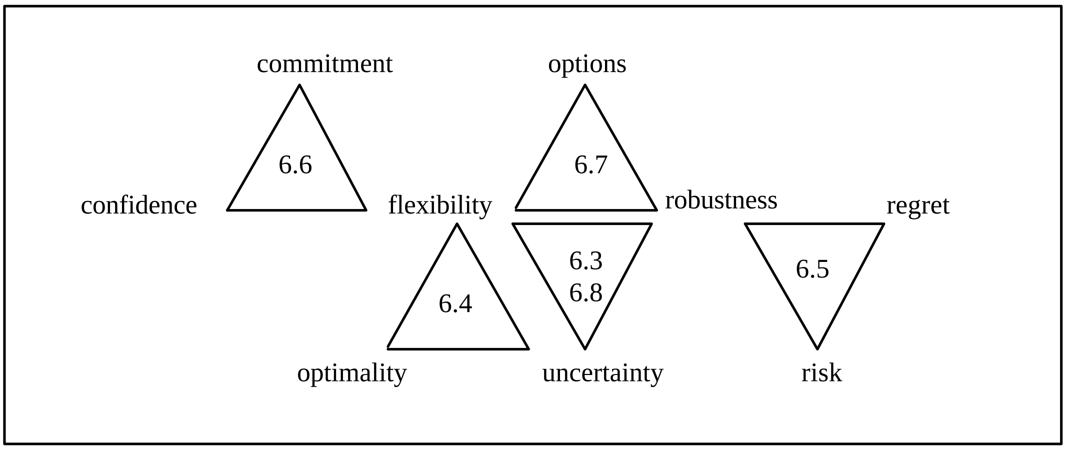
CHAPTER 6

Conceptual Development

6.1 Introduction

We first clarify and unify the multi-faceted meaning of flexibility by summarising a "***conceptual analysis***" (section 6.2) and then by developing a "***conceptual framework***" (sections 6.3 to 6.8). The conceptual framework examines how flexibility relates to more established concepts, like ***robustness***, ***optimality***, ***risk***, ***regret***, ***commitment***, ***confidence***, ***options***, and ***uncertainty***. Some of these relationships have been formally proven. Others are illustrated by examples. These conceptual relationships are depicted by triangles in figure 6.1 and discussed in the numbered sections. Following this, we determine the conditions under which flexibility is useful (section 6.9), discuss its downside (section 6.10), distill necessary elements to define flexibility (section 6.11), highlight the important concept of favourability (section 6.12), and suggest strategies to operationalise it (section 6.13.) The final section (6.14) concludes the main findings and raises the need for measuring and modelling flexibility.

Figure 6.1 Conceptual Framework



6.2 Conceptual Analysis

One way of understanding a concept is through word association. Evans' (1982) so-called ***conceptual analysis of flexibility*** involves a semantic assessment of related words. We briefly describe those words which share the closest meanings with flexibility: adaptability, elasticity, liquidity, plasticity, robustness, resilience, and versatility.

Adaptability is the ability to respond to *foreseen* changes, while flexibility is the ability to respond to *unforeseen changes* (Eppink 1978, Evans 1982). Adaptability is necessary but not sufficient to provide flexibility. ***Elasticity*** is similar in the context of return to a normal state. ***Liquidity***, meaning the ease of conversion, is also a kind of flexibility, being the ease of transition from one time period to a desired position in the next period (Jones and Ostroy, 1975). In this sense, flexibility as defined by Goldman (1974) is the capacity of a portfolio to furnish a variety of consumption plans. Both plasticity and flexibility denote some form of malleability. While ***plasticity*** denotes the ability to *maintain* a state, flexibility, in addition, embraces the ability to influence successfully a *transition* to other states. ***Robustness*** and ***resilience*** are closely related; the former refers to the ability to satisfactorily *endure* all envisioned contingencies while the latter refers to the ability to *absorb* or *accommodate* unforeseeable shocks and discontinuities. Hashimoto (1980) and Hashimoto et al (1982) make use of robustness in water resources planning. By far the closest resemblance to flexibility is captured in the word "versatility." ***Versatility*** is sought as a hedge against state changes, and as such, is optimal for an infinite sequence of decisions (Bonder, 1979).

6.3 Flexibility and Robustness

6.3.1 Two Types of Flexibility

Gupta and Buzacott (1988), Mandelbaum (1978), Eppink (1978), and Ansoff (1968) see two fundamental ways of responding to change and uncertainty, which correspond to two types of flexibility. ***Active or action flexibility*** is the ability to respond by changing or reacting. ***Passive or state flexibility***, on the other hand, exists when there is no need to react because of immunity, insensitivity, or tolerance. It is the innate capacity to function well in more than one state and thus possible to ignore changes. We refer to the second type of flexibility as ***robustness***. This dichotomous interpretation of flexibility is summarised chronologically in table 6.1.

Table 6.1 Flexibility and Robustness

Source	**Flexibility**	**Robustness**
Gupta and Buzacott (1988)	SENSITIVITY: the degree of a change tolerated before a deterioration in performance takes place. The higher the degree of tolerable change, the less sensitive the system is to that change.	STABILITY: the maximum size of a disturbance for which the system can still meet the performance targets via some corrective action.
Mandelbaum (1978)	ACTION: the ability to respond to change by taking appropriate action	STATE: the innate capacity to function well in more than one state
Eppink (1978)	ACTIVE: the response capacity of the organisation	PASSIVE: the possibility to limit the relative impact of a certain environmental change
Ansoff (1968)	INTERNAL	EXTERNAL

Mandelbaum (1978) observes that ***action flexibility*** is only needed when we have less than perfect information. It is acquired by taking appropriate action after the change takes place to take advantage of the new state. This kind of flexibility is only desirable when there is uncertainty about what actions to take and useful if that uncertainty is reduced.

State or passive flexibility, on the other hand, already exists in the new state when the change takes place. Therefore it is not necessary to learn about the present state. This built-in flexibility is analogous to prevention rather than cure. A system's ability to cope with changes is robust if it is independent of the choice of future actions. In other words, it is able to continue functioning despite the change.

These two types of flexibility agree with the conceptual analysis of Evans (1982). Flexibility is the inherent capability to *modify* a policy to *accommodate* and successfully *adapt* to such changes, whereas robustness refers to the ability to *endure* such changes.

The main argument against this dichotomous characterisation of flexibility is that it is neither exhaustive nor exclusive. Where flexibility denotes speed of change, diversity of alternatives, or abundance of possibilities, any planning approach to this end readily encompasses both notions of flexibility and robustness and more. The distinction between passive and active forms of flexibility becomes less clear when used simultaneously. In other words, a person may choose to be both flexible and robust or maintain a system that is robust overall but containing flexible elements. As flexibility and robustness are so closely related, we investigate the meaning of robustness in the next sub-section and then compare it with flexibility afterwards.

6.3.2 Robustness

Robustness is a term in its own right. It has several definitions. In quality control, robust quality represents the *zero defect concept*. In statistics, robust regression refers to *a resistance in the key components of a model to the effects of outlying* *observations*. Robustness to likely errors is *the ability of a procedure to give good results under less than ideal conditions*. Accuracy in problem representation can be increased by model robustness considerations which *reduce the sensitivities of individual variables.*

In the context of systems planning, robustness is a desirable goal. Hobbs et al (1994) define a robust plan as one whose cost varies little with changes in assumptions. Hence, robustness communicates the notions of ***predictability*** and ***stability***. Hashimoto et al (1982) associate robustness *with the probability that the actual cost of the system will not exceed some multiple of the minimum possible cost of a system designed for the actual conditions that occur in the future*. Hashimoto (1980) says that robustness is related to Stigler's (1939) concept of flexibility, i.e. "acceptable over a range." Merrill and Wood (1991) equate robustness with the proportion of possible futures a given plan would be best in. Gupta and Rosenhead (1968) state that it is closely related to the term "adaptability" in the context of the number of irrevocable decisions that must be made now versus the number and diversity of options left open. Paraskevopoulos et al (1991) pose robustness as the (in) sensitivity to different sources of uncertainty which directly translates to testing a plan that is optimal under a given scenario against other scenarios and parameter sensitivities.

Robustness is a necessary pre-requisite of a solution, a result, a model, and a method if it is to be generalisable, reliable, and widely applicable**.** ***Statistical robustness*** guarantees that a solution is not vulnerable to error**.** ***Robustness of results*** is tested by using alternative methodology. ***Model robustness*** is tested by using an alternative set of data or by changing parameters. Robustness demonstrates how powerful the method is, how applicable it is, and how well it performs regardless of changes. Other words that are implied by the word "robustness" are ***consistency***, ***insensitivity***, ***tolerance*** (of error and change), ***long-lasting***, ***durability***, and ***sustainability***.

6.3.3 Flexibility versus Robustness

The words "flexibility" and "robustness" often appear in the same articles and even used inter-changeably as if they mean the same thing. They have also been used to define each other, which causes a common source of misinterpretation. For example, CIGRE (1991) suggest *that flexibility at the planning stage ensures certainty of a robust power system in the future*. Rosenhead (1980) defines robustness *as the useful flexibility preserved by early decisions in the decision sequence*. Pye (1978) defines robustness as *a method of trading off flexibility against expected value*. Hobbs et al (1992) confuse this further by suggesting that *(the pursuit of) flexibility can result in a robust plan that will be satisfactory under a range of possible market and regulatory conditions* even if that plan fails to be best under any one of them.

In general, when we speak of flexibility, we mean *the ability to change by (quickly) moving to a different state, selecting a new alternative, or switching to a different production level*. Robustness, on the other hand, is associated with *not needing to change*. While flexibility is a ***state of readiness*** such as the ability to react to change, robustness is a ***state of being*** such as a resistance or an immunity to change. Flexibility and robustness are not opposite or the same, but merely two sides of a coin, corresponding to two ways of responding to uncertainty. We illustrate this distinction in six ways, as follows.

1) Characteristics of Electricity Planning

2) Functional Requirement of Systems

3) Present and Future Costs

4) Over and Under Capacity

5) Response to Uncertainty

6) Feature of Modelling Approach

CHARACTERISTICS OF ELECTRICITY PLANNING

Future uncertainty necessitates the introduction of more flexibility in the planning of power systems. The resulting plan will not be optimal for a particular future but satisfactory for most of the possible futures. CIGRE (1991) propose two approaches to meet this need: *devise a system sufficiently robust to withstand impacts* or *incorporate flexibility within system development*. Robustness indicates the *overall power system strength to withstand external impacts*. They argue that flexibility is superior to robustness because the latter is no longer adequate when the development parameter variations become too large and that providing robustness becomes too expensive. To support these arguments, it is necessary to trade off cost and optimal performance.

The degree of flexibility varies with different capacity mixes. A diversified portfolio is better equipped to cope with variations in electricity demand because each type of plant represents an open option. This aspect of flexibility is closely related to Stirling's (1994) notion of diversity in energy supply investment as a means to security of energy supply. Diversity in plant mix is measured by the number of different plants according to type of fuel, capacity size, and other characteristics like operating or scrapping lives and load factor.

FUNCTIONAL REQUIREMENT OF SYSTEMS

The notions of flexibility and robustness describe two mutually exclusive functional requirements of information or decision support systems. A flexible system is capable of performing many functions, thereby supporting multiple patterns of usage. Robustness, on the other hand, is a preventative, fail-safe, fault-tolerant, or fool-proof characteristic that ensures the system will not crash. A robust programming language has a consistent style to its syntax and semantics, whereas a flexible one can be manipulated to meet different needs.

PRESENT AND FUTURE COSTS

One of the main differences between robustness and flexibility is that the former infers a ***present cost*** whereas flexibility implies a ***future cost***. Robustness by means of keeping a reserve margin, i.e. over-capacity, contains a present holding cost which will not be eliminated until demand reaches that margin level in the future. This is the opportunity cost of providing flexibility as indicated by the level of idle capacity or the cost of over building.

On the other hand, flexibility is a potential change, reflecting a future cost that has not occurred yet. But the provision of flexibility, that is, the capability to be flexible, may incur a present cost. For example, importing electricity when demand rises implies a future cost, but the option to import in the future implies a present cost.

The use of fixed and variable costs to describe flexibility was first made by Stigler (1939) who proposed that ***flexibility increases when resources are transferred from the fixed to the variable***. A firm is more flexible if it is able to incur (variable) costs only when necessary.

OVER- AND UNDER-CAPACITY

The provision of flexibility implies an opportunity or idle cost usually associated with robustness. The capacity to accommodate future changes is the opportunity cost for under-utilisation (Son and Park, 1987). Reserve margins are typically built into capacity plans to ensure reliability, especially in meeting peak demand. Robustness and flexibility translate into over- and under-capacity to deal with demand uncertainty. To appreciate and quantify this distinction, we perform a separate study in Appendix D.

RESPONSE TO UNCERTAINTY: Uncertainty Reduction vs Adaptation

Robustness may be associated with ***uncertainty reduction***, by minimising surprises. Flexibility, on the other hand, refers to ***adaptation***, i.e. we expect there to be surprises to which we can react by changing. In this dichotomy, Gerwin (1993) offers several delivery methods ***to cope with uncertainty***, depending on the nature of uncertainty. Although he does not call these two methods by the names of robustness and flexibility, the parallelism is evident from his table on page 406, as reproduced below.

Table 6.2 Gerwin's (1993) Methods of Coping With Uncertainty

Nature of Uncertainty	Uncertainty Reduction Method (robustness)	Adaptive Method (flexibility)
Market acceptance of kinds of products	Long-term contracts with customers	Small setup times, modular products
Length of product life cycles	Life extension practices	Less hard tooling and backward integration
Specific product characteristics	Cross-functional design teams	CNC machines
Aggregate product demand	Leveling demand	High capacity limits, subcontracting
Machine downtime	Preventive maintenance	Redundant equipment
Characteristics of materials	Total quality control	Automated monitoring devices, human inputs
Changes in the above uncertainties	Large size	Re configurable equipment

In the context of electricity planning, Gerwin's distinction of responses to uncertainty applies to those areas of uncertainty identified in Chapter 2. Table 6.3 suggests some ways to respond to these uncertainties.

Table 6.3 Response to Areas of Uncertainties in Chapter 2

Areas of Uncertainty	Uncertainty Reduction Method (robustness)	Adaptive Method (flexibility)
plant economics: cost of production	contracts to stabilise pool prices	avoid plant with high capital cost
fuel supply	diversity of plant	co-firing
demand level and growth	over-capacity	extra production, demand side management
technology: lead time	plants at different stages of construction	import or export power when needed
financing requirements	back to back contracts	minimise commitments

FEATURE OF MODELLING APPROACH

Traditional approaches deal with the uncertainty of meeting demand by forecasting, setting reserve margins based on past volatility of demand, and optimising against this to produce a capacity expansion plan. This method of dealing with uncertainty exemplifies the deterministic and probabilistic approaches, which are oriented towards ***robustness***, i.e. *ensuring that the resulting decision or plan is acceptable* with respect to the uncertainties and scenarios considered. Robustness as a means to model completeness depends on the accuracy of the forecast and the extensiveness of scenario, sensitivity, and risk analyses. Robustness does not guarantee that the result will be optimal in the *actual* future, only that it is optimal against the *anticipated* future.

Hobbs and Maheshwari (1990) suggest the use of Monte Carlo Simulation (or ***risk analysis***) to assimilate total costs from different sources of uncertainty, ***sensitivity analysis*** to show the effects of changes in important parameters on a plan, and ***scenario analysis*** to check how well a plan performs under a particular future. These three types of analyses are different ways to show how applicable the object is without having to change it, i.e. robustness. ***Robustness analysis*** is a confusing term as it has been coined by Rosenhead (1989) to describe a heuristic in soft systems methodology (SSM), which is a problem structuring method to determine the sequence of decisions that would maximise future flexibility. In modelling terminology, however, robustness analysis refers to an analysis of robustness by means of the above techniques or by statistical tests.

Flexibility, on the other hand, is a measure of *contingency* against uncertainty. In this sense (of Knight, 1921), only the area of uncertainty is identifiable, as the uncertainty itself is unquantifiable. Techniques based on structures similar to ***decision trees***, such as ***decision analysis***, ***contingent claims analysis***, and ***stochastic dynamic programming***, have been used in valuing flexibility with respect to *uncertainty* and *contingency* (Dixit and Pindyck 1994, Kogut and Kulatilaka 1994, Smith and Nau 1990, Triantis and Hodder 1990, Trigeorgis and Mason 1987, and others.) Flexibility, in this sense, is a feature of the modelling approach, i.e. capable of representing uncertainty, choices, and contingency.

6.4 Flexibility versus Optimality as a Decision Criterion

The expected utility model follows the principle of optimisation, that is, maximising the expected utility to achieve the most desirable outcome. In environmentally dynamic situations, Heimann and Lusk (1976) argue that flexibility offers a better model than expected utility. In situations with multiple periods, uncertain availabilities of alternatives, and uncertain occurrences of states of nature, maximising the probability of achieving a pre-selected output level rather than expected value is a more feasible and sought after goal. When the decision maker does not have full confidence in the model, Mandelbaum (1978) argues that ***flexibility is preferred to optimality***.

The well established operational research criterion of optimality is often unacceptable in practice. Profit maximisation or cost minimisation disregards or distorts situations in which different objectives are not commensurate. In response to these issues, Rosenhead et al (1972) consider selecting an initial decision that leaves as many options open in the future as possible, rather than immediately seeking the course of action that will lead to the highest payoff.

6.5 Robustness, Risk, and Regret

The use of risk as a surrogate for uncertainty is seen in the utility theory of risk attitudes, risk profiles, and risk preferences. Montenegro (1978) develops a ***flexibility preference model*** based on parallel relationships between risk and flexibility, e.g. whereas risk relates to returns, flexibility relates to costs. He defines flexibility as *the management and engineering margins implemented in a system to cope with the uncertainties of its system requirements*. Increased flexibility maximises the expected risk utility function of the decision maker. He applies this flexibility preference theory to a telecommunications system, which shares similar traits with energy systems, e.g. capital intensiveness, long planning horizons, and heavy infrastructural investments. He constructs flexibility profiles as opposed to risk profiles. The resulting system is robust because of the margins set in place, i.e. the system need not change.

Risk is sometimes regarded as a negative consequence of uncertainty, such as the hazards to which an electricity company is exposed. [A more common understanding is given by Knight (1921) and discussed in Chapter 2.] Merrill and Wood (1991) proposes two measures for this type of risk: *the likelihood of making a regrettable decision* (which they call ***robustness***) and *the amount by which the decision is regrettable*. Concurrently, Merrill and Wood also advocate robustness as a way to manage risk. Robustness is defined as a measure of ***the safety or lack of risk of a decision***. A plan is robust if it represents a reasonable trade-off with 100% probability or for all possible values of uncertainties. A robust plan is one which could be selected from every future, no matter how the uncertainties turn out. The above analysis shows that robustness, risk, and regret are closely related.

One way to reduce risk is to select a course of action that minimises future regret. Minimax regret, otherwise known as the Savage criterion, follows the decision rule of selecting the path of least regret. Regret is defined as the opportunity cost of an action, i.e. the assessment of a lost or foregone opportunity made in hindsight. For some individuals, regret or remorse ranks high in terms of emotional distress. The relationship between risk, regret, and robustness is further supported by the robustness definition of Gerking (1987): ***a robust decision is one for which elements will not have to be regretted***.

6.6 Commitment, Confidence, and Flexibility

Commitment, confidence, and flexibility are also related in a similar fashion. If a decision maker is unsure about his preferences and also not confident of his model, then he will be reluctant to commit himself to a course of action. In this case, he would seek flexibility, for instance, by delaying the decision until he gets more information or by limiting the degree of his commitment. By reducing commitment, he increases his flexibility, i.e. *the ability to select another course of action*.

Commitment refers to the "bindingness" of a contract. A commitment becomes a liability when it is no longer needed. A commitment contains an irreversible element which prevents one from undoing the situation or choosing a different course of action easily. Once a person has committed to a course of action, he gives up the opportunity to wait for new information that might affect his decision, as he can no longer take advantage of this information.

Mandelbaum (1978) and others observe the relationship between a decision maker's confidence and his commitment. Confidence is a measure of the subjective certainty the decision maker has in his preferences, his perception of the future, and other specifications of the model. However, no one has subsequently made the link between commitment and flexibility.

We propose that flexibility also describes the quality or degree of commitment to an existing course of action, i.e. the degree of reversibility or opting out. Similarly, the amount of desired flexibility varies directly with the amount of uncertainty perceived by the decision maker, such as his confidence in the model, sureness of his own preferences, and his willingness to commit.

Kreps (1979) asserts that the decision maker's preference for flexibility is increased when he is unsure about his preferences. Being unsure is equivalent to lacking confidence. Mandelbaum and Buzacott (1990) show that flexibility compensates for model unease or lack of model confidence. Someone who is unsure is less likely to commit himself than one who is sure. Jones and Ostroy (1984) observe that the variability in a decision maker's beliefs is directly related to the amount of flexibility he desires. A decision maker who is unsure is more likely to retain some flexibility than one who is sure about his preferences. Similarly, a person with minimal commitment, i.e. few and breakable obligations, has more flexibility than one with more responsibility. The following relationship can be deduced from the above analysis: ***lack of confidence reduces the desire for commitment and increases the preference for flexibility***.

6.7 The Right But Not the Obligation

The two types of flexibility correspond to two basic ways of responding to uncertainty. Passive flexibility or robustness allows uncertainty to be ignored, that is, insensitivity to external stimuli. It need not respond or change. Active flexibility refers to the ability to change. These are incorporated in the finance definition of options, i.e. ***the right (ability) but not the obligation (need) to transact (change).***

In finance, an option is defined as *the right to purchase or sell the underlying asset at a specific price with the right lasting for a specific time period*. The right can be interpreted as the ability or capability to change, which defines action flexibility, i.e. the ability to respond to change by changing. Hirshleifer and Riley (1992) maintain that remaining flexible is like buying an option as to what later action will be taken: ***the more flexible position chosen, the greater is the value of the option***. This relationship suggests that techniques based on option pricing theory, e.g. contingent claims analysis, can be used to assess flexibility.

In the options framework, it can be shown that the value of managerial flexibility is greater in more uncertain environments and in periods of higher interest rates (higher opportunity cost) and investment opportunities of longer duration. Volatility and risk are surrogate measures of uncertainty, and Tomkins (1991) states that the greater the risk (or volatility), the higher the option value. The more volatile the underlying market, the riskier it is. The riskier the market, the greater the value of the option. Just as volatility determines the option value, we can expect uncertainty to determine the value of flexibility.

The traditional net present value (NPV) rule of investing in a project when the NPV of its expected cashflows is at least as large as its cost ignores the opportunity cost of making a commitment now and giving up the option of waiting for new information. NPVs do not take into account the considerable uncertainty, irreversibilities, and possibility of postponement associated with these investment decisions. Instead of using the NPV rule, Dixit and Pindyck (1994) advocate the options approach for more accurate analysis (and explicit consideration of flexibility, which they have narrowly defined as postponement of decisions).

In electricity generation, analysis of flexibility using the notion of options is explored by Yamayee and Hakimmashhadi (1984). What needs further development is the existence of such options, e.g. legal contracts allowing the postponement or cancellation of new plants without great penalty. The UK Electricity Supply Industry is just beginning to see some variations in contractual arrangements, although most new ventures are still completely hedged in "back-to-back" supply and fuel contracts. These completely hedged contracts reflect the ***robust*** rather than the ***flexible response***. The Regional Electricity Companies' entry into the electricity generation business is a form of ***strategic flexibility***, as is the investment of CCGTs.

Financial options are financial instruments that can be used for ***hedging*** purposes. Marschak and Nelson (1962) point out the difference between ***hedging*** and ***flexibility***. One hedges because of the uncertainty and desire to avoid high variance of returns. On the other hand, one takes flexible initial actions when expecting to learn more about the world and to take advantage of that learning before making subsequent moves. In short, ***flexibility can increase the variance of expected payoffs whereas hedging cannot***. Those who hedge are risk averse, but those who take flexible actions want high payoff. Evans (1982) also notes the difference between hedges and flexible responses. Hedges and compromises are options that make the worst outcome a little better at the expense of making the best outcome a little worse. Hedges involve a negative approach, while flexible responses cope with various unavoidable uncertainties about the future.

6.8 Uncertainty and Flexibility

The relationship between uncertainty and flexibility was first formally noted by Stigler (1939). Later Marschak and Nelson (1962, page 52) state "the value of flexibility is a function of variation in price and how well that variation can be predicted before the decision is made," i.e. the specific uncertainty to which flexibility deals with and the quality of information regarding this uncertainty. Based on this relationship, they prove that the greater the uncertainty, the greater the value of flexibility. From a decision theoretic perspective, Merkhofer (1975) confirms this complementarity of uncertainty, flexibility, and learning. If learning is expected through resolution of uncertainty, reduction of uncertainty, or acquisition of additional information, flexibility provides the ability to take advantage of that learning or new information. DeGroote (1994) formally proves several properties of flexibility and "***diversity***" , a term which conveys notions of ***variability***, ***variety***, or ***complexity***. He shows that an increase in diversity of the environment makes it more desirable to select a more flexible technology. Similarly, an increase in the flexibility of the technology makes it more attractive to operate in a more diverse environment. These properties support the relationship between uncertainty and flexibility as uncertainty encompasses diversity and complexity in the environment as well as any future unknown.

Fine and Freund (1990) suggest the use of flexible capacity to hedge against uncertainty in future demand. Flexible technology enables a firm to rapidly introduce new product models, reduce the need for interperiod inventories, and expand product scope to invade competitors' markets.

Related to uncertainty and flexibility are other concepts such as liquidity, learning, and risk which we mention now.

LIQUIDITY AND LEARNING

Uncertainties of the capital market, Hart (1937) argues, require the maintenance of flexibility, more specifically known as "liquidity." Marschak and Nelson (1962) observe: the greater the uncertainty as to what investment opportunities will be next period and the more the investor expects to learn about them between today and tomorrow, the more he should be willing to pay for flexibility (liquidity).

RISK AND UNCERTAINTY

Carlsson (1989) assigns Klein's (1984) type I and type II flexibility to risk and uncertainty respectively. Type I flexibility deals with foreseeable events and as such can be built into production processes. Type II flexibility is built into organisations, the risk-taking attitudes of its people, their expectations of change, and their interactions in the long term. Firms must be alert to new opportunities for new products and processes, i.e. they must be able to rapidly respond to uninsurable changes in market conditions and unprogrammable advances in technology. These two types of flexibility are not equivalent to the passive and active forms of flexibility described earlier.

6.9 Conditions Under Which Flexibility is Useful

The conceptual framework reveals that flexibility is useful when there is uncertainty. We identify three kinds of uncertainties which relate to our consideration of flexibility: the ***environment***, the ***model***, and the decision maker (***user*** of the model). Uncertainties in the environment have been described in Chapter 2 as ***areas of uncertainties***, e.g. plant economics, demand, regulatory, and public opinion. Uncertainties in the model refer to the lack of completeness, accuracy, or adequacy. Uncertainties in the user refer to his unease in the model, unsureness about his own preferences, and his lack of (detailed) information.

In Chapter 2, we had proposed two ways to deal with these uncertainties: ***modelling*** and ***flexibility***. The traditional approach of modelling uncertainties implicitly assumes ***completeness*** as a goal. We have earlier suggested model synthesis as a means to this end, but our subsequent investigation revealed the conceptual and technical difficulties of synthesis. In Chapter 4, we questioned the goal of completeness, whether it is indeed realistic and possible. If completeness is possible, then model synthesis and other types of rigorous modelling should eventually produce a complete model. Until then, we need to look for other ways to ***compensate for that lack of completeness***. If completeness is a futile goal, then the modelling approach may not be appropriate. The close relationship between uncertainty and flexibility suggests that flexibility may be a way to compensate for lack of completeness in modelling uncertainty, i.e. ***to cope with those uncertainties not captured in the model***, and ***to deal with uncertainties independent of the modelling approach***.

We also argue that even if a model is complete, there may still exist a gap between the model and the user. In other words, the user may not have full confidence in the model and, according to our conceptual framework, may seek flexibility instead. The uncertainty external to the model, i.e. model-exogenous uncertainty, calls for that extra-model flexibility.

In Mandelbaum's (1978) terms, ***"model unease"*** refers to the uncertainty felt by the user regarding the model, and he argues that it motivates the consideration of flexibility, but he does not elaborate on how flexibility can be used to compensate for this unease. We distinguish between intra-model unease and extra-model unease. ***Intra-model unease*** refers to the lack of completeness in a model as perceived by the user, who believes that completeness can be achieved. The user may request additional sensitivity analysis to ensure the ***robustness*** or completeness of the model. ***Extra-model unease*** refers to the lack of confidence the user has in the model, regardless of his belief in model completeness. If the model is incomplete, the user may turn to ***flexibility*** instead. However, even if the model is complete, the user may wish to retain ***flexibility*** as he may not wish to rely entirely on the model. In the latter case, robustness is no longer sufficient.

Because flexibility is not a free good (Stigler, 1939), there is no point being flexible or having flexibility if it is not needed or desired. [We use the word "useful" as opposed to "desirable" and "necessary", since the difference remains a research question.] This implies that uncertainty must be important or costly enough for the consideration of flexibility. ***Furthermore, there is a need to weigh the costs and benefits of flexibility, i.e. measuring flexibility***.

Flexibility can only be considered if there exists at least one other alternative other than status quo, i.e. staying in the present state or continuing with the present course of action. ***Means of operationalising flexibility are given in section 6.12.***

In table 6.4, we translate Mandelbaum's conditions under which flexibility is not useful to their converse, i.e. ***conditions under which flexibility is useful***, thereby showing that flexibility is useful to modelling uncertainty in electricity planning.

Table 6.4 Mandelbaum (1978)

When Flexibility is Not Useful (Mandelbaum, 1978)	***Why Flexibility is Useful for Electricity Planning*** (inferred from Mandelbaum, 1978)
A well modelled and solved problem	Presence of new types of uncertainties and inadequacies of existing techniques and modelling approaches.
The decision maker has enough faith in the model to implement results with little or no allowance for unexpected changes	Allowance for unexpected changes is made in the form of reserve margins or plants being built; even so this is very costly.
Learning is not expected (the value of flexibility depends on finding out more about what we do not already know)	Planning is a continuous process, with revisions to existing plants constantly being made as new information arises.
Delays are not possible or have a detrimental or negative impact	Regulatory delays are possible and sometimes inevitable.
Complex situation with multiple interested parties; changes are not desirable because lengthy debates are necessary	While limiting changes may reduce conflict of interest, it also reduces the responsiveness.
No uncertainty	Uncertainty prevails in many forms.

6.10 Downside of Flexibility

The literature on flexibility is dominated by discussions of its positive aspects, giving the illusion that it is always desirable. Little has been said about its downside. In this section, we identify the ***negative aspects*** of flexibility and those ***decision makers*** who do not desire flexibility.

The two-way relationship between flexibility and uncertainty suggests that there may exist an optimal level of flexibility, beyond which more flexibility is not useful. It also suggests that too much flexibility may be harmful. Too much flexibility, e.g. too many options, may complicate the analysis and confuse the decision maker.

The value of flexibility may follow the diminishing marginal return rule, i.e. the marginal benefit of an additional option decreases as the number of choices increases. ***To assess this, we need a method of measuring flexibility and trading off its costs and benefits.***

Postponing or delaying a decision could produce discomfort, the anxiety of waiting, or greater uncertainty. There are costs associated with continuous monitoring, waiting, acquiring more information, and the regret of expired options. There are also cost penalties to small unit sizes and shorter construction periods in the form of dis-economies of scale.

Gerwin (1993) notes that increasing (product) variety leads to complexity and confusion which in turn raises overhead costs. Technological developments may make existing flexible technology obsolete. Having flexibility makes one less careful to get it "right" the first time and thus may be more costly in the long run.

The close relationship between flexibility and uncertainty merely establishes that 1) flexibility is valuable when there is uncertainty, and 2) flexibility is a way of coping with uncertainty. ***There is no evidence that flexibility reduces uncertainty.*** In fact, thinking about flexibility, i.e. brainstorming and permuting the number of possible choices, may create more uncertainty for the decision maker.

Even though uncertainty is not necessarily undesirable, some decision makers seek to eliminate it completely. The ***intolerance of uncertainty*** motivates such decision makers into early or pre-commitment to get rid of uncertainty, hence flexibility altogether. The ***cautious decision maker*** may prefer fewer decision choices to avoid possible mistakes and heavy responsibility. The ***hesitant or indecisive individual*** may want less freedom of choice to avoid having to make decisions, i.e. he prefers not to have any difficult decisions to make, especially if many possibilities exist. Hence, even under conditions of uncertainty, not everyone desires flexibility.

6.11 Necessary Elements to Define Flexibility

Flexibility definitions as surveyed by Mandelbaum (1978) are all consistent. Flexibility reflects the ***potential*** (Slack, 1983) or the ***capability to respond to change***. Equivalently, it is the

- general capacity to deal effectively with the ***widest range*** of possibilities;
- ability to perform well both in the old state before a change and in the new state after the change;
- ability to ***switch*** from the first period position to a second period position at ***low cost***;
- set of ***remaining*** programmes after the initial choice has been made; and
- system's ability to perform ***different*** jobs that may occur or to perform one job under different environmental conditions.

We have described flexibility from a ***system's point of view*** as well as from a ***decision perspective***. These two ways of viewing flexibility are equivalent, i.e. inferring one another. Collingridge (1979) shows that a system which is easy to control can be seen as a sequential decision of high flexibility. The ease in control is a function of the number of options open to the decision maker. To keep one's options open is to invest in an easily controlled system. [In Chapter 7, we see that the systems and decision views of flexibility with respect to entropy are not equivalent.]

Common across different uses and classifications of flexibility are ***types of flexibility***, which are context-dependent, and ***elements of flexibility***, which are context-free. Types or kinds of flexibility relate to the conditions under which it is useful. We propose an ***uncertainty-flexibility mapping*** to identify types of flexibility. [This is clarified and applied in Chapter 7.] For example, volume flexibility addresses demand uncertainty. Types of flexibility have been defined and used in manufacturing where it has received the most attention. It is not necessary to have different types of flexibility to use the concept. However, any discussion of flexibility should include the essential definitional elements, which many authors have proposed as seen below.

Eppink (1978) identifies three dimensions of flexibility (***types***, ***aspects***, and ***components***) that are not independent of each other and to-date only apply to an organisational context.

Slack (1988) gives ***range*** and ***response*** dimensions for each type of flexibility he defines. Range refers to the ability to adopt different states, while response refers to the ability to move between states. In an earlier paper, Slack (1983) gives the dimensions of ***range*** and ***ease***, where ease is the cost and time to make the change. Cost and time are frictional elements to do with the difficulty of changing.

Gerwin (1993) stipulates three necessary elements in defining flexibility: ***range***, ***time***, and ***discretion***. We interpret these as follows. Discretion refers to the ability and potential (and willingness) to change or fill a gap. Range refers to the number and diversity of choices available. Time refers to responsiveness, lead time, and time to change.

In addition to ***range*** and ***time***, Schneeweiss and Kühn (1990) add five more elements: ***goal***, ***objective*** (relates to condition), ***stochastic*** and not deterministic (uncertainty), evaluation of ***elasticity***, and the ***possibility to plan*** for it. They assert that elasticity is a partial aspect of flexibility.

The above elements of flexibility are closely related to Kogut and Kulatilaka's (1994) three conditions under which options are valuable: ***uncertainty***, ***time dependence***, and ***discretion*** (the ability to exercise and change.) Decisions depend on time, and the value of flexibility comes from investing in the capability to respond favourably to uncertain future events.

In sum, five elements appear necessary to define flexibility.

1) Flexibility conveys a ***change***, usually in the future tense, i.e. a potential. This is implied by the transition between two states, choosing between alternatives, barriers to change, and switching cost.

2) Flexibility denotes more than one way of responding to change, hence the notion of ***range***. Range includes the ***size of choice set***, number of alternatives, the extent to which demand can be met, and levels of change.

3) Flexibility is different from gradual change. The ***time*** element is very important here, as typically we speak of a "rapid" response. Time includes responsiveness, lead time, and time to change.

4) The fourth element relates to the ***conditions*** posed in the previous section, i.e. existence of ***uncertainty*** and ***alternatives or strategies*** for the consideration of flexibility.

5) Inherent in the concept of flexibility is the notion of ***favourability*** which differentiates between the choices available. Favourability has not been addressed in the literature at all. It deserves a separate further discussion as some measures give attention only to this aspect of flexibility.

6.12 The Concept of Favourability

The concept of favourability reflects the value or benefits of change. These are the positive values associated with acquiring and realising the flexibility. Favourability is what makes flexibility desirable. We move from an initial position to a new position to take advantage of the new situation and get a better outcome. We move to a new position to avoid or minimise a bad outcome, such as the loss of revenue or incurring higher costs or not being able to get out of the situation. If there are several states we can move to, we will move to the one that gives the most benefit. Similarly, the choice we select in the second stage will be the one which gives the best outcome.

Favourability refers to the decision rule of value optimisation such as cost minimisation or revenue maximisation. Mandelbaum and Buzacott (1990) observe that flexibility and favourability are two separate decision criteria, requiring a trade-off between the ***number of choices*** and ***expected value***. They suggest either to satisfice on one attribute and optimise on the other or to determine a utility function over the two attributes and then optimise on it. In the latter case, the kind of utility function depends on the underlying probability. If the probability distribution of the uncertainty is uniform, the utility function is additive on the value function and flexibility (number of choices). If the underlying probability distribution is exponential, the utility function is multiplicative. In the former case, Heimann and Lusk (1976) give a treatment of satisficing on value but maximising on flexibility.

In summary**, *favourability is that aspect of flexibility which relates to value optimisation***. Besides this, the multi-faceted concept of flexibility contains other aspects, e.g. the ability to change, number of choices, and responsiveness, which may conflict with favourability.

6.13 Operationalising Flexibility

The conceptual development of flexibility provides a unifying theoretical basis for its application. The operationalisation of flexibility refers to practical means of introducing or increasing flexibility into a system, in planning, or in decision making.

We propose a distinction between two types of operationalisations, namely 1) ***options,*** which provide flexibility, exhibit characteristics of flexibility, or lead to more options in the future; and 2) ***strategies***, which preserve, introduce, or increase flexibility as courses of action. Short lead time, modular, and small unit technologies promote flexibility by faster responsiveness, incremental additions, and limited commitment. Technical means of achieving system flexibility are listed in CIGRE (1991). Hobbs et al (1994) and Hirst (1989) give examples of operationalising flexibility by such technological options. Strategies for increasing flexibility include selecting a portfolio that contains flexible elements (Hirst, 1990), Hart's (1937) ways to preserve flexibility as summarised below, SCE's (1992) scenario planning approach mentioned in Chapter 5, and Mandelbaum's (1978) sources of flexibility and other strategies described below.

Hart (1937) advises of several ways to preserve flexibility: holding inventory to avoid uncertainty, deferring decisions until more information arrives, offsetting uncertainties through a diversified portfolio, and eliminating uncertainty by purchasing futures contracts and insurance.

MANDELBAUM'S SOURCES OF FLEXIBILITY

Mandelbaum (1978) suggested six different ways to provide or increase flexibility. These sources of flexibility have also been suggested and confirmed by others such as Eppink (1978), Gustavsson (1984), and Collingridge and James (1991).

1) ***Sequentiality*** or ***staging*** limits the irreversibility of changes by dividing a decision into a sequence of decisions thus limiting the responsibility or commitment of each act. Limited commitment keeps options open and retains flexibility. Those decisions that do not need to be made immediately can be postponed. The planning process is made more frequent and decisions made more informed while simultaneously limiting the kinds of power plants committed. Legal contracts containing break clauses are more valuable for expensive capital investments than a totally irreversible signed and sealed agreement.

2) ***Partitioning*** the action space, resources, or opportunities as time proceeds not only enlarges the choice set but also allows more elements (members of the choice set) to move freely. By dividing what seems like one capacity size decision into several decision variables, we have more control over each unit. Partitioning also gives the ability to decide sequentially. In the power industry, modular and small unit sized combined cycle gas turbine plants exemplify this kind of flexibility as they can be built incrementally. Gustavsson (1984) supports the use of standardised modular components to increase flexibility design of products and systems. Standardisation improves economy while modularity increases flexibility by the allowance of different combinations of sizes and types of technology as well as incremental additions.

3) ***Postponement*** of action gives time and opportunity to obtain more information, for uncertainties to be resolved, and new options to open up and be developed simultaneously, such as the use of temporary arrangements. This delay is not usually free, neither is the additional information free, hence the value of this information must be worth the delay. Paying a premium for the option to delay, building reserves as in uncommitted funds (thereby enlarging the choice set), etc, are all examples of postponement.

4) ***Searching*** for additional actions is a way to enlarge the choice set. One definition of flexibility is the number and variety of choices available. Option-generating techniques as described in Keller and Ho (1988) assist in the search for more solutions to a problem. This is based on the rationale that the more choices available, the more and different types of futures (uncertainties) can be met.

5) ***Reducing the resistance to change*** makes it easier and cheaper to change. This is accomplished by removing or relaxing constraints as well as lowering the cost of change. Together with the fourth source, this strategy enables decisions to be made more frequently while increasing the number and quality of options available at each point. The removal of technological barriers results in the development and availability of new plants. Removing constraints enlarges the choice set. This is equivalent to reducing lead times, cost of changing, and other barriers to change, i.e. disablers.

6) Diversity, as Mandelbaum's sixth source of flexibility, encompasses two notions of ***variety*** and ***tolerance***. They increase the bearing capacity of a system, thereby meeting a broader spectrum of needs. Variety is akin to risk diversification or

having a balance of technologies. Tolerance is a way of increasing state flexibility, i.e. catering to many. Generating companies typically have a good mix of technologies by type and capacity size and timing (commission and retirement dates).

These six sources of flexibility are closely linked to the five criteria proposed by Collingridge and James (1991) for increasing flexibility in policy making. These criteria collectively ***reduce the time horizons of decisions, diminish their sensitivity to individual variables***, ***and increase organisational recognition of uncertainty***.

1) The first criterion is called ***incrementalism***, as incremental development strategies translate to small commitments in stages.

2) ***Maximum substitutability*** reduces the sensitivity of decisions to individual variables.

3) ***Maximum diversity*** decreases the dependence on any fuel, hence lowering risk.

4) ***Sophisticated monitoring and appraisal*** give more information and increase responsiveness and control.

5) The final criterion suggests sophisticated ***contingency planning*** to avoid panic responses.

Likewise, Eppink (1978) offers two ways to respond to uncertainty, equivalent to two ways to increase flexibility.

1) ***Reducing the relative impact of external changes*** makes oneself less vulnerable. For example, multi-product firms with highly diversified portfolios exhibit high external flexibility or robustness.

2) ***Increasing its response capacity*** is achieved by enhancing logistic flexibility or action flexibility. This is exemplified by early warning systems, e.g. the provision of information, multi-purpose equipment, and smaller units.

In the electricity context, Yamazee and Hashimmashhadi (1984) suggest four ways to achieve flexibility, paralleling ways to reduce uncertainty.

1) ***Shortening the lead time*** to acquire a resource or plant reduces the uncertainties surrounding future conditions.

2) ***Lowering capital costs*** limits fixed financial commitment. This re-iterates Stigler's (1939) view of flexibility as the transfer of costs and resources from the fixed to the variable.

3) ***Reducing resource sizes*** lessens the risk (and commitment).

4) ***Allowing interim or intermediate decisions*** reduces the size of investments.

6.14 Conclusions

We have answered the questions raised in chapters 4 and 5 by conceptual development.

1) First, we summarised the meaning of flexibility as elicited from an analysis of similar words. Flexibility is ***the ability to easily respond to unforeseen changes in a variety of ways.*** This definition of flexibility is later validated by the conceptual framework.

2) Second, we examined its relationships with more established concepts and developed a ***conceptual framework***.

   a) We identified two types of flexibility (passive and active) and clarified the distinction between ***flexibility and robustness***.

   b) We discussed its role as a preferred ***decision criterion*** under conditions of uncertainty. This was briefly posed in Chapter 4.

   c) We established by transitive argument the following relationships:

   • ***robustness as minimising risk and regret***

• ***lack of confidence leads to less commitment and more flexibility***.

d) We noted the concepts of flexibiltiy and robustness as embedded in the definition of a financial option: the ***right but not the obligation***.

e) We emphasized the important relationship between ***uncertainty and flexibility***.

3) That uncertainty makes flexibility valuable translates into ***conditions under which flexibility is useful***. We identified and distinguished between ***intra*** and ***extra-model unease*** which can be met by robustness and flexibility considerations.

4) Even with uncertainty, flexibility may not necessarily be desirable. We discussed the ***downside*** of flexibility, which has not received enough attention in the literature.

5) To preserve the multi-faceted meaning of flexibility, we identified necessary elements in its definition, rather than giving a single formal definition. These five elements are ***change***, ***range***, ***time***, ***uncertainty conditions***, and ***favourability***.

6) Finally, we proposed that flexibility may be operationalised via ***options*** or ***strategies*** and gave examples of how this may be achieved.

This conceptual development has unified and clarified the definitions and applications of flexibility from the cross disciplinary review. To make use of this conceptual framework, a utility in the UK ESI must be able to operationalise and, perhaps even, measure flexibility. Measures may be needed to defend plans, make comparisons between different strategies, and trade off conflicting objectives. In the next chapter, we give a rigorous assessment of three groups of measures which emerge as most popular and most promising from our cross disciplinary review.