Enabling Flexibility in Engineering Systems:

A Taxonomy of Procedures and a Design Framework

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Abstract

This paper presents a five-phase taxonomy of systematic procedures to enable flexibility in the design and management of engineering systems operating under uncertainty. The taxonomy integrates contributions from surveys, individual articles, and books from the literature on engineering design, manufacturing, product development, and real options analysis obtained from professional e-index search engines. Thirty design procedures were classified based on the kind of early conceptual activities they support: baseline design, uncertainty recognition, concept generation, design space exploration, and process management. Each procedure is evaluated based on ease of use to enable flexibility analysis, whether it can be used directly in collaborative design activities, and has a proven applicability record in industry and research. The organizing principles integrate the procedures into a cohesive and systematic design framework. Demonstration applications on engineering systems case studies show that it helps designers select relevant procedures in different phases of the design process, depending on the context, available analytical resources, and objectives. In turn, the case studies show that the design framework helps generate concepts with improved lifecycle performance compared to baseline concepts. The taxonomy provides guidance to organize ongoing research efforts, and highlights potential contribution areas in this field of engineering design research.

Keywords: conceptual design, design theory and methodology, systems design, systems engineering, uncertainty analysis
1 Introduction

This paper presents a five-phase taxonomy of systematic procedures to enable flexibility in the design and management of engineering systems operating under uncertainty. It has the dual goal of providing a review of the latest contributions in this field, and organizing existing procedures into a cohesive design framework. The taxonomy is geared specifically for engineering systems, in particular complex systems in the aerospace, defense, energy, housing, telecommunication, and transportation industries. Such systems are characterized by a high degree of technical complexity, social intricacy, and elaborate processes fulfilling important functions in society [1]. They are long-lived (+20 years), require large irreversible investments, will inevitably face much uncertainty over their useful lifetime, and have a significantly large number of design variables and parameters. Dynamic socio-technical elements like markets, operational environment, regulations, and technology play a significant role in their success and failure [2]. Crucial decisions have to be made in early conceptual design phases, regarding long-term strategic deployment and operations.

This paper builds upon the definition of flexibility in systems engineering and design “enabling a system to change easily in the face of uncertainty” considering technical and technological standpoints [3, 4]. It also builds upon the definition of a real option, which provides the “right, but not the obligation, to change a system in the face of uncertainty.” [5] The literature from engineering provides tools to help generate flexibility in complex systems. The literature from real options analysis provides analytical tools to assess the value of flexibility quantitatively, allowing for objective evaluation of systems design concepts. Combining the two literatures provides an extensive and complementary toolkit to create better performing systems. The ideas exposed in this paper are inspired from this unique perspective.

The paper proposes the notion of a flexible systems design concept to describe a design concept that provides an engineering system with the ability to adapt, change and be reconfigured, if needed, in light of uncertainty realizations. It is different conceptually from a robust design concept, which makes systems functions more consistent and invariant to changes in the environment, manufacturing, deterioration, and customer use patterns – inspired from the definition in [6]. A flexible systems design concept is typically comprised of two components: 1) a strategy, and 2) an enabler in design and management. A strategy is similar conceptually to the definition of a real option “on” systems by Wang and de Neufville [7], also referred as real option “types” by
Mikaelian et al. [8]. These can refer for instance to strategies suggested by Trigeorgis [5] – like abandonment, capacity expansion/reduction, switching inputs/outputs, deferring investments, etc. – to provide the system with better flexibility. A strategy represents the aspect of the design concept that captures flexibility, or how the system is designed to adapt to changing circumstances. The concept of enabler is similar to the definition of real option “in” systems by Wang and de Neufville [7], or “mechanism” by Mikaelian et al. [8]. It represents what is done to the physical infrastructure design and management to provide and use the flexibility in operations. Enablers take a different form for each system, depending on the flexibility strategy selected.

The following examples provide intuition on why flexibility is a worthwhile design paradigm. The HCSC building located in Chicago provides an example of a phasing – or staged capacity deployment – strategy [9]. While facing market uncertainty in the 1990s, the owner company designed the skyscraper carefully to accommodate 27 additional stories on top of an initial vertical development. The flexibility could be exercised only if there was a need for additional office space. A few years ago the company realized faster growth in personnel needs than expected. It decided to exercise the flexibility strategy to expand office capacity, and deployed the second phase. The strategy carefully enabled earlier in the design by allowing for stronger structure and additional floors allowed the company to deal pro-actively with market uncertainty at a strategic time. The Boeing B-52 Stratofortress provides an example of a switching real option [10]. Developed in the 1950s, the bomber’s configuration was changed many times to accommodate different missions, within and across different design variant generations. The aircraft was originally designed to deliver nuclear warheads at high altitude [11]. A few years later, the Soviet air defense incorporated surface-air missiles, forcing lower altitude flights. The belly of the current design variant was reconfigured to carry air-launched cruise missiles for lower-altitude missions. This capability was used later on in Vietnam to support ground troop operations.

Engineering design is getting increasingly complex. Designers must consider socio-technical elements in the design and long-term management of their system. Uncertainty is an important factor as it ultimately affects the system’s lifecycle performance. Volatile markets, fluctuating prices and consumer demands, changing regulatory frameworks, and evolving technology require that complex systems adapt over time to provide good lifecycle performance. Flexibility has been shown in many case studies to improve such performance (e.g. measured in financial terms) between 10% and 30% compared to the designs generated from standard design procedures [4, 12]. Embedding flexibility positions a system to reduce the negative effects from risky, downside
scenarios (e.g. economic downturns), while providing contingencies to capitalize on upside opportunities (e.g. better technology than planned, favorable regulations). Flexibility changes the goal from optimizing designs to a set of deterministic point forecasts to finding designs that will affect favorably the entire distribution of possible outcomes. It helps the designer “stack the cards” in the favor of the future operator and system owner.

Fig. 1 captures these ideas graphically, using cumulative distribution functions (CDF) to compare hypothetical performance outcomes for conceptual baseline and flexible design alternatives subject to uncertainty (e.g. demand). In this example, net present value (NPV) is used as an economic metric to assess lifecycle performance of different design concepts. The vertical dot-dashed line corresponds to the NPV of the baseline concept evaluated under one deterministic forecast, leading to only one possible value (i.e. $8.5 million). When dealing with uncertainty and flexibility, one has to first recognize that designs produce a distribution of performance outcomes, as opposed to one particular point value. What is often observed is that a flexible design provides better protection against downside scenarios (e.g. 5th percentile or P5 = -$1.9 > -$4.1 million, better for the flexible system), and also enables better ability to capitalize on upside potential (e.g. 95th percentile or P95 = $23.2 > $11.6 million, also better for the flexible system). As observed in many studies, the net effect is to improve the mean NPV performance as compared to the baseline concept (i.e. mean NPV $12.0 million > $6.7 million).

**FIG. 1 ABOUT HERE**

**Fig. 1**: Example cumulative distribution functions for conceptual baseline and flexible systems design concepts, using NPV as lifecycle performance metric.

History has shown that designing engineering systems with too much rigidity, and optimizing their design for a limited set of forecasts can lead to failure, even if the technology and design are working well. One example is the Iridium system sponsored in the early 1990s by Motorola. The 77 Low Earth Orbit (LEO) satellite infrastructure was designed to enable phone calls anywhere on the planet. The design and management was focused on a very optimistic demand forecast, expecting more than 3 millions subscribers by the end of the decade [13]. The technology was working well, and the entire constellation was deployed rapidly between May 1997 and May 1998. Unfortunately, demand did not materialize as planned over the following years. Because all capacity had been deployed and satellites were designed to remain in the same orbital configuration, nothing
could be done to adapt and reduce the economic impact of this downside scenario. Revenues did not grow fast enough to honor debt payments, and in the early 2000s, the system was sold in bankruptcy for less than 1% of the original $4 billion investment [14].

de Weck et al. [15] explained later that a flexible staged deployment strategy combined with satellites designed to change orbital configuration would have helped the system to cope better with changing market conditions, resulting in about 20% expected lifecycle cost (LCC) savings. The strategy would have been to deploy the constellation in phases instead of all at once to adapt gradually to rising demand, requiring the orbital configuration to change in space to accommodate growing coverage areas.¹ This strategy would have led to a significantly different design than the one considered and launched by Iridium.

These examples motivate the need to organize latest research efforts and the design process for flexibility more systematically. This process was observed as more systematic in some cases (e.g. HCSC example), but not necessarily in others (e.g. Iridium). In cases where flexibility was observed (e.g. HCSC, B-52), it played a significant role to improve the lifecycle performance of the system. In the Iridium example, the system failed from an economic standpoint, arguably because of a lack of flexibility [15].

While it is challenging to know what really happened in the design process for these systems besides what is available in publicly available sources, these examples – and many others discussed throughout the paper – provide sufficient motivation to organize the latest research efforts on this topic, and organize the process for flexibility so it can be applied across a wide range of engineering systems. The underlying assumption is that flexibility can and has been shown to improve lifecycle performance significantly in many studies. It brings in uncertainty and risk management considerations at the design and management levels of the infrastructures. The examples above motivate the need for 1) a taxonomy, to organize the latest research efforts in terms of tool and procedure development, so designers know the current state-the-art, and for what kind of design activities available procedures can be used, and 2) a design framework, to help structure these activities during the design process. The taxonomy aims to achieve these goals, relying on the one hand on recent research progress, a multi-disciplinary literature review, industry guidelines, and case studies. It also provides a cohesive framework

¹ The ex post case study by de Weck et al. [15] is described in more details in Section 4.2.
to organize such design activities more systematically by building upon and extending existing processes and frameworks in engineering design.

2 Background and Motivation

2.1 Existing Taxonomies of Design Procedures

This work is concerned with design procedures, defined here as “techniques or methods supporting the design process and/or artifact production”. Tomiyama et al. [16] provided a taxonomy of general procedures for engineering design, but little is said about flexibility and adaptability. Ferguson et al. [17] suggested a taxonomy to organize procedures for product flexibility, but it is unclear how the procedures can be used for engineering systems that are more complex, like urban infrastructure systems. The review by Sethi and Sethi [18] focuses on how to enable flexibility in manufacturing, and not engineering systems as a whole. The survey by Saleh et al. [19] organizes the field of engineering design for flexibility, but does not provide a clear account of existing procedures to support different phases of the design process. The taxonomy by DeLaurentis and Crossley [20] focuses on design methods for systems-of-systems, including decision-making, but not on the issue of design for flexibility.

2.2 Design Procedures to Enable Flexibility

An important motivation for this work is that designing engineering systems for flexibility is not easy. It requires guidance from research experience and industry applications. It is not clear what uncertainty sources to address, where to focus the design effort, how much flexibility is worth and costs, and how much flexibility is enough. Such design practice is present in some industries (e.g. manufacturing) but not in many others [4, 21].

This difficulty has led to the development of systematic procedures to assist engineering designers. The main gap in this body of work is that procedures and research efforts are not well organized into a consolidated framework, one that shows the different phases that designers must go through to ensure quality outcomes. It may not be clear to practitioners, researchers, and educators what is the right process to follow, what procedure should be used at what phase, what are the strengths and challenges pertaining to different procedures, and what is the purpose of a given procedure.
To illustrate this, consider the systematic four-phase process proposed by de Neufville and Scholtes [4], which includes estimating distribution of future possibilities, identifying candidate flexibilities, evaluating and choosing flexible designs, and implementing flexibility. This process shares great resemblance with the categories suggested by Tomiyama et al. [16]. For instance, generating new design solutions is similar to the idea of identifying candidate flexibilities, and enriching functional and attributive information of design solutions is similar to the idea of evaluating and choosing flexible designs. On the other hand, de Neufville and Scholtes [4] focus only on the steps leading to flexibility. Their process does not account for the need of an initial design solution prior to considering flexibility, which reduces the design space for flexibility considerably, and thus makes the design process more tractable. Also, it leaves out many procedures relying on dynamic programming like binomial lattice and decision analysis, design structure matrix (DSM), and other procedures developed lately to assist designers with concept generation and implementation issues. The integrated real options framework (IRF) by Mikaelian et al. [8] does not suggest procedures for the initial design, uncertainty recognition, and process management phases. In the design space exploration phase, it only considers flexibility valuation, and not the issue of computational efficiency. Similarly, the six element (6E) framework by Nilchiani and Hastings [22] shares some properties with the above processes and taxonomies, but does not provide a succinct description of the relevant design procedures in each phase.

3 Methodology

3.1 Identification of Relevant Design Procedures

To develop the taxonomy, a review of major research contributions was done to identify relevant procedures. The literature survey included journal and conference papers and books in engineering design research, manufacturing, product development, and real options analysis [4, 5, 16-19, 23-25]. All years where relevant publications existed were considered. Keywords such as “flexibility in engineering design” and “real options in engineering” – or different combinations of these words – were used in e-index search engines like Scopus®, Engineering Village®, IEEE Xplore®, and Web of Science®.

3.2 Development of the Taxonomy

A meta-analysis of the taxonomies and systematic design processes described in Section 2 was done to extract the five organizing principles of the taxonomy, which also represent different phases of the design framework.
For example, many authors suggested that the process for flexibility should start from an initial design created from existing engineering procedures [21, 22, 26, 27]. This first phase was captured explicitly as baseline design. The necessity to recognize explicitly and model the main uncertainty drivers affecting lifecycle performance [4, 8, 15, 21, 22, 26, 28] was captured as uncertainty recognition. The organizing principles in Tomiyama et al. [16], together with the phases suggested by de Neufville and Scholtes [4], Mikaelian et al. [8], and Nilchiani and Hastings [22] were merged into a smaller set of design phases to support concept generation, design space exploration, and process management.

3.3 Taxonomy of Design Procedures

The taxonomy summarized in Fig. 2 is the main contribution of this paper. A second contribution is a review and description of the procedures most relevant to each phase. The third contribution is an evaluation of each procedure along three dimensions to provide better guidance for designers in industry, academia, and to support better practical use. The first dimension is ease of use for flexibility analysis, defined as whether the concepts emerging from the procedures already consider uncertainty and/or flexibility, and therefore are better positioned for later phases of the process. The second dimension is suitability of a procedure for collaborative design activities – since design is fundamentally a collaborative process [29]. A procedure that is directly suitable can be used readily in a collaborative setting without much modification, otherwise it may require considerable efforts to adapt. The third dimension is whether a procedure has a proven industry record in real-world applications, and/or case study demonstrations. Each dimension is evaluated based on strong (S), moderate (M), or basic (B) assignments. The fourth contribution is a set of examples showing how the taxonomy can be used as a design framework. In turn, it shows how the resulting designs offer improved expected lifecycle performance compared to baseline designs generated in the initial phase. A fifth contribution is to highlight potential areas for future research contributions, based on latest efforts and developments in this area of engineering design research.

FIG. 2 ABOUT HERE

Fig. 2: Taxonomy of procedures to support the design of engineering systems for flexibility.
### 3.3.1 Phase 1: Baseline Design

Design for flexibility must start from an existing design configuration (referred here as *baseline design concept*). It is observed in industry practice that designs are often optimized based on a set of deterministic point forecasts for customer demands, markets, requirements, constraints, etc. This approach often leads to more rigid design concepts that cannot adapt flexibly to changing conditions [4, 21, 30]. If designers accept the underlying premise that explicit consideration of uncertainty and flexibility can improve the lifecycle performance of their system, a phased analytical approach may be more productive to consider uncertainty and flexibility.

Phase 1 helps designers start from what they know (e.g. existing design for satellite system, oil platform or real estate project), and helps structuring the thought process for flexibility. Because so many opportunities exist in complex systems, this task may be overwhelming. The proposal is to start from a set of baseline concepts that will be further expanded or enriched by explicit consideration of uncertainty and flexibility in subsequent phases. The design architecture must be developed enough to enable further consideration of uncertainty and flexibility in subsequent phases. This architecture can be captured by a conceptual word description, detailed sketch, physical prototype, computer-aided design (CAD) and/or economic model, etc.

Based on the taxonomy by Tomiyama et al. [16], a baseline design concept can be created using procedures (or part of procedures) that either help *generate new design solutions* like Pahl and Beitz [31], *enrich functional and attributive information of design solutions* like axiomatic design [32], or *manage the design process and represent design knowledge*, as for concurrent design [33]. Recent efforts not covered in this review but also structuring the conceptual design process include Concept-Knowledge (C-K) theory [34], function-based failure analysis [35, 36], and architecture generation using Bayesian network [37, 38]. The outcome of this phase is a set of baseline concepts that represent the starting point for further analysis. Such concepts may or may not have been generated considering uncertainty explicitly, unless using recently proposed methods [35-38].

#### Procedure Evaluation

Analyzing all existing design procedures is beyond the scope of this paper. For brevity, only a few examples are considered and summarized in Table 1. Many existing procedures are deemed basic in terms of ease of use for flexibility analysis because there is no clear mechanism to recognize and model uncertainty, and deal with it by means of flexibility. For example, the conceptual design phase described by Pahl and Beitz [31] focuses heavily
on generating concept (or principle) design solutions derived from market and/or customer domain requirements. The authors do provide a few suggestions for adaptable and evolvable products, which are akin conceptually to the idea of flexibility. There is, however, no clear mechanism to support design activities specifically focused on uncertainty modeling and flexibility analysis. The same assertion can be made about axiomatic design, C-K theory, and concurrent design, although these authors recognize uncertainty, and the need for flexibility. Function-based failure analysis moderately enables flexibility analysis because it recognizes the need to consider risk and uncertainty, which is an important step in this process. It does not, however, account for uncertainties other than functional failures (e.g. markets, regulations), and does not systematically consider available flexibility strategies for mitigation purposes. In terms of usability in a collaborative setting, concurrent design is strongly suited because it is crafted for this purpose. Axiomatic design, Pahl and Beitz, and function-based failure analysis are assigned moderate values, since they need to be adapted depending on the environment and context. C-K theory, however, is more abstract, and there is no documented way to instantiate it in a collaborative setting yet, hence the basic assignment. All procedures have a proven applicability record due to the significant number of case studies in the literature. Only C-K theory may be considered as basic at this stage, stemming mainly from its abstract and theoretical nature, and relative youth.

Table 1: Evaluation of example procedures in phase 1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Axiomatic Design</th>
<th>C-K Theory</th>
<th>Concurrent Design</th>
<th>Function-Based Failure Analysis</th>
<th>Pahl and Beitz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>M</td>
<td>B</td>
</tr>
<tr>
<td>Directly usable in collaborative design</td>
<td>M</td>
<td>B</td>
<td>S</td>
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<tr>
<td>Proven applicability in industry</td>
<td>S</td>
<td>B</td>
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3.3.2 Phase 2: Uncertainty Recognition

Uncertainty affects the lifecycle performance of engineering systems. It may create opportunities for better performance (e.g. profit), such as when market conditions are better than expected. It can also destroy value, for instance when technology is not working as planned or environmental conditions are unfavorable (e.g. hurricanes, storms, earthquakes). Engineering systems will inevitably face a wide range of changing conditions.
The procedures in phase 2 help designers identify and model major uncertainty sources affecting lifecycle performance, based on the taxonomy by de Weck and Eckert [39] and Halpern [40]. Formal and practical approaches were suggested to quantify, characterize, and model uncertainty. Formal approaches include probability, statistics, Bayesian, Dempster-Shafer (i.e. relying on separate pieces of evidence to construct the probability of events) [41, 42], and possibility theories (i.e. based on fuzzy logic) [43]. Practical procedures to model uncertainty include diffusion models – based on stochastic simulations – binomial lattice [44], decision trees, and scenario planning [45]. The outcome of this phase is usually one or several models – formal and/or practical – enabling explicit evaluation of the baseline and upcoming flexible design concepts under uncertainty.

**Procedure Evaluation**

As summarized in Table 2, all procedures are at least moderately useful for flexibility analysis. On the one hand, they induce designers to consider explicitly uncertainty; on the other hand they each present a set of challenges, as described below. Nonetheless, they are crucial for flexibility analysis, and to help against the human tendency to be over optimistic/confident about the future [46]. Bayesian, probability, and possibility theories are useful when knowledge is available about the underlying phenomena (e.g. joint and prior probability distributions), although these can be difficult to calculate. When information is not readily available, designers may tap into expert knowledge to elicit distributions, using Dempster-Shafer or scenario planning methods. Designers should be aware of the difficulties associated with combining multiple probability distributions [47], and implicit biases during elicitation [46]. When historical data is available (e.g. demand, price), statistical techniques can help to measure, for instance, the mean growth rate and volatility in diffusion and lattice processes. The main difficulties concern choosing an appropriate data range, mean trend profile (e.g. linear vs. polynomial), and stochastic model (e.g. geometric Brownian motion (GBM) vs. mean reversion vs. jump process).

Binomial lattice and diffusion models are better for continuous stochastic processes (e.g. market demand, price). It is difficult, however, to model more than one uncertainty source using lattices – see Copeland’s and Antikarov’s [48] quadranomial approach to model up to two. Diffusion models based on simulations offer most freedom, enabling the analysis of multiple uncertainty sources. They are, however, limited by the computational resources available. Decision tree and scenario planning are better for discrete events (e.g. uncertainty about government policy A vs. B). It is difficult to account for many scenarios and uncertainty sources because for decision trees, the number of paths becomes quickly intractable as the number of stages (e.g. time period) and
states (e.g. system status within a stage) increases. For scenario planning, considering many scenarios independently can be a lengthy exercise. All practical approaches suffer from the difficulties associated with parameter estimation, mainly relying on formal approaches for probability distribution modeling and elicitation.

Most approaches are basic in terms of direct usability in a collaborative design process. They are analytical in nature, and not necessarily designed to accommodate directly collaborative design interactions. Decision trees and scenario planning are better suited, however, since they can be used to steer collaborative discussions around relevant uncertainty scenarios and decision points. All formal approaches, including scenario planning and diffusion models, have a strong applicability record in industry [39, 40, 46]. Binomial lattice and decision tree, however, are not yet widely used in industry, and therefore have a moderate applicability record [49, 50].

Table 2: Evaluation of procedures in phase 2.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Bayesian Theory</th>
<th>Dempster-Shafer Theory</th>
<th>Possibility Theory</th>
<th>Probability Theory</th>
<th>Statistical Analysis</th>
<th>Binomial Lattice</th>
<th>Decision Tree</th>
<th>Diffusion Model</th>
<th>Scenario Planning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>M</td>
<td>M</td>
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</table>

3.3.3 Phase 3: Concept Generation

Here, designers generate flexible systems design concepts to deal pro-actively with changing operating conditions identified in phase 2. Each concept is comprised of 1) a strategy, and 2) enablers in design and management. A strategy is necessary to determine how the system will adapt in the face of uncertainty. The enabler determines the instantiation of the flexibility in the design, and how it is managed. Hence, both elements are necessary, related, and inter-dependent to support this crucial phase.

The procedures in this phase support concept generation either partially or completely, involving cognitive tasks to generate the flexible strategies, identify how to embed and enable concretely in the design, and determine when to exercise in operations subject to different uncertainty realizations. Some procedures focus more
specifically on the issue of generating flexible strategies, or the issue of identifying enablers. Procedures are classified according to where they are most useful, recognizing that some procedures may cover both aspects. One feature differentiating procedures focused on enabler identification is that they rely on a preliminary description, model or representation of the system. They require a more thorough analysis of the salient design variables, parameters, and/or interconnections between different sub-systems and components. They may also rely on a set of design principles to enable flexibility strategies. The outcome is a set of flexible systems design concepts that can arguably deal better with uncertainty than baseline concepts generated in phase 1.

3.3.3.1 Strategy Generation

Real Options Strategies

Trigeorgis [5] suggested a number of generic flexibility strategies that can be used to stimulate strategy generation: 1) defer capital investment until favorable market conditions arise, 2) stage or phase asset deployment strategically over time instead of deploying all capacity at once, 3) alter operating scale by expanding or contracting output production capacity, 4) abandon a project doomed to fail and resell assets at salvage value, 5) switch production inputs and/or outputs to accommodate different markets or missions, 6) invest in R&D to capitalize on future technology and additional cash flows if the initial investment is successful, and/or 7) combine the above. These strategies can take on different forms, depending on the system at hand, and help stimulate creativity since designers need to think how it can be instantiated for the system at hand.

Integrated Real Option Framework (IRF)

Mikaelian et al. [8] suggested the IRF to support strategy generation based on the characterization of real options in enterprises as a combination of a mechanism (e.g. modularity, buffering) and a type (e.g. expansion, switching). Upon recognizing the major uncertainty drivers, a mapping exercise stimulates designers’ creativity by having them connect flexibility types to different mechanism patterns. This favors generation of flexibility within and outside typical enterprise “silos” (e.g. strategy, process, product, IT).

Explicit Training and Prompting

Cardin et al. [51] suggested a technique integrating a short lecture on the topic of flexibility with a structured prompting mechanism to support mainly strategy generation. The lecture helps designers become more aware of the effects of uncertainty on lifecycle performance. It describes generic sources of uncertainty, explains how
flexibility improves lifecycle performance, discusses strategies for crafting valuable flexible design concepts, and provides real-world examples applications. Prompting scaffolds the thought process for flexibility, using a series of direct questions (or prompts) to identify major uncertainty drivers, generate flexible strategies, determine how to enable flexibility in design, and identify the best decision rules to manage flexibility in operations. It is a simple, intuitive, and quick approach to stimulate strategy generation.

Procedure Evaluation

Table 3 shows that explicit training and prompting procedure is strong in terms of ease of use for flexibility analysis. It provides a clear list of prompts to help designers generate flexible concepts quickly, easily, and intuitively, mainly relying on their expertise with the system. It helps designers consider salient uncertainty sources and decision rules, only requiring an hour of brainstorming activities.

Table 3: Evaluation of procedures in phase 3 – strategy generation.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Explicit Training and Prompting</th>
<th>Integrated Real Option Framework</th>
<th>Real Option Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>S</td>
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<td>M</td>
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<td>S</td>
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</table>

The IRF mapping mechanism provides a more systematic approach to guide this process, also bringing notions of how to enable the concepts in design as a way to stimulate creativity. Real option strategies provide a useful checklist that can be consulted quickly. There is, however, no clear mechanism to identify the major uncertainty drivers.

2 Decision rules are used to determine when it is appropriate to exercise the flexibility in operations, in light of some observation regarding the main uncertainty sources. They are crucial to the lifecycle value assessment of flexible systems design concepts [91-92]. A bad decision rule can destroy value instead of improving it. For example in the HCSC study, the company had a threshold for office needs after which they would expand the building vertically. They would expand once a particular personnel threshold was reached. Decision rules are crucial assessing quantitatively the lifecycle performance impact of flexibility, as described in Section 3.3.4.1.
drivers and decision rules in these two methods, hence the moderate assignment. For collaborative design activities, explicit training and prompting has been crafted explicitly for such purpose, building upon collaboration engineering techniques to minimize productivity loss and stimulate creativity [52]. This is not the case for the IRF mapping mechanism and for real option strategies, motivating the need to be revisited and adapted for such purpose. In terms of proven applicability record in industry, explicit training and prompting as well as the IRF mapping mechanism are relatively new to research circles, and do not have a clear industry record, hence the basic assignment. In contrast, many industry case studies exist for applicability of real option strategies in industry [4, 5, 12, 48], thereby supporting a strong assignment.

3.3.3.2 Enabler Identification

Industry Guidelines

Industry guidelines provide lessons and principles to enable better flexibility in design. Fricke and Schulz [3] suggested the principles of ideality, simplicity, and modularity as guiding principles. Gil and Tether [53] suggested embedding safeguards to deal with changing usage patterns and design requirements in complex systems and projects. Many authors have also contributed to the development of Change Modes and Effect Analysis (CMEA) to assess flexibility in products, where flexibility is enabled relying on a set of empirically derived principles (e.g. modularity, parts reduction, spatial principle, interface decoupling, adjustability, etc.) [23, 54, 55]. While complex systems differ from products in terms of scale and complexity, many principles suggested in this literature can be used to enable flexibility in engineering systems.

Design Structure Matrix-Based

DSM was introduced by Steward [56] to represent design tasks as a sequence of network interactions. It is a square matrix where the rows and columns list all the relevant system design and management components [57]. Matrix entries represent how the design and management components are connected, and how the information flows from one another.

Many DSM-based procedures were developed to identify specific areas where to embed flexible strategies within engineering systems. Change propagation analysis (CPA) looks at change multipliers as candidate areas. These are design elements creating more change in other design variables then they absorb when a design or functional requirement is changed [28]. CPA was applied in a car body-in-white platform case study, and
complex sensor system design [58]. Hu [59] developed a DSM-based method conceptually similar to CPA, but relying on Bayesian networks and risk propagation analysis. Koh et al. [60] also extended CPA by providing an estimate of system changeability, considering direct/indirect propagation of change, likelihood of change, and the impact or effort of change. The sensitivity DSM (sDSM) looks for design variables that are most sensitive to changes in design and functional requirements as candidate areas to embed flexibility, with application in offshore oil platform design [61]. The engineering system matrix (ESM) extends a technical engineering DSM by including social components like human stakeholders (e.g. managers, customers) and system drivers (e.g. purpose or mission). Bartolomei et al. [62] suggested incorporating CPA and sDSM within the ESM framework to identify candidate flexibilities, with application to unmanned aero-vehicle (UAV) design [63]. Mikaelian et al. [64] extended the DSM framework with the Logical Multiple Domain Matrix (MDM) framework for enabler identification in complex systems, with application to UAV design.

**Explicit Design Variable Evaluation**

This approach consists of identifying the main design variables in a system, and evaluating qualitatively their potential impact on lifecycle performance if changed. For example, de Weck et al. [15] represented the main architectural design decisions for a satellite system with a five design variable vector (e.g. orbital altitude, minimum elevation angle, etc.) They evaluated qualitatively each design variable to determine their impact if changed, as a way to single out a smaller number of candidate design variables for flexibility. Wang [65] used a similar approach to identify candidate flexibilities in the design of hydroelectric dams in China.

**Procedure Evaluation**

As summarized in Table 4, industry guidelines and explicit design variable evaluation are easy to use for enabler identification, as they rely on a quick first-pass analysis of a few core design variables and design principles. This contrasts with DSM methods that are moderately easy to use, because they require data collection and expert interviews before the analysis can be performed, which can be time-consuming and challenging. Given that DSM procedures require a pre-defined system model, there is no clear mechanism to explore enablers lying outside the initial model boundaries, and some may be missed [49]. DSM procedures are basic in terms of usability in a collaborative design process, since they have yet to be suited for this purpose. Explicit design variable evaluation and industry guidelines are better positioned due to their simplicity, hence the moderate assignment. Industry guidelines rely on a strong industry applicability record and literature [3, 23, 53, 66-69].
More applications are needed to demonstrate the benefits of DSM and explicit design variable evaluation, hence the basic assignment.

**Table 4: Evaluation of procedures in phase 3 – enabler identification.**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>DSM-Based</th>
<th>Explicit Design Variable Evaluation</th>
<th>Industry Guidelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>M</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Directly usable in collaborative design</td>
<td>B</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Proven applicability in industry</td>
<td>B</td>
<td>B</td>
<td>S</td>
</tr>
</tbody>
</table>

3.3.4 **Phase 4: Design Space Exploration**

Here, designers explore the design space for the most valuable systems design concepts and decision rules to operate the system, thus initiating the embodiment phase of the design process. Given that engineers often work with high-fidelity models, there is a need for computationally efficient and systematic procedures to speed up the analysis [4]. This phase involves using quantitative procedures to evaluate the concepts, and computational procedures to speed up the analysis. The outcome is a set of recommended flexible systems design concepts providing better lifecycle performance as compared to baseline concepts, with clear lifecycle performance quantification, more precise design specifications, and recommendations in terms of decision rule.

3.3.4.1 **Quantitative Concept Evaluation**

**Decision Analysis**

In decision analysis, a folding back process is used to determine the best design decisions at each stage, based on the development of dynamic programming by Bellman [70]. Starting at the final stage, the decision maximizing expected lifecycle performance is made at each decision point. The folding back process goes backward until the initial stage is reached, where the overall expected lifecycle performance of the system is calculated. The decisions available at each point represent how the system can adapt. In Babajide et al. [71] for instance, a flexible oil platform carefully designed with additional subsea tieback connection slots can expand production capacity, while a rigid system cannot. When oil reserves are higher than expected, the sequence of
decisions reflects the ability to expand revenues as compared to a rigid design, affecting terminal payoffs. The expected value of flexibility is the difference between the expected payoffs of the baseline and flexible designs. Cardin et al. [72] gave another application example in the design of innovative nuclear technology.

**Binomial Lattice**

Binomial lattice analysis is similar to decision analysis, with the exception that in each stage the uncertainty can either go up or down relative to the previous state. The lattice is a discrete formulation of the Black-Scholes formula [73] used to value financial options [44]. To reduce the number of possible outcomes, path independence is assumed, and lattice nodes are allowed to recombine. Path independence means that the value of the system after an “up-down” sequence is assumed the same as after a “down-up” sequence. A similar DP process is applied to quantify the value of flexibility compared to baseline designs. de Neufville [74] used this approach to value the flexibility to abandon a mine pit subject to copper price uncertainty using lattice.

**Simulations**

Here the stochastic scenarios and decisions enabled by a particular design are modeled explicitly. For example, de Neufville and Scholtes [4] quantified the value of flexibility to expand capacity of a parking garage as uncertain demand increases. This differs from building a fixed $n$-floor design based on deterministic demand projections. An initial discounted cash flow (DCF) model was developed to measure the NPV lifecycle performance of each $n$-floor alternative. Demand uncertainty was modeled assuming GBM. One NPV was measured for each scenario, leading to a distribution of outcomes. Flexibility was further integrated using a decision rule capturing how managers would respond to an observed demand scenario (e.g. expand current design by one level if demand exceeds installed capacity for two consecutive years).

**Procedure Evaluation**

As summarized in Table 5, binomial lattice and decision analysis are moderately easy to use for flexibility analysis. Decision analysis is well suited for discrete uncertainty sources, but can also handle continuous stationary, and non-stationary stochastic processes. Different decisions and many uncertainty sources can be modeled. The number of paths can explode quickly, however, making it difficult to go beyond two or three stages. In binomial lattice, mostly continuous processes can be handled. The path independence assumption has the benefit of reducing the number of paths, but this assumption may not be realistic in an engineering context.
Also, both approaches rely on DP, potentially making the procedures unintuitive to practitioners. It is also difficult to model more complex decision rules, since the procedures are better suited to value flexibility akin to financial call (e.g. capacity expansion) and put (e.g. abandonment) options. Simulations, on the other hand, provide much freedom in terms of uncertainty sources modeling, decision rules, design variables, and parameters, hence the strong assignment. It can be more demanding computationally, especially when a high fidelity model is used. In terms of usability in a collaborative design setting, binomial lattice and simulations are not well suited because they are more analytical in nature. Decision analysis is slightly favored because it is simpler, the decision trees are more graphical, and hence better as a way to support collaborative discussions.

For industry applicability, decision analysis has not been used as much as binomial lattice, hence a basic assignment. More case study applications exist using binomial lattice because it emerged from the traditional real options and finance literature [5, 24, 48]. Simulation is already widely used in industry, so even though it has not been used as prevalently for flexibility analysis, the barrier to industry applicability is lower, justifying a moderate assignment.

Table 5: Evaluation of procedures in phase 4 – quantitative concept evaluation.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Binomial Lattice</th>
<th>Decision Analysis</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>M</td>
<td>M</td>
<td>S</td>
</tr>
<tr>
<td>Directly usable in collaborative design</td>
<td>B</td>
<td>M</td>
<td>B</td>
</tr>
<tr>
<td>Proven applicability in industry</td>
<td>S</td>
<td>B</td>
<td>M</td>
</tr>
</tbody>
</table>

3.3.4.2 Computationally Efficient Search

These procedures help designers search efficiently and systematically the design space for the most valuable flexible design configurations, at it may be prohibitively large [2].

Decision-Based Design

Simon [75] developed the basis for design decision-making procedures. Hazelrigg [76] proposed decision analysis and utility theory to evaluate and select design configurations. Olewnik et al. [77, 78] extended Hazelrigg’s framework to incorporate considerations of flexibility in design space exploration. In their
framework, the system design vector is chosen from initial performance requirements. Relevant design variables are made flexible to fulfill these requirements. The process searches for the design configurations providing maximum utility to decision-makers, under budgetary and cost constraints.

**Multi-Attribute Tradespace Exploration**

Ross [79] suggested the MATE framework to explore the design space based on the configurations providing highest perceived value, based on decision-makers’ utility attributes and costs. A Pareto set characterizes the designs of highest utility for each possible cost value. This tradespace can be used to represent transitions from one design state to another, exploring design alternatives via filtered outdegrees. A filtered outdegree represents a design configuration that is changed from a previous design state, and is acceptable to a decision-maker in terms of development time and/or cost. Hu and Poh [80] suggested integrating MATE with set-based concept design to explore the design space more efficiently. Richards et al. [81] extended the framework to epoch-era survivability analysis of space systems. Ross et al. [82] also proposed the MATE-CON, which combines the MATE framework with concurrent engineering techniques.

**Screening Methods**

Jacoby and Loucks [83] were the first to suggest screening methods to shortlist candidate designs and explore the design space efficiently. Screening methods rely on simplified models, optimization algorithms, and design of experiments (DOE) techniques to speed up design space exploration. Three types exist: bottom-up, simulators, and top-down [4]. Bottom-up screening methods use simplified versions of a complex, detailed design model (e.g. [84]). Simulators use statistical techniques (e.g. response surface methodology) and/or fundamental principles to mimic the system’s response (e.g. [85]). Top-down screening methods use representations of major relationships between the parts of the system to understand system responses, as in systems dynamics (e.g. [86]). Wang [65] used screening methods to study hydroelectric dam design in China. Genetic algorithms and/or simulations were used to explore solutions in offshore oil platform design [87], maritime, and water systems [88-90].

**Design Catalogs**

In some cases, it may not be possible or desirable to reduce model fidelity. Cardin et al. [91, 92] proposed an approach based on a small set of representative uncertainty scenarios. Each scenario is associated to the best
flexible design configuration – called flexible operating plan – found using a fractional factorial analysis called adaptive One-Factor-At-a-Time (aOFAT) [93]. This approach leads to the creation of a design catalog of flexible operating plans, which limits the number of optimizations and simulations runs using a high-fidelity model. The method was applied in public infrastructure, real estate, and mining [91, 92].

**Procedure Evaluation**

As summarized in Table 6, all procedures are moderately easy to use for flexibility analysis. The design catalog approach and screening methods are most useful when quantitative performance metrics are involved, whether financial (e.g. NPV) or non-financial (e.g. utility). DBD and MATE are useful when economics is not the only metric of interest. It can be time-consuming to construct the models and/or find the representative scenarios. The design catalog approach has a slight advantage of requiring less computational and analytical resources, and being intuitive conceptually. For DBD and MATE, there are further difficulties in terms of eliciting aggregate preferences, and calculating expected utilities in a design context [94]. One drawback of eliciting aggregate preferences, and calculating expected utilities in a design context [94]. One drawback of eliciting aggregate preferences, and calculating expected utilities in a design context [94].

Table 6: Evaluation of procedures in phase 4 – computationally efficient search.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Design Catalogs</th>
<th>DBD</th>
<th>MATE</th>
<th>Screening Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Directly usable in collaborative design</td>
<td>B</td>
<td>M</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Proven applicability in industry</td>
<td>B</td>
<td>B</td>
<td>M</td>
<td>B</td>
</tr>
</tbody>
</table>

For usability in a collaborative setting, all procedures receive a basic assignment since they focus on quantitative computational analysis. DBD is moderately usable, because it requires inputs from many designers for multi-attribute utility modeling, although this process exhibits several difficulties [95]. In terms of industry
applicability, there is a growing number of studies using MATE in the context of flexibility and other “ilities”, hence a moderate assignment. There is, however, only a handful of industry studies using catalogs [91, 92], DBD [77, 78], and screening methods [65, 84, 85], hence the basic assignments.

3.3.5 Phase 5: Process Management

Phase 5 differs from phases 1-4 because it addresses the social and collaborative setting under which flexibility is generated. It proposes procedures to set favorable conditions for flexibility generation. It proposes research methodologies to reduce barriers to implementation, stimulate creativity, and study agency problems and information asymmetries affecting the value of flexibility. It provides grounds to set and/or understand favorable conditions to go through phases 1-4. The outcome of this phase is a set of recommended conditions and tested procedures for going through all phases most productively. It helps designers consider explicitly how the flexible design concepts can be deployed and managed at a later stage in operations.

The motivation is that managing the design process for flexibility is difficult, in part because it involves many stakeholders. A typical decision requires inputs from senior management or owners to determine what the system should do. Inputs are needed from marketing/economists about policy and market conditions. Designers need this information to craft better designs, and enable relevant flexibility strategies. Operators manage a system crafted through a chain of decisions. They must know what kind of flexibility has been designed, what kind of decision rules was assumed in the analysis, and when it is most appropriate to exercise.

Murman et al. [96] identified a “silo” culture (i.e. task division) in enterprises that may hinder multi-stakeholder thinking about flexibility. There are agency issues and information asymmetries affecting this process, and ultimately the value of flexibility. Decision-makers (e.g. a client company asking a contractor to build an oil platform) may simply not think about flexibility as an important design feature. Design teams, in this case, have no incentive to design for flexibility, especially if it requires more design time and resources. Flexibility may be embedded in the design, but it can be lost when the system is operated, or managers may not know when to exercise it. Also, managers may operate under tight budget constraints, not having the freedom to exercise a real option at the optimal time. For example, owners of the HCSC building exercised the flexibility they had carefully planned for because they remained in decision-making power since its inception. In contrast, the

3 See http://seari.mit.edu/publications.php.
flexibility to expand parking space capacity in de Neufville and Scholtes [4] was never exercised because the new owners did not know was embedded in the design.

**Collaboration Engineering**

Collaboration engineering “studies ways of designing recurring collaboration processes that can be transferred to groups […] using collaboration techniques and technology” [97]. It is motivated by the fact that collaboration may sometimes put barriers to creativity, resulting in productivity loss [98]. Evaluation apprehension, free riding, and production blocking are potential causes of productivity loss. Group Support System (GSS) technology helps minimize productivity loss, and stimulates creativity [52]. GSS is a set of “socio-technical systems consisting of software, hardware, meeting procedures, facilitation support, and a group of meeting participants engaged in intellectual collaborative work” [99]. It is used to identify barriers to implementation. It is useful to capture discussion content, record data efficiently, and structure the design process.

**Game Theory**

This topic has been explored recently to understand how different asymmetries affect the value of flexibility in major infrastructure systems [100-102]. These authors looked into the payoff structures and Nash equilibrium when two actors aim at exercising the same kind of real options over a similar timeframe. For instance, Smit and Trigeorgis [100] showed how information asymmetry and suboptimal timing affect the value of runway capacity expansion real option for two major European airports. Ferreira et al. [102] investigated the payoff structures for two mining companies and valued the flexibility to wait and defer an investment opportunity.

**Serious Gaming**

Ligtvoet and Herder [103] have defined serious games as “experience-focused, experimental, rule-based, interactive environments where participants learn by taking actions and by experiencing their effects through feedback mechanisms that are deliberately built into and around the game” [104]. Mostly used in business schools [105], these techniques are useful in engineering education and practice to understand the cognitive dynamics of design decision-making. For example, Sterman [106] studied the aggregate effects of individual decision-making processes in a simulated supply chain game. Serious gaming techniques can be used to understand agency and information asymmetries arising during the system lifecycle. They can be used to train practitioners and engineering students about the effects of flexibility in design. Serious gaming differs, however,
from game theory because it focuses on studying the dynamics of interactions, as opposed to the payoff structures, and finding Nash equilibrium.

Procedure Evaluation

In Table 7, one sees that all procedures are currently basic regarding ease of use for flexibility analysis. Only a handful of studies show how to use collaboration engineering techniques [51], and game theory concepts [100-102] in the context of flexibility. There is currently no published study combining serious gaming and flexibility besides the one by Cardin et al. [107]. In terms of usability for collaborative design, GSS techniques are specifically devised for such use, hence the strong assignment. They may still face resistance in industry, however, since many enterprises function under a “silo” culture [96]. Game theory and serious gaming can arguably be used to study the best conditions for collaborative design activities, in line with Frey and Dym’s [108] suggestion to study design procedures more thoroughly in an experimental setting. Not enough work exists to warrant better than a basic assignment at this stage. Proven applicability in industry for these procedures is still basic because too few studies exist at this time.

Table 7: Evaluation of procedures in phase 5.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Collaboration Engineering</th>
<th>Game Theory</th>
<th>Serious Gaming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of use for flexibility analysis</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Directly usable in collaborative design</td>
<td>S</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Proven applicability in industry</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

4 Application

This section discusses how to use the taxonomy as a design framework, and provides guidance to potential users. Application to two example engineering systems demonstrates the contexts in which procedures can be used, and support claimed improvements on expected lifecycle performance.


4.1 A Design Framework to Improve Lifecycle Performance

4.1.1 User Guidance

The taxonomy can be used as a design framework to guide designers more systematically. It is recommended to go through all phases to fully analyze an engineering system to achieve the goal of providing better lifecycle performance. Leaving one or more phases may affect the value of flexibility. Although Fig. 2 suggests a sequential flow, designers may go back and forth between phases as the analysis progresses, or explore them in any order suitable. There is no clear-cut termination point dictating the flow from one phase to another. The thinking catalyzed by procedures in one phase may help refine considerations in a previous or subsequent phase.

The taxonomy improves the contributions summarized in Section 3.2 because it merges into fewer principles many phases, elements, or steps suggested by other authors – which arguably makes it easier to use. It includes phases not explicitly considered in other taxonomies or design processes. Unlike existing work, it provides a clear lists of available procedures in each phase, with benefits and shortcomings along three dimensions that are relevant to user guidance in industry and academia.

While the taxonomy used as a systematic process can improve lifecycle performance before a more detailed embodiment analysis, one limitation is to offer no recommendations on the best procedure to use in each phase. This paper points out the characteristics of each procedure, and the conditions in which they are most useful. One cannot claim that a procedure is best for all possible design contexts. Analytical resources available and the objective pursued should dictate what procedure to use in each phase.

For example, a design team with limited time and analytical resources may choose an entirely different set of procedures than a team having more time and resources for conceptual analysis. The former might use a combination of procedures enabling a quick, first-pass analysis, while the latter may elect procedures enabling more detailed analysis. It is left to the design team to identify the procedures better suited in each phase. It is argued, however, that even a quick-pass analysis for flexibility can improve significantly the expected lifecycle performance of an engineering system, as compared to baseline concepts.
4.1.2 Extracting Value from Uncertainty

Flexibility can improve the expected lifecycle performance compared to a more rigid, baseline design. It is not sufficient to desire flexibility, however, one must enable it in the design concretely, and manage it intelligently in operations. Put-like real options (e.g. preparing for early abandonment) reduce the effects from downside scenarios, like buying insurance. Call-like real options position the system to capture better upside opportunities (e.g. preparing for capacity expansion), like buying a call option on a stock. Positioning the system to do better on both sides of uncertainty typically shifts the entire distribution towards better lifecycle performance outcomes, with the net effect of improving the expected value, as described conceptually in Fig. 1. This design philosophy represents a significant departure from typical design thinking focused on optimizing for a set of deterministic point forecasts [2, 21].

The literature on concept generation [109, 110] suggests that the effects of concept generation procedures can be evaluated by comparing the quality, quantity, novelty, and variety of the concepts produced for a particular design problem. It is argued that the taxonomy used as framework also improves the quality, the number of concepts, as well as the novelty and variety of the concepts generated, by using uncertainty as a catalyst for creativity. Phase 1 provides a baseline design as starting point, similar to Pugh’s idea of using a datum to stimulate collaborative design selection [111]. In phase 2, recognizing uncertainty explicitly stimulates concept generation. In phase 3, systematic procedures help increase the quantity, novelty, and variety of design concepts by introducing the idea of flexibility as a way to deal with uncertainty. Other procedures (e.g. DSM-based) help prepare the embodiment phase by identifying where flexibility could be embedded in the system. In phase 4, expected lifecycle performance of each concept is compared against one another and the datum, using modeling tools to pick the concepts with the highest performance — similar to the idea of quality. Procedures from phase 5 help coordinate the overall collaborative effort to minimize value-loss stemming from production blocking, information asymmetry, and other implementation issues. All phases result in a higher quantity of design concepts, with higher quality demonstrated by measuring lifecycle performance and selecting the best concepts in phase 4. This also gives rise to better novelty and variety of concepts because the concepts generated are typically different from the baseline designs in phase 1.
4.2 Example Applications

The following two examples show different combinations of design procedures to analyze different engineering systems. These examples support the claims that 1) the analysis performed by other authors followed a process similar to the framework in Fig. 2 – even though the authors did not explicitly formulate it this way, or because some steps were missing – and 2) the resulting design concepts provided better expected lifecycle performance than the baseline concepts. This section demonstrates that the taxonomy used as a design framework captures effectively the main steps involved in the design process for flexibility.

4.2.1 Example 1: Iridium Satellite System

This example is based on the work by de Weck et al. [15], who revisited the Iridium case study to evaluate whether flexibility could have improved LCC – the main lifecycle performance metric. This analysis is an example relying on relatively quick, first-pass analytical methods for phases 2 and 3, but requiring more analytical resources and modeling in phase 4. Phase 5 was not considered in this ex post study.

In phase 1, the authors determined the baseline design concept based on standard industry practice, trying to match Iridium’s publicly available target communication capacity and LCC. Their analysis led to a baseline concept of fifty satellites along five circular polar orbits, altitude of 800 km, and elevation angle of 5°. Communication capacity was for 80,713 duplex channels. Assuming a 10-years lifecycle, 10% discount rate, 3 million users, and average monthly activity of 125 minutes/month, the expected lifecycle cost of such architecture was $2.01 billion, very close to the quoted development cost [13].

In phase 2, the authors recognized market demand as the main uncertainty driver affecting LCC. Because demand is a continuous diffusion process, they used binomial lattice, assuming GBM.

In phase 3, they chose a flexible staged deployment strategy to deal with uncertainty, based on existing real option strategies [5]. Additional capacity would be deployed only when economic conditions warrant it, instead of rapidly deploying the constellation as done by Iridium [13]. To identify the relevant design variables to enable flexibility, they evaluated explicitly each design variable in a simplified vector representation of the satellite design. They determined that altitude and elevation angle were the design variables that could be adjusted to accommodate different staged deployment strategies. Their strategy required the ability to add more
satellites, and move them on-orbit to increase coverage capacity as demand increases. This would give rise to a design significantly different from the baseline concept optimized for fixed capacity in phase 1.

In phase 4, the authors explored the design tradespace for the best ways of staging and deploying the flexible engineering system. Each flexible design concept was evaluated using lattice analysis as part of an optimizations framework. The authors found that the optimal design path would start with twenty-eight satellites over four orbital planes at 1,600 km altitude and 5° elevation, slowly converging towards a full three hundred and sixty-four satellite constellation over fourteen orbital planes, 800 km altitude, and 35° elevation. They showed that the expected LCC of the flexible system would drop significantly to $1.46 billion as compared to the baseline at $2.01 billion, a 27% improvement. It would reduce initial investment and exposure to downside losses in case of low demand scenarios. Simultaneously, it would defer deployment until sufficient demand would warrant additional capacity, thus benefitting from the time-value of money.

This case study shows that explicit considerations of uncertainty and flexibility as suggested in the taxonomy in Fig. 2 helped 1) generate a different design concept than the baseline, and 2) the concept in turn significantly improved lifecycle performance (i.e. LCC) as compared to the baseline design.

4.2.2 Example 2: Oilfield Development

This example is based on the work by Lin [84] about the development of offshore oil extraction infrastructures in Azerbaijan and Angola by a major oil company. The study was motivated by the lack of an integrated model for flexibility analysis. Separate models existed for financial analysis, physics of oil and gas flow, and subsurface oil reserves analysis. The study was also motivated by the oil firm relying on detailed, high fidelity models for design decision-making. Finding the optimal configuration for one market price forecast, facility availability, and original oil in place (OOIP) scenario required days of computations. Analyzing the system for flexibility considering many scenarios, as well as different deployment strategies was intractable. The idea was to make this analysis more efficient, accessible, and less resource intensive.

Starting from an initial oil platform design, the authors relied on diffusion processes in phase 2 to model uncertainty in market price, OOIP reserve evolution, and facility availability. In phase 3, they relied on real option strategies to choose both phasing and capacity expansion strategies, and relied on designers’ expertise to
M.-A. Cardin, Paper MD-12-1468

enable the flexibilities in design – similar to the prompting mechanism in Cardin et al. [51], although not formalized. They relied on mid-fidelity screening techniques in phase 4 to perform flexibility analysis within reasonable computational time. Although not much detail was provided about phase 5, the authors claimed that the multi-domain uncertainty and integrated modeling frameworks enabled better collaborative work between engineers and decisions-makers in different expertise areas. This approach helped bridge the gap between different domains like finance, platform engineering, and sub-surface engineering.

In phase 1, the authors started from the designs generated from years of experience. Case study 1 involved exploitation of a large oilfield in Azerbaijan for a capacity of up to 180 thousand barrels per day (MBD). Case study 2 involved smaller oilfields in Angola with combined daily production capacity of 150 MBD. Both cases relied on direct vertical access (DVA) platform designs, combined with sub-sea tiebacks to capture oil further away from the DVA platforms. Full capacity deployment was planned at time zero in both design cases. NPV was used as economic lifecycle performance metric to evaluate different design configurations.

In phase 2, three major uncertainty sources affecting lifecycle performance were modeled. OOIP uncertainty was modeled using a reverse Wiener jump-diffusion process. Facility availability was modeled assuming a random walk process to simulate significant disruptive events like hurricanes. Market price uncertainty was modeled assuming GBM and a lattice diffusion model. In phase 3, the authors explored a combination of real option strategies to deal with the above uncertainties. They interviewed designers to identify relevant design variables (e.g. production capacity, facility size, sub-sea tieback connections) to enable the flexibilities in design, and the decision rules to decide when it was appropriate to exercise the flexibilities in operations. In case study 1, an inter-facility flexibility strategy to stage capacity deployment over time was explored. This strategy required deploying 75% of capacity at time zero, and deploying remaining capacity by 33%, 50%, 75%, or 100% depending on reserve estimate evolution. If less OOIP was observed than planned, only 33%, 50%, or 75% could be deployed, depending on observations. This strategy would help reduce initial capital expenditures, thus reducing exposure to downside risks in case OOIP was lower than expected. It would also position the system to capture full production capacity if needed. These flexible strategies were compared to an inflexible baseline design involving 100% capacity deployment at time zero.
In case study 2, the authors explored the flexibilities to connect up to six reservoirs to a centralized production facility (CPF) by means of additional sub-sea tiebacks (inter-facility flexibility). This would enable production capacity expansion at the CPF itself from 150 to 200 MBD (intra-facility flexibility) – without resorting to additional sub-sea tiebacks – while considering the operational flexibility to adjust fluid production rates dynamically. All strategies contributed to the ability to expand production capacity as oil estimates would be ascertained. If OOIP reserves were less than planned, unnecessary investments in additional production capacity would be avoided. The system would also be positioned to capture more oil if OOIP was higher than expected. This approach required carefully designing the platform to connect additional tiebacks as needed.

In phase 4, the design space was explored by developing a mid-fidelity model integrating economics, reservoir oil-gas production flows, and facility type (e.g. floating platform, DVA). The screening approach relied on simplified modeling assumptions from the high-fidelity version. This enabled quicker analysis of many uncertainty scenarios and design configurations. Simulations were used with full-factorial DOE analysis to assess the economic performance of all flexible design alternatives under uncertainty. In case study 1, the four design alternatives described above were analyzed. The flexible staged deployment strategy led to a mean NPV = $3.66 billion compared to the inflexible baseline design at mean NPV = $3.11 billion, an improvement of ~18%. In case study 2, combining inter-facility tieback flexibility with intra-facility capacity expansion and operational flexibility led to mean NPV improvement of up to 257% compared to the baseline inflexible design (financial figures kept confidential).

This case study shows that using the taxonomy as a design framework helped generate new design concepts, and these concepts also improved lifecycle performance compared to the initial baseline designs.

5 Discussion

This section discusses how the taxonomy is used to organize ongoing research efforts. It also discusses needed contributions in each phase, the limitations of the proposed taxonomy, and areas for potential improvements.
5.1 Organizing Ongoing Research Efforts

5.1.1 Developments for Phase 3

To this day, more work has been done in phases 1 and 2 of the proposed process for flexibility. Hence, this section focuses on phases 3-5, which offer more opportunities for ongoing and future research efforts. In phase 3, there is a need for contributions to develop and evaluate systematic procedures to support early flexible design concept generation. This is in line with Frey’s and Dym’s [108] call for more rigorous studies to validate and compare the effect of different design procedures. Many procedures used traditionally for concept generation (e.g. brainstorming, prompting, sketching) can be adapted for flexibility analysis. The work by Mikaelian et al. [8] is in that direction. Similarly, more efforts are needed to develop and evaluate tools to identify areas to embed flexibility. Recent efforts on DSM [28, 60, 61, 64] are along this line. As of now, too many studies rely on single case study demonstration, which makes results difficult to generalize to other systems with good statistical support. Such studies provide one sample point, and typically do not control for other factors that can affect the observed responses. For example, no study has yet compared the effects of CPA, sDSM or Logical MDM on the ability to identify areas to embed flexibility, or the differences in results generated when using MATE vs. the Epoch-Era paradigm. There is only one study [51] comparing directly the effects of different concept generation procedures for flexibility.

5.1.2 Developments for Phase 4

In phase 4, procedures based on decision analysis, binomial lattice, and simulations are relatively mature. Nevertheless, Silver and de Weck [27] proposed recently a new framework for valuing flexibility based on a time-expanded decision network, and shortest path optimization algorithm. More research is needed in phase 4 to develop computationally efficient techniques, and to compare the strengths and challenges associated with existing procedures more rigorously. The work on screening methods [65, 84, 85] requires more effort, as some frameworks may work in some industries, but not in others. More case applications are needed to demonstrate that the frameworks proposed are generalizable. This research area would benefit greatly from translating many of the techniques used in stochastic and robust optimizations, as well as operations research. For example, Kriging [112] can be explored to see whether it improves search efficiency and computational runtime, as compared to other screening methods. More work is needed to elicit flexible decision rules explicitly, and evaluate them quantitatively using computationally efficient search algorithms.
5.1.3 Developments for Phase 5

Phase 5 provides most opportunities for research. Much of the literature currently focuses on how to generate and enable flexibility in design, and how to value it, but little work exists on multi-stakeholder interactions and decision-making dynamics to make it happen. Several modeling techniques in phase 4 assume that the operator knows exactly when it is appropriate to exercise the flexibility under evaluation, or that it is always possible to exercise the flexibility. These assumptions may not be true, and may affect the true value of flexibility. Other barriers to implementation have been identified that prevent best uses of flexibility in public, private, or public-private partnerships, also ultimately affecting the value of flexibility [4, 53, 66, 113, 114]. The procedures in phase 5 provide the setting for studying these issues more rigorously, in an experimental or applied setting.

5.2 Other Limitations and Future Work Opportunities

It is possible that contributions of interest have been left out of this exercise. While the taxonomy is succinct and comprehensive, it is possible that other organizing principles can be found. The meta-analysis found fewer organizing principles than current work by integrating existing contributions, but other principles can be suggested and defended to improve the work. This taxonomy is a first proposal, subject to improvements.

It is possible that the effects of using the taxonomy as a systematic framework in the two example applications were not due solely to applying a similar conceptual process. In the interest of space, only two examples were provided, but more applications showing a similar process would alleviate these concerns. More examples exist for interested readers, who will most likely recognize a similar process as described here.4

An important issue with the study of engineering systems design is that lifecycle can be significantly long (i.e. +20 years). It is difficult to determine the impact of the design decisions made in early conceptual phases. Not many studies provide a clear account of this impact, +20 years hence. It is difficult to support the claims that expected lifecycle performance improvements necessary lead to actual measured performance. A few real-world examples exist nonetheless, and are described in Section 1. Currently, rigorous flexibility analysis – as done in the two example case studies – is the most useful approach to analyze different engineering system designs.

Taxonomies cannot provide a completely reliable guide to authentic engineering systems design work. There is no guarantee every real case will be covered. This is why more research is needed for practical applications of the taxonomy as a design framework. Research is needed to compare the lifecycle performance predicted by the design procedures, how designs actually performed in operations, whether the flexibility was used, and the impact on lifecycle performance. Many case studies have shown that flexibility is a promising approach to engineering systems design thinking. This paper accounts for the work done so far, focusing on main lessons, packaging them as design procedures, showing how they can improve lifecycle performance, and providing further orientations for upcoming research.

6 Conclusion

This paper presents a taxonomy of thirty systematic procedures to enable flexibility in the design of engineering systems. Explicit considerations of uncertainty and flexibility leads to very different designs offering on average better lifecycle performance, as shown in many studies [4, 5, 12, 24, 48]. The taxonomy has five phases: 1) baseline design, 2) uncertainty recognition, 3) concept generation, 4) design space exploration, and 5) process management. It is geared specifically for engineering systems with particular focus on urban systems, for example in the defense, energy, housing, telecommunications, transportation, and water industries. It assembles, organizes, and describes design procedures from the literature on engineering design, manufacturing, product development, and real options analysis. It can also be used as a framework to support design activities. Application on two engineering systems examples shows that it helps produce different designs with better lifecycle performance than the baseline concepts generated in phase 1. The taxonomy can also be used to organize ongoing research developments in this field. It helps researchers identify areas where contributions are needed, and organize their contributions as part of a coherent effort.

The taxonomy addresses the need to organize recent developments in this area of engineering design research into a unified and systematic framework. Currently, there is no clear account of what procedure should be used or taught at what stage of the conceptual design process, and for what purpose. Similarly, it may be unclear what are the strengths and challenges associated with each procedure. The taxonomy addresses these issues. It also calls for more active and systematic involvement from engineering design researchers in the exciting, timely, and multi-disciplinary field of engineering systems design and management. The study of how to enable
flexibility in engineering design is a promising avenue to design and manage complex systems. It has the potential of creating engineering systems offering better performance to society, and a better return on investment.
Acknowledgments

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### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>aOFAT</td>
<td>adaptive one-factor at-a-time</td>
</tr>
<tr>
<td>C-K</td>
<td>concept-knowledge</td>
</tr>
<tr>
<td>CMEA</td>
<td>change modes and effect analysis</td>
</tr>
<tr>
<td>CPA</td>
<td>change propagation analysis</td>
</tr>
<tr>
<td>CPF</td>
<td>centralized production facility</td>
</tr>
<tr>
<td>DBD</td>
<td>decision-based design</td>
</tr>
<tr>
<td>DCF</td>
<td>discounted cash flow</td>
</tr>
<tr>
<td>DP</td>
<td>dynamic programming</td>
</tr>
<tr>
<td>DOE</td>
<td>design of experiment</td>
</tr>
<tr>
<td>DSM</td>
<td>design structure matrix</td>
</tr>
<tr>
<td>DVA</td>
<td>direct vertical access</td>
</tr>
<tr>
<td>ESM</td>
<td>engineering system matrix</td>
</tr>
<tr>
<td>GBM</td>
<td>geometric Brownian motion</td>
</tr>
<tr>
<td>GSS</td>
<td>group support system</td>
</tr>
<tr>
<td>IRF</td>
<td>integrated real option framework</td>
</tr>
<tr>
<td>LCC</td>
<td>lifecycle cost</td>
</tr>
<tr>
<td>LEO</td>
<td>low Earth orbit</td>
</tr>
<tr>
<td>MDM</td>
<td>multiple domain matrix</td>
</tr>
<tr>
<td>MATE</td>
<td>multi-attribute tradespace exploration</td>
</tr>
<tr>
<td>MBD</td>
<td>thousand barrels per day</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
<tr>
<td>sDSM</td>
<td>sensitivity design structure matrix</td>
</tr>
<tr>
<td>OOIP</td>
<td>original oil in place</td>
</tr>
<tr>
<td>UAV</td>
<td>unmanned aero-vehicle</td>
</tr>
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</table>
References


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#### Table 1: Evaluation of example procedures in phase 1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Axiomatic Design</th>
<th>C-K Theory</th>
<th>Concurrent Design</th>
<th>Function-Based Failure Analysis</th>
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<td>B</td>
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<td>B</td>
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<td>S</td>
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Table 2: Evaluation of procedures in phase 2.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Bayesian Theory</th>
<th>Dempster-Shafer Theory</th>
<th>Possibility Theory</th>
<th>Probability Theory</th>
<th>Statistical Analysis</th>
<th>Binomial Lattice</th>
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Table 3: Evaluation of procedures in phase 3 – strategy generation.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Explicit Training and Prompting</th>
<th>Integrated Real Options Framework</th>
<th>Real Option Strategies</th>
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Table 4: Evaluation of procedures in phase 3 – enabler identification.

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Table 5: Evaluation of procedures in phase 4 – quantitative concept evaluation.

<table>
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Table 6: Evaluation of procedures in phase 4 – computationally efficient search.

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Table 7: Evaluation of procedures in phase 5.

<table>
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Figures

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fig2.tiff