A Survey of State-of-the-Art Methodologies and a Framework for Identifying and Valuing Flexible Design Opportunities in Engineering Systems

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Abstract

Flexibility in design increases the expected value of an engineering system, as demonstrated by numerous case studies. By adapting flexibly to uncertain events, operators capture additional value when upside opportunities occur (e.g. demand or price is higher than expected), and reduce losses in case of downturns. Very often engineers work to satisfy fixed design requirements based on analysts' forecasts of uncertain variables affecting value. If reality is more favorable than projected, the system may not capture additional benefits from uncertainty. In reverse, it may suffer big losses during downsides. Flexibility is the main tool to deal with uncertainty; it captures upside opportunities, and protects from downside events, thus its importance for design. Explicit considerations of flexibility lead to more informed, and thus better investment decisions.

This paper surveys existing state-of-the-art methodologies for identifying and valuing flexible design opportunities in complex systems. It emerges from the observation that several analytical methods exist to identify and value technical sources of flexibility. The current state of the field is however not clear on which methods are best suited depending on the design problem at hand, the system under study, and other contextual elements such as the economic sector, the uncertainty types, audience, etc. Different problems may require different methods to add value through flexibility, hence the need to organize the field in a coherent whole for real-world practitioners.

The paper paves the way to the development of a framework to choose appropriate analytical tools to identify and value flexible design opportunities, depending on the engineering system under consideration. The proposed framework is to be developed through applications of existing methods to real-world case studies in various industries.

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1 Introduction

Standard methods for designing complex systems often rely on requirements that come from a deterministic view of the environment in which the system operates. This approach is recurrent in several industries, including mining, real estate, aerospace, oil and automotive. Typically, no attempt is made prior to operations to recognize uncertainty and to factor it in the design process. Technical design requirements are based on projections of exogenous factor(s) affecting system value and performance, such as price or demand for a product, regulations, etc. This approach often results in suboptimal design choices and appraisal of value.

Flexibility is an important attribute for the design of systems operating under uncertain conditions. It provides "the right, but not the obligation" to modify a system in operations to adapt it to its changing environment. Ross et al. (2008) present this notion as a subset of the broader concept of "changeability". Flexibility is characterized as the change incurred in a system due to the influence of a change agent external to the system.

One benefit of a flexible system is to create value to its owner (e.g. operator, shareholder). A flexible system can take advantage of unexpected upside opportunities, and/or reduce exposure to downside risks. Recognizing flexibility in the value appraisal process also provides more information to enable better decisions on the appropriate threshold for investment. The value provided by flexibility can be significant for systems operating over long time scales, involving large investments, and facing substantial market, technological, and/or corporate risks. Several case studies in the mining, management, real estate, aerospace, manufacturing, energy production, automotive, and hydroelectric industries have shown that flexible engineering design can improve value significantly (Billington et al., 2002; Cardin et al., 2008; Chiara and Garvin, 2007; de Neufville, 2006; de Weck et al., 2004; Hauser and de Weck, 2006; Joppin and Hastings, 2003; Kalligeros and de Weck, 2004; Kalligeros, 2006; Kulatilaka and Marcus, 1992; Nembhard et al., 2005, 2006; Savva and Scholtes, 2006; Suh, 2005; Zhao and Tseng, 2003).

There are two ways of exploiting flexibility in engineering systems: "in" and "on" systems (de Neufville, 2002). Flexibility "in" systems exploits technical aspects of the design to make the system adaptable to its environment. A physical component enabling flexibility "in" the system is referred to as a Flexible Design Opportunity (FDO) in this paper. It may exist or be incorporated on purpose within the physical components of the system. It requires inputs from designers and engineers and leads to a different technical design than an original, inflexible one. For example, the capacity to redeploy telecommunication satellite constellations on different orbits and at different elevation angles is a source of flexibility that needs to be factored "in" the system explicitly prior to operations. FDOs "in" systems are the focus of this paper.

In contrast, flexibility "on" systems relates to management decisions that affect the system as a whole without necessarily modifying technical design components. For example, the flexibility to abandon a real estate project between two phases is a source of flexibility "on" the system that does not require prior technical inputs.

The study of flexibility "in" design typically requires 1) the identification of sources of flexibility and 2) an appraisal mechanism to value them. The latter is necessary to discriminate between possible sources of flexibility that are most beneficial. This is also because flexibility typically requires an additional upfront cost which needs to be justified to owner, senior managers, and operators of the system. The appraisal mechanism is important to determine how much value the flexible design adds in comparison to an inflexible design, given similar uncertain future scenarios. As long as the appraised value is higher than the cost of acquiring the flexibility, it is beneficial to incorporate it in the design.

Sources of flexibility "on" systems are well defined in the literature. Their valuation is done using methods based on Real Options Analysis (ROA). Examples of flexibility "on" project from Dixit and Pindyck (1994) and Trigeorgis (1996), are temporary or complete abandonment of a system, possible reactivation, investment deferral to collect more information about uncertainty, sequential or multistage deployment of assets to scale development to the evolution of uncertainty, and production expansion and reduction. Borison (2005a) presents a review of different "classical" ROA tools available to value flexibility "on" projects.

In contrast, there is no well-defined set of sources of flexibility "in" complex systems. This is because every system is different. Each system is unique and it is the role of the designer to identify sources of flexibility and choose, based on valuation and value requirements, which ones are most relevant.

Over the last five years, several methods have been developed to address the important problems of identifying and valuing FDOs "in" system. It may however not be clear to practitioners when it is appropriate to use one method over another, depending on the type of system being designed, the kind of source of uncertainty affecting its value, the context under which it is designed, etc. This is because some methods are better suited for certain types of design problems and systems. There is currently no holistic view of the different methods available that outline their strengths and weaknesses, and when it is advisable to use one method over another.

The paper aims at reviewing the current state-of-the-art in existing methodologies for identifying and valuing sources of flexibility "in" complex systems. It also purports to organize these methods in a manner that is coherent and useful to practitioners. It is complementary to the series of papers initiated by Borison (2005a) to discuss and organize the current state-of-the-art in terms of valuation tools for flexibility "on" systems (see also Borison (2005b), Copeland and Antikarov (2005), as well as Kretzschmar and Moles (2006) for more details on this insightful debate). Instead of focusing on the valuation aspect of flexibility "on" system as done by these authors, it is concerned with describing and organizing the tools that exist to determine where and how valuable flexibility can be implemented in a system, from an engineering design perspective. It paves the way for future research on a structured framework for guiding the choice of appropriate analytical tool depending on the kind of system under design.

The remainder of the paper is organized as follows. Section 0 and Section 0 present a review and classification of existing methods to identify and value sources of flexibility "in" systems. Section 0 compares the different methods, discusses and contrasts their benefits and drawbacks.

It opens up on the next logical step, which is to develop a framework for guiding the choice of appropriate method to identify and value FDOs "in" systems, supported by relevant case studies.

2 Methods for Identifying Flexible Design Opportunities "In" Systems

This section presents and classifies existing state-of-the-art methodologies for identifying flexible design opportunities "in" complex systems. Examples of how each methodology can be applied are provided in the Appendix section.

2.1 Interview Method

The most basic approach to identify FDOs is through interview of subject matter experts (SME). SMEs are expert engineers, managers, or operators of the system. As suggested by Shah (2008), interviews with SMEs can help determine the change that might occur to a system design as a result of a change in exogenous factor scenarios. Qualitative research methods are appropriate for interviewing experts to reduce bias in the interview process (Silbey, 2003). Methods developed by Bartolomei (2007), Kalligeros (2006), and Suh (2005) presented below incorporate interview methods to build a representation of the system and its intricacies.

2.2 Information-Flow Methods

The first category of methodologies is based on a codified representation of the system design. It shows the various design components, stakeholders, and/or users of the system and the interconnections between them. In essence, the three methods presented here aim at representing the flow of information between different components of the system. FDOs are identified using observed properties of this information flow.

2.2.1 Change Propagation Analysis (CPA)

The CPA method measures how changes in design components propagates through a system. It uses a network graph or Design Structure Matrix (DSM) to represent the system, its components, their interconnections, and how information flows between them. For a particular design component i, CPI_i (Change Propagation Index) expresses the difference between the amount of change information ΔE_{in} propagating "in" a component from components connected upstream, and the amount of change ΔE_{out} propagating "out" to other downstream components. For a system with n components, this relationship is expressed as:

$$\text{CPI}_i = \sum_{j=1}^{n} \Delta E_{j,i} - \sum_{k=1}^{n} \Delta E_{i,k} = \Delta E_{out,i-} - \Delta E_{in,i}$$

Based on the terminology developed by Eckert et al. (2004), a system component that receives more change than it creates is called an *absorber* (CPI < 0). A component that receives the same amount of change as it creates is called a *carrier* (CPI = 0). One creating more change to downstream components than it receives is called a *multiplier* (CPI > 0).

Suh et al. (2007) argue that change multipliers are prime candidates for incorporating flexibility in an engineering system. The more these components are changed, the more changes are propagated to the system, the harder it becomes to change the system as a whole, and the higher the total switching cost. Flexibility can be incorporated as a "buffer" component to reduce the number of components affected by the change, or the amount by which such components need to be changed, and their associated costs.

Carrier components are also important. It is worth determining which carrier components receive and transmit what amount of change. For example, a component receiving change information from five components and transmitting to five others might be more expensive to change as a whole than a multiplier component receiving change from one source and propagating to two or more components.

The switching cost of a component (K_i) is useful to determine whether it is worth incorporating flexibility in a particular area of the system. The higher the switching cost, the more it is worth designing a flexible component to lower the cost of changing that component.

Giffin et al. (2007) propose a variation to the change propagation method presented above. The *normalized CPI* shows normalized levels of change multiplication and absorption between different components of the system. It allows better comparison between these elements for the impact and propagation of design change.

The normalized CPI depicts the degree of propagation from component *i* to *j* of a system as a value between -1 and 1. Change absorbers, constant, and multipliers correspond respectively to $-1 \leq CPI < 0$, $CPI = 0$, and $0 < CPI \leq 1$. If $C_{in}(i)$ represents the total change affecting component *i*, and $C_{out}(i)$ the sum of all changes originating from this component, the normalized CPI is expressed as:

$$CPI(i) = \frac{C_{out}(i) - C_{in}(i)}{C_{out}(i) + C_{in}(i)}$$

2.2.2 Sensitivity DSM

The method based on sensitivity Design Structure Matrix (sDSM) uses a different paradigm to explore FDOs in engineering systems: platforms. This method explores components of a systems design that are kept unchanged in the DSM representation of the system from one design variant to another. Such components are called *standard* components. The assembly of *standard* components constitutes a platform from which variant designs can be created. For example in the automotive industry, elements of a car body can be used as the standard components for a variety of car models (or variants), differentiated by the power of the engine, thickness and quality of material used, optional equipment, and transmission type.

Flexibility can be introduced in platforms to ease transitions between variants of a system. This may reduce the switching cost between such variants. For instance, the body of a car can be designed such that engines of various sizes and power can be installed to accommodate different car models.

A sDSM expresses the sensitivity of design variables and functional requirements of a system to changes in other design variables and functional requirements. Design variables that are insensitive to changes in design variables and functional requirements are potential platform components. Those that are most sensitive are potential sources of flexibility. Here, a functional requirement is defined as the requirement that a system must fulfill, given the particular function or purpose that the system serves. Exogenous factors determine the functional requirements of a system, which determines how the system is designed. For instance, the smoothness of a road, one exogenous factor to the automobile designer, may affect how the suspension of the car reacts. An example of functional requirement is to require a certain level of suspension softness to deal with uncertainty in road smoothness. This requirement affects design choice, and is reflected through the set of design variables chosen.

2.2.3 Engineering Systems Matrix (ESM)

One drawback in Suh's and Kalligeros' approaches is that no consideration is made of the social, managerial, and environmental domains in the search for potential sources of flexibility. In these methods, the focus is devoted to the technical domain of the system.

Bartolomei (2007) presents the Engineering System Matrix (ESM) as an analytical tool to represent the engineering system and its socio-technical intricacies. The ESM is an improvement to existing system-level modeling frameworks, like traditional DSM, because it provides a dynamic, end-to-end representation of an engineering system. It considers the social, environmental, and managerial aspects through addition of system drivers and stakeholders DSMs.

The methodology incorporates the CPA and sDSM approaches into a unified framework to identify FDOs in engineering systems. In addition, it takes into consideration the human, managerial, and environmental aspects in the representation of the engineering system. These aspects are important in analyzing a system for potential sources of flexibility.

2.3 Screening Methods

Screening methods have been used for decades to explore the design space for valuable system configurations. They differ from one another in the level of complexity of the model used, and the type of search algorithm for exploring the design space. They typically trade-off model details for accelerated analysis of different design instances. Early examples are found in Jacoby and Loucks (1972), as well as de Neufville and Marks (1974).

Screening methods have been applied recently to explore the design space for valuable flexible design configurations. They rely on a model that incorporates a set of known FDOs found for instance by applying interview or information-flow methods. The methods described here use some of the valuation methods described in Section 0.

2.3.1 Optimization-Based

The approach proposed by Wang (2005) uses screening methods based on optimization to identify FDOs. It selects a set of representative scenarios of the exogenous factors (e.g. price or demand for product), and a set of possible designs by combining available design variables on a low-fidelity model (i.e. less detailed) of the system. It “screens” the different designs using various combinations of design variables to find the configuration that maximizes value under physical and budgetary constraints.

2.3.2 Approximation-Based

The methodology proposed by Cardin (2007) speeds up the analytical process to explore the design space in a way that differs from that proposed by Wang (2005). It does so by selecting a limited set of representative scenarios of uncertainty, and by limiting the number of possible design configurations to explore. The method is complementary to Wang’s approach since it applies to detailed system models. It explores different facets of the design problem to improve analytical speed while remaining transparent and intuitive to real-world practitioners. The method is particularly useful when the model requires much computational resources and takes a long time to run a single analysis given a particular exogenous factor scenario (e.g. demand, price).

3 Methods for Valuing Flexible Design Opportunities “In” Systems

The identification of FDOs often requires the use of an appraisal mechanism to determine which flexible elements are most valuable for insertion into the system design. Various appraisal methods exist to value sources of flexibility both “in” and “on” systems. This section reviews appraisal mechanisms most useful to value flexibility “in” system, with a particular focus on application to engineering. An example application of the methods is provided in the Appendix section.

3.1 Decision-Tree Methods

The two methods presented here rely on a structure akin to decision trees. One structural feature differentiating the methods is that decision analysis (DA) and the enumerative technique consider all branches in the tree, while binomial lattice reduces the combinatorial space by assuming path independence and path recombination.

3.1.1 Decision Analysis

In decision analysis, the analyst creates a structure similar to a tree to represent possible scenarios of uncertainty and associated decisions that occur as time evolves (Figure 8). The structure is typically built in sequence of one decision node, representing available decisions, followed by a chance node to represent possible uncertain outcomes with assigned probabilities. Each path terminates with a value associated with the scenario and decisions undertaken. In this framework, the value of flexibility is found by comparing the expected value of the decision path where the flexible system is used with the expected value of another path without flexibility.

3.1.2 Binomial Lattice

A binomial Lattice can be viewed as a decision-tree similar to those used in decision analysis (DA). In the case of a lattice, the world can be in either of two possible states in each time period: up or down. For each time period, or node of the lattice, a decision can be made to exercise or not the flexibility under consideration. To reduce the number of possible paths, path independence (or recombination) is assumed. This means the value of the system after an "up-down" sequence is the same as that after a "down-up" sequence. Mixed with another analytical tool called dynamic programming, lattice analysis is used to assess the value of flexibility.

The valuation of flexibility relies on the idea that markets are highly efficient and asset price is based on equilibrium between supply and demand. Hence, there is no opportunity for arbitrage, or for risk-free profit opportunities. The logic is that a new flexible project can be valued using the market valuation of stocks of a comparable company in a similar industry, and the valuation of a debt instrument with stable cash flows (e.g. bond). A replicating portfolio of stocks and bonds can always reproduce the projected cash flows of the flexible project, and therefore at equilibrium in the market, both the project and replicating portfolios should be priced the same. The unique value of the flexibility obtained with this method is thus valid from an economic standpoint. It incorporates the risk inherent to the project and appropriate pricing of the asset due to market equilibrium requirement of no-arbitrage opportunities.

The binomial lattice is particularly useful when valuing sources of flexibility "in" and "on" systems that are similar to call options (capacity expansion, or phasing, investment deferral) or put options (abandonment, temporary shutdown). It is essentially a discrete binomial formulation of the Black-Scholes (BS) formula (Black and Scholes, 1973) used to value financial options. Because of its discrete structure, it offers more flexibility for analysis than the BS formula. This is why it has been used in engineering and management as a valuation tools for flexible projects.

A good review of methods based on "classical" real options analysis and involving the binomial lattice (and others) is presented in Borison (2005a). The reader should also consider seminal work by Dixit and Pindyck (1994), Luenberger (1997), Schwartz and Trigeorgis (2001), and Trigeorgis (1995, 1996) for a deeper understanding of classical real options analysis methods.

3.1.3 Enumerative Technique

The valuation method presented by Wang (2005) explores one of the fundamental assumptions of the binomial lattice: path independency. One issue in applying a binomial lattice to a real engineering project is that path independence may not apply. Committing to a particular design in operations may not be reversible. Therefore, a sequence of states of exogenous factors "up-down" may not lead to the same decisions, designs, and value than if a "down-up" sequence occurs.

The method uses stochastic mixed-integer programming optimization to value flexibility "in" system where path-dependency is actually significant and needs to be considered explicitly. Therefore, even if more complex than binomial lattice, this approach can apply to all systems to value flexibility "in" system.

3.2 Design Transitions Method

Silver and de Weck (2007) present another alternative for valuing flexibility "in" systems. Their approach aims at finding the design, or sets of design, that minimizes lifecycle cost (LCC) under various scenarios of uncertainty. Under a particular scenario of uncertainty, all possible design transitions between different design variants are explored.

A Time-expanded Decision Network (TDN) displays all the possible transitions that may occur between one of the designs to another. A shortest-path minimization algorithm explores all possible design transitions to find the set of transitions (or switches) that minimize LCC. Note that revenues can be added to their model to consider value metrics like profits and net present value (NPV). With this information, designers can investigate how flexibility can be incorporated to ease transition between designs where switches occur most frequently. This flexibility potentially lowers switching cost, and adds value to the system.

3.3 Simulations Method

de Neufville et al. (2006) suggest an approach for valuing flexibility based on Monte Carlo simulations. In order to provide transparency to practitioners, the method typically involves three steps. First, the analyst performs a standard discounted cash flow (DCF) analysis on an inflexible system design (i.e. ignoring flexibility) using deterministic projections of the exogenous factor(s) affecting value. Second, a stochastic process is incorporated to simulate exogenous factor fluctuations over the project lifetime. Several stochastic scenarios are simulated, and a DCF analysis is performed on the inflexible system for each scenario. This Monte Carlo approach provides a distribution of possible value outcomes measured using a financial metric like NPV. Third, flexibility is incorporated in the DCF valuation tool using simple spreadsheet programming and logical statements (e.g. `if, else,` etc.). Under each stochastic scenario, the spreadsheet computes a NPV under the flexible design and managerial rules incorporated in the model. This third step also creates a distribution of NPV, one upon which the designer may act. The goal is to act on desirable properties of the entire distribution to take advantage of upside opportunities and reduce possible downsides.

4 Discussion

This section presents a summary of the different analytical tools available for identifying and valuing FDOs. It lists and describes a set of potential criteria to guide the choice of analytical tools depending on the system under study. It also proposes a research approach to develop a prescriptive framework, supported by case studies, to help real-world practitioners in their choice of appropriate tools.

A summary of the methods is shown in Table I. Benefits and drawbacks from each method are described in Table II and Table III. Each column should be read separately (i.e. a row does not list directly opposing benefits and drawbacks).

Table I: Summary of existing state-of-the-art methodologies for identifying and valuing flexible design opportunities "in" complex systems.

Methods for Identifying Flexible Design Opportunities	**Methods for Valuing Flexible Design Opportunities**
Interview	Decision-Tree (Decision Analysis, Binomial Lattice, Enumerative Technique)
Information Flow (Change Propagation Analysis, Sensitivity DSM, Engineering System Matrix)	Design Transition
Screening (Optimization, Approximation)	Simulations

Table II: Benefits and drawbacks of existing methodologies for identifying flexible design opportunities "in" complex systems.

Methods for Identifying FDOs	**Benefits**	**Drawbacks**
Interview	Basic and intuitive approach to familiarize with system	Information needs to be translated in a medium suitable for analysis and design (e.g. DSM, ESM)
	Good starting point for building a DSM in information-flow methods	Requires knowledge of qualitative research methods for unbiased interview accounts
Information Flow	Allow thorough analysis of the system to identify FDOs and standard components "in" system	Applied so far to platform development; not clear how to use on systems that require more frequent adaptations in operations
	Consider technical components through CPA and sDSM, managerial, and environmental components through ESM	Do not consider optimal conditions for exercise by operator, only look at the design representation (e.g. DSM, ESM)
	Provide good representation of the system and interconnections between components	Restricted to technically trained audience
Screening	Approximation methods transparent and intuitive to practitioners	Approximation method does not guarantee the optimal design solution is found
	Consider optimal exercise conditions in exploring the design space for worthy FDOs	Difficult to find the appropriate set of representative exogenous factor scenarios
	Provide computationally efficient way of exploring the design space for valuable design configurations	Optimization method restricted to technically trained audience

Table III: Benefits and drawbacks of existing methodologies for valuing flexible design opportunities "in" complex systems.

Methods for Valuing FDOs	Benefits	Drawbacks
Decision-Tree	Binomial lattice is useful for progressive sources of uncertainty (e.g. price, demand, market value, etc.)	Assumptions required for economic valuation may not hold in an engineering context (e.g. markets for trading the asset, path independence)
	Binomial lattice reduces the combinatorial problem of multiple exogenous factor states to a computationally tractable one by using path recombination and assuming path independence	Binomial lattice requires good understanding of economic options theory
	Binomial lattice provides probability and discount rate supported by economic theory, historical growth rate, and volatility (i.e. no arbitrary choice as in DA)	DA may not reflect well changes in risk profile (i.e. use same discount rate and probabilities for entire analysis)
	Binomial lattice and enumerative technique may provide true economic value of flexibility, one value accounting for risk and required return from investor	DA and enumerative technique trees may become difficult to handle with many states of exogenous factor (i.e. "messy bush")
	Enumerative technique is more appropriate to handle path dependent problems, often faced in real engineering design	Do not handle well more than one source of uncertainty
	DA is useful when there is a sudden change in uncertainty, creating a "jump" process (e.g. change in regulation, etc.)	
	Look explicitly at possible states of exogenous factor scenarios to investigate the best managerial decisions	
Design Transitions	A vast array of design and management decision rules can be implemented	Does not provide economically rigorous valuation of flexibility based on market equilibrium between supply and demand
	May represent switch between management decision rules occurring in real operations, in the valuation process	May be difficult to implement
	May treat several sources of uncertainty at once	Provides a distribution of possible values, hence no one clear metric for decision-making (e.g. mean NPV, maximum, minimum NPV, etc.). Choice depends on decision-maker's utility function
	May isolate the value of flexibility for decision-making	Restricted to technically trained audience
	No deep knowledge of economic, finance, or real optional analysis required	
	Runs on standard computers	
	Useful as an aid for designing and programming systems	
Simulations	More transparent for less technically trained audience	Other same disadvantages as design transitions, but not difficult to implement, and not restricted to technically trained audience
	Other same advantages as design transitions	

4.1 Guidance Criteria

It is the main argument of this paper that the choice of appropriate identification and valuation methods is greatly dependent on the system under study. As seen in Table II and Table III, each method has benefits and drawbacks. The methods are therefore not all equally efficient at dealing with all possible design problems. The criteria below are suggested to guide the choice of analytical tool depending on the system under study.

These guidance criteria can be used as the basis for matching a given system to its most appropriate analytical tools. They can be used to characterize a system, and each analytical method described above. Therefore, good matching between a system and the analytical tools based on these criteria should constitute an appropriate framework for choosing analytical tools depending on the system at hand. The guiding criteria are summarized as follows:

Main area of flexibility

The main area of flexibility of a system is based on the type of future activity it is involved in. This characterizes the kind of FDO that should be sought for, and thus the type of appropriate analytical tool. Such type can be based more on "operations" or on the "physical structure" of the system. For example, a mining system can exploit flexibility in operations, by varying the size of truck fleets, the routes, and the size of crushing mills used to exploit different areas of the mine. Similarly, an airline has a lot of flexibility in the choice of routes and destinations it exploits. In contrast, designing a flexible car platform so it can produce different vehicle variants might involve more work at the design level. In the former case, flexibility is available more in operations, while in the second case flexibility is available more in how the physical system is conceidve. Of course, both examples may involve some level of operations-based and design-based flexibility. The purpose of this criterion is to determine the main area of flexibility by looking at the overall purpose of the system.

Frequency of exercise

The frequency of exercise refers to the expected rate of possible exercise phases of the flexibility, which can be either "frequent" or "infrequent". The expected number of exercises over a given time period might affect the choice of analytical tool.

Intended audience

The intended audience is important in choosing an appropriate analytical tool for flexible design. The ultimate goal of the analytical process is to communicate design ideas that aim at improving the expected value of the system. This communication has to occur not only between designers and engineers, but also between different levels of the decision-making process. It may not be appropriate to use highly technical tools whenever communicating to an audience with no commensurate training. Similarly, using simple analytical tools may not extract all the potential of a highly qualified engineering design team. This criterion also encompasses the context under which the system is developed. Development of a system in the private sector might have different objectives than in the public sector, or even under a public-private partnership.

Therefore, a system or analytical tool can be characterized as being geared more for a "technical" or "non-technical" audience.

Intensity of lifecycle cost

The intensity of lifecycle cost (LCC) expresses the amount of capital expenditures required throughout the lifecycle of the system. This can be initial research and development cost, fixed and recurring operating costs, retirement cost, and cost of acquiring the flexibility. The LCC determines the level of details required in the analysis of the system. Presumably, the higher the LCC, the more investors are interested in a detailed analysis of the system. Therefore, "high" and "low" LCCs are used to determine the LCC intensity.

Nature of the uncertainty

The nature of the exogenous factor affecting value and performance also plays an important role in the choice of analytical tools. Some tools are more appropriate for progressive sources of uncertainty that evolve slowly in time (e.g. price, demand, market value, etc.). Some tools are more appropriate for drastic changes in exogenous factors (e.g. regulatory change, natural catastrophe), characterized by a sudden jump process. The nature of the uncertainty is thus characterized as either "progressive" or "drastic".

Table IV summarizes the guidance criteria and classification characteristics for each. Note that the criteria are subject to change as the research progresses and more case study applications are made.

Table IV: Summary of guidance criteria to characterize a system and analytical tools available for identifying and valuing FDOs.

Guidance Criteria	Characteristic	
Main area of flexibility	Operations (OP)	Physical structure (PS)
Frequency of exercise	Frequent (F)	Infrequent (IF)
Intended audience	Technical (T)	Non-technical (NT)
Intensity of lifecycle cost	High	Low
Nature of the uncertainty	Progressive (PR)	Drastic (DR)

4.2 Proposed Framework

The suggested prescriptive framework is to describe a system in terms of the guidance criteria suggested above, characterize each analytical tools using these criteria, and decide on a set of analytical tools based on an appropriate matching of these criteria.

Table V describes each analytical tool in terms of these guidance criteria. Although different tools might be used in very different contexts, the table presents the context in which each tool is most effective. Note that this characterization is subject to change as analyses with real case studies are performed.

Table V: Characterization of each analytical tool according to the guidance criteria presented in Table IV. The most appropriate tool is specified. A more specific tool is suggested in parenthesis when appropriate. Notation: (any): any tool is in this category is appropriate; (optim): optimization-based screening method; (approx): approximation-based screening method; (DA): decision analysis; (lattice): binomial lattice

Methods		Guidance Criteria				
		Main area of flexibility	Frequency of exercise	Intended audience	Intensity of LCC	Nature of uncertainty
Identify FDOs	**Information flow**	PS	IF	T	High	DR/PR
	Interview	PS/OP	IF/F	T/NT	High/Low	DR/PR
	Screening	PS (any) OP (approx)	F	T (optim) NT (approx)	High (optim) Low (approx)	PR
Value FDOs	**Decision-Tree**	PS/OP	IF (DA) F (lattice)	NT (DA) T(lattice)	Low	DR (DA) PR (lattice)
	Design Transition	PS/OP	IF	T	High/Low	PR
	Simulations	PS/OP	F	T, NT	High/Low	PR

4.3 Proposed Research Approach

The ultimate goal of this research project is to develop further the prescriptive framework to help real-world practitioners select appropriate analytical tools to identify and value FDOs. This framework is to be tested under several case studies to demonstrate how it can be applied to a variety of real systems. The purpose is to demonstrate that it is general and applicable to a wide range of complex systems across several industries.

The proposed research approach consists of the following steps:

1. Choose a particular case study

2. Classify the system according to the guidance criteria summarized in Table IV

3. Match the system to the most appropriate tools to identify and value FDOs

4. Perform analysis using tools recommend by matching, or use existing analysis by original authors of case study if available

5. Perform analysis using remaining tools not-recommended by matching, or use existing analysis by original authors of case study if available

6. Determine whether the framework is useful by commenting on the difficulties encountered when applying both recommended and non-recommended tools

In essence, the proposed research approach is a mixture of individual and meta-study analyses. The individual part of the analysis is required whenever a particular analytical tool has not been applied to a particular system case study. The meta-study component uses analyses and results by original authors that have applied a particular analytical tool to a particular system.

Table VI lists several case studies, each applying different analytical tools to either identify or value FDOs in a particular system. Note that this list is subject to change in the future as more case studies are found/documented.

Table VI: Summary of existing case studies applying the methodologies presented above to real-world systems. A particular analytical tool is specified in parentheses if necessary.

CASES time ⇓	Identification			Valuation		
Analytical Tools ⇒	Inform. Flow	Expert Opin.	Screening	Decision Tree	Simulations	Design Trans.
Mining (Cardin et al., 2008)			X (approx)		X	
Business partnership (Chiara and Garvin, 2007; Savva and Scholtes, 2006)				X	X	
Launch vehicle (Silver and de Weck, 2007)						X
Unmanned Miniature Aero-Vehicle (Bartolomei, 2007)	X (ESM)	X				
Real estate (Cardin, 2007; Kalligeros and de Weck, 2004)			X (approx)	X (lattice)	X	
Parking garage (Cardin, 2007; de Neufville et al., 2006; Zhao, Tseng, 2003)		X	X (approx)	X (lattice)	X	
Oil and gas (Kalligeros, 2006)	X (sDSM)	X		X (lattice)		
Manufacturing (Hauser and de Weck, 2006, Nembhard et al., 2000)				X (lattice)	X	
Hydroelectric dams (Wang, 2005)			X (optim)	X (lattice)		
Car platforming (Suh, 2005)	X (CPA)	X			X	
Satellite constellations (de Weck et al., 2004)				X (lattice)		
On-orbit satellite servicing (Joppin and Hastings, 2003)				X (DA)		
Supply chain management (Billington et al., 2002; Nembhard et al., 2005)		X			X	
Power plant burner (Kulatilaka and Marcus, 1992)					X	

4.4 Example Application of the Proposed Research Approach

An example application of the proposed research approach to the design of a parking garage case study goes as follows. A short description of this case study is provided:

Example Case Study: Development of a Parking Garage (de Neufville et al., 2006: Zhao and Tseng, 2003)

The real-world case study considered here is a parking garage offering parking spaces for potential customers at a nearby commercial center. The goal of the project is to make profit, or to find the design that provides the highest NPV possible. The audience for the investment decision is the board of directors, with fairly non-technical background education. The main source of uncertainty is demand for parking space. Two design instantiations exist for this system: a flexible and an inflexible design. The purpose of considering two designs is to enable the valuation of flexibility by comparing the appraised values difference between the two designs. The flexible system has the capacity to expand the number of floors and parking space capacity as demand increases. The system starts with a smaller number of floors but has stronger columns to allow construction of additional floors in the future. In contrast, the inflexible design cannot be expanded. The initial capacity remains the same for all years of the project lifetime.

Figure 1: Example of parking garage (http://www.flyhia.com/).

1. Looking at Table VI, one notices that for the parking garage system studied by Cardin (2007), de Neufville et al. (2006) as well as Zhao and Tseng (2003), interview and approximation-based screening methods were used to identify FDOs. Lattice decision-tree and simulation methods were used to value FDOs in the system.

2. The system can be characterized as follows in terms of the guidance criteria of Table IV:

Table VII: Characteristics of the parking garage system under guidance criteria of Table IV.

Guidance Criteria	Characteristic
Main area of flexibility	Physical structure
Frequency of exercise	Frequent
Intended audience	Non-technical
Intensity of lifecycle cost	Low
Nature of the uncertainty	Progressive

3. Looking at the characteristics for the parking garage system in Table VII and looking first at an identification tool, it appears that an interview approach or approximation-based screening method is most appropriate. The fact that this case study is mainly addressed at a non-technical managerial audience rules out the possibility of using information-flow and optimization-based screening methods. Since the system is fairly simple, interviews might be sufficient to identify valuable sources of flexibility. An approximation-based screening method is also sufficient to screen the system for the best flexible design configuration.

   With regards to the valuation tool, the fact that the audience is non-technical rules out the lattice decision-tree and design transition methods. Since the main source of uncertainty is progressive (demand for parking space), this also rules out the use of the decision-analysis method. Hence, the most appropriate tool for this system is simulation.

   Analysis results by Cardin (2007), de Neufville et al. (2006), and Zhao and Tseng (2003) can be used without repeating the analysis. These authors have already applied the interview, approximation-based screening, simulation, and lattice methods for this case study.

4. The tools that remain to be tested are the information flow and design transition methods. The lattice approach by Zhao and Tseng (2003) might also need revision since their study focused on application of a trinomial lattice to this case study. It is interesting to investigate application of a simpler, binomial lattice approach to this particular case study.

5. This part needs to be completed once the analysis from step 4 is performed.

5 Conclusion

This research paper provides a survey of state-of-the-art methodologies for identifying and valuing flexible design opportunities (FDO) in engineering systems. It outlines the strengths and weaknesses of each method. Based on this, it presents a potential framework for analyzing the choice of most appropriate analytical tool depending on the engineering system under consideration.

The development of the prescriptive framework is the main subject of this research project. The development is extensively based on case study applications of the different methods in different industries to demonstrate generality. Development of the framework is to be based on individual experience and results in applying the tools, as well as those from authors who have applied the analytical tools to different systems. This research project therefore involves a mixture of individual experimentations and meta-studies.

One hopes that the research approach proposed here will bring useful insights on appropriate attributes for choosing the best analytical tools to identify and value FDOs in complex systems. Furthermore, applying the framework to several case studies in different industries should be useful guidance to real-world practitioners. This should help choosing appropriate analytical tools for new systems, depending on the context under which they are designed.

Appendix

This section proposes several example applications of the methodologies presented above.

Flexible Design Opportunity Identification Tools

Change Propagation Analysis

Two examples of system representations are shown in Figure 2. The graph view shows that a change Δx in design component A propagates to the whole system through components B, C, and E. Component B receives change information from components A and C, and in turn propagates change to components D and F. The cost of changing a component i, also known as *switching cost* K_i, is shown above the component. In the DSM representation, reading across row below the diagonal shows that component B indeed receives change information from components A. Reading above the diagonal shows that it may also receive change information from component C through a feedback process. This creates total change information inflow $\Delta E_{in} = 2$ for component B, as seen in the last column of the DSM. Reading across column B below the diagonal shows that change information propagates out of component B to components D and F. A change in component B thus affects two other components of the system, and creates a total change information outflow $\Delta E_{out} = 2$. According to our definition of CPI, $CPI_B = 2 - 2 = 0$. The same analysis is performed for all $n = 8$ components of this generic system as shown in the penultimate row of the DSM in Figure 2. In the figure, absorber, carrier, and multiplier components are denoted **A, C,** and **M** respectively in the last row of the DSM representation.

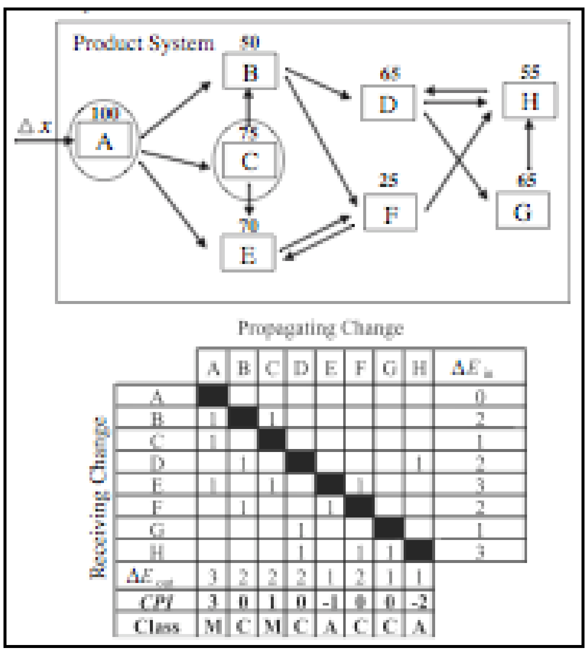

Figure 2: Graph (top) and DSM (bottom) representations of design change propagation in a generic system (Suh et al., 2007). The hypothetical switching cost *K* of changing a particular component to another is shown above the component.

An example application of the CPA method to the automotive industry is provided Suh et al. (2007).

Sensitivity DSM (sDSM)

Figure 3 is a theoretical representation of a sDSM, as suggested by Kalligeros (2006). The functional requirements (*FR*) and design variables *x* are listed in the column on the left (and in the top row, although not represented here). Each row of the southwestern quadrant represents the sensitivity of design variables x_i to changes in functional requirement *j* (FR_j). This can be thought as the percentage change incurred to design variable x_i with a percent change in FR_j. The southeastern quadrant is the main body of the sDSM. Each row represents the sensitivity of design variables to changes in other design variables resulting from changes in functional requirements.

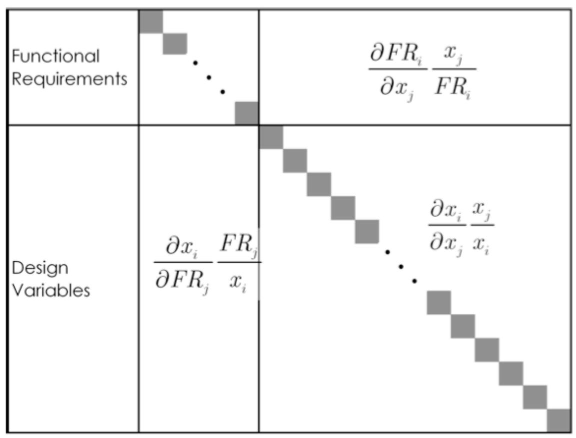

Figure 3: sDSM including both functional requirements and design variables (Kalligeros, 2006).

The *Invariant Design Rules* algorithm (Figure 4) is used to partition the sDSM of Figure 3 and to identify standard components in the system. Steps 1 to 4 create a list Π_k (*k* represents the number of iterations) of variables that are insensitive to changes in functional requirements. At the end of step 4, this list contains the maximum number of platform variables. Steps 5 to 7 prune out the list to remove all variables that can be sensitive to customizable variables. The algorithm stops when the list remains unchanged, or when it becomes empty.

The sDSM method is useful to search the design space for potential areas where flexibility can be incorporated in a system. Once platform components are identified, designers evaluate which components are worth making more flexible to ease transitions between various design variants. They can focus attention on a more limited set of components to explore flexibility in the system.

A detailed example of application of the methodology to the design of oil platforms is provided in (Kalligeros, 2006).

Step	Description	Variable stack
1	Establish running list of variables that are potential design rules	Π_k
2	Examine S-DSM element i. If i is not affected by changes in the changing functional requirements, then add element i to Π_k	
3	Repeat Step 2 for next element until all elements have been examined.	
4	Store running Π_k	Π_k contains maximum set of potential design rules
5	Check each element i against each element j. If $SDSM_{i,j} = 1$ and $x_i \in \Pi_k$ and $x_j \notin \Pi_k$ then remove element i from Π_k and go to Step 6. Otherwise, examine for next element $j = j + 1$	$\Pi_k = \Pi_k - \{x_i\}$
6	Repeat step 4 for next element i until all elements have been examined.	
7	If $\Pi_k = \Pi_{k-1}$ or $\Pi_k = \emptyset$ then the algorithm has converged; terminate. Otherwise, go to Step 4	

Figure 4: Algorithm for partitioning standardized DSM items (Kalligeros, 2006).

Engineering System Matrix

An example of generic ESM is shown in Figure 5. In addition to traditional technical DSMs, the system driver DSM represents the set of exogenous factors affecting the system. The stakeholders DSM represents the human agents involved in operating and managing the system, as well as those that benefit (or pay) for its use.

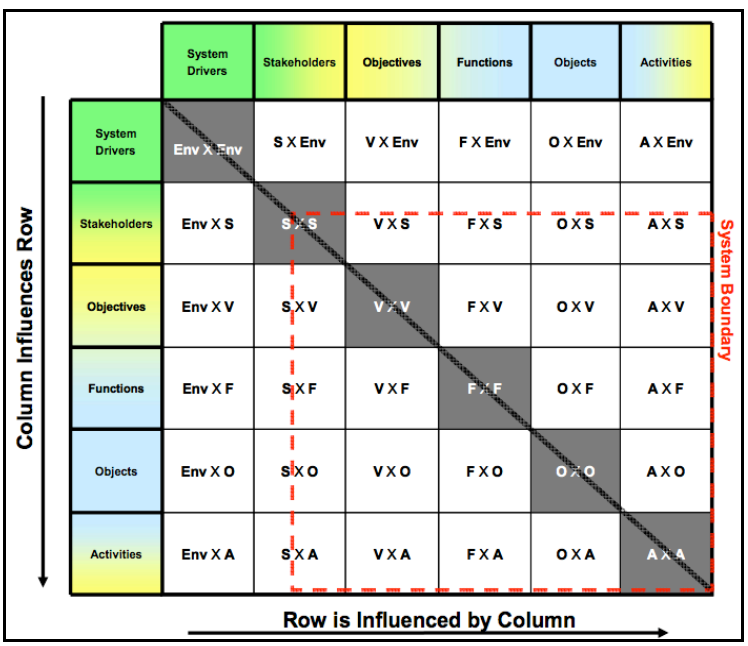

Figure 5: The Engineering System Matrix (ESM) (Bartolomei 2007).

In an example application of the ESM approach to identify FDOs, take a managing director with heavy responsibilities towards the well functioning of an organization. Presume it is found that the managing director will take an indeterminate leave-of-absence within two weeks, and that no notice-of-absence was made beforehand. This may greatly affect the outcome of the undergoing project.

This example helps understanding how flexibility can be acquired in the social and managerial environments of the system as well to deal with uncertainty. Here, flexibility is enabled by hiring a temporary director or by training another employee in advance to fulfill the managing director's tasks. This enhances the value of the project as compared to suffering the drastic loss of a key employee.

This FDO would not be identified in the CPA (Suh, 2005) and sDSM (Kalligeros, 2006) approaches since it is not of technical nature. In the ESM framework, this FDO is identified in the stakeholders DSM by noticing several connections to other system components, reflecting great dependence on the managing director. It can also be found through thorough application of the methodology presented in Figure 6, which involves the CPA and sDSM methods.

A conceptual application of this methodology to the design of a Miniature uninhabited Air Vehicle (MAV) is presented in Bartolomei (2007).

1. Construct the ESM for a particular system
2. Identify sources of uncertainty driving change
3. Define change scenarios
4. Determine the system sensitivity for each change scenario (e.g. Kalligeros' sDSM)
5. Identify change modes for each scenario (e.g. Suh's change propagation method)
6. Calculate the cost of change for each scenario (e.g. Suh's cost analysis)
7. Identify Hot/Cold Spots for each scenario
8. Examine Hot/Cold spots across scenarios
9. Value flexibility using Real Options Analysis

Figure 6: Methodology for identifying FDOs and standard components in a complex system (Bartolomei, 2007).

Optimization-Based Screening

Formally, the optimization problem introduced by Wang (2005) for each selected exogenous scenario is expressed as follows:

$$\max \sum_j \beta_j Y_j - c_j Y_j \quad \text{subject to} \quad \mathbf{TY} \geq \mathbf{t} \quad \text{and} \quad \mathbf{EY} \geq \mathbf{e}$$

In the equation above, **Y** is a design vector representing the design through a particular combination of design variable instances Y_j. $\boldsymbol{\beta}$ is a vector of coefficients representing the expected value-benefit β_j (often measured in financial terms) associated with a particular design variable. Similarly, **c** is a cost vector showing the cost associated to each design variable c_j. The constraints express limitations on economics (e.g. budget) **e** and technology **t** (e.g. available technology, physical capability, etc).

An optimal design is found for each exogenous scenario. The design variables that are altered from one optimal design to another represent good FDOs. In contrast, design variables that remain unaffected by changes in exogenous factor scenarios represent good standard platform components for the system.

Wang (2005) provides an application of this method to the design of a river dam for hydroelectric power production in China.

Approximation-Based Screening

The method suggested by Cardin (2007) to speed up the design exploration process for potential FDOs has five steps:

1. Develop an economic model of the system. This step consists of defining salient exogenous factors affecting value. It requires developing a quantitative model of the system and defining a metric to assess value under deterministic projections of exogenous factor scenarios. An example of economic model is shown in Figure 17.

2. Find representative uncertain scenarios. This step introduces uncertainty around deterministic projections selected in step 1. It requires a limited set of uncertain scenarios that are representative of the fluctuations that could occur in reality. Examples of uncertain scenarios are shown in Figure 16 and Figure 18. Designers then select a handful of such scenarios to show different trends (e.g. high growth, no growth, negative growth).

3. Determine the main sources of flexibility in the system. This step explicitly considers flexibility in design in light of the representative scenarios found in step 2. Specifically, it investigates the design components and management decision rules that can be adjusted to ease transition between the different scenarios. The information-flow and interview methods described above are useful here.

4. Explore the design space. This step introduces the adaptive One-Factor-At-a-Time (OFAT) algorithm developed by Frey and Wang (2006) to speed up exploration of the design space (Figure 7). The algorithm is applied to each representative uncertain scenario from step 2, incorporating FDOs identified in step 3 in the system model. It determines the best combination of flexible design components and management decision rules for each scenario without performing a full-factorial search of the design space.

   In Figure 7, one can think for example of a miniature airplane, with factors (or design elements) *A*, *B*, and *C* such as wingspan, engine power, and fuselage width. For each design instance, the factor takes one of two possible values, symbolized by + and –, like small or large for factor *A*, medium or high power for factor *B*, and medium or small width for factor *C*. The adaptive OFAT algorithms starts from a particular combination of design variables, measures the system response under a particular exogenous scenario, tests new designs by changing each factor level one at a time, and finds the best design configuration by retaining only combinations that improve the response each time.

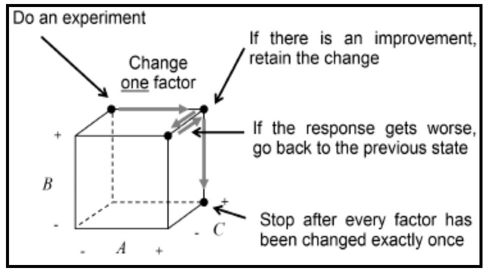

Figure 7: Adaptive OFAT applied to a system with three design elements and/or management decision rules (*A*, *B*, and *C*), each taking two possible values (+ or –) (Frey and Wang, 2006).

5. Assess the potential value added by the approximation method**.** This step simulates flexible adjustments in future operations to approximate the value added (or recognized) by the method. It uses Monte Carlo simulations of the main exogenous factors to create a variety of possible uncertain scenarios over the project lifetime. Each scenario is assigned to a particular representative scenario from step 2, and corresponding "best" design configuration from step 4. System performance is measured for each classification. The distribution of value results from simulations provides measures of central tendency and dispersion (e.g. mean value, standard deviation, median value, minimum and maximum values, etc.). Those measures can be useful to decision-makers in evaluating mutually exclusive investment projects.

This method is applied to the design of parking garage and real estate development systems (Cardin, 2007).

Flexible Design Opportunity Valuation Tools

Decision Analysis

In Figure 8, the two-stage decision tree has nine final possible outcomes, each associated with a different value V_i. Paths with final values V_1 to V_9 are associated with the flexible design where some flexibility (e.g. capacity expansion, asset redeployment, abandonment, etc.) can be exercised. Paths with final values V_7 to V_9 are associated with the inflexible design where operations continue as they are.

The analysis consists of "pruning" the tree, that is, selecting the paths corresponding to the most valuable decisions, and calculating the associated expected value. For example, assuming $V_1 > V_2$ at the end of the second stage, the branch with the option to exercise is selected and weighed by the probability of occurrence p_1. This represents the managerial decision to exercise if this particular scenario arises in operations. Suppose also $V_3 > V_4$ for paths 3 and 4 but $V_5 < V_6$ for paths 5 and 6 such that the flexibility would not be exercised. The expected value for the flexible system is therefore $V_F = p_1V_1 + p_2V_3 + p_3V_6$. In the inflexible case, the value is simply $V_I = p_1V_7 + p_2V_8 + p_3V_9$. The value of flexibility can therefore be approximated as $V_F - V_I$. Note that discounting can be incorporated in this analysis if cash flows are used as value metrics.

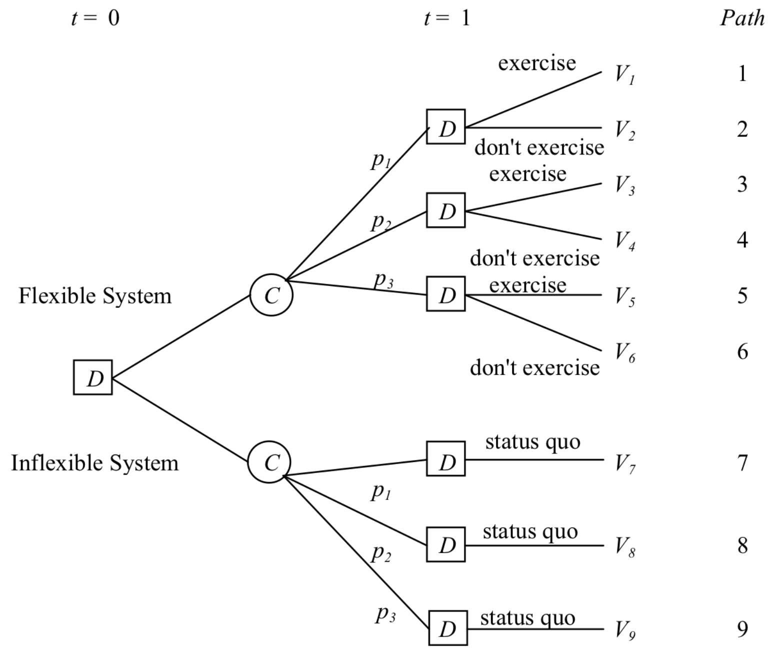

Figure 8: Example of tree structure for valuing flexibility using decision analysis.

Binomial Lattice

The method described by Cox et al. (1979) works as follows. First, the evolution of the uncertain factor (e.g. price, market value, demand, etc.) is depicted as a binomial model, as shown in Figure 9. This means a state with value V at time t can only progress to either an up state with value uV and with probability p, or to a down state with value dV and probability $1 - p$. Note that binomial lattice reduces the number of possible stochastic paths by assuming path independence, or path recombination. This means that the value of the system after an "up-down" sequence of the uncertainty is the same as "down-up" sequence. As mentioned before, this assumption may not hold in an engineering context. This is why Wang's enumerative approach (2005) is useful.

Note that the up parameter u, down parameter d, and risk-neutral probability parameter p are entirely determined by the economic model in use. In the risk-neutral model, one assumes a world that is risk-neutral since investors can hedge the cash flows of their project perfectly using a replicating portfolio of stocks and bonds. This justifies the use of a risk-free rate r for discounting. The parameters u, d, and p are determined also using the time increment between two periods Δt, the mean return growth μ, and the volatility σ of the uncertain factor:

$$u = e^{\sigma\sqrt{\Delta t}} \quad d = e^{-\sigma\sqrt{\Delta t}} = 1/u \quad p = \frac{1}{2} + \frac{1}{2}(\mu/\sigma)\sqrt{\Delta t}$$

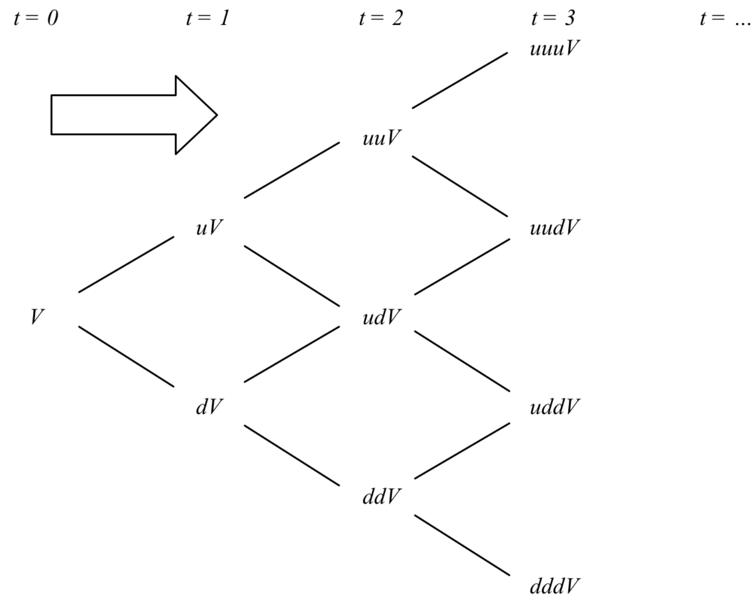

Figure 9: Evolution of uncertain factor (e.g. price, demand, market value, etc.) depicted by a recombining lattice model. The arrow shows progression in time.

The second part involves building a similar lattice where each node contains the value of the option at time *t*, as shown in Figure 10. For example, suppose higher value states in Figure 9 can only be attained if production capacity is increased for a given product (otherwise underlying value *V* of the project remains capped at a certain level V_{max} for later *t*). This is similar to a call option *C* to expand production capacity for the exercise cost *K* (since expanding production each time period has a cost). The value of the option at any time *t* is found as follows.

For a European option, exercise can only occur once in the final period when the option expires. For instance for C_{uuu}, the value of the option is C_{uuu} = max[0, $uuuV - K$]. For C_{uud}, it is max[0, $uudV - K$]. At each subsequent node, the value of the option is the weighted value of the option at time $t + 1$ in the up state plus its weighted value in the down state, discounted at the risk-free rate $1 + r$. For example, in the uppermost state at $t = 2$, C_{uu} is worth:

$$C_{uu} = \frac{pC_{uuu} + (1-p)C_{uud}}{1+r}$$

For an American option, exercise can occur anytime. The value of the option at each time node is the maximum between the value of immediate exercise and the value of keeping the option alive. The value in the final period, when it expires, is the same as for a European option. For previous time nodes, for example at C_{uu}, the value of the option is:

$$C_{uu} = \max\left[uuV - K,\ \frac{pC_{uuu} + (1-p)C_{uud}}{1+r}\right]$$

In both cases the overall value added by the flexibility to expand production capacity, which may capture higher value states in Figure 9, is the value of the call option C at $t = 0$. This is obtained by applying the dynamic programming "backtracking" approach described above for C_{uu} (for both American and European cases) at each node of the option lattice in Figure 10, until the first node at $t = 0$. Similar reasoning applies for a put option where $C_{u,d} = \min[0, K - V]$. This limits potential losses in case of lower value states. An example can be temporary shutdown of operations or complete abandonment of an unprofitable project.

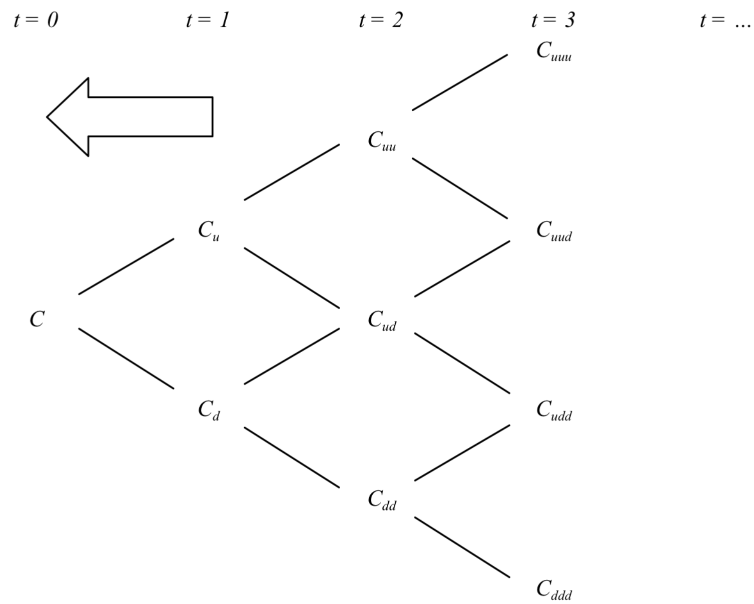

Figure 10: Option lattice used to compute the value of the option at t = 0. Dynamic programming or "backtracking" in time is used in this case, as depicted by the direction of the arrow.

Another economic model proposed by Arnold and Crack (2003) does not rely on the assumption of risk-neutrality, but rather of real-world probabilities. This is appealing because it may not be intuitive to real options neophytes and even experienced entrepreneurs to justify the use of a risk-free discount rate. The model by Arnold and Crack (2003) applies the same approach as above, and should provide the same option value. It merely brings modifications to the parameter p by incorporating the real-world discount rate r_V, and by subtracting a risk discount to the value C at each node of the option lattice (Geltner and Miller, 2006):

$$p = \frac{e^{r_V} - d}{u - d} \text{ and } C = \frac{\left(pC_u + (1-p)C_d\right) - \left(C_u - C_d\right)\left[\frac{r_V - r}{u - d}\right]}{1 + r}$$

Enumerative Technique

As seen in Figure 11, the method first creates a scenario tree of all future uncertain scenarios of interest to the analysis of the system. The index i is used to denote time stages ($0 \leq i \leq n$). k nodes are used to represent all states of the world in each stage. A particular path going through node k is denoted as $\boldsymbol{P}(k)$, with Q possible paths ($q = 1, 2, \ldots, Q$). Each path has probability of occurrence p^q.

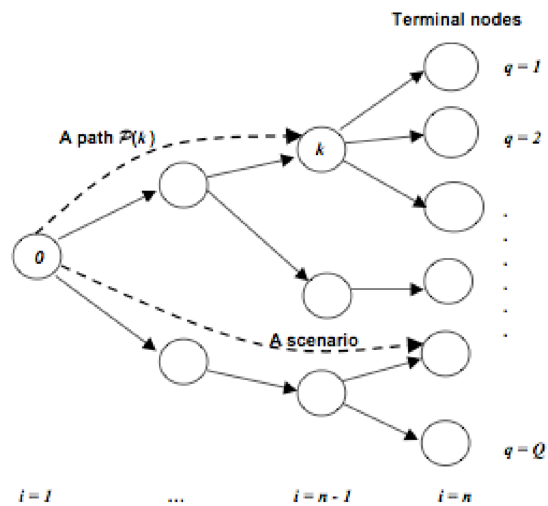

Figure 11: Scenario tree for the path-dependent valuation method (Wang, 2005).

The method uses a constrained stochastic mixed-integer programming algorithm to optimize the expected value of the real option across all possible Q scenarios, subject to a set of constraints. One example of constraint can be that that the option can only be exercised once for every scenario.

In essence, the approach can be viewed as one that "breaks" the path-independency typically assumed in binomial lattice models, as represented in Figure 12.

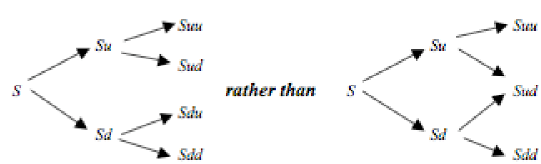

Figure 12: The path-dependent valuation method "breaks" the path-independency typically assumed in a binomial lattice approach to real options valuation (Wang, 2005).

Design Transition Method

As mentioned above, Silver and de Weck (2007) formalize LCC as:

$$C_{LC_i}(D,T) = C_{D_i} + C_{F_i}T + \sum_{j=1}^{T} C_{V_i} D_j$$

In the equation above, C_{LCi} is the lifecycle cost of design i considering demand scenario D and time duration of the lifecycle T. C_{Di} is cost of designing, developing, testing, and evaluating design *i*. C_{Fi} is the fixed cost occurring at all years of the project, and C_{Vi} is the variable cost recurring all years. To this cost model is added another cost, C_{SW}, which is the cost of switching from one design instance to another given a particular exogenous scenario over the project lifetime (e.g. price, value, demand for product, etc.). Note that one can also incorporate a discount rate in the equation to account for the time-value of money. For three hypothetical designs *A*, *B*, *C*, the switching cost between the different designs is represented graphically in Figure 13.

Assuming a particular system starts in a design state *S* at $t = 0$, and finishes in state *Z* at $t = T$, Figure 14 shows graphically all possible transitions and associated costs that may occur over the project lifecycle considering the three designs.

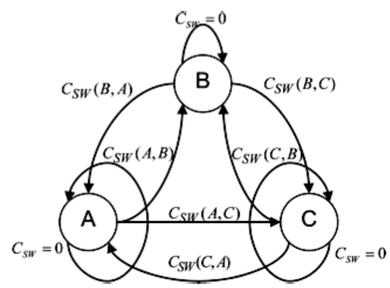

Figure 13: Graph representation of the switching costs between designs *A*, *B*, and *C* (Silver and de Weck, 2007).

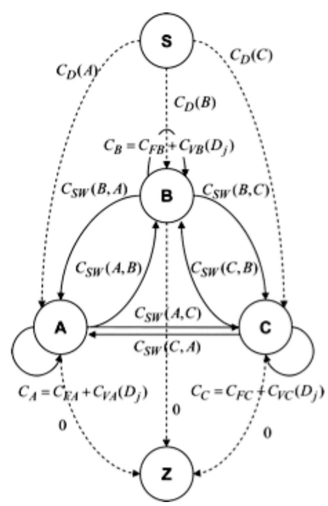

Figure 14: Complete static network representing all possible switching costs between designs *A*, *B*, and *C*, and costs of staying in any given design configuration. Development is represented by dotted lines from state *S* to any design, and retirement is shown by dotted lines from designs to state *Z* (Silver and de Weck, 2007).

Following these assumptions, the Time-expanded Decision Network (TDN) is shown in Figure 15. Note that the structure of the TDN is similar to a decision tree: circles represent chance nodes and squares represent decision nodes. In the structure, time evolves from left to right and is separated in three periods: T1, T2, and T3. Each node is numbered from to 1 to 18, with first and final states identified as nodes 19 and 20 respectively. Three design choices are shown on the left as *A*, *B*, and *C*. For a particular scenario of uncertainty (e.g. see for example Figure 16), the analysis begins in configuration S-19, which is one of the three possible designs, and terminates in state Z-20, which may or may not be the same initial configuration. Under a particular scenario, design *A* is selected, and a particular occurrence of demand is recorded at chance node 1 to compute the fixed and variable costs to the system. The decision to switch or not is made at decision node 2. If it is deemed valuable to switch under this particular scenario, the system configuration changes and moves to design *B*. The analysis moves forward in time at node 9, and then to other nodes until the lifecycle is completed.

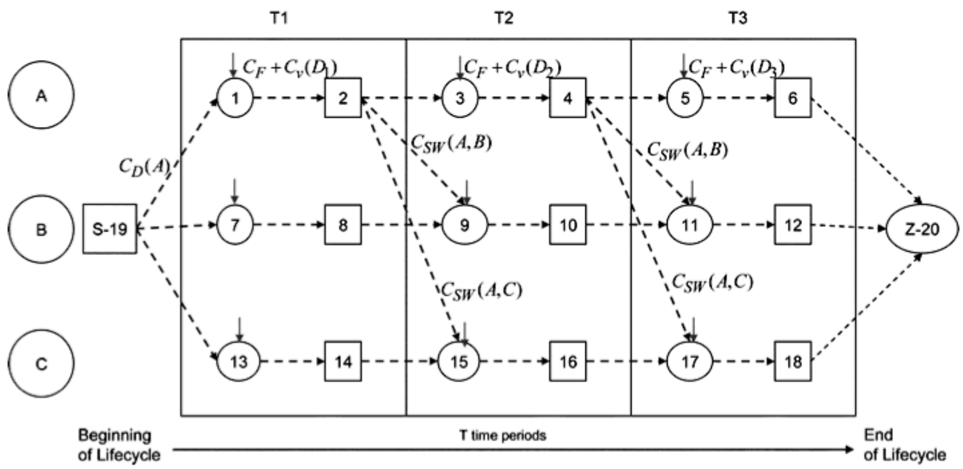

Figure 15: Time-expanded Decision Network (TDN). Circles represent chance nodes, and squares represent decision nodes. All nodes are numbered in topological order (Silver and de Weck, 2007).

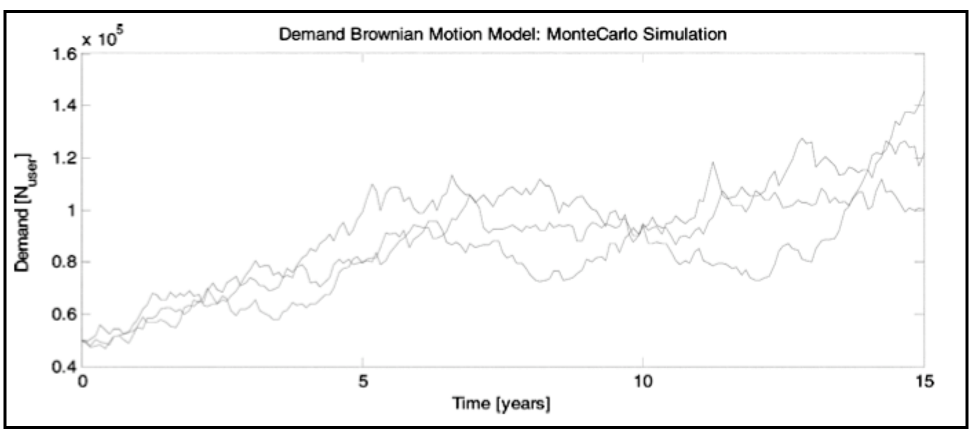

Figure 16: Example of three demand scenarios for a particular system generated via Geometric Brownian Motion (Silver and de Weck, 2007).

A shortest-path reaching algorithm (Ahuja et al., 1993; Lauschke, 2006) is applied to the network to find the path that minimizes total LCC. This algorithm intrinsically evaluates all possible combinations of transitions and determines, under a particular scenario, where it is valuable to switch design in order to minimize LCC. By running several scenarios of uncertainty, and considering analysis for all three designs, statistics are compiled on the switches that occur most frequently between designs. One can also measure the mean LCC, mean switching cost, etc, which provides the value measures of interest. Those can be used to determine where it is most valuable to insert flexibility in the system to minimize LCC. It also puts an upper bound on the amount to pay to acquire the flexibility.

Simulations Method

1. The standard DCF analysis on an inflexible system design can be done using standard spreadsheet software like Excel®. Figure 17 shows an example of typical DCF for a mining system producing ore, where price/metric ton is the exogenous factor. This is the typical analysis done in several industries, although it is not realistic because it does not recognize the stochastic nature of the exogenous factor(s) affecting value and performance.

Year (end of)	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Period	0	1	2	3	4	5	6	7	8	9	10
Price ($/metric ton)	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000	$2,000
Production (metric tons, millions)	0.000	0.600	0.606	0.612	0.618	0.624	0.631	0.637	0.643	0.650	0.656
Operating Costs ($/metric ton)	$0	$1,000	$1,010	$1,020	$1,030	$1,041	$1,051	$1,062	$1,072	$1,083	$1,094
Gross Operating Income ($, millions)	$0	$600	$600	$600	$599	$599	$598	$598	$597	$596	$595
Fixed cost ($, millions)	$0	$75	$75	$75	$75	$75	$75	$75	$75	$75	$75
Capital Investment ($, millions)	$1,650	$0	$0	$0	$0	$1,650	$0	$0	$0	$0	$0
Net Benefits ($, millions)	-$1,650	$525	$525	$525	$524	-$1,126	$523	$523	$522	$521	$520
Discount factor	1.00	1.10	1.21	1.33	1.46	1.61	1.77	1.95	2.14	2.36	2.59
PV Net Benefits ($, millions)	-$1,650	$477	$434	$394	$358	-$699	$295	$268	$243	$221	$200
NPV ($, millions)	**$543**										

Figure 17: Example spreadsheet for basic DCF analysis of a mining system under a particular exogenous factor scenario.

2. Simulating several scenarios of the exogenous factors affecting value provide central and dispersion measures like mean NPV, standard deviation, minimum NPV, maximum NPV, etc. An example of stochastic scenario for ore price is shown in Figure 18. An example of NPV distribution resulting from several simulations is shown in Figure 19.

3. Flexibility is incorporated in the spreadsheet model using standard programming logical rules (e.g. `if ore price > $x, expand current production capacity by y metric/ton`). Applying flexible management rules for each stochastic scenario also produces a histogram distribution of values similar to Figure 19. The distribution should have a different shape however as a result of inserting flexibility to react appropriately to different scenarios.

   Another useful graphical tool is the cumulative frequency distribution plotted as a function of the value metric, also called Value-At-Risk and Gain (VARG) curve. This curve depicts the likelihood of obtaining lower or higher value than a certain threshold, inspired by the concept of value at risk widely used in financial markets. For example in Figure 20, the VARG curve for the flexible system shows there is 10% of simulations that produced NPV values below -$300 millions, and 10% producing NPV above $2.4 billions. This is valuable information for decision-makers.

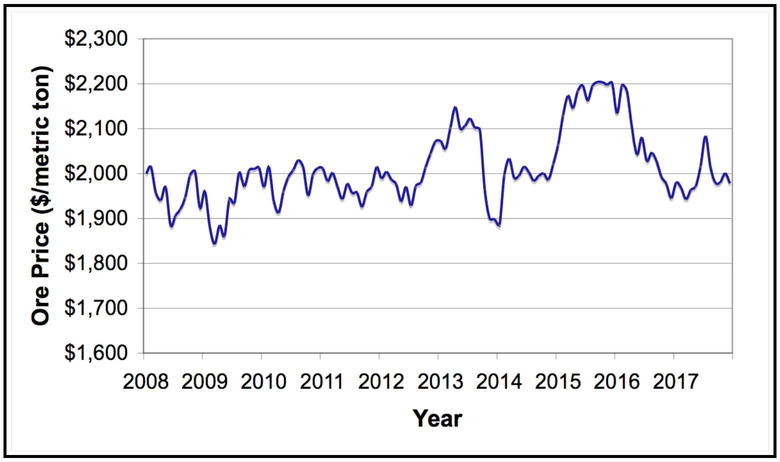

Figure 18: Example of stochastic process simulating fluctuations of an exogenous factor like ore price.

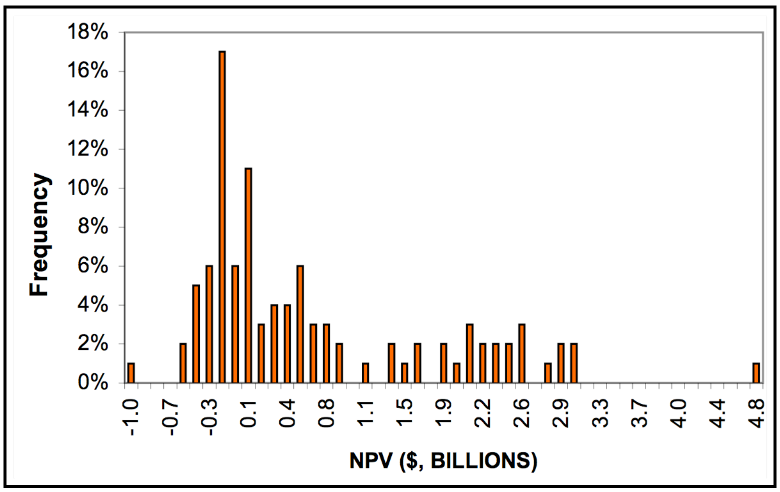

Figure 19: Example of histogram distribution resulting from Monte Carlo simulations of exogenous factor scenarios.

The VARG curve provides guidance on how much value is created/recognized by factoring flexibility explicitly in the appraisal process. One may contrast and compare the value obtained from a basic DCF of the inflexible system (step 1) to the VARG curves and mean values obtained for the inflexible (step 2) and flexible systems (step 3). For instance in Figure 20, comparison between the VARG curves of the flexible and inflexible designs shows for the flexible system an increase in mean NPV, a reduction in potential negative NPV projects (lower left tail of VARG curve), and an increase in potential positive NPV projects (higher right tail of VARG curve) compared to the inflexible version. For instance, one may choose mean NPV as the appropriate metric for comparison. Thus, the difference between the mean NPV of the flexible design and the mean of the inflexible designs leads to an approximate measure of the value of flexibility that can be used in comparison to its real acquisition cost:

$$V_{Flexibility} = \text{mean NPV}_{\text{Flex.}} - \text{mean NPV}_{\text{Inflex.}}$$

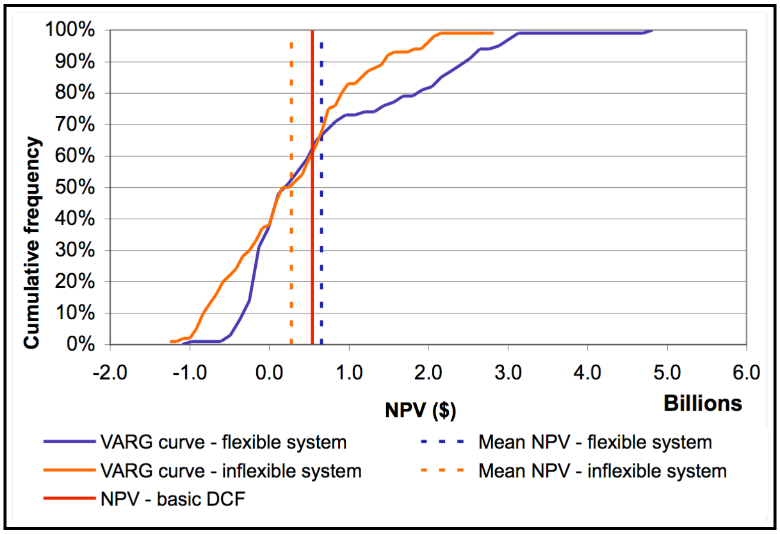

Figure 20: Example of VARG curves depicting the range of NPV outcomes for a particular system. Outcomes from both inflexible and flexible designs are shown. The figure also shows the NPV of the basic DCF model (vertical solid line from step 1), the mean NPV for the inflexible system (left vertical dashed line from step 2), and the mean NPV for the flexible system (right vertical dashed line from step 3).

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