A CLASSIFICATION OF UNCERTAINTY FOR EARLY PRODUCT AND SYSTEM DESIGN

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ABSTRACT

Complex systems and products evolve over years to meet new requirements, while applying tried and tested technology. To maximise the reuse of components through the life span, companies need to plan for changes that they can anticipate and cannot anticipate, and facilitate accommodation of such changes in the original architecture and design of the system. However, the degree to which future product changes can be planned depends on the *uncertainties* that the system, product or product family is subject to. A deeper understanding of these uncertainties is the focus of this paper. The paper first provides a brief literature survey, and discusses the sources and nature of uncertainty. This is followed by a classification of the types of uncertainties that are often encountered and that should be considered, as well as methods and techniques for modelling these uncertainties for incorporation in system design. The paper also provides examples of uncertainties for a variety of systems and products throughout and concludes with an uncertainty checklist for system architects and product designers.

Keywords: Uncertainty, Product Design, Flexibility, Engineering Changes

1   INTRODUCTION

1.1 Why is considering uncertainty in design important?

Traditional engineering design defines and freezes requirements early. This is helpful in giving clear guidance to designers as to the functions and performance levels that are to be achieved in a product or system. One of the dangers of this approach, when applied blindly, is that it does not adequately address situations where there is uncertainty. The term uncertainty is an amorphous concept that is used to express both the probability that certain assumptions made during design are incorrect as well as the presence of entirely unknown facts that might have a bearing on the future state of a product or system and its success in the marketplace.

Uncertainty can negatively or positively impact the proper functioning and market success any new or modified product. It can also have a significant impact on how easy or difficult it is to incorporate changes in future generations of existing products and systems. The following examples of past events illustrate how uncertainty can impact the success or failure of engineered products and systems. Some products and systems fail in the market place, even though they meet technical performance targets and – in some cases – are designed to cost and schedule [1]. This is often the case because forecasts of future usage or demand are easily confounded.

Example: Low Earth Orbit Satellite Constellations

Iridium and Globalstar pioneered mobile space-based telephony in the late 1990s [2]. Despite extraordinary technical breakthroughs, these systems were commercial failures, respectively resulting in losses of roughly $5 and $3.5 billion [3]. The proximate cause of these failures is that prior

forecasts and expectations were confounded, in particular that the market for wireless telephony went to ground-based competitors that arose between the conception around 1990 and the launch of the communication satellites starting in 1998 [4,5]. The systems were too inflexible to easily be downsized or to switch to a different type of service or coverage.

Example: Automotive Manufacturing Plant

Inflexibility can also lead to missed opportunities. A case in point is Daimler Chrysler's PT Cruiser. Based on the Neon compact car, the PT Cruiser was a big hit in the 2000 and 2001 model years; demand quickly exceeded the capacity of the Mexican plant where it was built. But Daimler Chrysler was unable to shift overflow production to its Neon plant in Belvidere, Illinois, which had capacity to spare. Why? Planners had neglected to make the Belvidere paint shop tall enough (or reconfigurable) for the PT Cruiser, which is a few inches taller than the Neon. The oversight meant the company lost approximately $480 million in forgone pre-tax profits according to estimates by Prudential [6].

Example: Military Equipment in Iraq

In 2004 Army Lt. Gen. Ricardo Sanchez, the top US commander in Iraq, wrote in a letter to Army officials, that the troops were struggling to maintain readiness rates on key combat systems such as the M1 Abrams tank. For M-1 Abrams tanks combat readiness had declined to 78% instead of 90%., in part because they were driven up to 4000 miles a year, five times their use when used at their home bases for training [7]. The M1 Abrams tank was developed in the 1980s, when the cold war was still raging and the main theatre of war was expected to be central Europe with a moderate climate. Due to the unanticipated use in the Middle East, sand clogged up the mechanisms and parts failed much earlier then expected. Unexpected military use upset the availability of spare parts and the profitability of service contracts.

Example: Fashion and Consumer Products

In January 1999 the U.S. put sanctions in place against European luxury goods as a response to an escalating argument over banana imports into Europe [8]. This affected the Scottish manufacturers of cashmere garments very badly and there were serious concern that long established companies would go out of business. However during this period, David Beckham, the well known footballer and fashion icon, appeared on television wearing a jumper manufactured by Pringle, featuring a pink and grey cashmere diamond pattern. Instead of selling the typical number of about 500 copies of this design, sales rocketed to over 20,000 within a very short time. This helped the company survive until the misunderstandings with the U.S. were overcome. Incidentally this garment also contributed to establishing pink as a trendy colour in men's clothing.

Traditional practice in design and marketing is to generate a *most likely* "forecast" for future demand. Products are then optimized for this expected future. However, forecasts are almost always wrong by either overestimating demand, or by underestimating it. Demand uncertainty is one – but not the only – type of uncertainty that must be considered during engineering design. *By ignoring uncertainty and relying only on past averages or best guesses systems become inflexible and once the true nature of demand reveals itself, necessary changes become slow and prohibitively expensive to make.*

1.2 Definition and Literature Review

Uncertainty is a term used in subtly different ways in a number of fields, including philosophy, statistics, economics, finance, insurance, psychology, engineering and science. *It applies to predictions of future events, to physical measurements already made, or to the unknown* [9].
Uncertainty is seen by some to be at the heart of complexity [10]. In a discussion of complexity in design, Earl at al. (2005) [11] classify uncertainty into four categories, *known* uncertainties, *unknown* uncertainties, *uncertainties in the data* (including measurements) and *uncertainties in the description*. Known uncertainties are those can be described and handled well based on past cases. Unknown

uncertainties are those where the specific event or type of event could not have been foreseen, for example the occurrence of 9/11 and its impact on the aerospace industry. Uncertainty of data includes factors such as completeness, accuracy, consistence and quality of the measurements themselves. This is different from uncertainty in the description (of a system), which focuses on the ambiguity of descriptions, the selection of elements and the lack of clarity in their scope. This is an important distinction for the mathematical modelling of uncertainty, because data can only be collected for the chosen abstraction of the problem space. If factors are unknown, they are not included in the list of elements in the description and will in consequence not be measured.

Another taxonomy of uncertainty, not too different than the one discussed by Earl et al. (2005), is the one proposed by Hastings and McManus [12]. While their paper establishes a framework for understanding uncertainty that also includes mitigation/exploitation strategies and outcomes, they distinguish between: *lack of knowledge, lack of definition, statistically characterized variables, known unknowns* and *unknown unknowns*. Both lack of knowledge and lack of definition are similar to Earl's et al. uncertainties "in the description". Hastings and McManus define lack of knowledge as "facts that are not known, or are known only imprecisely, that are needed to complete the system architecture in a rational way" and lack of definition as "things about the system in question that have not been decided or specified". What characterizes these uncertainties is that with additional effort, both the lack of knowledge and ambiguity definition can be reduced. In other words these uncertainties are not irreducible. There are, on the other hand, uncertainties that are irreducible, in other words only the occurrence of *future events* will turn these uncertainties into known facts.

 In our every day lives these are familiar to us as the score of tomorrow's football game or the value of our stock portfolio a year from now. No amount of probing will resolve tomorrow's events, even though with some effort we may attempt to (but never fully succeed) bound the range of tomorrow's outcomes. Another important distinction, often lost in the literature, is whether the source of uncertainty is *within or outside the system boundary or sphere of influence*. We will refer to the first case as endogenous uncertainty; otherwise we will talk about exogenous (external uncertainty).

In engineering design, in its simplest form, the relevance of *uncertainty* can be reduced to the following two questions:

1. Will the product, system or artefact that is being designed meet its functional and form requirements once it is on sale or in use? Will it function properly and perform adequately?

2. Are the functional and form requirements the right ones that will lead to market success?

In Section 2 we will examine the generic classification of uncertainty primarily from the point of view of a generic product development and manufacturing firm. In Section 3 we describe practical methods for modelling uncertainty for incorporation in system design. Section 4 concludes with a checklist for incorporating uncertainty in system design.

2   CLASSIFICATION OF UNCERTAINTY

2.1 Sources of Uncertainty

The sources of uncertainty range from known to unknown uncertainties by degree, as issues are more or less well understood. Many of the known uncertainties are those that are properties of the product itself, for example in the military equipment example, a company will have a pretty good idea, which parts are likely to need replacing in a given interval. External uncertainties are often much harder to predict. After all how could the cashmere knitters predict, that they would become the victims of protectionist banana growing policies? Figure 1 shows a variety of sources of uncertainty and their contexts.
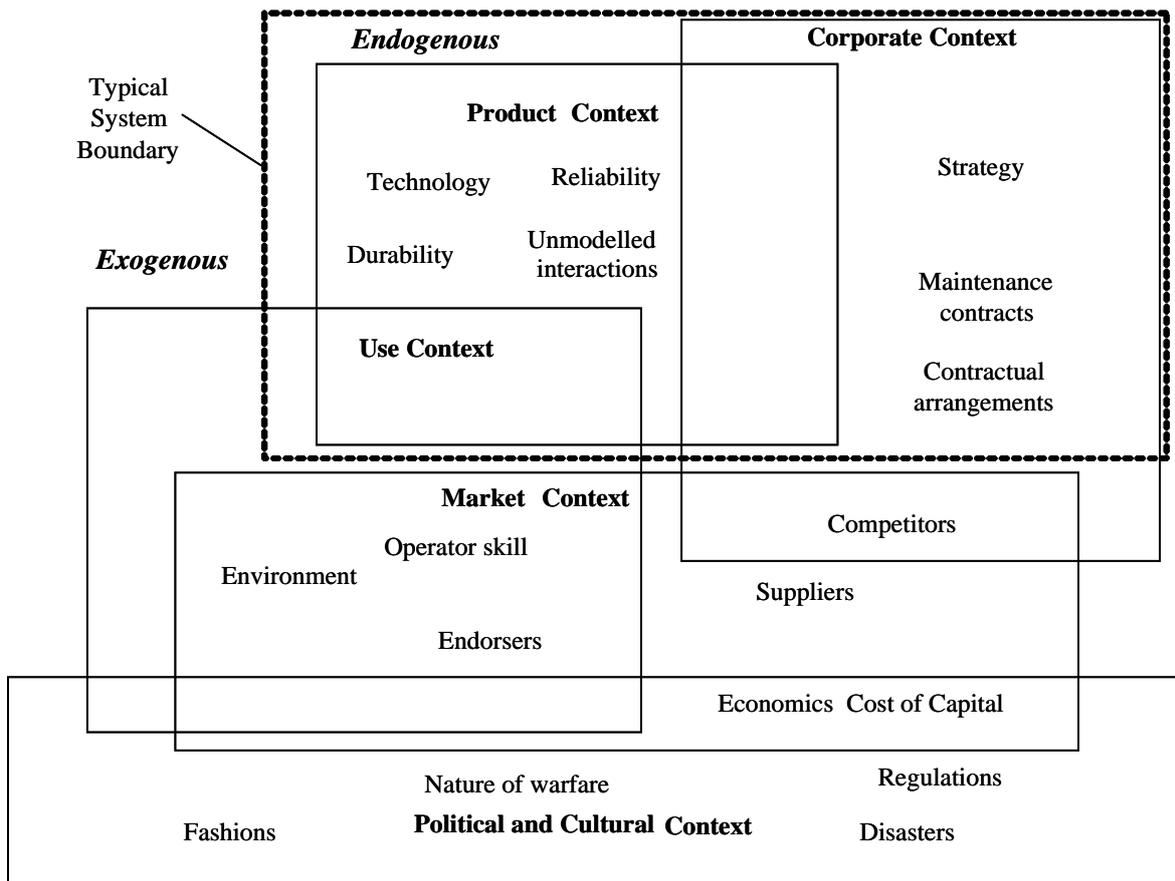
Figure 1: Sources of Uncertainty

2.2 Endogenous (Internal) Uncertainty

Each product or system carries its own uncertainties, which arise primarily from within. By "within" we are referring to the typical system boundary shown in Figure 1 (dashed box). Uncertainties within the dashed box can be influenced by the system designer(s) or firm to a greater extent. Uncertainties outside the system boundary can be influenced by the designer(s) or firm to a lesser extent.

Product Context

In each development process there is an element of *technical risk*, as most products have an element of novelty or at least are designed in this way for the first time in the firm. These technical uncertainties are assessed at the beginning of the design process and usually resolved over the design process. However even the reuse of existing ideas carries considerable uncertainty. A component that works well in one product might not do so in another, because a slightly different demand is placed on it, so that its tolerance margins are exceeded or the component is placed in a new context and needs to interact with different components than previously.

Ill understood and therefore *unmodelled interactions* between parts of a system frequently catch companies by surprise, as changes propagate through a system or unexpected failures occur [13]. How well a product behaves during a change process depends on the exact state of all components (hardware, software, human...), which are rarely understood. This also affects the *reliability* of a component over its life cycle. Issues of reliability and robustness are now increasingly addressed through means of quality management strategies [14, 15]. Companies are now also investing considerable effort in understanding the failure mechanism that could cause problems later throughout the products lifecycle [16]. This is an attempt to control the wear and tear of components as much as to increase the reliability. Catastrophic failures are of course high undesirable and often expensive, however life cycle cost is significantly affected by the details of aging and wear of a component.

Corporate Context

The pervious paragraph discussed endogenous uncertainties that affect a particular product, but there are also those that arise them from the business context in which the product in designed. As the car manufacturing plant example shows, corporate ill planning can destroy opportunities created by successful products. Each company develops its own product strategies, which can affect particular products, by redirecting resources to and from the design process. The product is also strongly affected by the contractual arrangement under which it is designed, which can require difficult to achieve properties or late changes to the product. For example the recently developed Trent 1000 engine, was designed for a total care arrangement, where Rolls Royce carried the cost of spares, service and overhaul, however half way through the design process, an Asian airline placed a large order for engines under a traditional spare part deal, which introduced conflicting requirements in the process.

2.3 Exogenous Uncertainty

Many other uncertainties are outside of a companies' direct control (outside the dashed box in Figure 1), as they arise from the market place the product is operated in, the way it is in operation and the cultural and political context at the time of its design and use.

Use Context

There is oftentimes huge uncertainty in the way a product is used and the conditions under which it has to operate. The *operational environment* of the product can change, requiring reliable operating in different terrains, different climate or weather conditions. This was at the heart of many of the troubles of the M1 Abrams tank, which was not initially built for desert warfare. Similarly the skills of the operators of the product are uncertain. This can be reflected in changing maintenance contracts, requiring companies to maintain products, that they never planned to maintain over this time span. For example the British Ministry of Defence recently issued a 25 year maintenance contract to Rolls Royce for the remaining four Nimrod planes, which are powered by Spay engines designed in the 1950s. However, companies also make wrong predictions about the skills of their potential users, as the example of many mobile phones that could not be used by elderly users showed. While companies can counteract this with inclusive design strategies, much about the capabilities and interests of different user groups is unknown to them [17].

Markets

Markets carry a large amount of uncertainty, as the satellite mobile telephone example shows, where the companies totally underestimated changing market trends and did not initially see the terrestrial mobile phones as a significant competitor [3]. The degree and spread of change in the market, depends on the nature and life span of the product. In the fast moving fashion industry everybody is well aware how fickle market trends are and how fads can change the behaviour of large market segments. *Demand* profiles for a product can change very quickly, as environmental conditions change, or as in the case of the pink jumper, the product is boosted by forces outside the control of the company. The exact nature and time of competitor offerings also introduces uncertainty into the market. If any other players offer a comparable product earlier, they can conquer the market. Alternatively new *innovations* by competitors can change the demand profile very rapidly, as the speedy decline of well established consumer products, such as VHS video recorders or 35mm cameras illustrates.

Market forces are also at work on a deeper level through changes in the *economy* at large. Changing exchange rates have a huge impact on the cost of manufacturing, as well as the ability to sell products abroad. Prices are dictated in many industries by demand and supply, rather then by the costs of production, pushing many products to the limits of financial viability.

Political and Cultural Context

The market in turn is influenced by the wider political and cultural forces at work, which can translate themselves into very concrete uncertainties for specific products. Changing regulations, for example

emissions and fuel economy legislations [18], can require major changes both in the design of products and the operability of existing products. For example currently the diesel engine industry is preparing for tier 4 with significantly tightened emission regulation, which can not be met with current technology. The different manufacturers are working in parallel on very different technological solutions, which could change the diesel engine market for ever. Efforts are underway to model both the performance as well as the cost associated with infusing such exhaust treatment technologies into existing and future vehicle designs [19, 20].

Political decisions and policy affect the behaviour of markets, for example when entire countries change their preferences in where they purchase from. This can be in the form of activity patronage, or implicit rejection. For example U.S. truck manufacturers suffer noticeable dips in their sales, during internationally unpopular political actions by the U.S. government, such as the Iraq war. Even deeper then the policies are great changes in cultural and political trends, such as the changing nature of warfare, as illustrated in the tank example. An example of one such global trend is the changing role of woman in society, which has a fundamental impact on the way the fashion industry works, as the total decline of the corset industry testifies.

2.4 Layered uncertainties

As illustrated by the overlapping areas in Figure 1, the multiple uncertainties affect each other, but don't all overlap. Many endogenous uncertainties are independent of the exogenous uncertainties. A product needs to reliable and durable regardless of the mode or environment in which it will operate. The construction of a facility on the other hand may be deeply affected by access to critical supply routes (e.g. Suez Canal) for its raw materials and specialized equipment. In many ways the exogenous uncertainties provide the backdrop on which the endogenous ones need to be accessed and mitigated against. One useful mental model is to think of these uncertainties as occurring in layers around each other, see Figure 2. This representation (according to Lessard [21]) shows an inner layer comprising the direct technical/project risks, roughly corresponding to the *Product Context* shown in Figure 1. The next layer is the *Industry/Competitive* layer corresponding to the *Corporate Context* in Figure 1. The next outer layer is the *Country/Fiscal* layer followed by the *Market* layer. This is again similar to Figure 1, whereby the ordering of the layers differs slightly. The most outer layer corresponds to Natural events such as large scale weather phenomena or geological formations, which are particularly important for those industries extracting natural resources such as oil and gas.
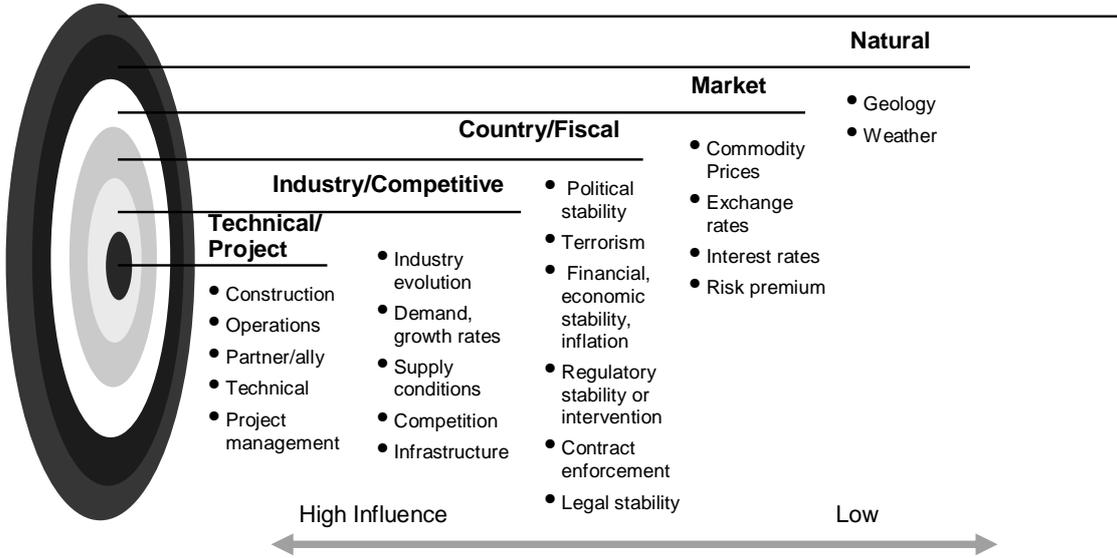
Figure 2: Layers of uncertainty (according to Lessard [21])

The key to understanding the layers of uncertainty model (Fig.1) is that the degree of influence in being able to mitigate risks or exploit opportunities arising from the uncertainties decreases sharply when going from the inner to the outer layers. A firm may have more or less full control in choosing

its technical architecture, its suppliers and operational strategy, but it may only have limited impact on future regulations (e.g. through lobbying efforts) and it has no influence on the occurrence of natural disasters such as a Class 5 Hurricane. This does not mean that nothing can be done about the consequences of outer layer events (e.g. the procurement of flood insurance, redundancies in a global supply chain [22] etc…) but their occurrence in the first place cannot generally be influenced. We note that companies individually can't change aspects of the environment, such as regulations or fashion, but collectively they may shape it very much.

A useful way for dealing with uncertainties is usually to develop separate models for the endogenous uncertainties (primarily in the technical/project and industry/competitive layers) and the exogenous uncertainties, and to *later bring these together in an integrated uncertainty model*. Such an approach can be characterized as uncertainty management [23], which includes both protections against downside risks as well as taking advantage of potential upside opportunities. In some cases the uncertainties can be resolved immediately or in a short time frame with some deliberate efforts (building and testing prototypes, some market surveys, quality audits …), while in other cases no amount of today's effort will be able to fully resolve them, because they depend on future events.

3 MODELLING UNCERTAINTY

3.1 Formal Approaches to Uncertainty Modelling

Entire books have been written about how to mathematically model and grapple with uncertainty in a formal way. Halpern [24] for example goes into great depth in his book on "Reasoning about uncertainty". In this comprehensive work, the following representations of uncertainty are considered (definitions are extracted and adapted from [24] and [25]):

- *Probability*: Probability is the extent to which something is likely to happen or be the case. Probability theory is used extensively in areas such as statistics, mathematics, science, philosophy to draw conclusions about the likelihood of potential events and the underlying mechanics of complex systems.

- *Bayesian Probability*: Bayesian probability is an interpretation of probability suggested by Bayesian theory, which holds that the concept of probability can be defined as the degree to which a person believes a proposition. Bayesian theory also suggests that Bayes' theorem can be used as a rule to infer or update the degree of belief in light of new information.

- *Dempster-Shafer* Belief Functions: The Dempster-Shafer theory is a mathematical theory of evidence based on belief functions and plausible reasoning, which is used to combine separate pieces of information (evidence) to calculate the probability of an event.

- *Possibility*: Possibility theory is a mathematical theory for dealing with certain types of uncertainty and is an alternative to probability theory. L. Zadeh first introduced possibility theory in 1978 as an extension of his theory of fuzzy sets and fuzzy logic.

The above theories all require a numeric expression of the likelihood of future events or "possible worlds" [24]. There have also been efforts at placing nonnumeric relative likelihood on events, which Halpern (2003) sums up under the concept of *plausibility measures*. While the above methods are solidly rooted in probability theory, logic and epistemology, they are often inaccessible to designers and engineers seeking to incorporate future uncertainty into their thinking and design work. This is in part so because the formalisms in which the above theories are formulated oftentimes remain obscure and are not taught in a general engineering design curriculum. Other reasons are that intense schedule and money pressure can force rapid generation and launch of a viable design on the market in a hasty manner, leaving little or no time for consideration of such uncertainty methods.

3.2 Practical Approaches to Uncertainty Modelling

In this section we will take a less formal and more practical approach and summarize some of the uncertainty modelling approaches that we have been able to apply to uncertainty problems in system design. The first high-level distinction is whether the uncertainties can be represented as continuous variables or as discrete events or scenarios:

- *Continuous Variables*: representing uncertainty as a random variable on the real number scale (we have not thought about using complex numbers to represent uncertainty) is both useful and common. Examples include the future prices of commodities and raw materials (oil, gas, aluminium…). When representing uncertain demand in terms of numbers of units sold per unit time (# sales/year), this specializes to integer numbers. The main methods for representing this type of uncertainty in engineering design are *diffusion models* and *lattice models*.

- *Discrete Events or Scenarios*: this type of uncertainty is more discrete in nature and involves either estimating the likelihood, time of occurrence and magnitude of certain discrete events (e.g. earthquakes, hurricanes,…) or representing the future as a set of more or less well defined scenarios. The main method we discuss here is *scenario planning*, a close cousin the *Delphi method*.

The following sections summarize these uncertainty modelling approaches and provide brief examples, but do not provide detailed step-by-step instructions for brevity's sake.

Diffusion Models

The general class of diffusion models assumes that the initial state of a system (or value of a variable) at time $t=0$ is known, but that there is diffusion due to randomness. The most popular model is based on a mathematical description of Geometric Brownian Motion (GBM) [3]. GBM is a continuous-time stochastic process in which the logarithm of the randomly varying quantity follows a Brownian motion, or a Wiener process. This is used extensively to model the uncertain evolution of stock prices. If applied to uncertain demand, D, the expectation of the relative change of demand, $\Delta D/D$, in one time period Δt, can be expressed as (the time-discretized version of GBM):

$$E\left[\frac{\Delta D}{D}\right] = \mu \Delta t \tag{1}$$

where μ represents the mean trend over time. In some cases the trend can be evaluated based on averaging past time history. The variability around the trend can be represented as the variance of $\Delta D/D$ in one time period, whereby

$$\mathrm{var}\left[\frac{\Delta D}{D}\right] = \sigma^2 \Delta t \tag{2}$$

σ represents the volatility (can be estimated based on the standard deviation of past time history) and ε is a uniformly distributed random variable between 0 and 1. The combined equation (3)

$$\frac{\Delta D}{D} = \mu \Delta t + \sigma \varepsilon \sqrt{\Delta t} \tag{3}$$

specifies that uncertainty grows as a function of the square root of the underlying time period Δt. Figure 3 shows application of the GBM modelling approach to estimating uncertain demand over time of a satellite constellation system [3], see the earlier example.
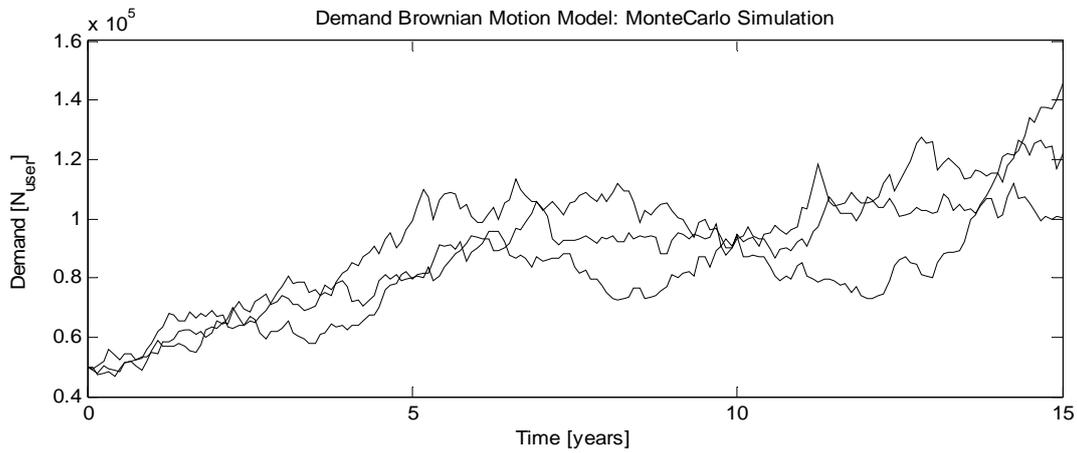
Figure 3: GBM model of uncertain demand, $\Delta T = 1$ month, D (t=0) = 50,000, μ = 8% p.a., σ = 40% p.a. – 3 scenarios are shown (from de Weck et al. 2004)[3]

Lattice Model

One of the issues with diffusion models in general and the GBM method in particular is that there are, in fact, an infinite number of future scenarios that might occur. This can be handled through statistical sampling (e.g. Monte Carlo simulations). If, one is willing to forego prediction of future states at any intermediate time period and resorts instead to modelling the future state at relatively large time intervals, Δt, one may apply a lattice model [23] to uncertainty modelling. In this method the initial state of the system is known and – in the binomial lattice – the quantity of interest (future demand, stock price, uncertain customer requirement …) may either go up (*u*) or down (*d*) with a probability *p* and *1-p*, respectively. Figure 4 depicts a binomial lattice, representing a discretized version of the uncertain future demand modelled in Figure 3.
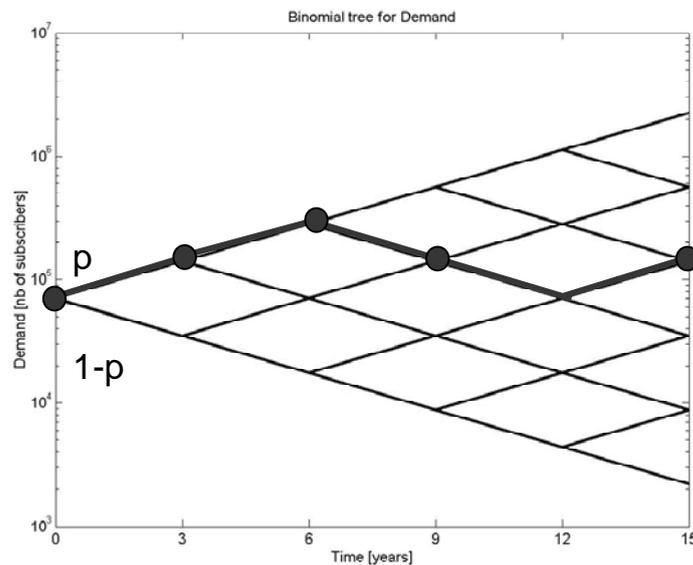

Figure 4: Binomial Lattice model for uncertain demand, Δt=3 years

In order to maintain statistical equivalence between the GBM model and the binomial lattice model, the following Equation (4) holds. The size of the up movement *u* and down movement *d*, depends on both the volatility and the length of the time period.

$$u = e^{\sigma\sqrt{\Delta t}}$$

$$d = 1/u$$

$$p = \frac{e^{u\Delta t} - d}{u - d} \qquad (4)$$

The probability of occurrence of a particular scenario (path through the lattice, such as the highlighted path in Figure 4) can then be computed as:

$$P(i) = p^k (1-p)^{n-k} \qquad (5)$$

where k is the number of time periods in the model. In this example the number of future paths (scenarios) is simply $2^5=32$. This avoids costly sampling of an infinite number of scenarios.

Scenario Planning

A third very common and useful approach to uncertainty modelling, is scenario planning. While different incarnations of this technique have been proposed, it basically comes down to defining a finite set of future scenarios that hopefully, collectively, capture the range of future "worlds" that might occur. Table 1 shows an example of a scenario plan [26] where the uncertain number of manned missions to the Moon and Mars has been captured by a set of 10 traffic scenarios.

Table 1: List of uncertain scenarios for launch demand for crewed missions to the Moon and Mars [26] post 2010. The time periods T1, T2 … corresponds to 5 years each.

Scenario	Time Period				Scenario Description
	T1	**T2**	**T3**	**T4**	
1	1	1	0	0	Low Moon; No Mars
	0	0	0	0	
2	5	5	0	0	High Moon; No Mars
	0	0	0	0	
3	1	1	0	0	Low Moon; Low Mars
	0	0	1	1	
4	3	3	0	0	High Moon; Low Mars
	0	0	1	1	
5	2	1	0	0	High-Low Moon; Low-High Mars
	0	0	1	2	
6	5	5	5	0	High Moon; Hi Mars
	0	0	5	5	
7	3	2	1		Fade from Moon to Mars
	0	1	2	3	
8	1	1	0	0	Low Moon; High Mars
	0	0	3	3	
9	0	0	0	0	No Moon; Low Mars
	0	0	1	1	
10	0	0	0	0	No Moon; High Mars
	0	0	5	5	

These scenarios can be used for estimating the uncertain demand for launch vehicles for carrying crew and cargo to Earth orbit. The choice of launch vehicle may depend on the occurrence of these scenarios. Such scenarios can then be assigned a weighted probability (if such estimates are available) or they may be assumed to occur with equal likelihood. The Delphi Method (RAND 1959) [27] describes a formal way for generating such discrete future scenarios based on expert group opinion.

4 UNCERTAINTY IN DESIGN: RISK AND OPPORTUNITY

Uncertainty is ubiquitous and should not be ignored by system designers. The more complex and expensive a system or product is and the more difficult it is to incorporate future engineering changes, the more important an explicit treatment of uncertainty will be. This is amplified in those situations where there is large volatility around future demand and expectations for success. The classification of uncertainty presented in this paper can be distilled down to a simplified checklist (Table 2) that should help system designers to explicitly consider uncertainty in their designs.

Table 2: Uncertainty Checklist in System Design

Sources of Uncertainty	Resolvability	Discreteness	Modelling Approach
Where does uncertainty come from that could affect future success of my system/product?	Can the uncertainty be resolved by simply delaying decisions and waiting until time x?	Can the uncertainty be represented as a random variable or as a discrete future scenario?	What modelling approach can be used to quantitatively capture the uncertainty?

Endogenous
    Product Context
    Corporate Context
Exogenous
    Use Context
    Market Context
    Political/Cultural
    Context
 	
(see Fig. 1)
	Resolvable (= with enough investment or waiting long enough the uncertainty is removed or significantly diminished)[1]
	
	Irresolvable (= uncertainty will always persist because it is subject to an ongoing random process)[2]
		Continuous Variable (see Fig. 3)
		
		Discrete Scenario (see Table 1)
		
		Probability-weighted Scenario
			Geometric Brownian Motion (see Fig. 3)
			
			Lattice Model (see Fig. 4)
			
			Scenario List (see Table 1)

The uncertainty checklist in Table 2 does not claim to be comprehensive, but is a good starting point.

5 SUMMARY AND CONCLUSIONS

This paper summarizes some of the key considerations in capturing uncertainty for early product and system design with emphasis on exogenous uncertainties that can lead to future changes. The key is that for exogenous uncertainties, these have to be projected into the system architecture and design embodiment to identify hardware and or software components that are most likely to be changed in the future as a function of the exogenous uncertainties. Such mitigation and/or exploitation may come in different forms and it is collectively referred to as Design for Changeability. The first step is to capture the source(s) and type(s) of uncertainty as it may impact a product or system in the future. However, it should be clear that these methods can only help design for the known uncertainties, but the unknown unknowns will still occur and may either harmfully or beneficially impact the system or product.

Some general observations and conclusions, based also on our experience in this area are that:

- Random variables are appropriate for known uncertainties such as market needs and trends, where future evolution can be modelled as trends from historic data.
- Other uncertainties, such as fashion fads are not as easily modelled using statistical approaches and have to be handled via discrete scenarios using expert opinion.
- Products and services satisfying basic needs based on Maslow's (1943) pyramid [28], such as food, shelter, and transportation have more statistical data and typically evolve slower than more volatile areas at the top of the pyramid, e.g. entertainment or fashion.

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[1] Example of resolvable uncertainty: drilling extra exploration wells will significantly reduce reservoir uncertainty in oil & gas exploration.

[2] Example of irresolvable uncertainty: the price of crude oil on the open spot market in 6 months, 1 year etc… will always remain uncertain because it is associated with an ongoing dynamic (exogenous) process.

Future work includes studying ways in which to modify processes recommended for design [29], ways to handle correlated sources of uncertainty in system design and establishing catalogues of generic mitigation and exploitation strategies across a larger range of systems and products.

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