CHAPTER 8

Modelling Flexibility

8.1 Introduction

The title of this chapter, "Modelling Flexibility," refers to the structuring and assessment of flexibility. The terminology of chapters 6 and 7 is used to ***represent*** flexibility. Decision trees and influence diagrams are used to ***structure*** flexibility. Indicators and expected values of Chapter 7 are used to ***measure*** flexibility.

We present practical guidelines for the representation and assessment of flexibility via

1) the application of indicators and expected value measures as studied in Chapter 7;

2) the construction of basic decision models relating to capacity planning in the UK Electricity Supply Industry as discussed in Chapter 2, i.e. uncertainties affecting ***plant economics*** and ***pool price***; and

3) illustrative examples of the ***operationalisation*** of flexibility through ***options*** and ***strategies*** as given in Chapter 6.

We show the application of these guidelines to structure and assess ***strategies*** in the relevant ***context*** of capacity planning in the UK ESI to answer two outstanding questions concerning the usefulness of flexibility.

1) How can we model flexibility?

2) How can modelling flexibility apply to electricity planning?

These guidelines have been developed from extensive analysis to test the breadth of application. However, we present only a few illustrative examples to support the main points, as they have already been analysed to the same level of depth as those in the previous chapter.

This chapter is organised as follows. Section 8.2 presents the guidelines for ***structuring***. Section 8.3 presents the guidelines for ***assessment***. Section 8.4 presents basic models of ***plant economics*** and ***pool prices***, respectively, using the terminology and guidelines of previous sections. Section 8.5 presents generic examples of ***operationalising strategies*** of partitioning, sequentiality, postponement, and diversity. The final section 8.6 summarises the ***guidelines*** in brief.

8.2 Structuring

The examples in Chapter 7 indicated some essential requirements in structuring flexibility for further assessment. "Structuring" refers to the representation of ***types*** and ***elements*** of flexibility to facilitate the analysis of flexibility and uncertainty. We propose the use of 1) decision trees and influence diagrams for structuring the model (section 8.2.1) in 2) a minimum of two stage sequence (section 8.2.2) with 3) three types of uncertainties, namely trigger, local, and external events (section 8.2.3).

8.2.1 Decision Analytic Framework

The term "decision analytic framework" first appeared in Chapter 4 of this thesis as a proposal to make use of decision trees and influence diagrams to organise other techniques. Here the same term refers to a modelling framework of decision tree-based techniques capable of ***representing*** and ***assessing*** flexibility. This framework is appropriate for "modelling flexibility" for the following reasons:

1) Flexibility is a ***feature of modelling approach***;

2) Decision trees and influence diagrams are ***structuring tools*** for uncertainties, decisions, and contingency; and

3) This framework facilitates the representation of options and strategies in the ***operationalisation of flexibility***.

FEATURE OF THE MODELLING APPROACH

Previous chapters have shown that flexibility has value only in the presence of uncertainty. Therefore measuring flexibility requires an approach that considers uncertainty by including and representing it in some form. This precludes the deterministic approach, i.e. one that assumes all uncertainties do not exist or have only one state. Other conceptual aspects of flexibility call for multi-contingency. This precludes the probabilistic approach, where the expanded risk analysis considers all uncertainties simultaneously. The formulation of a strategy to proceed, i.e. a course of action, requires the identification of paths. Decision analysis through use of decision trees allows the consideration of uncertainty, in terms of chance events and decision points.

Other methods of assessing and representing flexibility, as described in recent literature, are variants of the decision tree method of analysis, e.g. stochastic dynamic programming and contingent claims analysis, as discussed in chapters 4 and 6.

STRUCTURING TOOLS: DECISION TREES, INFLUENCE DIAGRAMS

The decision analytic framework relies on influence diagrams and decision trees for structuring the problem. Influence diagrams are used to define conditionality and variable relationships. In influence diagrams, probabilities and values of dependent events can be assigned and expressed easily. Decision trees are used to define chronological sequences and uncertainty-flexibility mapping. In decision trees, decisions and uncertainties can be ordered as they occur. The combination of influence diagrams and decision trees facilitates the modelling of multi-staged decisions and uncertainty sequences.

OPERATIONALISATION OF FLEXIBILITY

As already shown in Chapter 7, this modelling framework facilitates the consideration of flexibility in at least 3 operationalisations: 1) options that exhibit flexible characteristics or provide flexibility in some way, 2) the sequentiality strategy by node decomposition, and 3) the postponing strategy by node re-ordering. The latter two strategies (illustrated in section 8.5) are based on Merkhofer's proposal of EVPI for decision flexibility, involving the evaluation of knowing before deciding versus deciding before knowing.

1) Decision analysis is specifically about decisions and choices. Options are represented as states of a decision. In Chapter 7, Hobbs et al (1994) and Schneeweiss and Kühn (1990) operationalise flexibility via options.

2) Decomposing a decision into sub-decisions is an example of sequentiality or staging, one of Mandelbaum's (1978) sources of flexibility, as it gives the decision maker more control over each sub-decision as well as the opportunity to obtain more information pertaining to each sub-decision.

3) One way of obtaining flexibility is by examining the extent to which decisions and trigger events can be re-ordered to get higher payoffs. Insight into timing gives the possibility of postponing a decision until its trigger event occurs. Likewise, flexibility is increased if trigger events can be identified and introduced.

In addition to the above supporting arguments for decision analysis as a modelling framework, we recall that expected value measures of Chapter 7 have succeeded in capturing the favourability aspect of flexibility and generally perform well albeit with caution. Since expected values are based on decision analysis, this suggests that decision trees provide an automatic "flexibility calculus." We also cite the rationale for such a framework from Chapter 4, e.g. technique familiarity, software availability, sophistication of presentation, computation, and nodal linkages between decision trees and influence diagrams.

8.2.2 Two Stage Decision Sequence

We represent the potential or capability to change as a decision sequence in a minimum of two stages, in which flexibility is associated with the first stage but only realised in the second stage.

FIRST STAGE

The first stage contains at least two choices, each providing a different level of flexibility. The two choices correspond to the activating initial position and default option. The choice that provides future flexibility, i.e. the activating initial position, is assigned a payoff, i.e. the purchase of this flexibility at a cost, called the ***enabler***.

SECOND STAGE

The second stage includes an ***uncertainty-flexibility mapping*** in which the area of uncertainty is mapped to the type of flexibility, i.e. ***trigger event*** to flexibility decision. Within this mapping, there is also an implicit assignment of ***trigger state*** to the choice that leads to a favourable outcome. ***Likelihoods,*** reflecting the probability of realising this future favourable potential, are assigned to trigger states.

For example, flexibility of capacity size, as defined by the ability to adjust total capacity in the system according to need, depends on demand uncertainty. The variation in demand levels can be met by adjusting capacity size. There may be several choices in the second stage, but they lead to favourable payoffs only if trigger states of the uncertain event occur. If demand is high, then high capacity is useful. If demand is low, then low capacity is useful. Thus the flexibility of capacity size purchased by the first decision is determined once the trigger event is known. The alternative that does not lead to flexibility is not affected by the trigger event. For example, if flexibility of capacity size is not provided, then demand uncertainty has no effect on the subsequent payoff.

The choices available at the second stage depend on the choice selected in the first stage. The second stage consists of the exercise decision which carries possible further cost (***disabler***) and a return payoff (***motivator***). The payoff depends mainly on the outcome of the trigger event, an uncertainty that is resolved after the first decision but before the second.

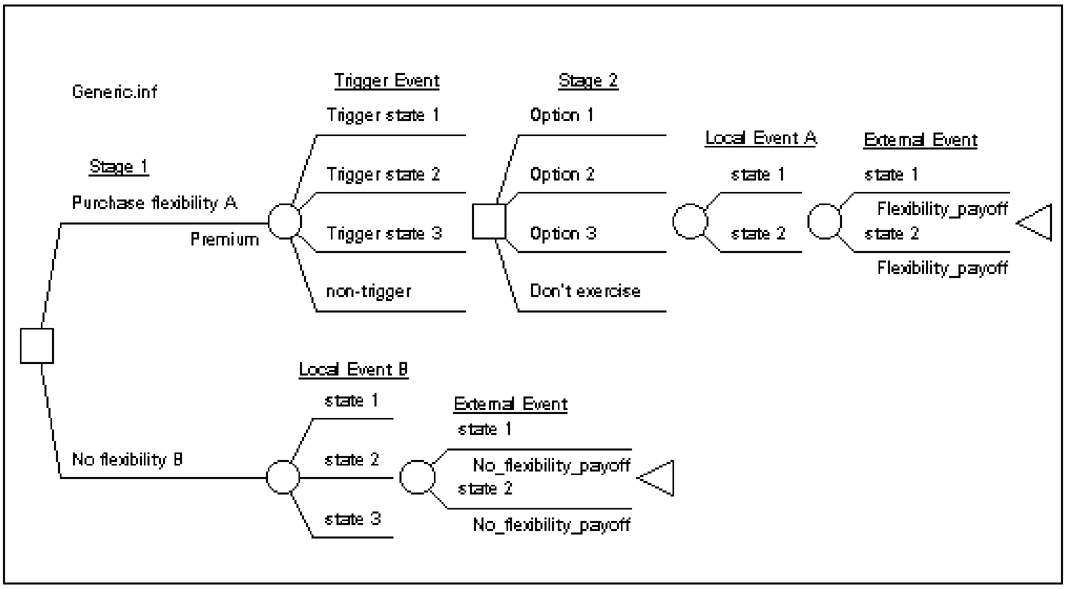
This two stage cycle can be repeated. Furthermore, each stage can be composed of decision/chance node sequences, i.e. nested sub-trees.

8.2.3 Local and External Events

Besides trigger events, there are other uncertainties that affect final payoffs. Local and external events occur after the second stage decision. ***Local events*** are those that affect payoffs irrespective of flexibility. For example, in considering flexibility of the capacity size of a coal-fired plant, the uncertainty of renewable technologies has no effect on the second stage decision but has consequences on the final payoff. ***External events*** are those uncertainties that affect all choices in the first stage decision: to provide or not to provide flexibility. For example, pool price uncertainty affects all choices of plant investment. These uncertainties are not usually independent. We distinguish these three types of uncertainties (trigger, local, and external events) as they are important in modelling flexibility.

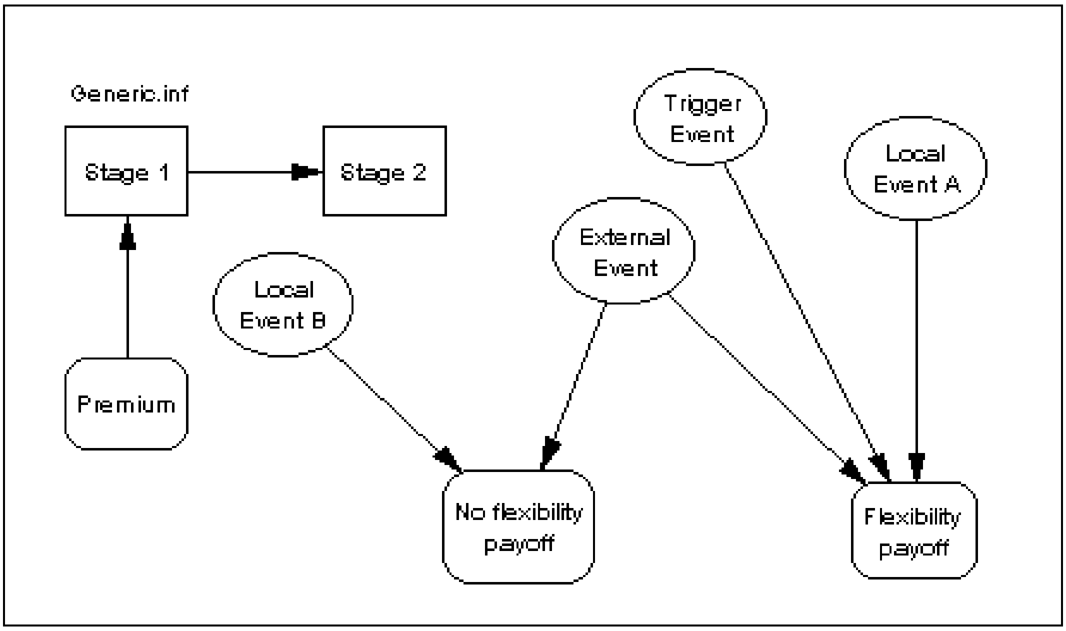
Figure 8.1 depicts the above terminologies. In <u>Stage 1</u>, the decision maker chooses between "Purchase flexibility A" at a cost (enabler) called "Premium" and stay with the status quo of "No flexibility B." The existence of Stage 2 is only meaningful if the Trigger Event precedes it. "Option 1" in Stage 2 gives the best payoff if "Trigger state 1" occurs. Similarly "Option 2" gives the best payoff if trigger State 2 occurs. If none of the trigger states occur, the "Don't Exercise" option in Stage 2 gives the most favourable payoff. The payoffs associated with the first stage choice of "Purchase flexibility A" are affected also by the states of Local Event A and External Event. For the "No flexibility B" case, the payoffs are affected by Local Event B and External Event.

Figure 8.1 Decision Tree of Generic Example



The associated influence diagram in figure 8.2 shows that Trigger Event does not affect the payoffs for B. Similarly, Local Event B does not affect A. However, External Event affects both A and B.

Figure 8.2 Influence Diagram of Generic Example



Such a model of flexibility may contain several trigger events, local events, and external conditions associated with first and second stage decisions. There may be many stages in such a decision tree, but each stage that realises a type of flexibility is preceded by its corresponding trigger event. Modelling flexibility contrasts the flexibility provided by a course of action with the lack of flexibility in another, which is called the "status quo case" or "default option".

8.3 Assessment

The assessment of flexibility refers to measuring flexibility, trading off aspects of flexibility, and comparing options or strategies that differ in the degree of flexibility they provide. This assessment depends on the level of complexity, which spans the spectrum from "simple" to "complex." For simple problems, structuring is not necessary, and ***indicators*** are sufficient for measuring flexibility. More complicated problems require model structuring and assessment using indicators and expected values.

8.3.1 Simple Problems

Simple problems do not require structuring, although structuring helps to identify the relevant indicators for measuring flexibility. These problems include 1) options; 2) strategies that concern individual elements (aspects) of flexibility, e.g. reducing resistance to change; and 3) strategies related to options, e.g. searching for additional options. The latter two examples are means to increase the boundaries of the solution space, thereby enlarging the choice set. We explain these three types of problems below.

1) ***Operationalisation by options*** has already been discussed in Chapter 7, e.g. examples of Hobbs et al and Schneeweiss and Kühn. Simple problems involve the choice between two investments that offer different levels of flexibility, whether or not to enter into a contract that provides flexibility, and adding a plant that exhibits a characteristic that promotes flexibility. Hirst (1989) discusses plant characteristics that offer more flexibility.

2) ***Reducing resistance to change*** by removing or relaxing constraints is another way to increase the number of second-stage options. Examples of this source of flexibility in the electricity industry are buying permits to pollute (this relaxes or eliminates the emissions constraint), entering into contracts to fix electricity prices (so that the pool volatility does not have an influence), and supply contracting to eliminate volatility in fuel prices.

3) ***Searching for additional options or actions*** obviously increases flexibility because it increases the number of choices (if available and if found). However, the benefits gained from this strategy must be weighed against the costs of searching.

The uncertainty to flexibility mapping is used to identify the relevant indicator in each case. We suggest the use of appropriate indicators to trade off conflicting aspects of flexibility, such as number of choices vs expected returns, responsiveness vs likelihood, and enabler vs motivators. Formal methods of trade-off analysis can be found in the decision analysis literature, e.g. dominance, ranking, elimination by dominant criteria, and multi-attribute analysis.

8.3.2 Complex Problems

More complicated problems require structuring, as they involve several indicators, multiple stages, multiple states, etc. Because of the dimensionality implied by these problems, indicators may not be sufficient for assessment. In such cases, it is also necessary to examine the structure of the decision tree, e.g. counting and tracing the decision paths.

The type of measure to use for assessment depends on the structure of the problem. With respect to the examples studied for the development of these guidelines, we classify complex problem structure into four categories in table 8.1.

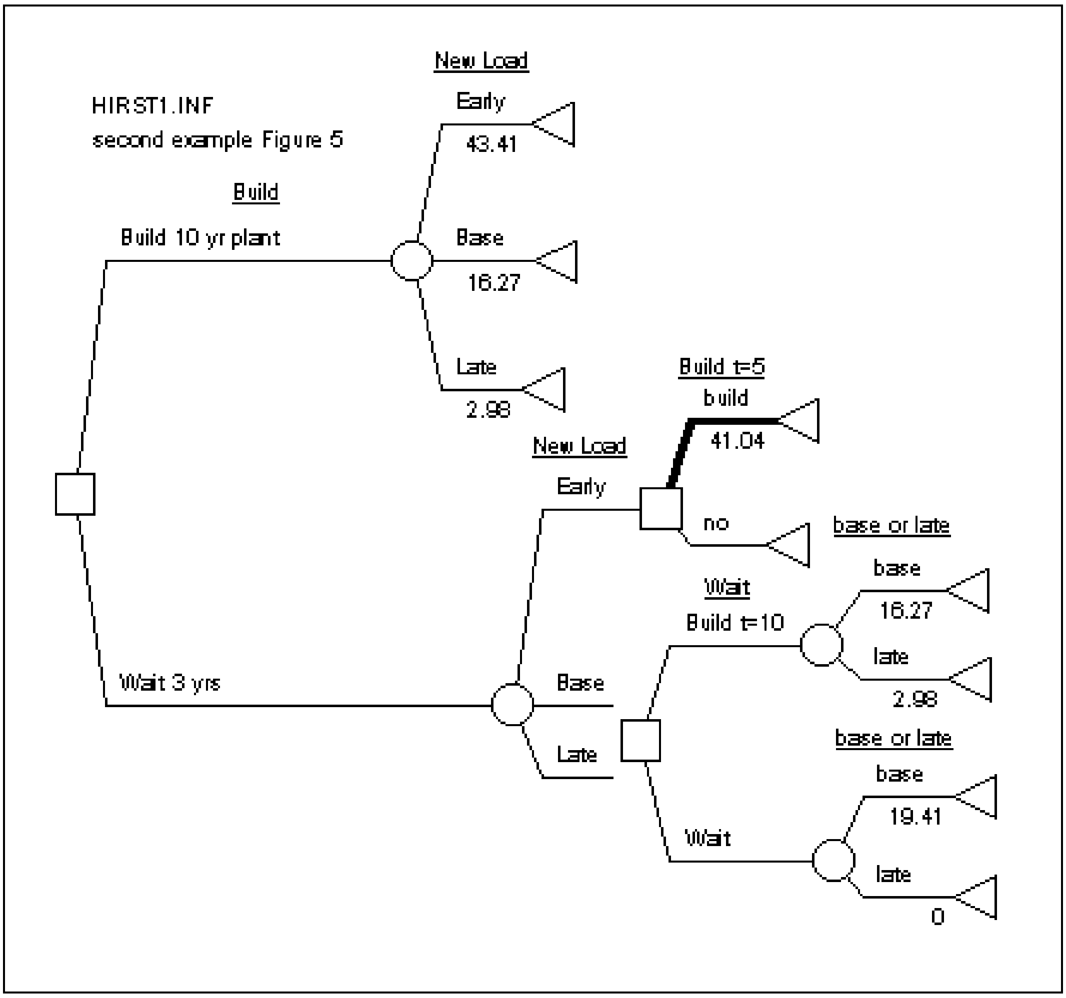
Table 8.1 Problem Categories and Expected Value Measures

Category	Description	EV Measure
1)	Flexibility vs No flexibility	Hobbs' Relative Flexibility Benefit
2)	Different degrees of flexibility due to calibration, partitioning, special cases of diversity	Schneeweiss and Kühn's Normalised Flexibility Measure
3)	Postponement, sequentiality, and staging (to do with re-ordering or decomposing a decision tree)	Merkhofer's EVPIGUF
4)	Others	Use expected value measures with care, and supplement with indicators (to resolve conflicting aspects of flexibility, e.g. favourability)

To give an example of the 4th category of problem structure, we discuss the ***timing decision***, which is one of the main decisions in capacity planning. In the decision analysis context, Hirst (1989) treats the timing decision as a function of ***waiting for perfect information*** (advance notice of future load requirements) or

relying on imperfect information (forecast of future demand) and shows that plants with short lead time and small modular unit size are more flexible than those with long lead time and large unit sizes. Figure 8.3 illustrates his example which demonstrates the trade-off between the costs and benefits of flexibility. A utility must provide for new load, the timing of which is uncertain. If it chooses to build a plant that takes ten years but new load arrives before the plant is ready, it will incur a high cost of 43.41 ¢/kWh. On the other hand, if it chooses to build a short-lead time plant, it can afford to wait three years to get more information. The uncertainty to flexibility mapping in this case corresponds to the ***timing of the new load*** and the ***lead time of the new plant***.

Figure 8.3 Hirst's (1989) Example



8.4 Capacity Planning in the UK Electricity Supply Industry

For illustrative purposes, we simplify capacity planning to focus on individual decisions for the operationalisation of flexibility. We consider a typical utility's decision of whether or not to add a plant to its existing portfolio, similar to Hobbs' example in the previous chapter.

The uncertainties affecting the decision can be grouped into those affecting generation ***cost*** and those affecting ***revenue***. We categorise the areas of uncertainties in table 2.6 into uncertainties affecting costs (***plant economics***) and revenues (***pool price***) in the following table 8.2.

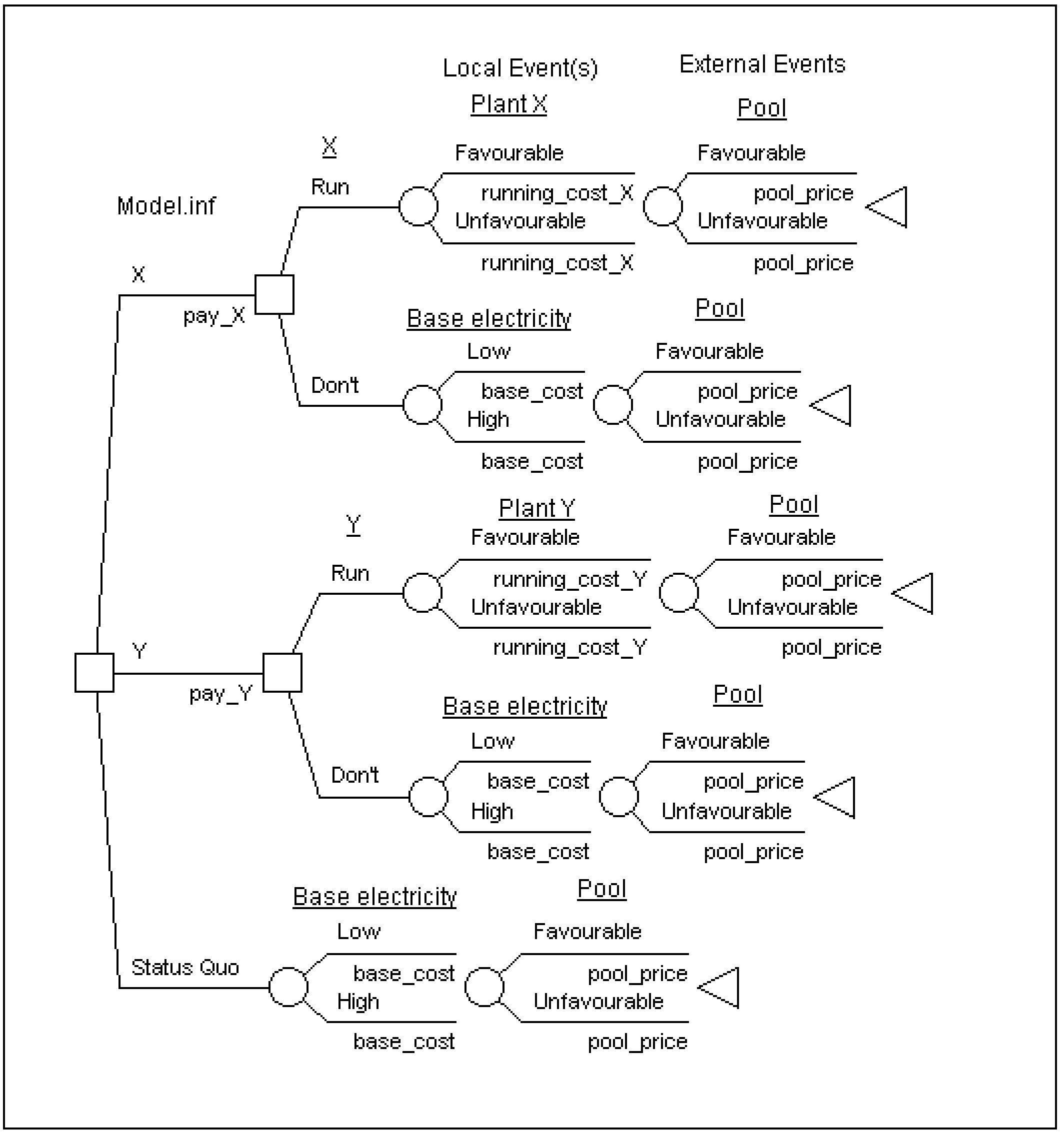
Table 8.2 Areas of Uncertainties Affecting Costs and Revenues

Areas of Uncertainty	**Cost**	**Revenue**
Plant Economics: capital, running costs	*	
Fuel: price, supply	*	
Demand: shape, growth	*	*
Technology: performance, lead time, competitors	*	*
Financing requirements	*	
Market: volatilities of the pool		*
Political/regulatory	*	*
Environment	*	
Public	*	*

Figure 8.4 depicts the decision tree, where the first stage decision consists of choosing to invest (in X or Y technologies) or not invest (status quo). The uncertainties surrounding the running cost of X called <u>Plant X</u> act as the local event for X and uncertainties surrounding the pool price called <u>Pool</u> act as the

external event for all three choices in the first stage. In the next two sub-sections, we decompose the corresponding chance nodes Plant and Pool to show how uncertainties and decisions can give insight to flexibility.

Figure 8.4 Electricity Planning Example



8.4.1 Plant Economics

We discuss how to represent and deal with uncertainties that affect plant economics using the concept of flexibility. We have already extensively studied plant economics in the first pilot study of this thesis (appendix A). These formulae are based on IAEA's (1984) method of levelised costs to approximate the average costs over the life of the plant.

We translate and extend the spreadsheet model of appendix A into a decision model via an influence diagram in figure 8.5. Proceeding from left to right, this diagram shows how the variables are related. The left most nodes are direct inputs to the plant economics model, often areas of great uncertainty, as described in Chapter 2. The nodes in the middle correspond to levelising constants. The nodes on the right are components of the final levelised cost, namely, Invest/kWh, Fixed O&M/kWh, Variable O&M/kWh, Fuel Cost/kWh, and Carbon Tax/kWh. The Carbon Tax component indicates the plant's environmental performance. It is included to reflect environmental and regulatory uncertainty.

Figure 8.5 Plant Economics Influence Diagram

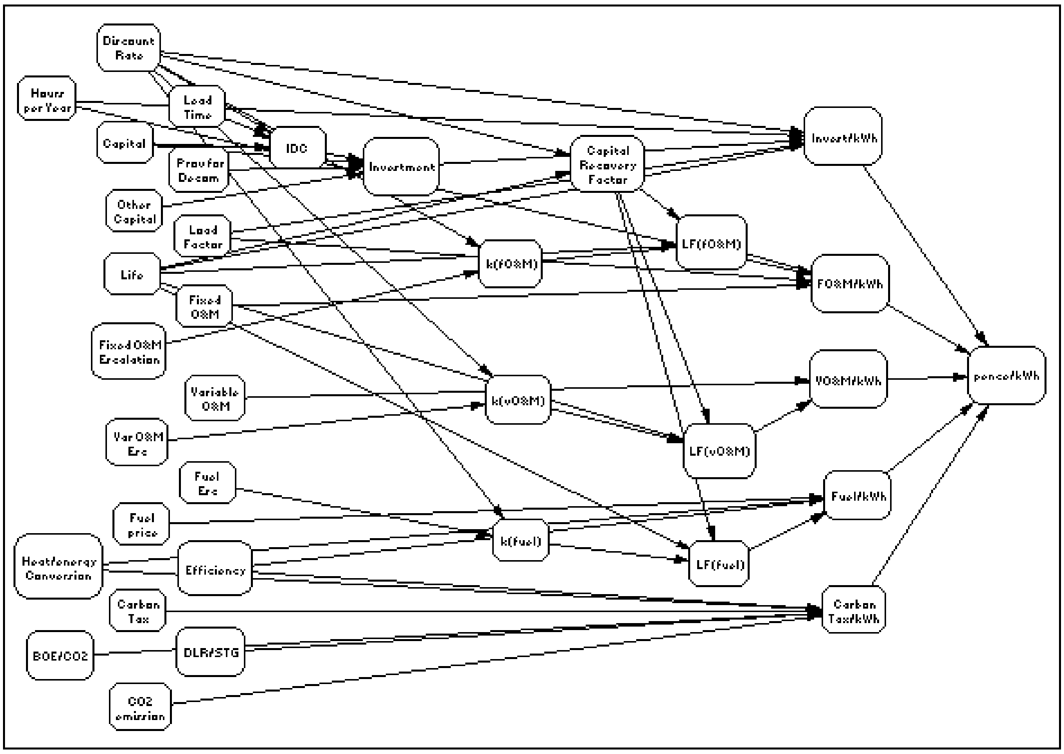
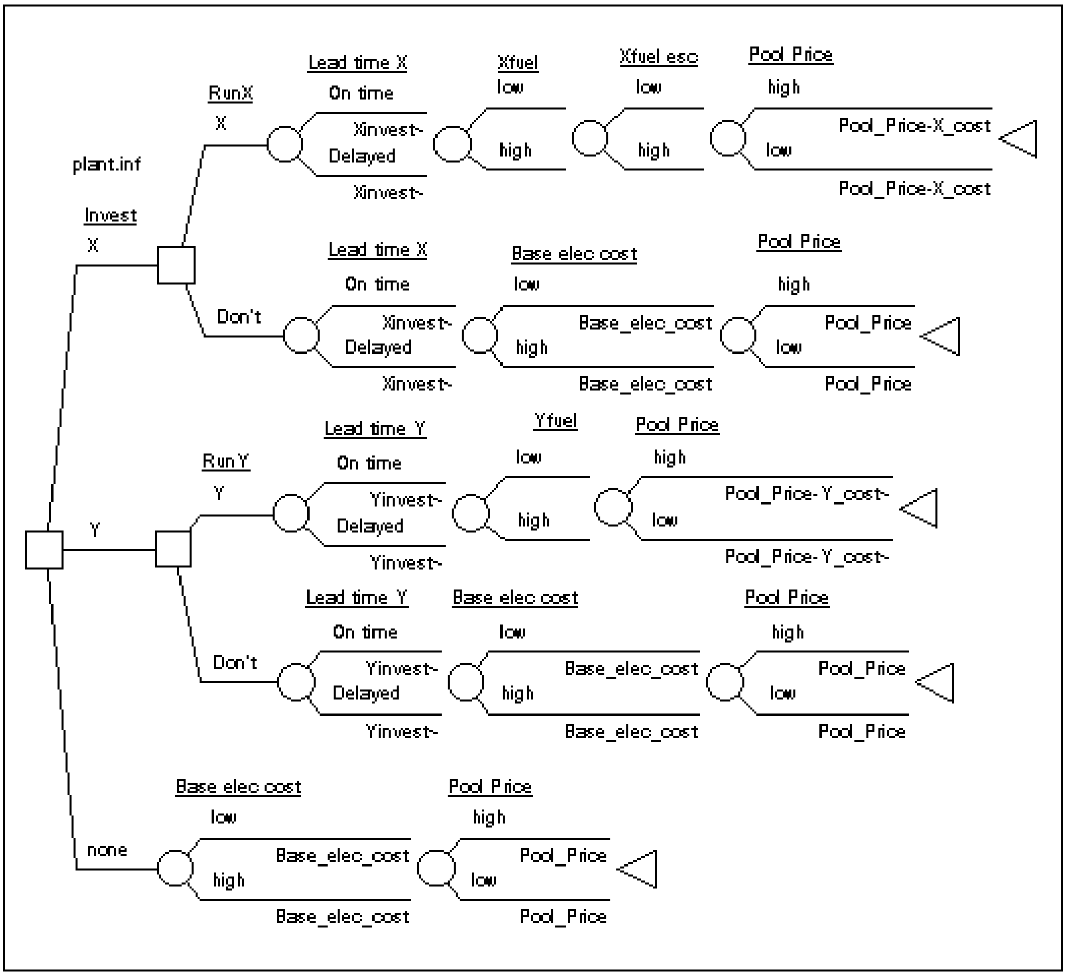


Figure 8.6 shows a possible configuration of the capacity planning problem any operationalisation of flexibility. Typically, we would invest and then run the plant when it is ready. The local events for plant X include the uncertainties of lead time, fuel price of plant X, and fuel escalation rate for plant X. The local events for plant Y are lead time and fuel price. The no-investment option serves as the status quo. The external events Pool Price and Base_elec_costs affect the payoffs of investing in X, Y, and None.

Figure 8.6 Plant Economics Decision Tree



Flexibility can be introduced in several ways: 1) option X or Y exhibits flexible characteristics or provides flexibility in response to given uncertainties; 2) plant characteristics, such as lead-times, are changed; and 3) decisions on investment are delayed until relevant uncertainties (trigger events) are resolved.

To analyse the flexibility provided by the investments X and Y, we must re-order the nodes so that the trigger event precedes the second stage decision. The first stage investment decision precedes the trigger event for the flexibility decision of whether to run or not. Without this trigger event, there is no additional flexibility that X and Y can introduce to the system. The flexibility that investment X or Y brings to the picture is simply the second stage decision of running the new plant if the trigger states of the trigger events occur.

If the external event <u>Pool Price</u> is made a trigger event for both X and Y, we see immediately that X and Y are more flexible than the status quo "none" option. If lead time is made the trigger event, then the fixed capital cost is known before any running costs are incurred. However, the subsequent decision that determines the amount of flexibility must be able to capitalise on this information.

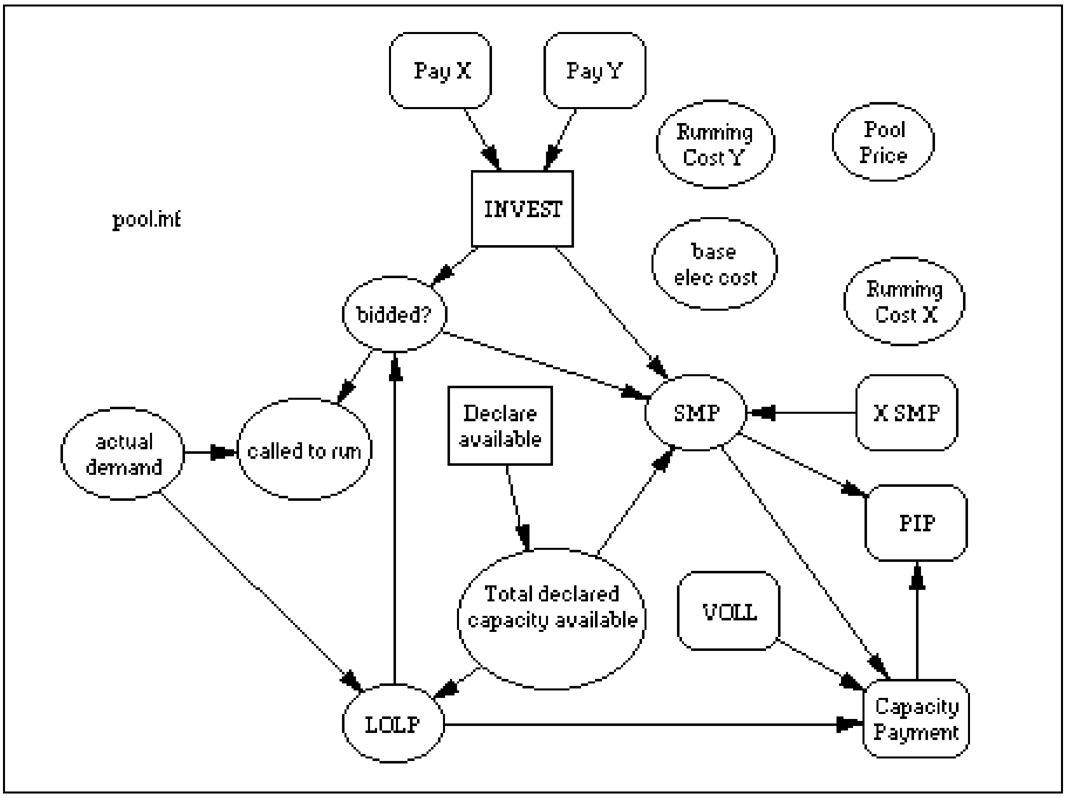
8.4.2 Pool Price

The elements in the pool price have been designed to encourage or discourage new capacity investments. Described in greater detail in Chapter 2, the ***capacity payment***, also called the availability payment, is the expected cost of unserved energy given to the generators in addition to the SMP for those plants called to run during a given half-hour. The capacity payment, (VOLL - SMP)LOLP, is composed of the Value of Loss of Load, the System Marginal Price, and the Loss of Load Probability. Together (SMP + capacity payment) they comprise the Pool Input Price (PIP).

A plant that has been declared available may or may not get bid into the pool. A plant that gets bid into the pool may or may not set the SMP for that half-hour. A plant that gets bid into the pool may or may not get called to run. These uncertainties together with actual demand level and total capacity in the system are market uncertainties that affect the overall price of electricity. Those plants that have been bid into the pool but not called to run receive the capacity payment because their declared availability ensures against loss of load.

The influence diagram of figure 8.7 shows the relationships between variables in the pool price formula which indicate market uncertainty and also affect the investment decision. This influence diagram is similar to the causal loop diagram of the system dynamics study of Bunn and Larsen (1992) but without cycles.

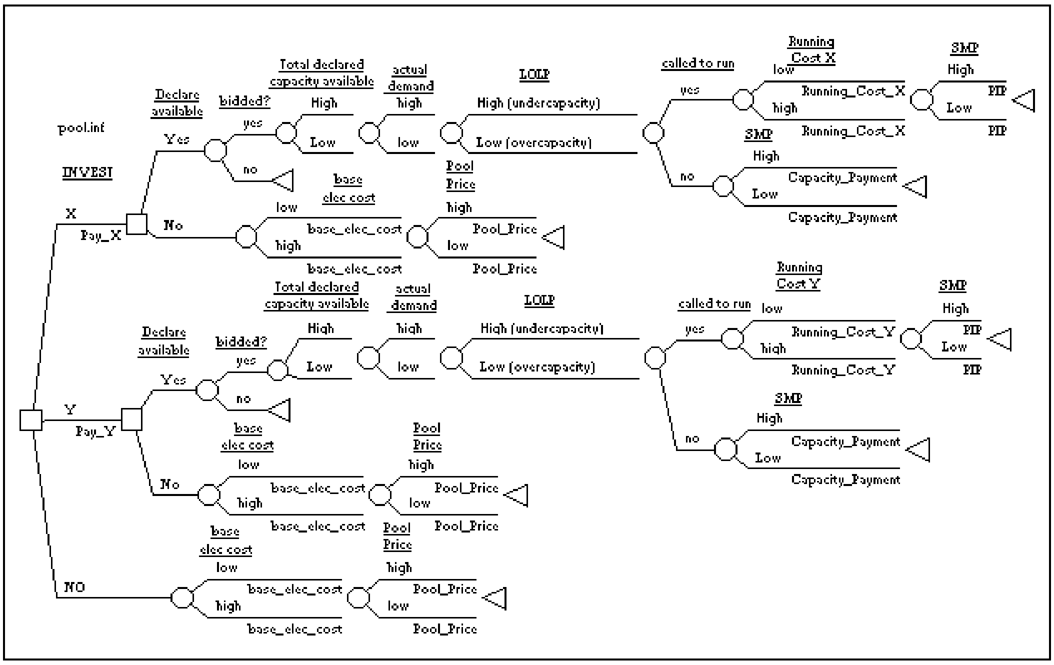
Figure 8.7 Pool Price Influence Diagram



We construct the decision tree (figure 8.8) to parallel the plant economics formulation of the previous sub-section. The utility has three choices in the first stage: invest in plant X, invest in plant Y, or do not invest at all. The levelised investment costs (pence/kWh) for X and Y are Pay_X and Pay_Y respectively. After investing in a plant, it can be declared available and bid into the pool.

Whether or not the plant gets bid depends on the expected demand and total declared capacity available, which determine the LOLP. Whether or not it actually gets called to run in the corresponding half-hour next day depends on the actual demand.

Figure 8.8 Pool Price Decision Tree



We specify X and Y such that if X is successfully bid, it is almost surely the most expensive plant bid within the half-hour, in which case the SMP will be equivalent to its bid price X_SMP. If Y is successfully bid, it is unlikely to be the most expensive plant bid, and therefore will not set the SMP for that half-hour. The probability of X's bid success is much lower than that of Y. If X or Y is bid into the pool but does not get called to run, the plant still receives the capacity payment. [For simplicity's sake, we have not included the possibility that plants not declared available will be called to run if actual demand is much higher than expected.] The do-nothing case assumes that the existing old plant has an equal chance of being bid into the pool and called to run, but the event has no effect on the level of SMP or LOLP. Focussing on market uncertainties for the moment, we assume that the running costs are of two states only (high or low) and not further affected by other uncertainties. These running costs, which depend on plant conditions, come from the extreme scenarios, i.e. minimum and maximum of plant costs, from the previous section 8.4.

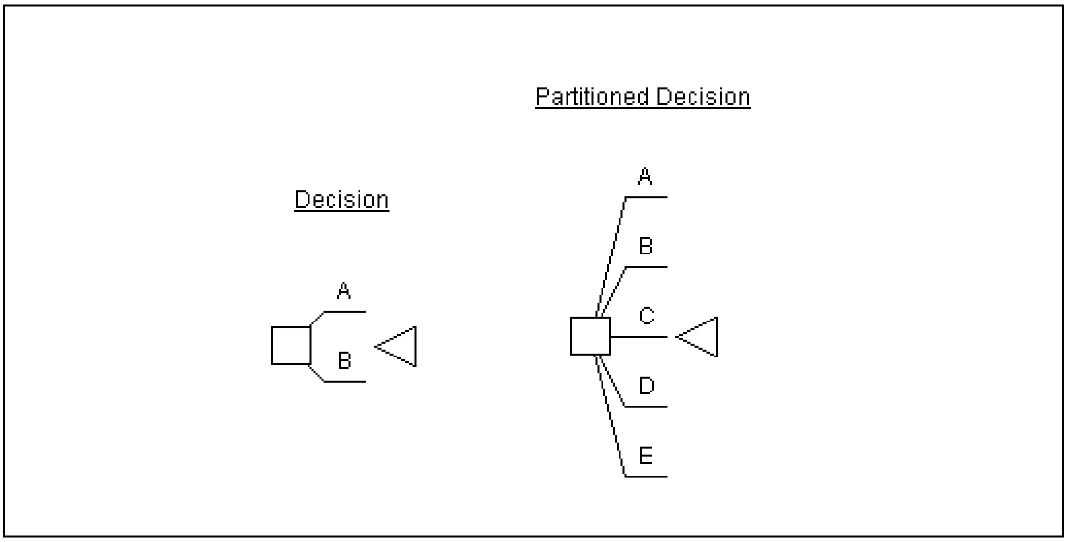
Flexibility is introduced in the same manner as described in the previous section. In other words, re-order or add nodes to the original structure to get a flexibility configuration specified in section 8.2. After structuring, we follow the assessment guidelines of section 8.3, especially table 8.1 to determine which measure of flexibility to use.

8.5 Operationalising Strategies

8.5.1 Partitioning, Sequentiality, Staging

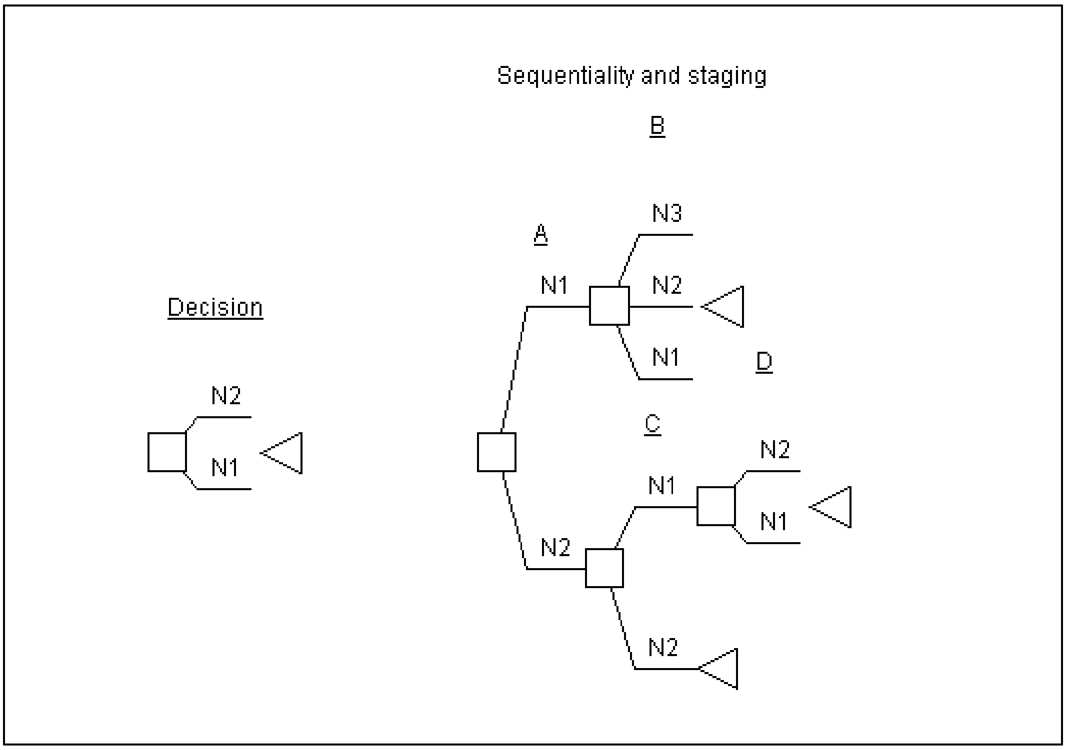
Previously described in Chapter 6, Mandelbaum's (1978) two sources of flexibility (partitioning and sequentiality) are means of decomposing a decision node. Figure 8.9 illustrates the meaning of partitioning. Partitioning the action space implies redefining the original choice set to enlarge it. The left decision with two choices A and B is partitioned into the right decision with five choices. The states of the trigger event may be defined to trigger the choices in the second stage decision.

Figure 8.9 Partitioning



Sequentiality or staging partitions the decision space over time. Flexibility is introduced by increasing the frequency of decision points. As each decision is a commitment, breaking up a decision into a sequence of smaller decisions reduces the amount of commitment made at each stage and thereby frees up resources to commit to better alternatives that arise. If re-ordered to capture new information, sub-decisions that are spread over a period of time gain from the resolution of uncertainty or acquisition of information. Figure 8.10 illustrates the meaning of sequentiality and staging.

Figure 8.10 Sequentiality and Staging

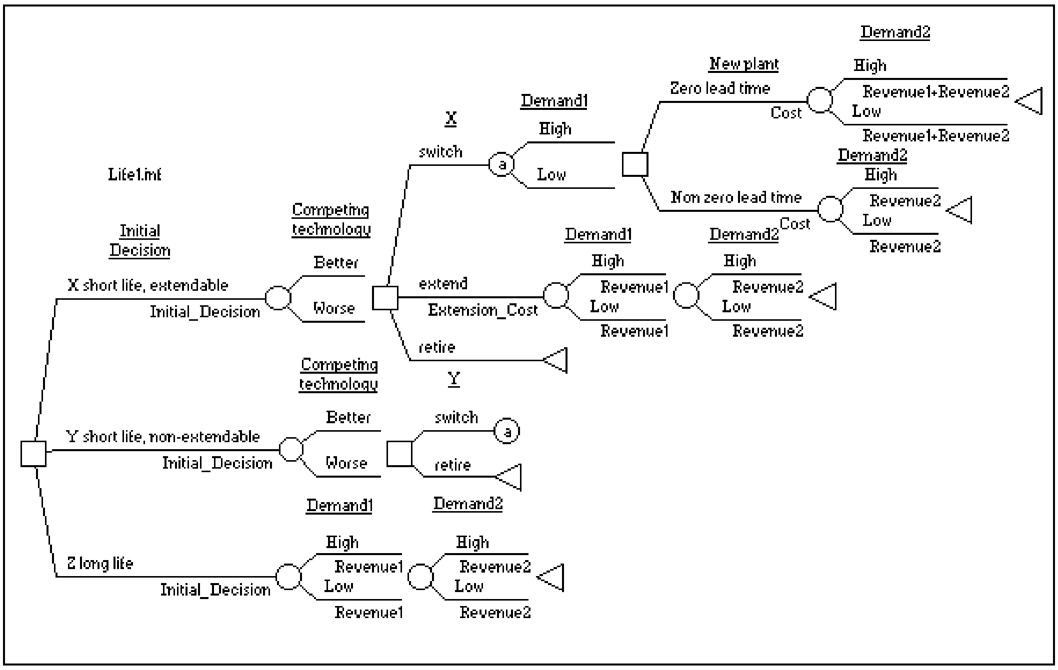


Increasing the frequency of decision points can be accomplished in a number of ways, such as 1) shortening the life of a plant, 2) adjusting the construction lead time or time to commission, and 3) introducing additional capacity in stages, e.g. modularity of unit size. Plants which can be built in incremental modular units and run as they are built offer flexibility by minimising commitment. We discuss next an example that concerns flexibility of plant lives against the uncertainty of new competitive technology.

FLEXIBILITY OF PLANT LIFE

The well-known phenomenon of technological obsolescence arises from the availability of more competitive technologies which may reduce running costs or take advantage of new conditions. Figure 8.11 compares plants with varying lives and the costs of switching to a new technology at the end of a plant's life. It shows that plants with extendable lives provide more flexibility than those without. As plant lives reflect the amount of commitment, reducing commitment increases flexibility. This supports the relationship between commitment and flexibility earlier established in the conceptual framework of Chapter 6.

Figure 8.11 Flexibility by Plant Lives



[Note: the chance node labelled ***a*** appears twice in the decision tree. It refers to the repetition of that portion of the tree to the right of the first labelled node.]

At time t, plant X and Y reach their end of life, while plant Z has not reached its end of life. At this time, there may be new technologies available for investment. Market and plant conditions may favour these new technologies, i.e. higher pool price and lower running costs. If the competing technology gives better performance, then it may be worthwhile to purchase or “switch” to it. In this case, X and Y are both more flexible than Z. If the competing technology gives worse performance, then it is not favourable to switch. In this case, investment X is more flexible than Y because X’s life can be extended. We assume that it will not be economically feasible to retire early and invest in the better performing technology at the same time. If the utility firm switches to the better performing technology, it makes a third stage decision, that of deciding on lead time. If demand is high, then a zero-lead time technology will capture the high revenue. If demand is low then the less costly non-zero lead time switched technology is preferable. This demand uncertainty acts as the trigger event for the third stage decision. Plant Z with remaining life is neither able to take advantage of the competitive technology nor get rid of the commitment, as early retirement implies a further cost.

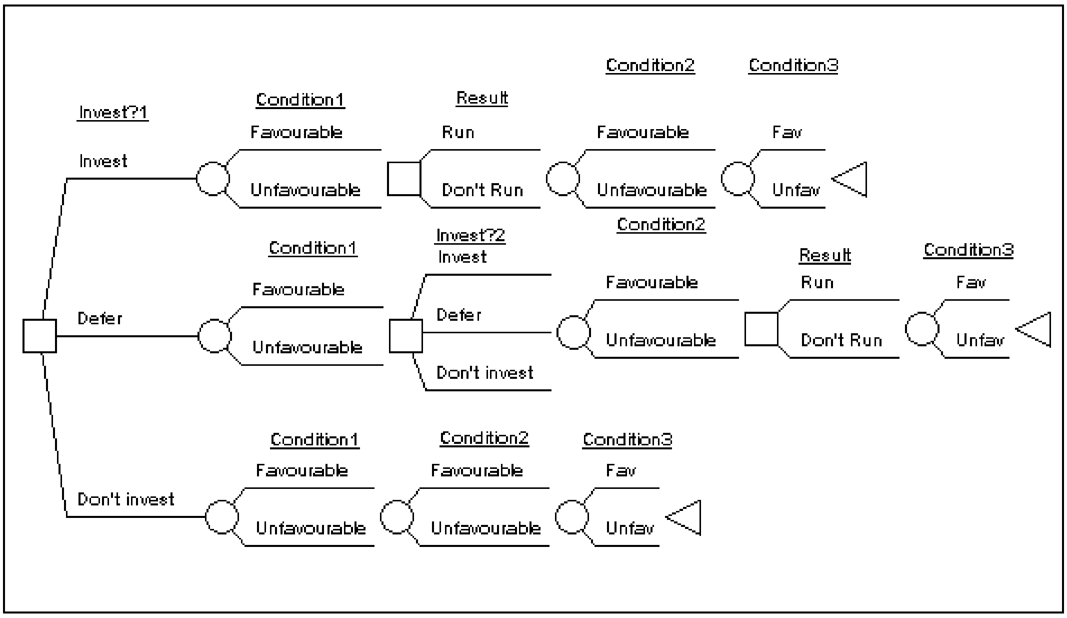
We analyse this example using expected value measures described in the previous chapter. The ***relative flexibility benefit*** (Hobbs et al, 1994) and the ***normalised flexibility measure*** (Schneeweiss and Kühn, 1990) both indicate that investing in plant X provides the most flexibility out of all three choices in the first stage. Investing in X, as opposed to Y, depends on the trade-offs between the ***enabler*** of investment cost, the ***likelihood*** given by the probability of better competing technology performance, and ***motivator*** of future demand levels. If a more competitive technology is not likely at all, then plant Z could be the best initial choice as the inflexible option gives the highest expected value when no uncertainty is considered. If there is no information about the competing technology until after plants X and Y have been retired, then there is no flexibility.

8.5.2 Postponement and Deferral

The timing decision is much discussed in option-pricing literature, that is, “when is the optimal time to invest and to exercise your option?” The timing decision is relevant if uncertainty can be resolved by waiting for or acquiring more information before deciding (thus deferring the decision). Postponement or deferral is illustrated by reversing the order of decision and chance nodes. Better payoffs can be attained if these uncertainties are trigger events for the decisions they precede. During the period of delay, new options may arise as well as expire. For simplicity’s sake, we assume that the choice set remains the same in spite of re-ordering. The timing decision of investing the first stage or exercising the second stage can be portrayed as a multi-staged decision tree, where the decision to invest or run a plant depends on the occurrence of the trigger state of the trigger event. Deferral can be achieved by adjusting the construction lead time of new plants, shortening or extending plant lives, or any number of ways, at a deferral cost. The analysis reduces to a trade-off between the cost of deferral and the expected benefits from this flexibility.

Figure 8.12 shows the basic structure of such a decision tree. <u>Condition1</u> triggers the decision to run in the second stage. <u>Condition2</u> triggers the decision to run if the initial investment decision is deferred. If <u>Condition1</u> also triggers the <u>Invest2</u> decision, then deferral is useful. By deferring the investment decision, one gets information about the conditions before deciding to invest. <u>Condition1</u> which affects the decision to run after <u>Invest</u> in the first decision also provides information for <u>Invest2</u>. The choice that corresponds to the more favourable state of its preceding trigger condition gives a better payoff. If these conditions (trigger events) are independent of each other, then deferring the decision provides no flexibility.

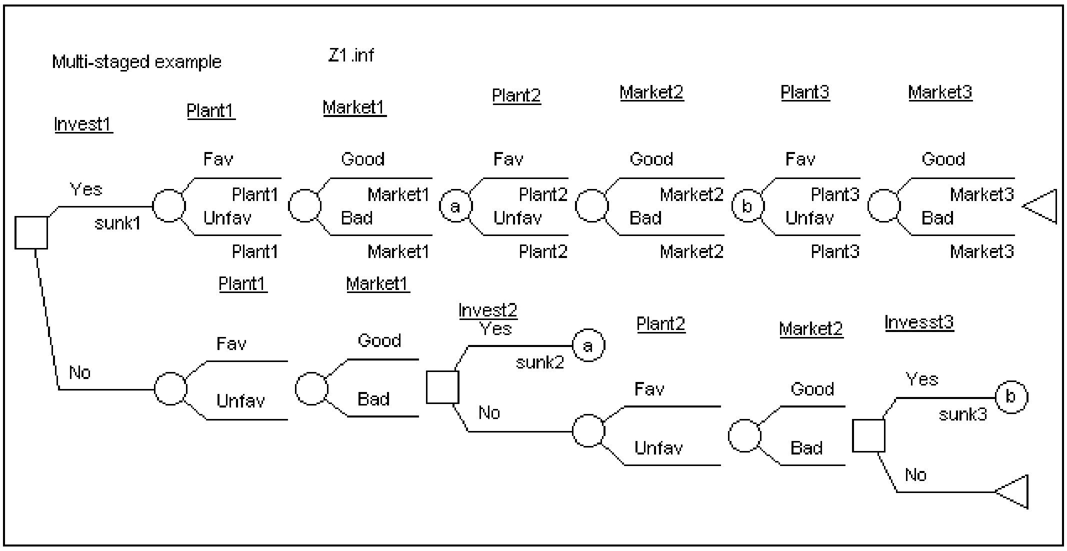
Figure 8.12 Postponement and Deferral Decision Tree



Extending this to multiple stages captures the opportune time to invest or exercise. We see that deferring only makes sense if the conditions are related and not independent.

Merkhofer (1977, p. 719) suggests that the decision maker's time preferences should be considered to determine the value of flexibility obtained from delaying a decision. Extending the previous example to an annual cash-flow model of figure 8.13, we should take the discount rate into consideration. Sunk1, Sunk2, and Sunk3 correspond to the investment premiums at different periods in time. Plant1, Plant2, and Plant3 are plant costs incurred in each of the three periods. Market1, Market2, and Market3 are revenues gained in the corresponding periods.

Figure 8.13 **Deferral with respect to Market and Plant Uncertainty**

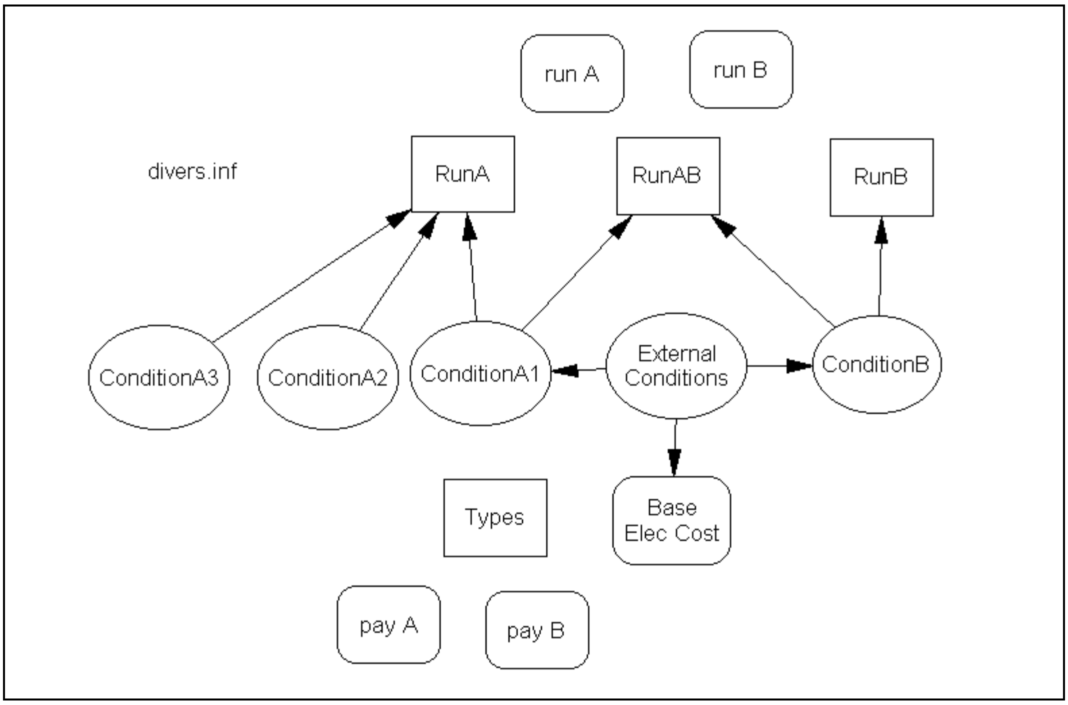


8.5.3 Diversity

Diversity implies a collection of different areas of uncertainties mapped to different types of flexibility. Our example in figure 8.14 shows that adding plant X with three attributes catering to three different uncertain conditions gives more flexibility than plant Y that only caters to one uncertain condition. Equally, adding both types of plants gives the most flexibility.

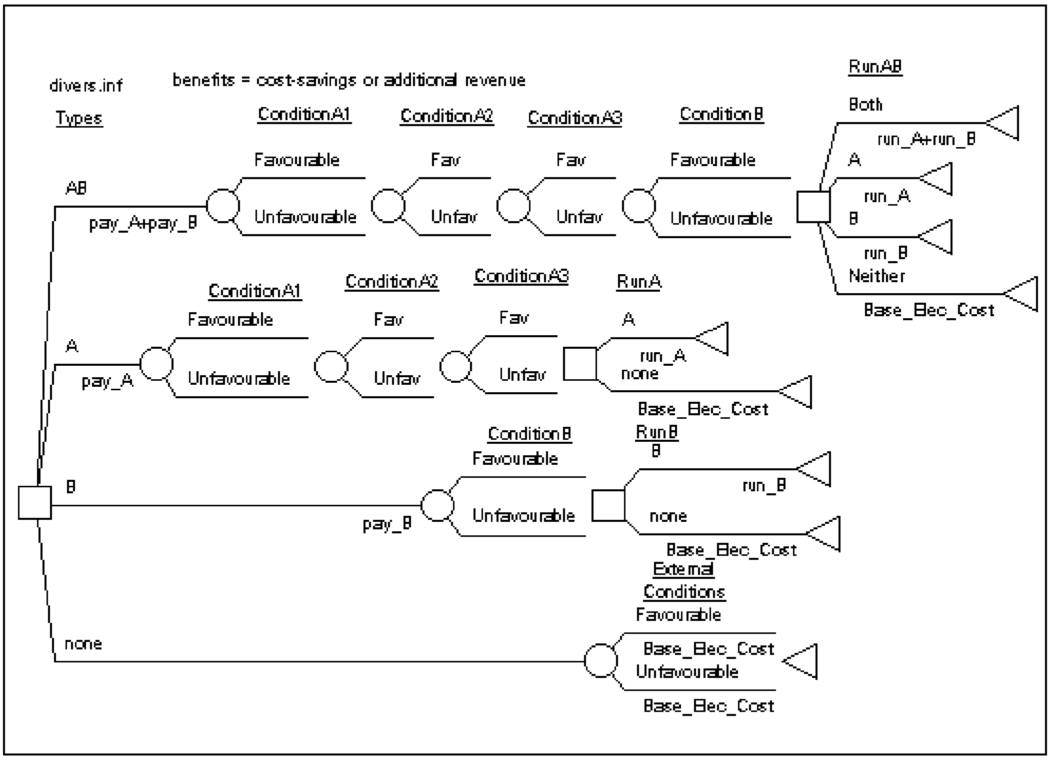
To build the decision model, we identify the uncertainties which flexibility answers or responds to, effectively a one-to-one uncertainty to flexibility mapping. We are asking, “Which uncertainties can we manage with the attributes of our plant or plant (mix)?” Flexibility in size answers uncertainty in level of demand (condition A1). Flexibility in performance of plant answers the uncertainty of environmental regulations (condition A2). Flexibility in the timing of investment answers uncertainty in demand growth (condition A3). A well-diversified portfolio contains different types and sizes of plants with different lives and retirement dates.

Figure 8.14 Diversity Influence Diagram



The three conditions A1, A2, and A3 trigger second stage decisions for plant A. If condition A1 is favourable, i.e. demand level goes up, then we can add another unit of plant A to meet the higher level of demand. The trigger state is high demand growth, and the associated flexibility choice is adding another unit to meet the higher demand. If environmental uncertainty is resolved, i.e. condition A2, then an appropriate action can be taken on plant A. These second stage decisions have not been explicitly illustrated in the decision tree but follow the same kind of decision sequences shown in the examples of plant economics and pool price in section 8.4.

Figure 8.15 Diversity Decision Tree



Selecting a plant with three attributes that contribute to flexibility is similar to selecting three plants that increase flexibility in three ways. In Chapter 7, Schneeweiss and Kühn's (1990) example of machine investment followed by production level adjustment captures this source of flexibility. The machines differ in the number of production levels, the selection of which are triggered by appropriate trigger states of the trigger event (demand) preceding the second stage decision. Adding options that contribute to the overall diversity in the system, plant mix, or portfolio contributes to overall flexibility because these options cater to different states of external conditions. Adding such options will always increase flexibility provided they are free. Because they are not free, it is necessary to make cost and benefit trade-offs, and this assessment requires the use of indicators and expected values.

8.6 Conclusions

We have shown the applicability and practicality of our guidelines for structuring and assessing flexibility in the context of capacity planning in the UK Electricity Capacity Planning. These guidelines are summarised briefly below.

Practical Guidelines for Structuring and Assessing Flexibility

1) ***Identify*** important areas of uncertainties, as we have done in Chapter 2 table 2.6, to facilitate the mapping of uncertainty and flexibility

2) ***Operationalise*** flexibility as in Chapter 6 by devising "flexible responses" for each by
    a) options
    b) strategies

3) ***Structure*** the problem in the decision analysis framework, i.e. with decision tree and influence diagram, to include

a) uncertainty-flexibility mapping, and

b) minimum 2-stage decision sequence

The decision tree is asymmetric because of the default status quo case in the first stage. Specify the decision tree with relevant indicators, i.e. enabler, disabler(s), motivator(s), trigger event(s), trigger states, likelihood.

4) ***Assess*** flexibility with indicators and expected values. For simple problems, use indicators. For complex problems, follow the categories in table 8.1.

The problems in capacity planning have been greatly simplified to focus on the contribution of flexibility to uncertainty. This simplification facilitates the mapping of uncertainty to flexibility, i.e. trigger event to decision, and treatment of multi-staged decisions and relevant uncertainties. The illustrative examples constructed in this chapter show that flexibility is a useful response to uncertainty. Flexibility does not replace the need for rigorous modelling, as completeness is still necessary. It merely compensates for the lack of completeness or the model unease found in the decision making style of the industry. In other words, the traditional modelling approach (with the trend in model synthesis) is still necessary but no longer sufficient.