	*Inflation rate on transportation cost*	Y^{A}_{ztij}	*Binary variable which equals 1 if product j is produced in plant i in year t under scenario z; and 0, otherwise*
σ^{VAT}_{r}	*Value added tax in region r*	Δ^{Unmet}	*Inflation rate on unmet demand penalty*	Y^{A}_{zti}	*Binary variable which equals 1 if plant i is is subject to depreciation (either open or mothballed) in year t under scenario z; and 0, otherwise*
K^{Initial}_{i}	*Nominal capacity of plant i, before any volume change*	I^{New}_{i}	*Capital investment to establish new plant i*	Z^{New}_{zti}	*Binary variable which equals 1 if plant i is established in year t under scenario z; and 0, otherwise*
μ^{Max}_{i}	*Normal capacity ratio (out of maximum cap.) of plant i*	I^{Exp}_{i}	*Capital investment to expand plant i*	Y^{Exp}_{zti}	*Binary variable which equals 1 if plant i is expanded in year t under scenario z; and 0, otherwise*
$\varepsilon^{\text{Fr}}_{i}$	*Redundancy rate on labour cost, in case of plant i mothball*	I^{Fr}_{i}	*Capital investment to mothball plant i*	Y^{FrAll}_{zti}	*Binary variable which equals 1 if plant i has a mothballed capacity in year t under scenario z; and 0, otherwise*
$\varepsilon^{\text{Exp}}_{i}$	*Increase rate on labour cost, in case of plant i expansion*	I^{OprExp}_{i}	*Extra annual operations cost of plant i, if it has been expanded*	Y^{ExpAll}_{zti}	*Binary variable which equals 1 if plant i has ever been expanded till year t under scenario z; and 0 otherwise*
$\varepsilon^{\text{Ou}}_{i}$	*Increase rate on labour cost, in case of overutilisation in plan i*	I^{Ou}_{i}	*Capital investment to overutilise plant i*	Y^{Ou}_{zti}	*Binary variable which equals 1 if plant i is overutilised in year t under scenario z*
η^{RD}_{j}	*Investment time-table to design the new product j (in form of percentage over a few time intervals)*	I^{RD}_{j}	*Cost of designing product j in research centre/headquarter*	Y^{RD}_{ztj}	*Binary variable which equals 1 if product j is designed in year t under scenario z*
η^{New}_{i}	*Investment timetable to establish plant i (in form of percentage over a few time intervals)*	I^{Re}_{i}	*Capital investment to reopen plant i, if it has been mothballed*	Y^{Re}_{zti}	*Binary variable which equals 1 if any capacity is reopened in plant i in year t under scenario z*
η^{Exp}_{i}	*Investment timetable to expand plant i (in form of percentage over a few time intervals)*	I^{OprFr}_{i}	*Annual maintenance cost of plant i, if it has been mothballed*	Y^{Fr}_{zti}	*Binary variable which equals 1 if plant i is mothballed in year t under scenario z; and 0, otherwise*
η^{NPL}_{ij}	*Timetable of launching product j in plant i for the first time (in form of percentage over a few time intervals)*	I^{NPL}_{i}	*Cost of launching product j in plant i for the first time*	Y^{NPL}_{ztij}	*Binary variable which equals 1 if NPL occurs for product j in plant i in year t under scenario z*
l_j	*Maximum number of plants to produce product j*	I^{PL}_{ij}	*Cost of relaunching product j in plant i, after a production break*	Y^{PL}_{ztij}	*Binary variable which equals 1 if PL occurs for product j in plant i in year t under scenario z*
n^{Max}_{i}	*Maximum possible products to be produced in plant i*	I^{W}_{i}	*Annual work force cost of plant i*	Y^{ExpW}_{zti}	*Binary variable which equals 1 if in-use plant i has ever been expanded until year t under scenario z*
d_{ztrj}	*Demand for product j in region r in year t under scenario z*	I^{Opr}_{i}	*Annual operations cost of plant i*	Y^{ExpW}_{zti}	*Binary variable which takes 1 if plant i is in use in year t under scenario z*
b_t	*Maximum investment budget in year t*	I^{Cl}_{i}	*Fixed cost of shutting down plant i*	Y^{Cl}_{zti}	*Binary decision variable which equals 1 if plant i is closed in year t under scenario z*
n^{Merge}_{i}	*How many plants should be merged together to form plant i*	C^{Sup}_{ij}	*Unit cost of supply for product j in plant i*	K^{Max}_{zti}	*Nominal capacity of plant i in year t under scenario z*
M	*A sufficiently large number*	C^{D}_{rij}	*Unit cost of transp. product j from plant i to region r*	K^{Cl}_{zti}	*Shutdown capacity amount of plant i in year t under scenario z*
P_z	*Probability of scenario z*	C^{Penalty}_{ij}	*Unit unmet demand penalty for product j in region r*	K^{FrAll}_{zti}	*Cumulative amount of mothballed capacity for plant i in year t under scenario z*
P^{Merge}_{i}	*The combination of the plants that should be merged to form plan i*	C^{Unit}_{ij}	*Any other unit cost of producing product j in plant i*	K^{Fr}_{zti}	*Amount of capacity mothballed in plant i in year t under scenario z*
γ_{ij}	*Cap. volume rate of product j in plant i*	C^{Sale}_{ztrj}	*Unit sales price of product j in region r in year t and scenario z*	K^{Exp}_{zti}	*Expanded capacity amount of plant i in year t under scenario z*
E_i	*Maximum number of times for possible expansion for plant i*	ρ	*Discount rate*	K^{Re}_{zti}	*Reopened capacity amount of plant i in year t under scenario z*

3.2 Variable/Operations Costs

Transportation costs and unmet demand penalties are both unit-based costs. Unmet demand penalties should at least cover the net profit margin of the loss of sales, but it can also include the opportunity lost and brand damage (Eppen et al. 1989). However, penalties must have no tax-related implications. Annual workforce cost is a function of the plant location and can be different if a plant is normally utilised or overutilised, and if they are expanded or mothballed (ε is the proportion which adds to or cuts from the normal utilisation situation due to overutilisation and expansion, or mothball). Besides, to make the model sensitive to global capacity decisions and location/relocation decisions VAT and tariff taxes must be directly employed to the model as a function of location of the plants and sales regions. Other annual operations costs, maintenance costs and overheads also apply whenever a plant is functional (utilised or mothballed, but not closed). This model is not aimed to design the supply chain network. However, to avoid unrealistic simplification of ignoring the impact of supply chain network design on capacity location and planning, a location-sensitive supply cost has been applied to the model, as also supported by other researchers (Dal-Mas et al. 2011).

3.3 Objective Function

This model aims to maximise the net present value (NPV) under demand and sales price uncertainty (scenarios). A one-year time interval is set for the model, as cited for the strategic capacity planning by Fleischmann et al. (2006). A minimum of 10 years is suggested for capacity management models in manufacturing (Bhutta et al. 2003) and automotive industry (Kauder and Meyr 2009). Since R&D activities in large and multi-national manufacturing firms often happen in their headquarters and research centres rather than their individual plants, R&D investments do not depend on the sales regions or plant locations. Thus the tax/incentive rates on these investments are not included in the objective function below,

$$\max(NPV) = \max \sum_{z} P_z \sum_{t=1}^{T} \left\{ (1+\rho)^{-t} \left[\sum_{i=1} (1-\sigma_i^{\text{Tax}})(\mathcal{R}_{zti} - \mathcal{I}_{zti} - \mathcal{O}_{zti}) - \mathcal{D}_{z,t} \right] \right\} \quad (1)$$

where $\mathcal{R}_{zti}$, $\mathcal{I}_{zti}$ and $\mathcal{O}_{zti}$ respectively denote revenue, investment cost and operations cost for plant i at year t under scenario z while $\mathcal{D}$ corresponds to R&D cost.

Profit is the sum of sales in different regions over years under different demand and sales price scenarios minus the aforementioned costs. The objective function is extended in (2) to enable the decision-makers to test the impact of different inflation and tax scenarios on the location decisions, or different inflation rates (Δ) on investments, operations, supplies and distributions logistics as,

NPV:	$\max \sum_z P_z \sum_{t=1}^{T} (1+\rho)^{-t} \Big\{$
Revenue:	$+\sum_{r,i,j} (1-\sigma_i^{\text{Tax}})(C_{ztrj}^{\text{Sale}} X_{ztrij})$
Investment cost of new plants establishment, expansion or mothball of an existing plant:	$-\Big[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Inv}})^t \left(I_i^{\text{New}} \eta_i^{\text{New}} Z_{zti}^{\text{New}} + I_i^{\text{Exp}} \eta_i^{\text{Exp}} Y_{zti}^{\text{Exp}} + I_i^{\text{Fr}} Y_{zti}^{\text{Fr}}\right)\Big]$
Annual investment (fixed) cost of overutilization, re-opening a mothballed plant and closing an existing plant:	$-\Big[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Inv}})^t \left(I_i^{\text{Ou}} Y_{zti}^{\text{Ou}} + I_i^{\text{Re}} Y_{zti}^{\text{Re}} + I_i^{\text{Cl}} Y_{zti}^{\text{Cl}}\right)\Big]$
Investment cost of NPD or fixed cost of product re-launch:	$-\Big[\sum_{i,j} (1-\sigma_i^{\text{Tax}}) \left(I_i^{\text{NPL}} \eta_{ij}^{\text{NPL}} Y_{ztij}^{\text{NPL}} + I_i^{\text{PL}} (Y_{ztij}^{\text{PL}} - Y_{ztij}^{\text{NPL}})\right)\Big]$
Unit cost of trans-portation and Logistics:	$-\Big[\sum_{r,i,j} (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{D}})^t C_{rij}^{\text{D}} X_{ztrij}\Big]$
Annual workforce cost of the normal-utilised, over-utilised, expanded and mothballed plants:	$-\Big[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Opr}})^t I_i^{\text{W}} \left(Y_{zti}^{\text{A}} + \varepsilon_i^{\text{Ou}} Y_{zti}^{\text{Ou}} + \varepsilon_i^{\text{Ou}} Y_{zti}^{\text{ExpW}} - \varepsilon_i^{\text{Fr}} Y_{zti}^{\text{FrAll}}\right)\Big]$
Custom duty (tariff) and value added tax on sales:	$-\Big[\sum_{r,i,j} (1-\sigma_i^{\text{Tax}}) \left(\sigma_{ri}^{\text{Tariff}} + \sigma_r^{\text{VAT}} (1+\sigma_{ri}^{\text{Tariff}})\right) C_{zrj}^{\text{Sale}} X_{ztrij}\Big]$
Annual operation and over-head costs of operating, ex-panded or mothballed plants:	$-\Big[\sum_i (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Opr}})^t \left(I_i^{\text{Opr}} Y_{zti}^{\text{ExpW}} + I_i^{\text{OprExp}} Y_{zti}^{\text{ExpW}} + I_i^{\text{OprFr}} Y_{zti}^{\text{FrAll}}\right)\Big]$
Unit cost of supply:	$-\Big[\sum_{i,j} (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Sup}})^t C_{ij}^{\text{Sup}} X_{ztij}^{\text{A}}\Big]$
Other unit cost of operations:	$-\Big[\sum_{i,j} (1-\sigma_i^{\text{Tax}})(1+\Delta^{\text{Opr}})^t C_{ij}^{\text{Unit}} X_{ztij}^{\text{A}}\Big]$
Unmet unit cost of operations:	$-\Big[\sum_{i,r} (1+\Delta^{\text{Unmet}})^t C_{ij}^{\text{Penalty}} X_{ztrj}^{\text{Unmet}}\Big]$
R&D cost of designing a product (no tax implementation - not function of plants, is done in headquarters & research centres):	$-\Big[\sum_j (1+\Delta^{\text{Inv}})^t I_j^{\text{RD}} \eta_j^{\text{RD}} Y_{ztj}^{\text{RD}}\Big]$
	$\Big\}. \qquad (2)$

3.4 Mathematical Model

$$\max \quad NPV$$

s.t.

$$K_{zti}^{\text{Max}} = K_{z,t-1,i}^{\text{Max}} + Z_{z,t-1,i}^{\text{New}} K_i^{\text{Initial}} + K_{z,t-1,i}^{\text{Exp}} - K_{z,t-1,i}^{\text{Fr}} - K_{z,t-1,i}^{\text{Cl}} + K_{z,t-1,i}^{\text{Re}} \quad \forall z,t,i \tag{3}$$

$$Y_{zti}^{\text{Exp}} \leq K_{zti}^{\text{Exp}} \leq M Y_{zti}^{\text{Exp}} \quad \forall i,t,z \tag{4}$$

$$Y_{zti}^{\text{Fr}} \leq K_{zti}^{\text{Fr}} \leq M Y_{zti}^{\text{Fr}} \quad \forall i,t,z \tag{5}$$

$$Y_{zti}^{\text{Re}} \leq K_{zti}^{\text{Re}} \leq M Y_{zti}^{\text{Re}} \quad \forall i,t,z \tag{6}$$

$$Y_{zti}^{\text{Cl}} \leq K_{zti}^{\text{Cl}} \leq M Y_{zti}^{\text{Cl}} \quad \forall i,t,z \tag{7}$$

$$\sum_j X_{ztij}^{\text{A}} / \gamma_{ij} \leq K_{zti}^{\text{Max}} \quad \forall i,t,z \tag{8}$$

$$\sum_j (X_{ztij}^{\text{A}} / \gamma_{ij}) - M Y_{zti}^{\text{Ou}} \leq \mu_i^{\text{Max}} K_{zti}^{\text{Max}} \quad \forall z,t,i \tag{9}$$

$$\sum_j (X_{ztij}^{\text{A}} / \gamma_{ij}) + M(1 - Y_{zti}^{\text{Ou}}) \geq \mu_i^{\text{Max}} K_{zti}^{\text{Max}} \quad \forall z,t,i \tag{10}$$

$$\sum_{t=1}^{T} Z_{zti}^{\text{New}} \leq 1 \qquad \forall i, z \tag{11}$$

$$\sum_{t=1}^{T} Y_{zti}^{\text{Exp}} \leq E_i \qquad \forall i, z \tag{12}$$

$$K_{zti}^{\text{Exp}} \leq Y_{zti}^{\text{Exp}} \vartheta^{\text{E-max}} K_i^{\text{Initial}} \qquad \forall z, t, i \tag{13}$$

$$Y_{zti}^{\text{Exp}} \vartheta^{\text{E-min}} K_i^{\text{Initial}} \leq K_{zti}^{\text{Exp}} \qquad \forall z, t, i \tag{14}$$

$$K_{zti}^{\text{Fr}} + M(1 - Y_{zti}^{\text{Fr}}) \geq K_{zti}^{\text{Max}} \qquad \forall z, t, i \tag{15}$$

$$K_{zti}^{\text{Fr}} \leq K_{zti}^{\text{Max}} \qquad \forall z, t, i \tag{16}$$

$$K_{zti}^{\text{FrAll}} = K_{z,t-1,i}^{\text{FrAll}} + (K_{z,t-1,i}^{\text{Fr}} - K_{z,t-1,i}^{\text{Re}}) \qquad \forall z, t, i \tag{17}$$

$$K_{zti}^{\text{Re}} + M(1 - Y_{zti}^{\text{Re}}) \geq K_{zti}^{\text{FrAll}} \qquad \forall z, t, i \tag{18}$$

$$K_{zti}^{\text{Re}} \leq K_{zti}^{\text{FrAll}} \qquad \forall z, t, i \tag{19}$$

$$\sum_{t=1}^{T} Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \tag{20}$$

$$K_{zti}^{\text{Cl}} + (1 - Y_{zti}^{\text{Cl}})M \geq K_{zti}^{\text{Max}} \qquad \forall z, t, i \tag{21}$$

$$K_{zti}^{\text{Cl}} - MY_{zti}^{\text{Cl}} \leq K_{zti}^{\text{Max}} \qquad \forall z, t, i \tag{22}$$

$$K_{zti}^{\text{Cl}} \leq K_{zti}^{\text{Max}} \qquad \forall z, t, i \tag{23}$$

$$(1 - Y_{zti}^{\text{Cl}})M \geq K_{zti}^{\text{FrAll}} \qquad \forall z, t, i \tag{24}$$

$$Z_{zti}^{\text{New}} n_i^{\text{Merge}} \leq \sum_{\hat{i} \in P_i^{\text{Merge}}} Y_{zt\hat{i}}^{\text{Cl}} \qquad R \in I, \forall z, t, i \tag{25}$$

$$(Y_{ztij}^{\text{A}} - \sum_{\tau=0}^{t-1} Y_{z\tau ij}^{\text{A}}) - 1 + M(1 - Y_{zti}^{\text{NPL}}) \geq 0 \qquad \forall z, t, i, j \tag{26}$$

$$(Y_{ztij}^{\text{A}} - \sum_{\tau=1}^{t-1} Y_{z\tau ij}^{\text{A}}) \leq Y_{ztij}^{\text{NPL}} \qquad z, t, i, j \tag{27}$$

$$(Y_{ztij}^{\text{A}} - Y_{z,t-1,ij}^{\text{A}}) - 1 + M(1 - Y_{ztij}^{\text{PL}}) \geq 0 \qquad \forall z, t, i, j \tag{28}$$

$$Y_{ztij}^{\text{A}} - Y_{ztij}^{\text{A}} - Y_{z,t-1,ij}^{\text{A}} \leq Y_{ztij}^{\text{PL}} \qquad z, t, i, j \tag{29}$$

$$Y_{zti}^{h} \leq \sum_{i} \sum_{\tau=0}^{t} Y_{ztij}^{\text{A}} \leq M.Y_{ztj}^{h} \qquad \forall z, j \tag{30}$$

$$(Y_{ztj}^{h} - Y_{z,t-1,j}^{h} - 1) + M(1 - Y_{ztj}^{\text{RD}}) \geq 0 \qquad \forall z, t, j \tag{31}$$

$$Y_{ztj}^{h} - Y_{z,t-1,j}^{h} \leq Y_{ztj}^{\text{RD}} \qquad \forall z, t, j \tag{32}$$

$$Y_{zti}^{\text{Exp}} + Y_{zti}^{\text{Fr}} + Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \tag{33}$$

$$Y_{zti}^{\text{Re}} + Y_{zti}^{\text{Fr}} + Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \tag{34}$$

$$\sum_{j} Y_{ztij}^{\text{PL}} + Y_{zti}^{\text{Fr}} + Y_{zti}^{\text{Cl}} \leq 1 \qquad \forall z, t, i \tag{35}$$

$$\sum_{j} Y^{\text{NPL}}_{ztij} + Y^{\text{Fr}}_{zti} + Y^{\text{Cl}}_{zti} \leq 1 \qquad \forall z, t, i \tag{36}$$

$$K^{\text{Exp}}_{ti\hat{z}} = K^{\text{Exp}}_{ti\bar{z}} \qquad \forall t, i, \hat{z} \neq \bar{z} \in S_t \tag{37}$$

$$Z^{\text{New}}_{ti\hat{z}} = Z^{\text{New}}_{ti\bar{z}} \qquad \forall t, i, \hat{z} \neq \bar{z} \in S_t \tag{38}$$

$$Y^{\text{Cl}}_{ti\hat{z}} = Y^{\text{Cl}}_{ti\bar{z}} \qquad \forall t, i, \hat{z} \neq \bar{z} \in S_t \tag{39}$$

$$Y^{\text{RD}}_{tj\hat{z}} = Y^{\text{RD}}_{tj\bar{z}} \qquad \forall t, j, \hat{z} \neq \bar{z} \in S_t \tag{40}$$

$$Y^{\text{Fr}}_{tj\hat{z}} = Y^{\text{Fr}}_{tj\bar{z}} \qquad \forall t, j, \hat{z} \neq \bar{z} \in S_t \tag{41}$$

$$Y^{\text{Re}}_{tj\hat{z}} = Y^{\text{Re}}_{tj\bar{z}} \qquad \forall t, j, \hat{z} \neq \bar{z} \in S_t \tag{42}$$

$$Y^{\text{NPL}}_{tij\hat{z}} = Y^{\text{NPL}}_{tij\bar{z}} \qquad \forall t, i, j, \hat{z} \neq \bar{z} \in S_t \tag{43}$$

$$Y^{\text{FrAll}}_{zti} + \sum_{\tau=0}^{t} Y^{\text{Cl}}_{z\tau i} \leq 1 - Y^{\text{ExpW}}_{zti} \qquad \forall z, t, i \tag{44}$$

$$Y^{\text{ExpAll}}_{zti} \leq \sum_{\tau=0}^{t} K^{\text{Exp}}_{z\tau i} \leq M Y^{\text{ExpAll}}_{zti} \qquad \forall z, t, i \tag{45}$$

$$Y^{\text{ExpAll}}_{zti} - Y^{\text{FrAll}}_{zti} - \sum_{\tau=0}^{t} Y^{\text{Cl}}_{z\tau i} \leq Y^{\text{ExpW}}_{zti} \qquad \forall z, t, i \tag{46}$$

$$Y^{\text{ExpAll}}_{zti} \geq Y^{\text{ExpW}}_{zti} \qquad \forall z, t, i \tag{47}$$

$$\sum_{i} Y^{v}_{ztij} \leq l_j \qquad \forall z, t, j \tag{48}$$

$$\sum_{j} Y^{\text{A}}_{ztij} \leq n^{\text{Max}}_{i} \qquad \forall z, t, i \tag{49}$$

$$\sum_{z} \Big(\sum_{i} \mathcal{I}_{zti} + \sum_{j} \mathcal{D}_{ztj} \Big) \leq b_t \qquad \forall t \tag{50a}$$

$$\mathcal{I}_{zt} \leq \alpha \sum_{r,i,j} C^{\text{Sale}}_{z,t-1,r,ij} X_{z,t-1,rij} \qquad \forall z, t \tag{50b}$$

$$\sum_{i} X_{ztrij} + X^{\text{Unmet}}_{ztrj} = d_{ztrj} \qquad \forall z, t, r, j \tag{51}$$

$$\sum_{r} X_{ztrij} = X^{\text{A}}_{ztij} \qquad \forall t, i, j. \tag{52}$$

$$Y^{\text{Cl}}_{zti}, Y^{\text{Ou}}_{zti}, Y^{\text{Fr}}_{zti}, Y^{\text{Re}}_{zti}, Y^{\text{FrAll}}_{zti}, Y^{\text{ExpAll}}_{zti}, Y^{\text{ExpW}}_{zti}, Y^{\text{A}}_{zti} \in \{0,1\} \qquad \forall z, t, i \tag{53}$$

$$Z^{\text{New}}_{zti} \in \{0,1\} \qquad \forall z, t, i \tag{54}$$

$$Y^{\text{Exp}}_{ztj}, Y^{\text{ExpAll}}_{ztj}, Y^{\text{RD}}_{ztj} \in \{0,1\} \qquad \forall z, t, j \tag{55}$$

$$Y^{\mathcal{P}}_{ztij}, Y^{\text{Cl}}_{ztij}, Y^{\text{NPL}}_{ztij}, Y^{\text{PL}}_{ztij} \in \{0,1\} \qquad \forall z, t, i, j \tag{56}$$

$$X^{\text{A}}_{ztij}, X_{ztij}, X^{\text{Unmet}}_{ztij} \geq 0 \qquad \forall z, t, i, j \tag{57}$$

$$K^{\text{Max}}_{zti}, K^{\text{Cl}}_{zti}, K^{\text{Fr}}_{zti}, K^{\text{Re}}_{zti}, K^{\text{Exp}}_{zti}, K^{\text{FrAll}}_{zti} \geq 0 \qquad \forall z, t, i. \tag{58}$$

As summarised at ICOM framework (Figure 1), the following subsections present the corresponding constraints of the model.

3.4.1 Capacity Volume

Constraint (3) holds the capacity balance equation according to the initial capacity, new plants, expansion, mothballed, reopened and the shutdown capacity. Constraints (4)–(7) detect each of these decisions via their corresponding binary variables.

3.4.2 Possibility matrix and production rate

The fitness of producing product j in plant i is determined via possibility matrix γ_{ij} where $\gamma_{ij} \in [0, 2]$ and,

- $\gamma_{ij} = 1$ indicates that plant j is a normal fit for product i
- $0 < \gamma_{ij} < 1$ product i can be made at plant j, but is not the best fit (the production efficiency is between 0% to 100%)
- $1 < \gamma_{ij} \leq 2$ product i can be made at plant j and with more than normal rates (up to twice faster).
- $\gamma_{ij} = 0$ product i cannot be made in plant j.

Constraint (8) sets the production capacity based on the fitness of the products.

3.4.3 Normal and Overutilisation

A plant i is called overutilised, if it uses more than certain amount of its capacity which is determined by factor μ_i^{Max}. Constraints (9) and (10) force Y_{zti}^{Ou} to get 1 if plant i is overutilised in period t under scenario z and 0, otherwise.

3.4.4 New Capacity Establishment

Constraint (11) guarantees that a new plant can be opened at most once within the entire planning horizon.

3.4.5 Capacity Expansion

Capacity expansion is limited to a certain number as set in constraint (12) while its lumpiness nature is addressed in constraints (13) and (14). That is, every expansion is limited to a certain range of capacity increase, and not less or more ($\vartheta^{\text{E-min}}$ and $\vartheta^{\text{E-max}}$).

3.4.6 Capacity Mothball

If mothballing decision is made for plant i, i.e., $Y^{\text{Fr}}_{zti} = 1$, then its all available capacity are mothballed: Constraints (15) and (16).

3.4.7 Capacity Reopen

Only plants with mothballed capacity can be reopened. The overall mothballed capacity is calculated in (17). Moreover, if reopen decision is made, it opens all the mothballed capacity at once: constraints (18) and (19).

3.4.8 Capacity Shutdown

Shutdown of a plant can only happen once, constraint (20) , and it can never be reopened if closed down. The corresponding capacity and binary variables are set in constraints (21)–(23). In addition, to avoid sub-optimised solutions, no mothballed capacity can be closed at any time. If a plant is not needed in the future at all, it must be closed down and not mothballed which is set by constraint (24).

3.5 Relocation and Merge Constraints

Relocation of a plant means closing a current plant and opening a new one in another location. Similarly, in the case of merging plants, a few plans are closed down to open a new one. Merging portfolios (possible cases) is defined as inputs to the database. It requires investment and lead-time, as well as information on how many (n^{Merge}) plants and which one of them from the possible potential plants (P^{Merge}) could/should be merged to open a new plant as set in (25). For the relocation case (i.e., no merge), $n^{\text{Merge}} = 1$.

3.5.1 Product Development Constraints

Y^{NPL} and Y^{PL} respectively indicate if a product is launched for the first time at all or after a time break. To avoid mixing PL and NPL, the term $Y^{\text{PL}} - Y^{\text{NPL}}$ is applied into the objective function for product relaunch case. Moreover, to formulate whether R&D has performed or not (i.e., Y^{RD}), the auxiliary binary variable Y^{h}_{ztj} is used to identify if product j has ever been produced in any plants before or not. Constraints (26)–(32) define the above relations and logics.

3.5.2 Non-Simultaneous and Non-Anticipative Constraints

Reopening, expansion and product launch (NPL or PL) can simultaneously be done for the same plant, as well as new plant and new product launch. However, mothballing and reopening, mothballing and expansion, reopening and shutdown, expansion and shutdown, NPL/PL and shutdown and finally NPL/PL and capacity mothball cannot be done simultaneously for the same plant: constraints (33)–(36).

Furthermore, non-anticipative constraints are needed for stochastic models (Sterman 2000), indicating that strategic capacity decisions are irreversible and the decision variables corresponding to the scenarios with the same history have the common value. Let S_t denote the set of scenarios with a common history and decisions at time t. These decisions are capacity expansion, shutdown, new plant establishment, new product launch decision, R&D, plant mothball, and finally plant reopening as given in (37)–(43).

3.5.3 Other Constraints

Workforce Constraints

Recalling from the objective function, expanded capacities need extra workforce cost if they are operational (not mothballed or closed). In such situations $Y_{zti}^{\text{ExpAll}} = 1$, and 0 otherwise.

- If capacity has been closed down sometime before year t or mothballed and not reopened, then $Y_{zti}^{\text{ExpAll}} = 0$: constraint (44).
- If the plan has been ever expanded before (i.e., Y^{ExpAll}=1), and is not currently mothballed nor closed down, then $Y_{zti}^{\text{ExpAll}} = 1$: constraints (45) and (46).
- If the plant has never been expanded then $Y_{zti}^{\text{ExpAll}} = 0$: constraint (47).

Maximum Plant and Maximum Product Constraints

The company policy might be not to launch each product j in more than a certain maximum number of plants as shown in (48) . Likewise, a maximum product constrain as (49) can be applied to limit the maximum number of product types launched in certain plants in each period of time.

Budget Constraints

Often companies define a maximum annual budget, b_t, for total investment: (50a). Also, the investment budget can be defined as a proportion of the total annual sales (revenue) as (50b) where $\alpha < 1$ is a constant corresponding to proportion of revenue which is assigned for reinvestment.

Demand and Distribution Constraints

Unmet demand associated with a penalty is considered in this model and (51) formulates the total production with relate to overall demand. Moreover, all products of year t must be transported within the same period: (52). Note that since this model is a strategic planning one, with a time interval of one year, no inventory term and constraint is required if a first-in-first-out stock management applies (Chen et al. 2002).

4 Solution and Validation

This model is a scenario-based stochastic model. After extending the scenarios in the programming (coding in Visual Basic), the model can be reformulated to a mixed integer liner optimisation problem. To validate the model, fourteen hypothetical cases are designed and used, as explained in an ICOM form validation plan in Figure 3. This figure illustrates how all decision outputs of the model and their interactions are validated in this study. Cases 1 to 5 are deterministic cases to validate the model's ability to handle slight, medium and significant capacity changes (increase and decrease). Deterministic cases 6 to 8 are designed to validate model's location decision capability. Case 6 studies the impact of different financial terms (tax, VAT and inflation) on the global decisions, and cases 7 and 8 study the impact of location/relocation capability on capacity volume decisions (relocation versus expansion in demand increase scenarios and relocation versus underutilisation in demand decrease scenarios, respectively). Case 9 and 10 validate stochastic form in capacity volume cases. Although demand is stochastic for the case 9, the expected value of demand is designed to be exactly the same as case 2, in order to study the model's stochastic capability and value of stochastic solutions (VSS) in the increasing demand scenario. Likewise, to study the decreasing demand scenario, case 10 represents a stochastic demand with the same expected value as in the case 5, and calculates VSS in demand decrease scenarios. Similar to Case 7, in case 11 the impacts of global solutions in oppose to local decision (for instance, a new plant in China versus an expansion of a current European plant) is studied in the stochastic form. Cases 12 and 13 validate technology management capability of the model, and respectively volume flexibility and product-mix flexibility. Finally, case 14 validates the model's strategic product development and planning capability. All validation cases are available on request from the corresponding author, but in this paper only cases 5, 9 and 11 are reported to validate the capacity volume and location decision capability of the model in deterministic and stochastic forms. Although the model can be used for a wide range of production industries, to be more specific in this paper, the general rates and figures for the automotive industry is used for the hypothetical cases, and the input data is adjusted to an average car manufacturer.

Cases 5&9: In these cases an existing plant in the UK is operational with a slightly increasing demand forecast. To simplify the case, only one product family and one sales region is considered. Table 6 shows the general information about the plant. The VAT is 20%, and no tariff is applied since the plant and sales regions are located in the EU. Unit cost of operations (transportation, dealership and warehouse cost of the product family) in this sales region has been set at £4,000 per unit.

Running this case in the deterministic form (case 5: deterministic demand similar to the expected value of demand in case 9) and in stochastic form (case 9), the model results in different solutions. The expected demand is more than the normal capacity but just under the maximum capacity of the plant. Table 7 shows two possible solutions (overutilization or expansion) in deterministic case (case 5), overutilization seems to be the best solution. Setting unmet demand penalty as £5K per unit and running the model in the deterministic mode and with expected values, the same solution was suggested by the model as well. However, in stochastic mode and including demand scenarios, the model suggests expansion as the best solution. Table 8 compares two possible solutions in stochastic mode and explains why different solutions are suggested for these cases. The result shows VSS in this example which results in a saving of £347m over 10 years.

Figure 3: Validation plan

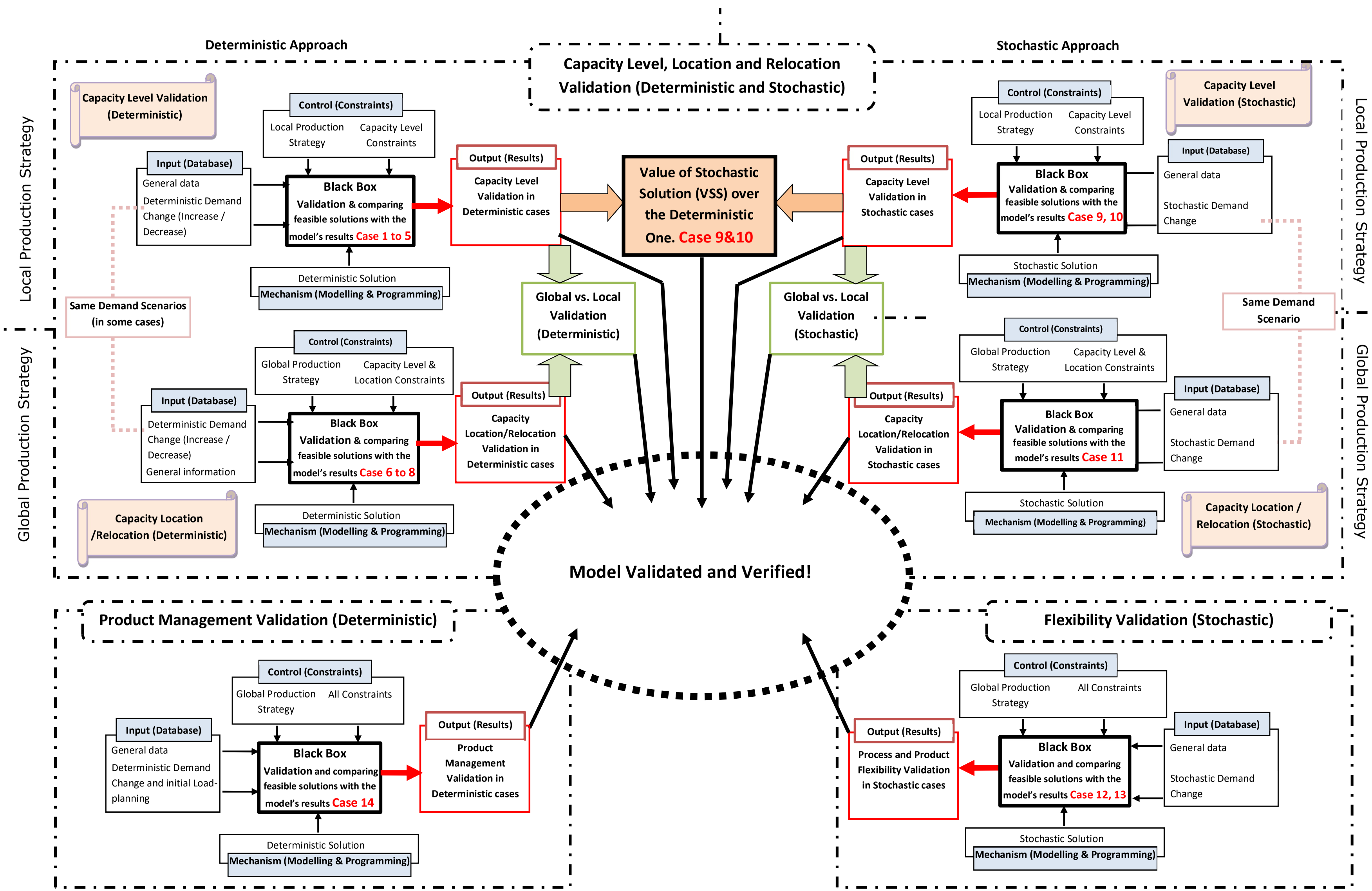


Table 6: General information about the UK plant for the cases 5, 9 and 11

Plant Location	Maximum Capacity (product/ year)	Maximum normal capacity rate	Initial Capital Investment	Annual Operations cost	Annual normal Workforce Cost	Any unit-based cost of production excluding supply	Profit Tax rate
UK	300	0.7	£200m	£150m	£130m	500	0.2

Capacity expansion					**Overutilisation**	
Number of possible Expansions	Maximum Expansion rate	Capital investment - Expansion	Extra operations cost of expansion	Extra workforce cost of expansion	Extra workforce cost of overutilisation	Extra operations cost of overutilisation
1	0.4	£70m	£40m	£39m	£26m	£30m

Table 7: Total cost of different solution in deterministic form (case 5)

Expansion	Expansion Fixed Cost	Extra Operations cost of expansion (in 7 years)	Extra Workforce Cost of expansion (in 7 years)	Overutilisation fixed cost (in 7 years)	Overutilisation Work force cost (in 7 years)	**Sum**
	0.4	£70m	£40m	£39m	£26m	£30m
Overutilisation	Overutilisation fixed cost in 10 years		Overutilisation Workforce cost in 10 years			**Sum**
	£260m		£300m			£560m

Table 8: Total cost of different solutions in stochastic form (case 9) and VSS

Expansion Solution						**Scenario**	Overutilisation and No Expansion Solution Capacity is capped to 3						
Overall gross profit	Total investment (from Table 7)	Expected value	Unmet demand unit	Gross Profit after cost of goods	Total sales number	*p*=probability GP=Unit Gross Profit (sales price-unit operations and supply cost)	Total sales number	Gross Profit after cost of goods	Unmet demand unit	Total penalty (penalty=£5k/unit)	Expected value	Total investment (from Table 7)	Overall gross profit
£12297m	-£880m	£2306m	0	£7686m	2562k	*p*=30% GP=£3k £(29-26)k	2562k	£7686m	0	0	£2306m	-£560m	**£11950m**
		£7720m	0	£15440m	3088K	*p*=50% GP=£5k £(31-26)k	3035k	£15175m	53,000	-£265m	£7455m		
		£3151m	0	£15755m	3151k	*p*=20% GP=£5k £(31-26)k	2950k	£14750m	201,000	-£1005m	£2749m		
Value of Stochastic solution (VSS) = £12297m - £11950m = £347m over 10 years													

Case11: This case is designed to compare local and global cases and calculates the value of global solutions (VGS). The expected demand volume remains the same as the one in cases 5 and 9, but different sales regions (UK, US and China) are introduced with 3 different demand scenarios for each region given in Table 9. In this case, besides the existing plant in the UK (Table 6), an optional new plant in China can also be opened by the model as an alternative solution to overutilisation and expansion of the UK plant. Investments and financial figures for the plant in China are listed in Table 10. Sales price, transportation costs and tariff rates are shown in Table 11. Running the model in global mode for this simple case, it suggests opening a new plant in China and utilise it at normal level, rather than expanding the plant in the UK. Although as Table 12 shows this option needs £1,780m investment in fixed and variable costs over 9 years (as oppose to £924m for expanding the existing plant in the UK), major savings on tariff and transportation fees justifies this new capacity establishment. Table 12 illustrates that the value of global solution (VGS) in this case is £4,189m over 9 years of planning. This result shows the importance of global location decisions embedded in a capacity management model.

Table 9: Demand scenarios in different sales region (expected demand is similar to case 5 & 9)

	Scenario	UK Demand	US Demand	China Demand	Expected Demand
$t = 0$	S1	133	80	53	265
	S2	133	80	53	
	S3	133	80	53	
$t = 1$	S1	130	78	52	275
	S2	140	84	56	
	S3	143	86	57	
$t = 2$	S1	128	77	51	285
	S2	145	87	58	
	S3	158	95	63	
$t = 3$	S1	125	75	50	293
	S2	153	92	61	
	S3	163	98	65.2	
$t = 4$	S1	126	76	50.4	295
	S2	154	92	61.6	
	S3	163	98	65	
$t = 5$	S1	125	75	50	298
	S2	156	94	62.4	
	S3	168	101	67	
$t = 6$	S1	128	77	51	295
	S2	154	92	61.6	
	S3	160	96	64	
$t = 7$	S1	128	77	51	298
	S2	155	93	62	
	S3	165	99	66	
$t = 8$	S1	130	78	52	296
	S2	153	92	61	
	S3	163	98	65	
$t = 9$	S1	130	78	52	296
	S2	153	92	61	
	S3	163	98	65	

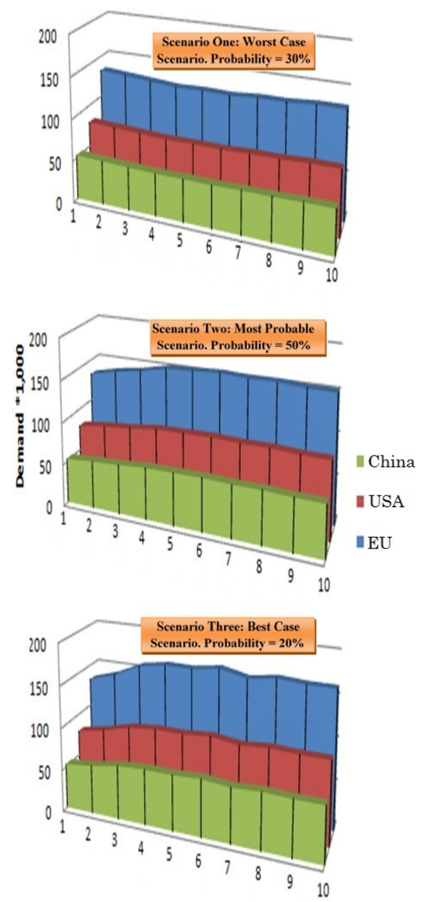


Table 10: Input data for the optional plant in China

Plant Location	Maximum capacity (product/ year)	Maximum normal capacity rate	Initial capital Investment	Annual operations cost	Annual normal workforce Cost	Any unit-based cost of production excluding supply	Profit tax rate
China	200,000	0.8	£200m	£100m	£60m	£500/unit	0

Capacity Expansion					**Overutilisation**		
Number of possible Expansions	Maximum expansion rate	Capital investment for expansion	Extra annual operations cost in case of expansion	Extra annual workforce cost in case of expansion	Capital investment for overutilisation	Extra operations cost in case of overutilisation	Extra workforce cost in case of overutilisation
1	0.4	£50m	£20m	£15m	£5m	£5m	£10m

Table 11: Sales price, transportation costs and tariff rates for different plants in different sales regions

	EU	USA	China
Sales Price in different sales regions	£31,000	£32,000	£33,000
Cost of transportation from the UK plant to dealers within different sales regions	£1,000	£4,000	£8,000
Cost of transportation from China plant to dealers within different sales regions	£4,000	£6,000	£2,000
Tariff rates for products coming from the UK plant to different sales regions	0%	10%	20%
Tariff rates for products coming from China plant to different sales regions	20%	20%	0%

Table 12: Total difference between local capacity options (case 9) and global mode (case 11)

UK Plant Expansion Solution	Scenario	Fixed cost of expansion	Extra operations cost of expanded plant for 8 years	Extra work force cost of expanded plant For 8 years	Extra Cost of transp., warehouse and dealership for Chinese market in 9 years	Extra tariff cost for export to China in 9 years (m£)	Total in scenarios	Total expected	**Value of global solutions (VGS)= £4,189m**
	S1				£2,756m	£3,032m	£6,712m		
	S2	£80m	£480m	£364m	£3,268m	£3,594m	£7,786m	£7,546m	
	S3				£3,463m	£3,810m	£8,197m		

New Plant in China	Scenario	Initial Capital Investment	Operations cost for 9 years	Workforce cost for 9 years	Fixed capital investment for overutilisation	Extra operation cost of overutilising the plant for 9 years	Extra workforce cost of overutilising the plant for 9 years	Extra cost of material supply to the Chinese plant in 9 years	Total in Scenarios	Total expected
	S1							£1,378m	£3,248m	
	S2	£200m	£900m	£540m	£5m	£45m	£90m	£1,634m	£3,504m	£3,357m
	S3							£1,732m	£3,602m	

5 Verification of the model: The case of Toyota UK [1]

Having two assembly lines in Burnaston, Toyota UK (TMUK), with a maximum capacity of 285,000 vehicles per year, was one of the top 5 car manufacturers in Britain in 2009 (Bekker 2010). During the last economy recession in 2010, TMUK forced to mothball one of their production lines towards the end of 2010 (Lea 2010). Using publicly available data and simple assumptions, this section employs our model in this real scale case. Financial information of TMUK (FAME Database. 2010) reveals that after the recession in 2008, TMUK lost almost £1 billion in annual sales, from £2.774 billion in 2007 to £1.82 billion in 2009. In the first months of 2010, Toyota faced with another disaster, "safety problems", which forced the company to recall around 8 million passenger cars all over the world, including around 200,000 cars in the UK (Telegraph 2010). To react, TMUK firstly scaled down its second production line in Burnaston to one shift in September 2010, and then mothballed this line by the end of 2010 (Lea 2010). Although no labour layoff happened at the time, TMUK supported their mothballed policy, stating that having one fully utilised production line is more feasible than having two underutilised lines (Bawden and Lewis 2010). Table 13 shows total sales and operations cost of the company.

Table 13: Total annual cost of the company (in £million)

	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
TMUK car production (×1,000)	212	211	245	263	282	275	164	127
Supply costs (Total)	1,004	1,594	1,609	1,823	1,800	1,942	1,419	1,267
Total remuneration	129.2	165.5	175.9	179.2	172.1	162.4	154.6	124.1
Depreciation	135.6	97.4	114.1	103	115.1	115.5	106.1	87.2
Operation expenses	33.3	39.9	37.8	39.2	39.2	33.4	31.4	22
Other costs of operations	198.8	307.6	267.8	358.4	399.7	484.8	476.9	363

Source: (FAME Database. 2010) and (Toyota Motor Annual Report. 2010, Toyota Motor Corporation. 2010)

To generate scenarios only the data and information available prior to mothball decision (end of 2010) was used in this case. The sales estimation for Europe expected a 19.2% decline, to 858,000 units, and Toyota's total production in the EU was expected to decline by 10.2%, to 433,000 units in 2010 (Ruddick 2010). Despite such downtime, what was promising for TMUK sales was the fact that the company was preparing to launch Toyota Auris Hybrid model in the Burnaston facility in 2010, which had been expected to be a game-changer for TMUK. Toyota's first forecast for 2011 fiscal year (ending March 31, 2011) were a vehicle sales of 7.29 million units (Toyota Motor Corporation. 2010). However, due to some evidence of the recession recovery

[1] A verification with the case of Jaguar Land Rover (JLR) investment in China is also available on request from the authors.

signs by early 2010, Toyota revised its sales forecast to 7.41m units for 2011 (Costea 2010). Based on these facts and information, three main scenarios for 2010 and 2011 were defined in this study, comprising demand decrease, stable demand and demand increase. In an interview with TMUK senior management team at the time (2009), demand decrease was found to be the most probable scenario (with 50% probability allocation), in which a 5% and a 10% sales reductions were estimated for 2010 and 2011, respectively. The other 50% probability was divided equally to stable demand scenario (p=25%) and a demand increase scenario with 5% sales increase estimations for 2010 and 2011.

This case consists of 3 products, 2 production lines, 3 scenarios, 3 time periods, and 2 stages. To set the input parameters data from table 13 was used and a two-stage scholastic version of our model was employed for the case. This example contains three binary decision variables of capacity under-utilisation, capacity mothball, and capacity shutdown, as well as two continuous decision variable of production lot allocations to both lines. Unmet demand penalty for each of three cars was set to their gross profit margin plus a fixed penalty as called "trust image penalty". Other decision variables, input parameters and constraints that were not tied to capacity volume module were turned off and The model suggests to mothball the second production line and fully utilise the first production lien in 2010 which verifies the model with the actual decision taken by TMUK at the time. In the second run, the model was given the data available in 2007 and 2008, which shows early signs of global recession, and the model suggested a mothball in 2009, which could have saved the company over £10m of operations cost of running both lines under-utilised for one extra year, before the actual mothball in 2010.

6 Discussion and Conclusion

Although many peers had raised a need to apply external and market uncertainty into capacity management models, as Table 14 shows, the use of stochastic programming in embedding uncertainty into capacity design and planning has only taken off very recently [after 2009] while most of the models in the field were deterministic before that. However, comparing Tables 14 and 15 indicates that the stochastic models are still not as multi-functional and versatile as the deterministic ones, and they can handle less capacity decision terms than what their deterministic counterparts can manage. Thus, it shows although existing stochastic capacity management models may be able to handle market scenarios, they lack taking a global and comprehensive approach into their decision terms, which limits them to limited applications and can cause sub-optimal solutions. It shows a gap for a more holistic and integrated capacity management model in stochastic form that can handle market uncertainty, while not compromising on decision terms and boundary conditions. This work aimed to address this gap and to develop a stochastic model that can simultaneously handle capacity level management (in increase and decrease scenarios and in realistic terms of sight, moderate and significant changes), capacity location, relocation merge and decomposition, product development (R&D, new product introduction and re-launch cases), and technology management (product and process flexibility and technology life-cycles). Cumbersome data requirements of stochastic models and the size of the extended models (which causes long solution times) have been often blamed for limited decision terms in the stochastic practices (Snyder 2006; Tenhiälä 2011). However, this paper showed these limitations can be overcome by the use of enumerated scenarios, detailed constrains, and right programming approach, which all can reduce the size of the final model to a manageable scale. Enumerated scenario approach causes no limitation to the strategic capacity management modelling, as after all, the number of possible scenarios is inherently limited in strategic planning. A systematic model development approach, which is often called open-box validation was adopted, using ICOM logic (Matta et al. 2005), as explained in Section 1 and employed in Section 3. Using the same logic, a holistic validation plan was developed in ICOM format and employed to test and validate the model. As frequently raised by other authors in this area, verification of the resource management models with real-scale and industrial cases has yet been remained widely unattempted (Hammami et al. 2008; Julka et al. 2007), and there is still a widespread need in the field to make managers and industrial decision-makers aware of what operation research (OR) and optimisation-based capacity management models have to offer to the world of practice (Ackermann et al. 2014). This paper briefly applied this model to the case of Toyota-UK (and the case of Jaguar-Land Rover is also available upon request from the corresponding author), in an attempt not only to verify the model in real scales, but also to illustrate the potential contribution such models can offer to strategic decision-making in practice.

Appendix

Table 14: Selected papers for the comparison study, their uncertainty management approach and their capacity management strategic decision terms

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
1	Syam (2000)	✓	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
2	Inman and Gonsalvez (2001)	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	Inman and Gonsalvez (2001)	✓	-	-	-	-	-	✓	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-
4	Verter and Dasci (2002)	✓	-	-	-	-	-	✓	-	-	-	-	✓	-	-	✓	-	-	-	-	-
5	Chen et al. (2002)	-	-	✓	Demand & producing lead-time	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
6	Bhutta et al. (2003)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
7	Bhutta et al. (2003)	✓	-	-	-	-	✓	-	-	-	✓	-	✓	-	-	-	-	-	-	-	✓
8	Gatica et al. (2003)	-	✓	-	Success of New Products	-	✓	✓	-	-	-	✓	✓	-	✓	-	✓	-	-	-	-
9	Goel and Grossmann (2004)	-	-	✓	Uncertainty in gas reserves	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
10	Chauhan et al. (2004)	✓	-	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Barahona et al. (2005)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
12	Chakravarty (2005)	✓	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
13	Chandra et al. (2005)	-	-	✓	Demand	✓	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
14	Snyder (2006)	✓	-	-	-	-	✓	✓	-	-	✓	✓	-	-	-	-	✓	-	-	-	-
15	Melo et al. (2006)	✓	-	-	-	-	✓	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	✓
16	Fleischmann et al. (2006)	✓	-	-	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓
17	Snyder et al. (2007)	-	-	✓	Demand	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
18	Snyder et al. (2007)	-	-	✓	Demand and Freight Rate	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓
19	Zhang (2007)	-	✓	-	Demand, consumption of stochastic capacity	-	-	✓	-	-	✓	-	✓	-	-	-	-	-	-	-	✓
20	Katayama et al. (2007)	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-

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No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
21	Ahmed and Sahinidis (2008)	-	-	✓	Demand and capacity cost	-	✓	✓	-	-	-	-	-	-	-	✓	✓	-	-	-	-
22	Nagar and Jain (2008)	-	-	✓	Demand	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
23	Azaron et al. (2008)	-	✓	-	Demand, Supply, Transp., Capacity	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
24	Hamad and Fares Gualda (2008)	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
25	Nodem et al. (2008)	-	✓	-	Maintenance and repair time	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
26	Naraharisetti and Karimi (2010)	✓	-	-	-	-	✓	✓	-	-	✓	✓	✓	✓	-	✓	-	-	-	-	✓
27	Tarhan and Grossmann (2008)	-	-	✓	Process Yield	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
28	Francas et al. (2009)	-	✓	-	Demand	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
29	Kauder and Meyr (2009)	-	-	✓	Demand	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-
30	Wagner et al. (2009)	-	✓	-	Demand	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-
31	Hammami et al. (2009)	✓	-	-	-	-	-	✓	-	-	✓	-	-	✓	-	✓	-	-	-	-	✓
32	You et al. (2009)	-	✓	-	Demand and Freight Rate	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
33	Geng et al. (2009)	-	-	✓	Demand and Capacity	-	✓	-	✓	-	-	-	-	-	-	-	✓	-	-	-	-
34	Kauder and Meyr (2009)	✓	-	-	-	✓	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	✓
35	Colvin and Maravelias (2009)	-	-	✓	Success of New Products	-	✓	-	-	-	-	✓	-	-	-	-	✓	-	-	-	-
36	Bihlmaier et al. (2010)	-	-	✓	Demand	-	✓	✓	✓	-	-	-	-	-	-	✓	✓	-	-	✓	-
37	Aghezzaf et al. (2010)	-	✓	-	Demand	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	Frausto-Hernandez et al. (2010)	-	✓	-	Demand and supply	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
39	Naraharisetti and Karimi (2010)	✓	-	-	-	-	✓	✓	-	-	✓	✓	-	-	-	-	-	-	-	-	-
40	Wu and Chuang (2010)	-	-	✓	Demand, Price and Yield	-	✓	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-

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Table 14: continued from previous page

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
41	Lin et al. (2010)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
42	Durksen and Dangelmaier (2010)	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-	✓	-	-
43	Lusa and Pastor (2011)	-	-	✓	Capacity	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
44	Dal-Mas et al. (2011)	-	-	✓	Row material cost and product price	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
45	Claro and Pinho de Sousa (2012)	-	-	✓	Demand	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-
46	Chien et al. (2012)	-	-	✓	Demand	-	✓	-	-	-	-	✓	-	-	-		-	-	-	-	-
47	Chen and Lu (2012)	-	✓	-	Demand	-	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	-	-
48	Nickel et al. (2012)	-	-	✓	Demand & Interest Rates	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	✓
49	Pimentel et al. (2013)	-	-	✓	Demand	✓	✓	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-
50	Erbis et al. (2014)	-	-	✓	Demand, safety regulations, technology	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-
51	Lin et al. (2014)	-	-	✓	Demand	✓	✓	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-
52	Kaya et al. (2014)	-	✓	-	Demand & return	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓
53	Lee and Johnson (2014)	-	✓	-	Demand	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-
54	Chen et al. (2014)	-	✓	-	Demand	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
55	Verma et al. (2014)	-	✓	-	Demand, Sales Price, material Price	✓	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-
56	Chen and Fan (2015)	-	✓	-	Demand	✓	✓	-	✓	-	-	-	-	-	-	✓	-	-	-	-	-
57	Gupta and Mohanty (2015)	✓	-	-	-	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-
58	Hamta et al. (2015)	-	✓	-	Demand	✓	✓	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-	✓
59	Liu et al. (2015)	-	✓	-	Demand	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	✓	-
60	Garcia-Herreros et al. (2016)	✓	-	-	-	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-

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Table 14: continued from previous page

No.	Reference	Det. vs Stoc.			Source of Uncertainty	Capacity Level Management							Facility Location / Relocation			Product & Process Management				HR & Shift Management	Supplier Selection
						Capacity increase			Capacity decrease												
		Deterministic	Stoc.(two-stage)	Stoc.(Multi-stage)		Over-utilisation	Expansion	New Plant	Under utilise	Mothball	Close-down	Lead-time	Location	Re-location	Lead-time	Tech.& Proc. Flex.	NPD	Re-launch	Lead-time		
61	Afrouzy et al. (2016)	-	-	✓	Demand, Supply Capacity	-	-	-	-	-	-	-	-	-	-	-	✓	-	✓	-	✓
62	Wang and Nguyen (2017)	-	-	✓	Technology uncertainty	✓	✓	✓	✓	-	-	-	-	-	-	✓	-	-	-	-	-
63	Medina-González et al. (2017)	-	✓	-	Open to a set (example: demand)	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
64	Liu et al. (2018)	-	-	✓	Demand, investment, technology	✓	✓	-	✓	-	✓	-	-	-	-	✓	-	-	-	-	-
65	Chien et al. (2018)	✓	-	-	Demand, Capacity capability, Technology migration	✓	✓	-	✓	-	✓	✓	-	-	-	✓	-	-	-	-	-
66	Wang et al. (2018)	-	✓	-	Demand, technology	✓	✓	✓	✓	-	✓	✓	-	-	-	✓	-	-	✓	-	-
67	Yu and Solvang (2018)	-	✓	-	Material quantity, quality and price	✓	✓	✓	✓	-	-	-	✓	-	-	✓	-	-	-	-	-
68	Zhou and Li (2018)	-	✓	-	Demand	✓	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	✓
69	Shiina et al. (2018)	-	-	✓	Demand	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 15: More detailed terms and constraints in the selected Capacity management models

Paper No. (Table 14)	Cost Parameters								Financial Parameters						Prod./Proc.				
	Transportation	Unmet Demand	Production Cost	Labour Cost	Material / Supply Cost	Maintenance	depreciation / Replacement	Operation / Overhead Cost	Discount / Interest rate	Tax	Duty	VAT	Inflation rates	Exchange rates	Possibility Matrix	Capacity Rate	Economies of Scale	Capacity lumpiness	Budget Constraint
1	✓	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-
2	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	✓	-
3	-	-	✓	✓	✓	-	✓	✓	✓	✓	-	-	-	-	✓	✓	✓	✓	✓
4	✓	-	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
6	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓
7	✓	-	✓	-	-	✓	✓	✓	-	-	✓	-	✓	✓	-	-	✓	✓	-
8	-	✓	✓	-	✓	✓	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓
9	✓	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	✓	-
10	✓	-	✓	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-
11	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	✓	✓
12	✓	-	✓	✓	-	-	-	✓	-	✓	✓	-	-	✓	-	-	✓	-	-
13	-	-	✓	-	✓	✓	-	✓	✓	-	-	-	-	-	✓	-	-	-	✓
14	✓	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	-	✓	✓	-
15	✓	-	✓	-	-	-	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓
16	✓	-	✓	-	✓	-	-	✓	✓	-	-	-	-	-	✓	-	✓	✓	✓
17	-	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	✓	-	✓	-	✓	✓	✓	-	-	-	-	-	-	-	-	✓	✓
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-
21	✓	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	✓	✓	✓
22	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
24	✓	-	✓	-	-	-	-	-	-	✓	-	✓	-	✓	-	-	-	-	-
25	-	✓	✓	-	-	✓	-	-	✓	-	-	-	-	-	-	-	-	✓	-
26	✓	-	✓	-	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	✓	✓	✓
27	-	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-
28	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
29	✓	✓	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	✓	✓	-
30	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
31	✓	-	✓	✓	✓	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-
32	✓	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
33	✓	✓	✓	-	✓	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
34	✓	-	✓	-	✓	-	-	✓	✓	✓	-	-	-	-	✓	-	-	✓	-
35	-	✓	✓	-	-	✓	-	✓	✓	-	-	-	-	-	-	-	-	✓	-
36	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-
37	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
38	-	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓
39	✓	-	✓	-	✓	✓	✓	✓	✓	✓	-	-	✓	-	✓	✓	✓	✓	✓
40	-	✓	✓	-	-	-	✓	✓	✓	-	-	-	-	-	-	-	-	✓	✓
41	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	✓	-
42	✓	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-	-	-	✓	✓	-
43	-	✓	-	✓	-		-	-	-	-	-	-	-	-	-	-	-	-	-
44	✓	✓	✓	-	✓	-	-	✓	✓	-	-	-	-	-	-	-	✓	✓	-
45	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-
46	-	✓	-	-	-	-	✓	✓	✓	-	-	-	-	-	✓	✓	✓	✓	-
47	✓	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-	✓	✓	✓	✓	-
48	✓	-	✓	-	✓	-	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓
49	-	-	✓	-	-	-	✓	✓	-	-	-	-	-	-	✓	-	✓	✓	-
50	-	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	✓

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Table 15: continued from previous page

Paper No. (Table 14)	Cost Parameters								Financial Parameters						Prod./Proc.				
	Transportation	Unmet Demand	Production Cost	Labour Cost	Material / Supply Cost	Maintenance	depreciation / Replacement	Operation / Overhead Cost	Discount / Interest rate	Tax	Duty	VAT	Inflation rates	Exchange rates	Possibility Matrix	Capacity Rate	Economies of Scale	Capacity lumpiness	Budget Constraint
51	-	-	✓	-	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	✓
52	✓	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	✓	-	-	-	-
53	-	-	✓	✓	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	-
54	-	-	✓	-	-	-	✓	✓	-	-	-	-	-	-	✓	✓	✓	✓	-
55	✓	✓	✓	-	✓	-	-	✓	-	-	✓	-	-	-	-	-	-	✓	-
56	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	✓
57	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
58	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	-	-
59	-	✓	✓	✓	-	-	-	✓	-	-	-	-	-	-	✓	✓	-	✓	-
60	✓	-	-	-	✓	✓	-	-	✓	-	-	-	✓	-	-	-	✓	✓	✓
61	✓	✓	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-
62	-	✓	✓	-	-	-	-	-	✓	-	-	-	-	-	✓	-	-	-	-
63	✓	-	✓	-	✓	-	-	✓	-	-	-	-	-	-	✓	✓	-	-	-
64	-	✓	✓	-	-	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	✓
65	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-
66	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	✓	-
67	✓	-	✓	-	✓	-	-	✓	-	✓	-	-	-	-	✓	-	-	-	-
68	✓	✓	✓	-	✓	-	-	✓	-	-	-	-	-	-	-	-	✓	-	✓
69	-	✓	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	✓	✓

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