CHAPTER 9

Conclusions

9.1 Main Themes

This thesis has proposed and investigated the feasibility and practicality of model synthesis and the usefulness of flexibility to modelling uncertainty in electricity capacity planning. The main conclusion is that 1) model synthesis is feasible but has practical limitations and 2) flexibility is useful but not in the same sense as model synthesis. This conclusion is supported by the main themes listed below and the research answers that follow in the next section.

COMPLETENESS AND "UNEASE"

From the beginning, there appeared no link between "model synthesis" and "flexibility". In many respects, they seemed totally unrelated. Model synthesis is a methodological concern, problem-driven, and rooted in the modelling domain. Flexibility is a conceptual idea, solution-driven, and not familiar to the modelling tradition. Until their contribution to this research problem was evident, it did not seem feasible to consider both model synthesis and flexibility. Model synthesis seems to fit into the discussion of model management systems and model integration issues in the decision support systems literature. Yet there does not exist a taxonomy suitable for it, hence the conceptualisation of model synthesis in Appendix C. The wide application and polymorphous nature of flexibility complicate the task of clarification and unification as different interpretations are very confusing. Several prior attempts were made to reconcile the two apparently unrelated concepts from the means-ends angle. In other words, is model synthesis a means to flexibility or vice versa? Is it possible to incorporate flexibility in modelling as a means to completeness?

Modelling for completeness is still necessary. But it is not sufficient, as completeness is independent of model unease, which may exist inspite of completeness. Completeness is intra-model, i.e. internal to the model, whereas model unease is extra-model, i.e. external to the model. Model unease is an unavoidable feature of decision making in this industry, referring to the gap between the decision maker (the user of the model) and the model itself. The relationship between completeness and unease (both intra- and extra-model) as earlier discussed in chapters 4 and 6 resolves the themes of model synthesis and flexibility. Model synthesis is a feasible but impractical means to completeness. Flexibility is a practical means to compensate for the extra-model unease.

MODEL SYNTHESIS: Issues of c*omplementarity, compatibility, comprehensiveness, comprehensibility*

Completeness or comprehensiveness is the implicit aim of the modelling approach. Model synthesis has been proposed as one way to achieve completeness, as it makes use of techniques that are complementary to each other in terms of functionality and desirable features. To facilitate synthesis, compatibility at the theoretical and data levels is required. Manageability (comprehensibility) is essential for a usable model. Model synthesis makes use of complementary and compatible techniques to meet the conflicting criteria of comprehensiveness and comprehensibility. It is also appealing for the following reasons.

1) Intuitively, it communicates the notion of “best of both worlds,” harnessing the balance of hard and soft techniques to address the intricacies of power generation and the strategic nature of uncertainties in capacity planning. It reflects the idea of using complementary techniques, models, or approaches as a means to completeness.

2) Synthesis capitalises on economies of scale, reflecting “the whole is greater than the sum of its parts.” It exploits the synergies between its component parts.

3) Synthesis implies co-existence, i.e. some level of interaction or communication amongst its components. Co-existence requires compatibility of assumptions, data, and functionality.

FEASIBILITY AND PRACTICALITY OF SYNTHESIS: CONCEPTUAL AND OPERATIONAL ISSUES

The noticeable trend of building larger energy models through synthesis demonstrates the feasibility but not the practicality of model synthesis. This thesis investigated one form of synthesis to capture the two important but complementary features of the three archetypal modelling approaches: decision analysis and optimisation. A decision analysis framework was proposed as an organisational tool to capture the details of the core capacity planning optimisation model. To facilitate this, a “model of model” to reduce and approximate the inputs and outputs of the optimisation model was proposed and tested. Although regression analysis for model fitting is an established and acceptable response surface method and indeed a similar optimisation model has been successfully “reduced” in this manner, the series of experiments found that such a “model of model” is infeasible, impractical, and not re-usable for purposes of uncertainty analysis.

A conceptualisation of model synthesis suggests different possibilities for synthesis, non-trivial issues in structuring, different forms of synthesis, and various strategies to achieve synthesis. These conceptual issues far out-number the tests achievable in the model experiment. As a result of these conceptual and operational difficulties, this thesis concludes that model synthesis is impractical for a utility faced with the kinds and range of uncertainties described in Chapter 2 in the UK electricity industry, where decision making is not totally dependent on models.

FLEXIBILITY AS A DECISION CRITERION

Under conditions of uncertainty, flexibility has been proposed as a preferred decision criterion instead of optimality (Mandelbaum, 1978). That flexibility only has value when there is uncertainty has been proved by several authors (Marschak and Nelson 1962, Merkhofer 1975). However, the trade-off between flexibility and optimality has not been sufficiently addressed in the literature, except for a brief formal attempt by Mandelbaum and Buzacott (1990). To investigate this further, the elements necessary to define the multi-faceted concept of flexibility are distilled from the cross disciplinary review of definitions, measures, and applications. In sum, the concept of flexibility conveys a ***change***, encompasses the notions of ***range*** (size of choice set) and ***time***, requires uncertainty ***conditions***, and includes the value optimisation notion of "***favourability***." Under deterministic conditions, i.e. no uncertainty, "favourability" dominates flexibility, so that optimality is the preferred decision criterion. Under conditions of uncertainty, flexibility dominates, although "favourability" is still present.

FLEXIBILITY AND ROBUSTNESS

An important distinction between two kinds of flexibility, displayed in table 6.1, is made on the basis of previous studies. 1) Active flexibility, or otherwise known as "flexibility", refers to the ability to react with minimal penalty on cost, time, and effort. 2) Passive flexibility, or otherwise known as "robustness", refers to a state of being, in which no reaction is required as it is tolerant or insensitive to the uncertainty. This distinction is made by argument, examples, and specific application to clarify the meaning of flexibility in different contexts. The specific application in Appendix D reveals the conditions under which flexibility and robustness is more or less valuable. It concludes that under uncertainty, robustness is no longer sufficient, i.e. flexibility becomes necessary.

FEATURE OF MODELLING APPROACH

"Flexibility" is a feature of modelling approaches which facilitates the multi-staged resolution of uncertainty, such as the decision tree based techniques of decision analysis, contingent claims analysis, and stochastic dynamic programming employed in the literature. Robustness characterises modelling approaches which aim for completeness of coverage, to ensure all likely ranges of uncertainty are covered, e.g. sensitivity analysis, scenario analysis, and risk analysis.

VERSATILITY OF DECISION ANALYSIS

The literature review of existing modelling approaches (Chapter 3) reveals the potential for using decision analysis as an organisational tool for synthesis. With user-friendly software which incorporate both decision trees and influence diagrams such as DPL (ADA, 1992), decision analysis becomes even more attractive as a structuring tool. However, decision analysis assumes that the model is built in direct consultation with decision makers, which is not the case with the modelling and decision making styles of the electricity supply industry. Thus it is more appropriate as a framework for structuring and assessing flexibility external to the modelling approach, i.e. to compensate for model unease, rather than as a platform for model synthesis within the modelling approach.

9.2 Research Questions and Answers

The argument of this thesis is dominated by the main themes discussed in section 9.1, woven by research questions and answers listed below, and distinguished by types of contributions listed in section 9.3. Figure 9.1 illustrates how the chapters are related to each other. The numbers correspond to chapters while the arrows carry the messages. Chapter 2 links the two parts together by "uncertainty." The two themes of model synthesis and flexibility are related by the use of the decision analytic framework and replication/evaluation method (Chapters 4 and 7). While model synthesis addresses completeness (Chapters 2, 3, 4), flexibility addresses model unease and uncertainty.

Figure 9.1 Research Messages

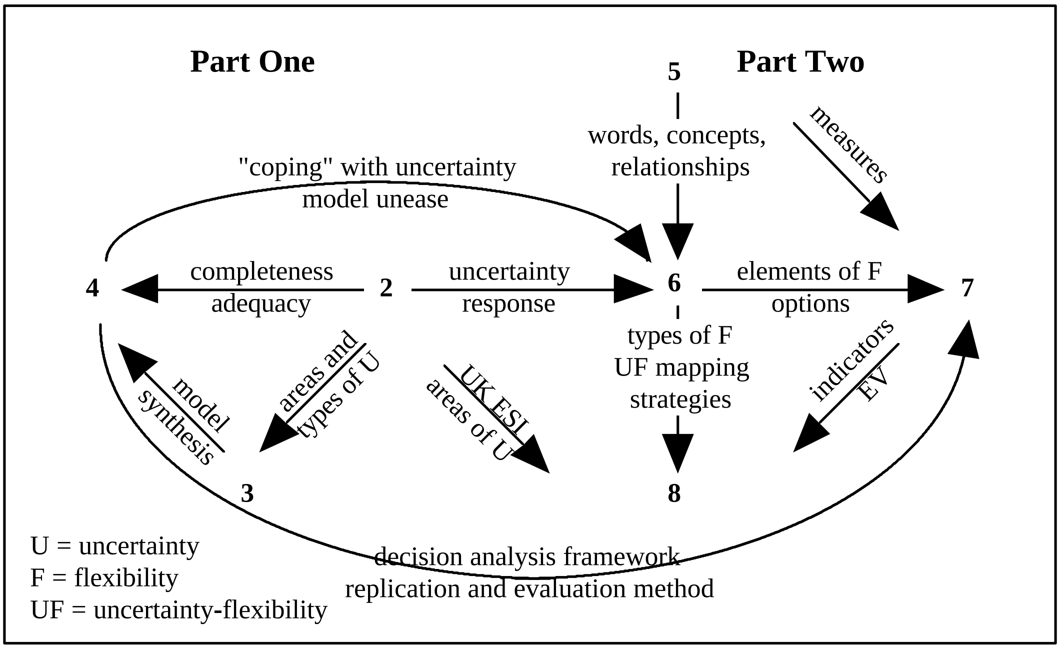

Table 9.1 answers the ten questions raised initially in Chapter 1 table 1.1. Each of these are discussed briefly afterwards.

Table 9.1 Research Questions and Answers

	Question	Location*	Answer and Contribution
1)	What are the new requirements for capacity planning in the privatised and restructured UK ESI?	2	Table 2.6 Areas of uncertainties Types of uncertainties
2)	What are existing approaches to this problem and how well do they treat these uncertainties?	3, B	• All kinds of OR techniques given in figure 3.13 • Critique summarised in table 3.4
3)	How can we compare different modelling appoaches more objectively, systematically, fairly, and deeply than by reviewing the literature?	4, A, B	4-step method of • criteria • replication • evaluation • comparison
4)	Is model synthesis feasible and practical for these purposes? What are the conceptual and operational issues involved in model synthesis?	4, C	• feasible, but conceptual and operational issues • practical limitations • compatibility requirements • weak and strong forms of synthesis
5)	What is flexibility? How is it defined? How does it relate to other words and concepts?	5, 6	• necessary definitional elements • types of flexibility • robustness • Figure 6.1 Conceptual Framework
6)	In what way(s) can flexibility be useful in addressing uncertainty in electricity capacity planning?	5, 6	• decision criterion (under uncertainty) • feature of approach (vs robustness) • operationalisation • against model unease
7)	When, i.e. under which conditions, is it useful or not useful?	6	• conditions of uncertainty • available options, strategies • downside of flexibility • Table 6.4
8)	How can we operationalise flexibility?	6, 7, 8	• options • strategies
9)	How can we measure flexibility?	7, D	• indicators (Table 7.1) • expected values not entropy
10)	How can flexibility be modelled and applied to electricity planning?	7, 8	practical guidelines: • decision analytic framework • 2 stage decision sequence • uncertainty-flexibility mapping • Table 7.1: enabler, disabler, motivator, trigger event, trigger state, likelihood, number of choices and states • Table 8.1

** numbers correspond to chapters; letters to appendices*

1) Requirements

Chapter 2 distinguishes between types and areas of uncertainties. Types of uncertainties refer to the nature of uncertainty, not what it affects or where it comes from. Areas of uncertainties refer to the source of uncertainty, i.e. the factor which is uncertain. Different factors that affect capacity planning but are uncertain are identified and discussed. This classification and enumeration is the first step towards the completeness of addressing different areas of uncertainties and the adequacy of treating different types of uncertainties. In addition to these uncertainties, intricacies in power generation and other aspects of the business are discussed. Together, they form a list of model requirements in table 2.6.

2) Existing approaches and performance

Performance of existing modelling approaches is assessed by literature review and by replication.

Chapter 3 reviews the techniques (figure 3.13) used in electricity capacity planning, and critiques the associated applications (models) with respect to completeness in modelling areas of uncertainties and adequacy of treating them. The review concludes that all kinds of OR techniques have been used for this but models based on individual techniques are incapable of addressing all aspects of capacity planning due to inappropriate level of detail, lack of decision focus, and insufficient attention to multi-criteria and uncertainty. These additional modelling difficulties are summarised together with limitations of techniques in table 3.4. Applications based on two or more techniques show better performance than singular technique-based models.

Appendix B replicates three archetypal modelling approaches (deterministic, probabilistic, and decision analytic) to evaluate model performance in greater depth than by literature review and to enable a fair comparison. It concludes (in Chapter 4) that each approach is incapable of meeting the conflicting criteria of comprehensiveness and comprehensibility. Instead, a synthesis of relevant but complementary features of these approaches is suggested.

3) Objective, systematic, fair, and in-depth model critique

To overcome the limitations and biases in model assessment by literature review, a four step method is proposed and tested. The four steps consist of the following:

1) Criteria: Identify requirements from the literature.

2) Replication: Replicate the model with available software tools.

3) Evaluation: Assess replicated model against the predefined criteria.

4) Comparison: Compare models against each other.

The feasibility of this method has been established by two detailed pilot studies, the first of which is documented in Appendix A. This method is used for the first stage of the modelling experiment (Appendix B and Chapter 4). This four step method is later employed in Chapter 7 to assess different measures of flexibility by replicating cited examples.

4) Feasibility and practicality of model synthesis: conceptual and operational issues

Multi-technique based applications, particularly evident in the trend in large energy models, indicate the feasibility of model synthesis. However, the conceptualisation of model synthesis in Appendix C and experimental results in Chapter 4 highlight the conceptual and operational difficulties that must be overcome for feasibility. Some of these difficulties, such as exemplified by the detailed study of "model of model" are so costly that model synthesis becomes impractical. Chapter 4 concludes that model synthesis is feasible but not practical for a utility in the UK ESI.

5) What is flexibility? How is it defined? How does it relate to other words and concepts?

Many attempts at giving a precise definition of flexibility end up restricting its rich, multi-faceted content to a narrow context. Instead, this thesis identifies and collates necessary definitional elements to preserve the multiple aspects. These context-free ***elements*** consist of the important concept of favourability, number of choices, change, time, and conditions of uncertainty. The context-dependent ***type*** of flexibility depends on the uncertainty-flexibility mapping.

The meaning of flexibility is also clarified by contrasting and analysing it against other closely related words and concepts in a Conceptual Framework depicted in 6.1. Six relationships are studied:

a) Flexibility and robustness

b) Flexibility is preferred to optimality under uncertainty

c) Robustness as safety or lack of risk in a decision; a robust decision is one for which elements will not have to be regretted.

d) Lack of confidence reduces the desire for commitment and increases the preference for flexibility.

e) Flexibility and robustness are embedded in the finance definition of an option: the right but not the obligation

f) Close relationships exist between uncertainty and flexibility, liquidity and learning.

6) Usefulness of flexibility

Chapter 5 shows the wide range of contexts in which flexibility is found. Chapter 6 discusses and supports its use as a decision criterion (as opposed to optimality) under uncertainty, as a feature of the modelling approach (as opposed to robustness), as a practical means to cope with uncertainty by operationalisation, and as a hedge against model unease.

7) Conditions for usefulness and downside

Chapter 6 identifies conditions which together make flexibility useful: uncertainty, availability of means to flexibility, and that it must be worthwhile to consider flexibility. In addition, Mandelbaum's (1978) conditions under which flexibility is not useful is translated into its converse in table 6.4, to show that capacity planning in the UK ESI can make use of flexibility.

These three conditions are suggestive but not guaranteed, i.e. the mere existence of these conditions do not guarantee that flexibility will be useful, as it may be undesirable for the particular decision maker or situation. Flexibility is not desirable for a decision maker who is intolerant of uncertainty, cautious, hesitant or indecisive. The downside of flexibility is briefly discussed to warn against treating all types of flexibility, and indeed, all degrees of flexibility as useful or valuable. In other words, there may be a limit to the usefulness of flexibility. There is also no evidence that flexibility reduces uncertainty.

8) Operationalisation of flexibility

Operationalisation refers to the implementation of the conceptual aspects of flexibility. Chapter 6 distinguishes between options and strategies. Options are those alternatives which provide flexibility by increasing the number of future options or by their characteristics, e.g. short lead time. Strategies introduce flexibility by sequentiality, partitioning, postponement, diversity, searching for more options, resistance to change, substituting, incrementalism, contingency planning, etc.

9) Measuring flexibility

Instead of developing a single best overall measure, this thesis has found two groups of measures which meet the criteria for measuring flexibility. Partial measures form the largest group in the literature, and they support the classification of indicators. Expected value based measures are useful, but caution is needed as expected value over-emphasize the favourability aspect of flexibility. The third group of entropic measures is misleading and therefore not recommended for further use.

In addition to these measures, flexibility and robustness are contrasted and measured in a specific application of over and under capacity in production and inventory control (Appendix D). This example shows another way to assess flexibility.

10) Modelling and application of flexibility

Ultimately, to make use of flexibility, we must be able to operationalise and assess it. Chapter 8 uses the terminology of Chapter 7 to develop practical guidelines for structuring flexibility in a decision analysis framework and assessing it using indicators and expected values. The terminology is summarised in table 7.1 of indicators: enabler, disabler, motivator, trigger event, trigger state, likelihood, number of choices and states. The practical guidelines consist of four steps: identify uncertainties, operationalise flexibility, structure by decision trees and influence diagrams, and assess with indicators and expected value-based measures as given in table 8.1.

Table 9.2 summarises the questions raised in Chapter 4 and answers concluded in Part Two regarding flexibility.

Table 9.2 Flexibility

Questions and Answers Chapter 4	**Cross Disciplinary Review** Chapter 5	**Conceptual Framework** Chapter 6	**Measuring Flexibility** Chapter 7	**Modelling Flexibility** Chapter 8	**Flexibility and Robustness** Appendix D
What is flexibility?	interpretation, applications	relationships with other concepts contrast against robustness	definitional elements; types of flexibility	expressed in a decision analysis framework	contrast against robustness
How to use it?	characteristic of systems (manufacturing), decision preference, desirable goal	reflecting degree of commitment, compensate for lack of confidence; conditions under which it is useful	as a decision criterion	feature of the modelling approach	as under and over capacity in production and inventory application
How to measure it?			indicators (partial measures) expected value entropic measures	path in a decision tree	costs of under and over capacity
How to use it in modelling uncertainty in capacity planning?	electricity planning literature, as a characteristics of plants and portfolios (capacity mix)		operationalisation via options and strategies	examples of pool price, plant economics, and strategies	supply versus demand of electricity

9.3 Research Contributions

We discuss the above "answers" to research questions from Chapter 1 in terms of four types of contributions: critical, methodological, conceptual, and synthetic (synthesis).

1) CRITIQUE

A ***critique*** refers to an assessment against given criteria. Four critiques have been made in this thesis: a) requirements, b) technique and applications, c) modelling approaches, and d) flexibility measures.

a) A critical review of the industry and history of capacity planning provides the basis for the identification and classification of different areas of uncertainty relevant to this thesis in Chapter 2.

b) Based on capacity planning applications reported in the literature, Chapter 3 assesses all kinds of OR techniques and models against the areas and types of uncertainties identified previously. These evaluations reveal the additional modelling requirements that must be met.

c) Through a modelling experiment, 3 archetypal modelling approaches are replicated and evaluated against the criteria compiled from the list of uncertainties in Chapter 2 and additional modelling requirements in Chapter 3.

d) From an extensive cross disciplinary review, different measures of flexibility emerge. Grouped into three main categories, they are assessed according a pre-defined criteria: partial measures (indicators), expected value, and entropy.

2) METHODOLOGY

Methodological contributions refer to methods developed, tested, and applied in this thesis. Three kinds of methods have been contributed by this thesis: a) the four step model replication and evaluation, b) two staged modelling experiment, and c) practical guidelines for flexibility.

a) A method of model assessment that is more objective and fair than mere literature review is developed and successfully tested in two separate pilot studies. This four step method is applied in the two stage modelling experiment and again in the critique of measures of flexibility. The four steps consist of criteria, replication, evaluation, and comparison.

b) A two staged case study based modelling experiment is designed and conducted to facilitate prototyping of model synthesis and comparison against existing approaches.

c) Practical guidelines for structuring and assessing flexibility are developed and applied to UK ESI capacity planning examples of plant economics and pool price behaviour. Four models of operationalisation strategies are structured. These guidelines make new uses of decision analysis and expected values.

3) CONCEPTUAL DEVELOPMENT

Conceptual development or conceptualisation refers to a creative and logical process of analysis. What emerged from this are a) the conceptual issues in model synthesis and b) the conceptual framework of flexibility relationships and new terminology.

a) To fill the void in the literature, issues in model synthesis, including a taxonomy and typology, are conceptualised.

b) Following the same manner of conceptual analysis of flexibility and closely related words, Chapter 6 analyses the relationship between flexibility and more established concepts. Important relationships, definitional elements, conditions, and other conceptual aspects of flexibility are developed. The following new terms are introduced: favourability, uncertainty to flexibility mapping, indicators, trigger events, enabler, disabler, motivator, local event, and external event.

4) SYNTHESIS

Three different kinds of synthesis have been examined in this thesis: a) model synthesis, b) optimisation and decision analysis, and c) expected value and entropy.

a) ***Model synthesis*** refers to configuring existing models or techniques to meet the conflicting modelling criteria of comprehensiveness and comprehensibility.

b) ***Optimisation and decision analysis*** techniques are complementary in many ways. While optimisation uses lots of data, decision analysis uses few. Optimisation is single staged and deterministic, while decision analysis is multi-staged and contains probabilities and decisions. Optimisation contains constraints, hence constrained optimisation. Decision analysis is a kind of unconstrained optimisation. Attempts at synthesizing the two types of techniques included embedding optimisation in decision analysis. However, incompatible data size and interface prevented a direct formulation. Furthermore, the multiple alternative stages of the decision tree are not utilised, only terminal nodes.

c) ***Expected value and entropy*** exhibit complementarity in capturing the favourability and uncertainty aspects of flexibility. This at first suggested that a synthesis would lead to a better measure. However, differences and inconsistencies in underlying assumptions prevented any form of "co-existence." Furthermore, entropy was rejected as a meaningful and reliable measure of flexibility.

9.4 Further Research

Our investigation into model synthesis and flexibility has opened up a number of areas for further research. The following three areas are suggested.

ON MODEL SYNTHESIS

1) Other Forms of Synthesis

We have only examined the synthesis between optimisation and decision analysis via a “model of model”. We cannot generalise from this limited experience that we have found all the conceptual and operational difficulties in model synthesis.

2) Different Levels of Synthesis

The weak and strong forms of synthesis pertain to the degree of interaction between the components. Does the level of synthesis (or integration) contribute to the completeness of modelling?

ON FLEXIBILITY

1) Measuring Flexibility

Appendix D showed that flexibility is useful when there is a chance that actual demand may exceed forecasted demand. The probability that actual demand exceeds forecasted demand indicates a need for flexibility. This suggests that flexibility requires a measure of uncertainty.

Gerwin (1993) mentioned that the type of flexibility corresponds to the type of uncertainty. Others have proved that flexibility has no value if there is no uncertainty. This thesis proposes an uncertainty to flexibility mapping, but this does not imply that type of flexibility can only be analysed with respect to (area of) uncertainty. Furthermore, a more formal method of incorporating indicators in assessment may be helpful, such as some kind of multi-attribute ranking and trade-off to score the value of flexibility with respect to each of the key uncertainties. Do we aggregate flexibility with all uncertainties or weight individual flexibilities conditional on type of uncertainty?

The uncertainty to flexibility mapping assumes a one to one correspondence. How do we deal with the permutation of flexibility characteristics of options or flexible options or different strategies? This is not a straightforward one to one uncertainty to flexibility mapping.

Trade-off analysis becomes more troublesome in complicated problems. We may need to define a preference function. We may need to aggregate the indicators. We may need to use multi-attribute weighting and ranking. Guidelines are required for defining these functions.

2) Comparing different strategies

How do we compare different strategies, e.g. different sources of flexibility?

Most discussions of flexibility have concentrated on evaluating a single source of flexibility. Including all sources of flexibility in one model enables us to compare different strategies. However, it adds to the dimensionality (and complexity) of the decision tree as each source of flexibility is necessarily meaningful only in relation to its triggering uncertainty and reflected by the structure of the decision tree, i.e. the order of decisions, branches of decision nodes, etc.

ON CAPACITY PLANNING

1) Extension of Capacity Planning Models

According to Paraskevopoulos et al (1991), capacity expansion models determine the type, size, and sequencing of productive facilities to optimally meet expectations about future market conditions. These models are thus important for industries characterised by 1) commitment of substantial resources for new investment with long payout times, 2) low resale or scrap value of newly installed equipment, 3) substantial economies of scale (both static and dynamic) due to technology. The modelling approaches and measures researched in this thesis should be applicable to capacity planning problems elsewhere, particularly in capital-intensive industries involving long lead-times, huge investments, and high uncertainty. Likewise, these capacity planning models should be extensible to the electricity supply industries of other countries as they all share the unique features of non-storability and high sunk costs.

2) Combining Model Synthesis and Flexibility

The modelling approach is still necessary for completeness, and model synthesis is a means to this. To hedge against model unease and to cope with uncertainties, flexibility becomes necessary. This thesis has addressed the two themes separately. To use model synthesis and flexibility *together* for model completeness and uncertainty remains an open question.