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A multidisciplinary overview of the literature and a research plan for the design of flexible engineering systems

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Research Article

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Abstract:

Compared to concepts like optimality and robustness, for instance, flexibility is not yet a fully developed academic notion, despite its widespread use. Nonetheless, flexibility is acknowledged as a crucial quality of a system, a procedure, or an organization; it is required to deal with uncertainty and change and indicates the capacity to adjust to a variety of circumstances. It's noteworthy to note that the idea of flexibility is now where the idea of quality was around 20 years ago: "vague and difficult to improve, yet critical to competitiveness." In this essay, we examine the notion of flexibility as it has been addressed in many academic fields, highlighting the main ideas, difficulties, and constraints in each. We examine flexibility in relation to engineering design, production processes, actual alternatives, and decision theory. Additionally, we provide a critical evaluation of how the term "flexibility" is used and misused in technical literature. Lastly, we provide a number of research topics that may assist develop the notion of flexibility to the level of optimization and robustness in system design and turn it into a measurable technical feature.

Keywords: Design, production systems, flexibility, genuine alternatives, and decision theory

Introduction: flexibility, a popular but not academically mature concept

Flexibility is a widely accepted idea that is often cited as an admirable quality of a system, a procedure, or an organization. Nevertheless, despite its widespread use, flexibility has not gotten the same academic attention and acknowledgment as other

foundational ideas like optimality or robustness (in design or controls). According to Upton (1995), who was also cited in De Toni and Tonchia (2008), the idea of flexibility is where the idea of quality was around 20 years ago: "vague and difficult to improve, yet critical to competitiveness." The idea of flexibility is multidisciplinary and varies depending on the individual. For instance, Sethi and Sethi (1990) found more than 50 definitions of various forms of flexibility in a manufacturing setting and pointed out that these definitions "are not always precise, and sometimes naïve" (p. 289). The capacity or propensity to alter and adapt to a variety of conditions is fundamental to the concept of flexibility (Gupta and Goyal 1989). All disciplines agree that flexibility is necessary to deal with uncertainty and change, and that it entails ease of adjustment and a lack of inflexible or irreversible commitments. Flexibility is harder to monitor and quantify than system performance since it is more about the capacity for change. However, how can one get flexibility? How much does it cost? And what kind of adaptability is necessary in a certain circumstance? Carlson noted the following after reviewing the several definitions of flexibility in the literature on economics and management:

According to the business literature, flexibility seems to be just as significant a factor in determining competitiveness as cost. However, it turns out that there isn't much to be discovered when looking through the economic literature to see what economists have to say about this topic. (1989, page 180)

In a similar vein, Ku (1995) observed that while "the importance of flexibility in planning is widely acknowledged, the concept is rarely defined, much less quantified" (p. 282).

We first searched the academic database Web of Science, which offers references to over 8000 scholarly journals, for publications with flexible or flexibility in their titles or keywords in order to assess the relative popularity and academic maturity of flexibility compared with the concepts of robustness and optimality. This allowed us to determine whether the observations made by Carlson (1989) and Ku (1995) were justified. Next, we looked for optimality or optimal/optimization and robustness or robustness. Following the Web of Science, we looked for the aforementioned ideas online using the well-known search engine Google. The normalized number of instances of these terms on the Internet, a widely used public place, is contrasted with their prevalence in the Web of Science, an academic database, in Figure 1. Flexibility is used twice as often as the notions of robustness and optimality, as seen in Figure 1, although it is used far less in academic contexts than robustness and optimality—2.5 and five times less, respectively.

Although flexibility is a popular term, the data do indicate that it is not as developed academically as robustness or optimality, despite the rough nature of the method.

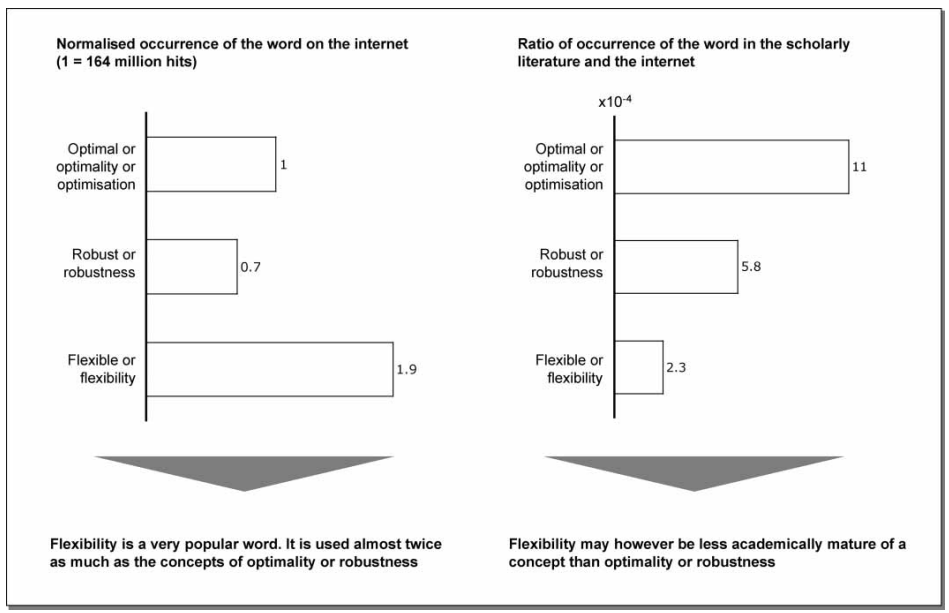


Figure 1. Relative popularity and scholarly maturity of *flexibility* compared with the concepts of robustness and optimality (as

of 1 October 2005).

In this paper, we review the concept of flexibility as it has been discussed in various academic disciplines, highlighting the key themes, difficulties, and constraints in each case: flexibility in manufacturing systems (Section 2.3), real options and managerial flexibility (Section 2.2), and flexibility in decision theory (Section 2.1). Next, we examine the growing body of research on engineering design flexibility (Section 2.4) and make a distinction between design process flexibility (Section 2.4.1) and design flexibility (Section 2.4.2). Additionally, we address the connection between the ideas of robustness and flexibility in system design (Section 2.4.3) and provide a critical evaluation of the misuse of the term flexibility in the literature (Section 2.5). Lastly, we suggest a number of study topics to go further into design flexibility difficulties.

Our ultimate goal is to assist in making flexibility a measurable engineering quality and to develop this idea to the point of system design robustness and optimization.

Flexibility: a multi-disciplinary literature review

Flexibility in decision theory

A framework for flexibility in the context of decision theory is developed by Mandelbaum and Buzacott (1990). They examine a two-period decision issue where A and B are sets of decisions made during the first and second periods, respectively. The remaining options in the second period are limited to a subset of B, $B(a) \subseteq B$, after a selection is taken in the first period, $a \in A$. Mandelbaum and Buzacott (1990) defined flexibility as the number of possibilities that remain available in the second period after a decision made in the first. To put it another way, flexibility is the amount of options that remain after a first commitment is made (see Figure 2); more options indicate more flexibility. This measure of flexibility was really initially proposed by Gupta and Rosenhead (1968). They utilized the example of a consumer products firm that is growing and researching how many additional facilities should be constructed and in which locations as a case study to highlight flexibility in the context of sequential investment choices under uncertainty. Over a period of five to fifteen years, the authors took into account a series of investment choices regarding the quantity of plants and places. They quarreled

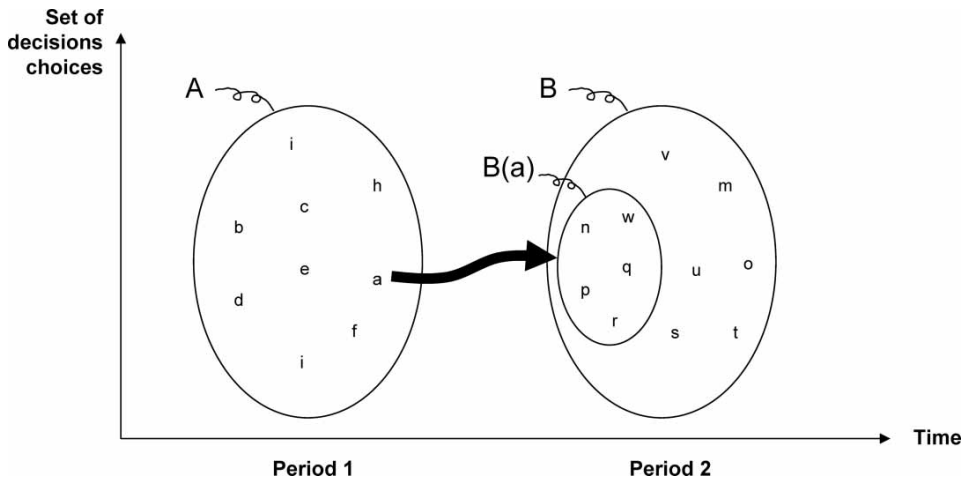


Figure 2. Following a decision in period 1, here decision *a*, flexibility in decision theory is related to the remaining choices available in the second period, here *B(a)*. The larger this set, the more flexibility the decision-maker retains. This idea can be generalised to staged choices over multiple periods.

that when there is appreciable uncertainty in market conditions, it is important to ensure that initial investment decisions do not limit the choices of future investments. In their words:

Rather than try to identify the best alternatives, we can ensure that our early investment decisions permit the achieve-ment of as many end-states as possible. Subsequent stages of the investment plan are left to be determined at later dates, when more recent information is available [.. .]. In the context of our discussion, flexibility of a decision must be measured in terms of the number of end states which remain as open options [after a first decision is made]. (Gupta and Rosenhead 1968, p. B20–B21).

The results and mindset advocated by Gupta and Rosenhead (1968) have found strong support in the growing literature on real

options and managerial flexibility, as we discuss in the next subsection.

Real options and managerial flexibility

It is no surprise that management scholars and practitioners have been strongly interested in flexibility as it pertains to resource allocation and planning under uncertainty. A growing literature addresses the concept of flexibility in relation to investment decisions and market uncertainty. The argument within this literature goes as follows. Today's markets are often characterised as hyper-competitive (Fricke *et al.* 2000). Uncertainty and volatility are the main attributes of such markets in which important information needed to make investment decisions is either not known, or known to change with limited predictability (e.g. competitors' moves or intentions, fast-changing technology base, market upheavals). The best course of action, or investment plan, developed today – and which commits resources for a long period of time – based on the current information about market conditions may prove inadequate as the future unfolds (Amram and Kulatilaka 1999). Assumptions on which management plans were based may be invalidated shortly after these plans are rolled out (Evans 1991). Flexibility is introduced in this context as a way of dealing with market uncertainty, and it characterises both management and the project itself.

Managerial flexibility is defined as the ability of management to adjust the course of a project by acting in response to the resolution of market uncertainty over time (Trigeorgis and Mason 1987, Amram and Kulatilaka 1999). Evans (1991) makes the case that 'organizations seek flexibility in order to increase the speed and extend the scope of maneuver' (p. 74). In other words, managerial flexibility reduces a project's exposure to market uncertainty (Saleh *et al.* 2003b).

Projects or investments plans are characterised as flexible if they contain contingent decisions that allow both downside protection against future negative market conditions (should market uncertainty unfold unfavourably), and growth opportunities should market uncertainty be resolved favourably (Triantis and Hodder 1990, Faulkner 1996, Trigeorgis 1996).

On a parallel note, a plan of action is called rigid if it contains few contingent decisions, and called flexible if it contains many such decisions. Plans made long in advance of the 'action' are normally associated with rigidity. Hence, flexibility in this context implies remaining uncon-strained to the extent of allowing oneself some leeway to adopt ways of dealing with unforeseen developments (Rappaport 1969).

A growing body of literature within the resource allocation and managerial context, called Real Options and based on the options

theory in finance, is focused not on flexibility *per se*, but on the financial value of flexibility. It is important to note the difference between the value of an attribute, here flexibility, and the measure of that attribute. For example, how reliable a system is differs from how much its reliability is worth. Similarly, while Real Options calculates the value of project flexibility in a managerial context,[1] it does not address the measure of flexibility, nor is this literature focused on how to embed flexibility in a project or an engineering design. Several authors, in their attempt to bring the Real Options mindset to engineering design, fail to recognise this distinction between the value of an attribute, such as flexibility, and the measure of that attribute (for example, Nilchiani *et al.* 2005). Consider the following: in his Nobel Lecture,

Robert Merton, who received the Nobel price in economics in 1997 with Myron Scholes for their work on option pricing, described the purpose of option pricing and the relationship between uncertainty and flexibility in the following terms: 'The future is uncertain, and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value. Option-pricing theory provides the means for assessing that value'. Merton (1997, p. 339) describes a positive correlation between uncertainty and the value of flexibility. But 'how much is flexibility worth? A lot if uncertainty is high' (Copeland and Keenan 1998, p. 7). The Real Options literature provides a way of calculating the financial value of flexibility. In summary, the Real Options literature focuses primarily on capturing the financial value of managerial flexibility (e.g. flexibility of delaying or of staging an investment decision). Its applicability to engineering design, as has been recently proposed (Markish and Willcox 2003, Saleh *et al.* 2003a, de Weck *et al.* 2004), is useful but limited: it is useful on the one hand because it provides one important element in the design trade-offs, namely the financial value of having options; it is limited on the other hand because it cannot address the interesting engineering problems of how to design these options – or embed flexibility – in the system, and how to trade them against other system attributes such as performance, risk, and cost.

For more information on real options and managerial flexibility, the reader is referred to the excellent introductory book by Amram and Kulatilaka (1999), or the more analytically advanced work by Trigeorgis (1996).

Flexibility in manufacturing systems

In addition to decision theory and real options, manufacturing is another area that is strongly associated with issues of flexibility. Research on flexibility in manufacturing systems has grown dramatically over the past 30 years. The major focus of the literature is

on defining and classi-fying different types of flexibility for manufacturing systems (for example, Browne *et al.* 1984, Carter 1986, Sethi and Sethi 1990, De Toni and Tonchia 1998, Koste and Malhotra 1999). In the following, we briefly review a handful of these definitions and highlight the major topics in this literature.

Flexibility in this area is generally accepted to be an attribute of a manufacturing system that is capable of changing in order to deal with uncertainty and a changing environment (Sethi and Sethi 1990). Flexibility thus implies an ability to reconfigure manufacturing resources in order to continue producing efficiently different products in response to, or to preempt, changes in the system's environment (Gupta and Goyal 1989, Sethi and Sethi 1990, De Toni and Tonchia 1998). One of the earliest papers we found that touches on manufacturing flexibility was written by an economist, George Stigler (who won the Nobel prize in economics in 1982), and published in the *Journal of Political Economy* in 1939. In discussing production theory, Stigler suggests a difference between flexible and non-flexible plants, and proposes that a flexible plant has a cost curve (as a function of production output) that is flatter than that of a rigid plant. In other words, a flexible plant can accommodate output fluctuations with a smaller cost penalty than a non-flexible plant. In addition, Stigler argues that flexibility is to be sought when there is demand uncertainty for the produced good, but that it will not be 'a free good' (Stigler 1939):

So far we have tacitly assumed that technology dictates a single most desirable arrangement of the fixed plant which is independent of fluctuations in output. In fact, this is rarely, if ever, true. Adaptability can also be built into a plant, and entrepreneurs in trades where fluctuations are frequent will endeavor to secure flexibility in their operations. But flexibility will not be a free good: a plant certain to operate at X units of output will surely have lower costs at that output than a plant that is designed to be passably efficient from X/2 to 2X units per week. (Stigler 1939, pp. 310–311)

Stigler was in fact discussing what later came to be called 'volume flexibility' in manufacturing systems, which we will discuss shortly. The last sentence in the previous paragraph indicates a tension between flexibility and optimisation in system design, a point that we will revisit in the following sections.

Another important point that Stigler makes in the paragraph above, which was expanded upon by many subsequent researchers, is the connection between flexibility and uncertainty. Flexibility is needed in order to cope with uncertainty; uncertainty in turn may exist for 'the level of demand, product prices, product mix, and availability of resources; it may arise out of actions of com-petitors, changing customer preferences, technological innovations, new regulations, etc.' (Sethi and Sethi 1990, p. 295). Recently, Shi and

Daniels (2003) presented flexibility as a hedge against uncertainty in rapidly changing environments that are the 'inevitable consequence of complexi-ties generated by technological advances' and changing customers' preferences and needs. Since different uncertainties exist, different types of flexibility have been defined. There are over 50 different types of flexibilities defined in the manufacturing literature (Sethi and Sethi 1990). It is important to note, however, that these definitions are not standardised or widely accepted. In the following, we review a handful of these definitions.

Volume flexibility, for example, is defined in relation to uncertainty in the level of demand for a product, and is considered to be 'the ability of the system to accommodate shifts in
volume for a given part' (Gupta and Goyal 1989, p. 132). Similarly, Sethi and Sethi (1990, p. 307) define volume flexibility of a manufacturing system as 'its ability to be operated at different output levels'. Browne *et al.* (1984, p. 15) introduce into the definition a notion of cost-effectiveness: 'volume flexibility is the ability to operate efficiently a manufacturing system at varying production volumes'.
Routing flexibility is defined as the ability to produce the same part either on different machines, or through a different sequence of operations, or by alternate routes through the manufacturing
system (Sethi and Sethi 1990). For Gupta and Goyal (1989, p. 121), the definition of routing flexibility is restricted to 'the ability to vary machine visitation sequences, for example in the case of breakdowns, and to continue producing the given set of part types'.
Expansion flexibility of a manufacturing system is defined as the ease with which its productive capacity can be increased (Sethi and Sethi 1990). Unlike volume flexibility, expansion flexibility
is concerned with the maximum feasible output level, not fluctuations in production schedule.
Product mix flexibility is defined as the ability to manufacture a variety of products without major modification of existing facilities (Slack 1983).

Alternatively, Sethi and Sethi (1990, p. 302) define product mix flexibility as the 'set of part types that a manufacturing system can

produce without major setups'.

Different types of flexibility are not necessarily correlated. In other words, being flexible in one respect (or having one type of flexibility, e.g. routing flexibility) does not imply being flexible in other area (e.g. volume flexibility). Upton (1995) conducted empirical studies of manufacturing flexibility, and documented this lack of correlation between various types of flexibility in a manufacturing context: 'Just because a plant is flexible in one way doesn't mean it will be flexible in another' (Upton 1995, p. 77).
In addition to the above definitions, and a host of others not discussed here, we find in the literature other classifications for different types of flexibility in manufacturing systems. There are, for example, discussions of operational or tactical flexibility (Barad and Sipper 1988) and strategic flexibility (Evans 1991, Koste and Malhotra 1999). The former refer to flexibility at the machine level whereas the latter refers to flexibility at the plant or business unit level. Koste and Malhotra (1999) provide an interesting representation of the hierarchy of different types of flexibility, from machine and material handling flexibility, to shop floor flexibility, plant level flexibility, and strategic business unit flexibility. It is generally agreed that strategic flexibility is achieved through a combination of factors that include technical considerations, operating policies, and management practices (Gupta and Buzacott 1989). In addition, there is consensus that manufacturing flexibility is not an improvisation or a one-time consideration, but must be carefully thought out, planned for, and continuously managed (Sethi and Sethi 1990).
In summary, the literature on manufacturing systems recognises that flexibility provides com-petitive value to the manufacturer, and that this value is intrinsically related to the ability to deal with uncertainty in its various manifestations.
One difficulty noted in this literature is how to measure flexibility. Since flexibility indicates an attribute of a manufacturing system, it is a potential that is not observable under nominal operating conditions. Gupta and Goyal (1989, p. 134) noted that 'a single all encompassing measure of flexibility has yet to be developed', and more recently De Toni and Toncha (1998, p. 1605) lamented that 'notwithstanding the importance and constant interest raised by flexibility in academic and managerial circles, the measure of flexibility is still an under-developed subject'. For further information, the interested reader is referred to the excellent review of flexibility in manufacturing systems by Sethi and Sethi (1990), to the work by Gerwin (1987) on defining an agenda for research in this area, and to Raouf and Ben-Daya (1995) for technical developments
in flexible manufacturing systems.

Flexibility in engineering design

In recent years, an emerging literature has proposed to bring the concept of flexibility to the realm of engineering system design. This literature has been driven to a large extent by academics affiliated with mechanical and aerospace engineering departments whose research revolves around issues of multi-disciplinary (or multi-objective) design optimisation. In the following, we briefly review this literature and highlight its major themes.

The literature on flexibility in engineering design addresses two distinct problems: the first one focuses on the flexibility of the design process, and the second one on the flexibility of the design itself (not the process through which a product or a system is designed). This distinction between the flexibility of the process and flexibility of the design is not often made in the literature, and it sometimes adds to the confusion in this emerging literature. We believe it is important to make this distinction because these two types of flexibility are considerably different and are achieved through different means, as will be shown shortly.

Flexibility in the design process

Researchers investigating flexibility in the design process have developed various methods for dealing with uncertainty in requirement specification in the early stages of design. Typical approaches have consisted of incorporating designers' preferences with degrees of satisfaction in specifying design requirements. Thurston (1991), for example, uses utility theory-based pref-erence functions to express designers' preference over single or multiple attributes. Wallace *et al.* (1996) define specification functions to indicate the subjective probability that perfor-mance levels are achieved. Mohandas and Sandgren (1989) recommend the use of fuzzy goals to model the degree of satisfaction level. These approaches, along with others such as the interval methods and probabilistic-based methods, were developed, according to Chen and Yuan (1999, p. 77), in response to the following concern: 'How does one capture the uncertainty – which characterizes the early stages of design – and offers flexibility in specifying the design require-ments so that the designs that are marginally outside the precise level of performance are not worthless?'.

One aspect of flexibility in the design process therefore entails expressing degrees of desirability in specifying design requirements. A report by the US Government Accountability Office on *Best Practices* in requirements specifications (General Accounting Office 2001) echoes this description and emphasises the need for *flexible* behaviour on behalf of the customers and developers in setting

requirements:

Flexibility in setting requirements is key to closing gaps between customer expectations and developer resources. While knowledge is essential to identifying gaps between expectations and resources, it takes *flexibility* on part of both the customer and the product developer to close the gaps. Flexibility represents the customer's ability and willingness to lower product expectations, coupled with the product developer's willingness and ability to invest more resources to reduce technical risks and other gaps before program start [.. .]. In successful cases, requirements were flexible until the decision was made to commit to product development [.. .]. This made it acceptable to reduce, eliminate, or defer some customer wants so that the product's requirements could be matched with the resources available to deliver the product within the desired cycle time. (General Accounting Office 2001, p. 46)

Chen and Lewis (1999) propose a slightly different understanding of flexibility in the design pro-cess, which is focused on the interaction between different teams engaged in a multi-disciplinary design endeavour:

Our aim is to provide flexibility in the design process [.. .]. By flexibility we mean that instead of looking for a single point solution in one discipline's model, we look for a range of solutions that involve information passing between multiple players (disciplines). (Chen and Lewis 1999, p. 382)

The authors proposed an interesting extension of the robust design methodology, or Taguchi's method (Taguchi 1987, Phadke 1989), in which teams working on different subsystems of a passenger aircraft do not overly constrain each other early in the design process: 'With this flexibility in the design [process], freedom of individual disciplines, especially the ones that take a follower's role, could be significantly improved. Ultimately, this process will result in better products in less time because fewer iterations are needed' (Chen and Lewis 1999, p. 982).

In summary, flexibility in the design process is the opposite of rigidity in specifying require-ments during the early phases of a design. It denotes a willingness and an ability to accommodate requirement changes during the design process (i.e. before the system is fielded), and it charac-terises either the interaction between the customers and designers – as in the case of the General Accounting Office (2001) analysis – or between different teams of designers working on separate subsystems of a complex engineering design – as in the case discussed by Chen and Lewis (1999).

Flexibility of a design (or flexible systems)

A increasing corpus of study has lately examined the flexibility of a design or a system in addition to the work on flexibility in the design process. For instance, Olewnik et al. (2004) suggested a concept for a flexible racecar, while Mark (2005) looked at methods to use flexibility in the design of an unmanned aerial vehicle. The term "flexibility of a design" has varied meanings for different academics. This variety of definitions shouldn't be seen as a barrier to this field's current expansion. Instead, it is important that the suggested definitions be precise, unambiguous, and produce beneficial outcomes. The most practical definition that permits a quantitative evaluation of a design's flexibility and offers helpful guidance on how to incorporate flexibility into a design and trade it against other attributes (cost, performance, risk, etc.) can only be agreed upon by researchers in light of these findings.

According to Suh (1998), a system is considered flexible if its functional needs change over time. According to Suh's axiomatic design theory (Suh 1990), modifications to the system's design variables enable flexible systems to satisfy various functional requirements at different times: "When the set of FRs (functional requirements) changes, the corresponding DPs (design parameters) must be selected anew" (Suh 1998, p. 19). Suh (1998) does not address the work required to adjust these design parameters in order to meet the functional requirements that change over time. A concept of efficiency in altering the design parameters is added to the definition of Suh by Roser and Kazmer (1999); they describe .According to Roser and Kazmer (1999, p. 1), flexible designs are those that may "change performance while requiring minor time and cost to change the design parameters." Saleh et al. (2003b, p. 934) define flexibility as "a property of a system that allows it to respond to changes in its initial objectives and requirements – both in terms of capabilities or attributes2 – occurring after the system has been fielded, in a timely and cost-effective way." This definition builds on Roser and Kazmer's definition as well as other definitions of flexibility in manufacturing systems. This definition's corollary is that a flexible system can be readily adjusted to meet various needs at various times. This relates to Suh's definition of the system's time-varying requirements and Roser and Kazmer's definition of efficiency in modifying the design parameters.

Beyond definitions, however, how is flexibility included into system or product design? Unfortunately, unlike the theory of robustness in feedback control systems (see, for instance, Ackerman 1993, Doyle et al. 1992) or robust design (Taguchi 1987, Phadke

1989), both disciplines have a wealth of theoretical and practical results. However, there is currently no coherent set of results that shows how to incorporate flexibility into engineering system design or how to assess and trade it against other system attributes like performance, risk, or cost. However, a rising body of literature has started to address some of these problems. As we will soon explore, this literature focuses on platform architecture, modularity, and certain trade-offs between performance and commonality in multi-disciplinary optimization.

Flexibility has historically been linked to platform design and modularity (as an intuitive or self-evident reality, but there is little theoretical support of this). Generally speaking, a product platform "can be easily modified through the addition, substitution, and exclusion, of modules to realize a module-based product family" (Simpson et al. 2001, pp. 2, 3), giving the product or product family flexibility. According to Simpson et al. (2001, p. 3), a product platform is "the set of common parameters, features, and/or components that remain constant from product to product, within a given product family." A product family is described as a "group of related products that is derived from a product platform to satisfy a variety of market niches" (Simpson 2003, p. 1).

The mass customization paradigm of the late 1980s gave rise to product platform design theory (Da Silveira et al. 2001). Davis (1989) first used the phrase "mass customization" to describe the capacity to provide highly varied goods that are suited to the requirements of various consumer segments. The creation of product families, which include a platform shared by all goods and a collection of alternatives from which a line of variations may be effectively generated, is often used to accomplish mass customization. Businesses are able to take advantage of economies of scope and save costs because of the product platform's flexibility, or how easily it can be modified to create product variants that meet various consumer wants and requirements (Gonzalez-Zugasti et al. 2001). Two fundamental strategies have been used by designers to create product families. Selecting a representative design parameter that may be scaled to generate variations is one strategy (Simpson et al. 2001). Creating a modular product architecture that can be effectively changed by exchanging modules is the alternative, more popular strategy (Robertson and Ullrich 1998, Tu et al. 2004). The reader is directed to Jose and Tollenaere (2005) and Simpson (2003) for two outstanding evaluations of the product platform literature that provide a comprehensive overview of the current definitions and methodology in the product family literature.

In conclusion, to use an example from electrical engineering, the concept of design flexibility may be seen as the opposite of a system's resistance to change. A flexible system is one that has been created with certain features, such as extra design parameters, design margins, or a specific architecture (platform/modular, or other). In the context of optimizing the system for the current mission (or set of requirements) for which it is being deployed, certain features may not be required or justified (Mark 2005). But these features will make it simple to change the system if these .The design is adaptable because requirements change after it has been deployed. Changes in requirements may be known or unforeseen in advance.

Flexibility and or versus robustness in design?

The words flexibility and robustness are sometimes used interchangeably, or it is assumed that one provides the other or is subsumed under the other. Chen and Lewis (1999, p. 984), for example, discussed the 'concept behind Type II robust design for providing flexible solutions', while Pye (1978, p. 215) defined robustness as 'a method for trading flexibility against expected value'.

We believe that such definitions are confusing if applied to engineering design, as we will argue shortly.

Mandelbaum (1978, p. 17) defines flexibility as the 'ability to respond effectively to changing circumstances'. He correctly identifies two ways of 'responding' to changes: he entitled the first one 'action flexibility', or taking action to meet new circumstances; and the second one 'state flexibility', which he defines as the capacity to continue functioning despite changes in the environment – that is, a resistance to change (Ku 1995).

The confusion lies in what Mandelbaum (1978) calls 'state flexibility', and which is more akin to robustness than flexibility. Both robustness and flexibility of a design refer to the ability of a system to handle change. However, what is different in each case is the attitude to this change (what is changing, and how is the change dealt with):

Robustness of a design is the property of a system that allows it to satisfy a *fixed* set of require-ments, *despite* changes in the environment or within the system (or noise factors). In other words, robustness implies de-sensitising the system's performance or quality characteristics to

changes in the system environment, or within the system. Ku (1995) described robustness as 'a resistance or immunity to change'.

Flexibility of a design, on the other hand, implies an ability to satisfy *changing requirements* after the system has been fielded. These

changes in the system's requirement are driven by
changes in the system's environment, as we discussed in Section 2.4.2. Flexibility thus implies an ability of the design to be changed in order to track requirement changes.

Flexibility and robustness are thus separate characteristics of a design. The following thought experiment may help further clarify the distinction between these two concepts. Imagine (being capable of) designing a spacecraft for 50–100 years. Two major challenges in striving for such a spacecraft lifetime are the following (Saleh *et al.* 2003b):

Maintaining on-board functionalities after launch, despite changes in the system environment (e.g. from transfer orbit to planetary capture), or despite changes in spacecraft characteristics
due to radiation impacts, malfunctions, and aging. This is indicative of the need for robustness of the design; that is, robustness has to be built into the spacecraft.
Creating new functionalities on-board after launch, as events unfold, new environments are explored, and/or new data become available. Such changes are likely to happen given the
extensive spacecraft design lifetime (if the spacecraft cannot accommodate them, it will become useless and obsolete). This is indicative of the need for flexibility of the design; that is, flexibility has to be embedded in the spacecraft.

We hope this discussion disentangled the concepts of robustness and flexibility, and showed that they are distinct attributes of a system or a design.

Critical assessment: the use and abuse of the word flexibility
This brief multi-disciplinary literature review of the concept of flexibility is not meant to be exhaustive. There are other disciplines that have grappled with this concept; for example, labour markets – with flexible workforce in terms of time commitment or skills (Esping-Andersen 1999) – and organisational science (Mintzberg 1979).
In an interesting article entitled 'The Magic Word Flexibility', Kickert (1985) criticises the over-use of the word 'flexibility' as a

silver-bullet solution to a variety of problems in industrial and government organisations. He convincingly shows that 'it is rather gratuitous to propose the magic word flexibility as a solution to various problems, as the concept appears to be [still] unclear, to put it mildly' (Kickert 1985, p. 28). We partly agree with Kickert, and hope that the literature review provided here makes a convincing case that flexibility without further qualification, that is without characterising the context and uncertainties it is meant to deal with, remains ill-defined and more apt to confuse a problem rather than to clarify a solution. In addition, we believe that what matters, whether in a managerial or engineering context, is to demonstrate how to operationalise flexibility (i.e. how to achieve it in a given context); and this is likely to be significantly different depending on the domain of applicability.

Consider the following parallel in language use and connotation conveyed by the words flexi-bility and optimal/optimised. When one says that a system is optimised or optimal, the statement conveys an intuitive understanding that the system is *best* at what it does. However, upon further examination, the statement 'the system is optimal' is ill-defined and can lead to a suboptimal use of the system unless one specifies the objective function or what the system is optimised for. For example, an unmanned aerial vehicle optimised for speed and aggressive manoeuvring will have a different design from an unmanned aerial vehicle optimised for endurance. In addition, the former will not be 'optimal' if used *in lieu* of the latter (Mark 2005). Similarly, flexibility has a compara-ble potential for confusion. When one says a system is flexible, the statement conveys an intuitive understanding that the system can be easily modified to do other things than those for which it was designed. However, the statement 'the system is flexible', just like 'the system is optimal', remains ill-defined unless one specifies what the system is flexible with respect to.[3] This can be accomplished either by stating the type of uncertainty that the system can deal with, or the range of output that it can deliver. For example, in a manufacturing context we have discussed 'volume flexibility' as the ability to deal with uncertainty in the level of demand for a given product. But having volume flexibility does not imply that the production line also has 'routing flexibility' (see Section 3.3).

In summary, if Upton (1995, p. 75) is correct in his assessment that flexibility is 'vague and
difficult to improve, yet critical to competitiveness', then it might help as a first step to be more precise in the use of the word, especially in the context of engineering design.

Research agenda for designing flexible systems

Our objective from this multi-disciplinary review of flexibility, as articulated in the introduction, was to provide the background and context necessary to transform flexibility into a quantifiable engineering attribute and grow this concept to the level of maturity of optimisation and robustness in system design. Based on the discussion in the previous two sections, we propose the following:

What is flexibility of a system design? It is a property of a system that allows it to respond to changes in its initial objectives and requirements – both in terms of capabilities or attributes – occurring after the system has been fielded, in a timely and cost-effective way.

When and why is flexibility needed? System flexibility should be sought when the uncertainties in a system's environment are such that there is a need to evolve the system after it has been fielded in order to mitigate market/environment risks, and when the system's technology base evolves on time scales considerably shorter than the system's design lifetime, thus requiring a solution for mitigating risks associated with technology obsolescence.

How can the design community tackle flexibility problems? Traditionally, system optimisation has sought to identify the 'best' point design given a fixed set of requirements for the entire lifetime of the system. Progress in design flexibility will be made when this principle is relaxed

– of deterministic optimisation over a single period – when requirements are allowed to evolve stochastically over the lifetime of the system, and when design optimisation is carried out over multiple periods of operation of the system (with multiple sets of requirements). In short, design flexibility can be accomplished when provisions to evolve the system after it has been fielded are embedded in the initial design of the system, and are derived systematically and analytically (see Figure 3a, b).

In the following, we propose three broad research themes, based on our literature review, to further investigate issues of design flexibility. We believe the answers to these questions will prove useful contributions to the engineering design community.

Optimising, satisficing, and design flexibility

Since Dantzig published his work on linear optimisation in 1947, and later in 1955 (Dantzig 1955), which generalised his earlier

method and included linear inequality constraints, optimisation has become a favourite paradigm for decision-making and rational choice in a number of disciplines, including engineering design. Optimisation today consists of a set of mathematical techniques (e.g., linear, non-linear, and integer programming) for determining the 'best' choice (or design) out of a set of alternatives and a given set of constraints: 'a decision-maker who chooses the best available alternative according to some criterion is said to optimize' (Simon 1987, p. 243).

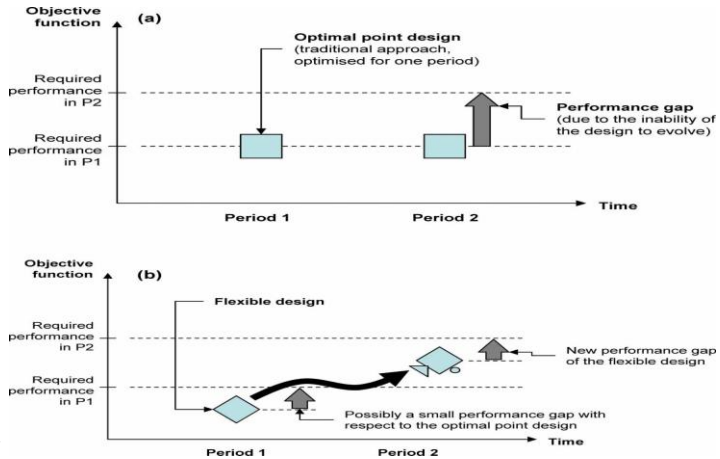
Optimisation, however, 'is not the only paradigm for rational choice [.. .]. Simon (1955) intro-duced the concept of a satisficing decision as one that, although perhaps not optimal, meets minimum requirements or is *good enough*' (Goodrich *et al.* 1998, p. 763). Satisficing is thus an alternative theory of choice, often contrasted with optimisation theory (Winter 2000), and by which one seeks to find a solution (or a design) that:

meets or exceed specified criteria, but that is not guaranteed to be either unique or in any sense the *best* … [The contrast] is between looking for the sharpest needle in a haystack' (optimizing) and 'looking for a needle sharp enough to sew with' (satisficing). (Simon 1987, p. 244)

The concept of satisficing has been put forward because in 'most real-word situations, genuine optima, maxima or minima, are simply not computable within feasible limits of effort' (Simon 1987, p. 244).

Given this brief background on optimisation and satisficing, it is fair to ask how flexibility relates to optimisation and satisficing in the context of engineering design. Are flexibility and optimisation competing paradigms for system design? Is flexibility obtained at the cost of some performance penalty, and do flexible designs/systems exhibit a performance gap compared with the alternative optimised designs/systems? If this is the case, then what drives the dynamics along the performance gap, and how can designers trade flexibility for performance penalty? Similarly, one can ask what is the relationship, if any, between flexibility and satisficing as alternative theories of choice?

In a formal sense, however, optimisation and satisficing are not competing theories of choice. A process of satisficing can always



be converted into an optimisation problem by

Figure 3. (a) Optimal point design: optimisation over a single period and the resulting performance gap should require-ments change in a second period (represented here as a simple change in required performance for visualisation). Compare with Figure 3b. (b) Flexible design: design evolution and the resulting performance gap in the second period. the latter's objective function and including in it the cost of the search (Simon 1987). Would the same apply for flexibility? Are flexibility and optimisation truly competing paradigms for system design, or can the former, flexibility, be obtained by appropriately modifying the objective function of the latter?

Flexibility, durability or design lifetime, and obsolescence

Another research theme that we believe is interesting and useful to explore is the relationship between design flexibility and the concepts of (system) obsolescence and durability or lifetime.

Consider the following. Complex engineering systems are being designed and fielded for increasingly longer lifetimes. Over the past two decades, communications satellites for exam-ple have seen their design lifetime increase on average from seven to 15 years (Saleh *et al.* 2002).

This trend can be explained by converging engineering and economic considerations. On the one hand, technical advances have enabling this increased durability and life extension; for example, in the satellite industry, improved battery technology and power amplifiers, among other things, have enabled the life increase from seven to 15 years. On the other hand, financial pressure to maximise return on investments in capital assets often forces engineers to design increasingly longer-lived systems.

Unfortunately, fielding systems with longer lifetime increases the likelihood or the risk that these systems will become obsolete, technically[4] or commercially,[5] before the end of their lifetime. George Terborgh, in 1949, articulated an insightful, albeit dramatic, description of the issues hindering system's lifetime:

[Machines] live out their mortal span in an atmosphere of combat, a struggle for life. [They] must defend themselves in a world where species spring up overnight, where the landscape is never twice the same, where the fitful winds of change are never stilled. [In the world of engineering systems] death comes usually by degrees, through a process that may be described as functional degradation. It is a kind of progressive larceny, by which the ever-changing but ever-present competitors of an existing machine rob it of its function, forcing it bit by bit into lower grade and less valuable types of service until there remains at last nothing it can do to justify further existence. (Terborgh 1949, p. 16)

In other words, engineering systems are constantly faced with changes and unpredictability in their environments, as well as functional aggression from competing products. All this tends to hustle a system towards obsolescence and shorten its useful operational life (Saleh 2005). System obsolescence and retirement can therefore be attributed to the inability of said systems to meet changing mission requirements resulting from changing environments (Mark 2005). This suggests a correlation between the concepts of (system) obsolescence, durability or lifetime, and flexibility in system design: If flexibility is the ability of a system to be easily modified to accommodate requirement changes, then flexibility can be conceived of as the antidote to obsolescence – or the system characteristic by which the slip into obsolescence is postponed. As a corollary of this observation, from an analyst's perspective, flexible systems can therefore outlive more 'rigid' (or optimised?) designs. Conversely, from a designer's perspective, flexibility is an important characteristic to embed in the design of systems that are intended to have a long lifetime.

We believe that the relationship between design flexibility and obsolescence is an important area to investigate, and the findings can prove useful contributions to the design and innovation literatures (innovation and obsolescence have long been identified as the two

sides of a same coin, ever since Schumpeter introduced the concept of creative destruction (Schumpeter 1939)). More specifically, one can ask how does flexibility modify a system's exposure to uncertainty, and therefore minimise its risk of obsolescence? Similarly, how does flexibility impact a system's service life or its ability to remain usefully operational despite changes in its environment?

In the previous set of questions (Section 3.1), we asked how to trade flexibility against per-formance penalty. In addition, recalling Stigler's observation that 'flexibility is not a free good' (1939, pp. 310, 311), it is likely that flexibility can only be obtained through performance and/or cost penalties. Given the cost(s) of flexibility, it is important to ensure that the value of flexibility is worth the penalties. Hence, it is important to ask: what is the value that flexibility provides? One component of the value of design flexibility, as the previous discussion suggests, is in the increased service life (hence more value) that is likely to result from flexibility. Can we quantita-tively capture this value of flexibility? Or is flexibility, like system safety, doomed to have clear cost but difficult to quantify benefits?

Flexibility enabling design guidelines and architecture

It is reasonable to wonder what additional design principles and architectures provide flexibility, other from product platforms and modular design (covered in Section 2.4.2). As an example, how does a distributed

How flexible is architecture in comparison to a monolithic design? Alternatively, how should a network be built to maximize flexibility (e.g., routing flexibility)? Can we provide formal evidence that these architectures—whether distributed, modular, or otherwise—do, in fact, produce flexible designs? We covered flexibility in relation to the engineering system's "hardware" in the preceding session. However, it is as vital to consider how software contributes to system flexibility. How and to what degree, for instance, can software provide complicated engineering systems flexibility? Keep in mind that this is not the same as the question, "How can a flexible software be designed?" In this article, we started the conversation by pointing out that flexibility is a widely accepted yet underdeveloped term. When Upton (1995) proposed that flexibility is now where quality was around 20 years ago, "vague and difficult to improve yet critical to competitiveness," he accurately summed up the situation. Upton's description of flexibility as ambiguous and challenging to enhance (or design for) will likely be addressed by investigating the concerns and research topics put forth here, and the idea of flexibility will be developed to the degree of optimization or robustness in system

design.

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