IDENTIFICATION, CLASSIFICATION AND MODELING UNCERTAINTY IN EARLY STAGE DESIGN OF MANUFACTURING SYSTEMS - A SURVEY

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ABSTRACT
Technological advancements, social and market changes, and policies evolution introduce new challenges in dealing with the planning and design of complex engineering systems with a long operational life. In the last two decades, several studies have analysed and proposed frameworks to identify, understand, classify, manage and model uncertainties in complex systems. However, a deeper understanding on how to design in order to accommodate uncertainty is still a difficult issue deserving research and development on design practices and methods. Thus, the purpose of this paper is to present a review of the literature on design approaches intending to incorporate the life cycle uncertainty of engineering systems since the very front end of their design process, aiming to highlight research gaps, identify opportunities and guide future research efforts. In particular, this paper is focused on the challenges raised by uncertainties in the design of complex manufacturing systems in their early development stages. The nature and sources of uncertainty and frameworks for its classification is discussed, as well as techniques to model and integrate uncertainties in early design phases. Finally, insights into the main focus in future research efforts are addressed.

Keywords: Uncertainty, Flexibility, System Design, Manufacturing Systems.

INTRODUCTION
One of the central problems when designing an engineering system is the challenge of answering readily and successfully to: what to build, and at what time (De Neufville, 2011). Those are questions raised in all stages of the design process in engineering but they are especially difficult in the preliminary phases due to the intrinsic imprecisions and uncertainties on the info on the information available. There are several methodologies well develop to apply in later design stages (e.g. solid modelling and mechanism analysis) by which designers may rely to analyse performance or make main configuration choices (Wood, 1990), but lack of information and ill-defined requirements create large obstacles to early design development and validation. Most of the times initial stages of engineering design projects make use of development methodologies that are incomplete or inappropriate, making those initial stages quite dependent of the expert judgment. The first challenge in a complex system design is to understand the environment in which it will perform, and how it will affect and be affected by its surroundings, meaning that the system's scope and frontiers must be identified. Together with high level requirements, these are major inputs to the development of the system architecture, understood as a description model of the system structure, including the system components and the interactions between them.
Large manufacturing systems must be seen as complex systems. In fact, they interact and are affected by a complex exogenous environment, which evolves over time in a difficult-to-predict way, and consist of a large number of components with complex behaviours and often non-linear internal interactions. These systems built to operate for long life cycles have to accommodate different sources of uncertainty, both internal and external, and be resilient to changing conditions. This resilience issue is especially important when designing manufacturing systems to deal with innovative products, materials, and technologies in turbulent market contexts. Moreover, as Pierre et al. (2007) pointed out engineering design of innovative products also introduce an extra part of uncertainty in their manufacturing systems when compared to “routine design”, which introduces needs for flexible design for these manufacturing systems.

In summary, besides a decision-making process based on insufficient and ill-defined information, the early stage design of a manufacturing system must deal with imprecise judgements on future evolution on markets, technologies and products that introduce that are subject to a wide range of uncertainties difficult to deal with. Systematic tool to identify, classify and model these uncertainties are the cornerstone for success in engineering design process.

Uncertainty Definition

Uncertainty is an unintelligible expression without a straightforward characterization nor clear definition (Antunes, 2015). Its description is communally related with unpredictability, indeterminacy and indefiniteness. It's a transversal term, yet it's definition, the formalism that's put into it and the way is mitigated and exploited changes when treated in the scope of different sciences such as social, formal, physical, life, or applied sciences. Uncertainty can be found in future events' prediction such as weather forecasting, where currently is common practice to include data on the degree of uncertainty. In financial markets, namely stock markets, stock prices uncertainty is highly significant and it's dealt with tools such as Monte Carlo simulation. In economics, where market systems experience rapid changes, uncertainty reduction and risk mitigation are crucial since more often than not risk translated directly to money loss. Uncertainty is also present in fields with high mathematical formalism such as quantum mechanics, where Heisenberg's uncertainty principle forms the basis of fundamental theory of nature at small scales and low energies of atoms and subatomic particles. (Feynman, 1965).

This illustrates the broad spectrum of areas that consider, treat and incorporate uncertainty in their models. From that, one broad yet fundamental insight can be withdrawn: Uncertainty is what is not known, or known only at some extent, and must be framed and incorporated in developed models in order to, with higher accuracy, mimic the behaviour of real complex systems. This is the starting point to develop a consistent and flexible model that is able to deal with uncertainties.

Uncertainty Research in Engineering Design

Uncertainty research has seen an increase in relevance within engineering design community in the last decade as stated by Kreye et al. (2011). In 2012 the American Society of Mechanical Engineering published a special issue of its Journal of Mechanical Design solely dedicated to design under uncertainty. Over 60 technical papers were submitted for review, (De Weck et al., 2012), being the published issue comprised of 14 papers organized into four common themes: (1) New Problem Formulations for Design under Uncertainty, (2) Strategies

Kreye et al. (2011) presented a rather complete research about the growing role of uncertainty-related investigation in articles published in one of the main design conferences, International Conference on Engineering Design (ICED). Kreye et al. (2011) exalts the fact that it has been published 32 papers in ICED in the past 10 years, with the numbers growing from 2 papers in 2003 to 17 in 2009. Extending Kreye’s et al. (2011) research to years that followed, can be seen a constant trend since 9 articles were published in ICED’11, 10 in ICED’13 and 8 in ICED’15. Table 1 presents, in a structured manner, all the articles published in ICED’s last three editions separated by their topic content regarding uncertainty. No particular order was given to the topics, and the authors appear by alphabetic order within each Uncertainty Topics.

Table 1 - Articles considering some level of uncertainty in the last 3 ICED’s conventions.

<table>
<thead>
<tr>
<th>Uncertainty Topics</th>
<th>Objective</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty in all phases of design process</td>
<td>Support system suppliers to identify and offer customer relevant and effective flexible design concepts.</td>
<td>Allaverdi et al. (2015)</td>
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<td></td>
<td>Design process improvement through modelling and management of complexity and uncertainty.</td>
<td>Hassannezhad et al. (2015)</td>
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<td></td>
<td>Approach to assess the influence of different design parameters in a network of physical effects.</td>
<td>Eifler et al. (2011)</td>
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<td></td>
<td>Systematic reduce the inherent uncertainty and to enable a dependability-oriented design process.</td>
<td>Wendland et al. (2011)</td>
</tr>
<tr>
<td>Uncertainty analysis in Product design</td>
<td>Product design through the extraction of consumer opinion and sentiment. Uncertainty analysis is conducted in order to assess the effects of sentiment classification accuracy.</td>
<td>Stone &amp; Choi (2013)</td>
</tr>
<tr>
<td>Uncertainty in early stage design</td>
<td>Development of an Agent Model for Planning and reSearch of eaRly dEsign (AMPERE) aiming to support early design planning.</td>
<td>Fernandes et al. (2015)</td>
</tr>
<tr>
<td></td>
<td>Exploration of decision making in early phases of product development, and reporting of empirical findings from a case study conducted in an automotive firm.</td>
<td>Kihlander (2011)</td>
</tr>
<tr>
<td>Uncertainty in project management</td>
<td>Application of Agile Project Management to two Root Cause Analysis (RCA) projects with high degree of uncertainty.</td>
<td>Kim &amp; Mont (2013)</td>
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<td></td>
<td>Study that compares how the managerial activities of managers with a technical background differed from those with a non-technical background.</td>
<td>Rekonen et al. (2013)</td>
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<tr>
<td>Uncertainty classification</td>
<td>Description and classification of the manifestation of uncertainty.</td>
<td>Kreye et al. (2011)</td>
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<tr>
<td>Uncertainty in usability</td>
<td>Development of an uncertainty scale to:</td>
<td>Harkema et al. (2011)</td>
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<td></td>
<td>▪ Relate usability techniques to the different types of uncertainty</td>
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<tr>
<td></td>
<td>▪ Relate usability problems to different types of uncertainty</td>
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<td>Uncertainty in modular systems</td>
<td>Characterization of what interfaces are and how they can be described through adequate properties, functions and other characteristics in order to control Interface Uncertainty and Configuration Uncertainty.</td>
<td>Freund et al. (2015)</td>
</tr>
<tr>
<td>Managing design commissions</td>
<td>Description of how commissioned Fuzzy Front End (FFE) development work may be managed in order to mitigate uncertainty</td>
<td>Linse (2013)</td>
</tr>
<tr>
<td>Uncertainty in mechanical design</td>
<td>Elaboration of what challenges mechanical design automation faces to reach the level of design automation in the embedded systems domain.</td>
<td>Otto et al. (2013)</td>
</tr>
<tr>
<td>Uncertainty treatment in design analysis</td>
<td>Design analysis process model that tries to eliminate some integration issues (transmission of incorrect information, disagreement on activities…) using quality assurance techniques and procedures.</td>
<td>Eriksson &amp; Motte (2013)</td>
</tr>
<tr>
<td>Decision-making and strategic design under uncertainty</td>
<td>Methodology to support strategic design and management decision-making in entrepreneurial systems that are called to evolve towards more complexity.</td>
<td>Lessio et al. (2013)</td>
</tr>
<tr>
<td>Uncertainty in expectation effect</td>
<td>Simulation model of the expectation effect that explains the conditions of contrast and assimilation.</td>
<td>Yanagisawa &amp; Mikami (2015)</td>
</tr>
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</table>
### Uncertainty in Conceptual Design Stage

- Expansion of SOS (System-Of-Systems) method of generating product design alternatives to introduce more information to help reduce uncertainty and explore design solutions. (Rosenstein et al. 2011)
- Examination the nature of objectives and generates a conceptualization of four generalized dimensions of objectives: degree of maturity, degree of rigidity, leverage and impact. (Albers et al. 2011)
- Analysis of empirical data from a case study of organizational performance in relation to institutional theory in connection to organizational tensions and conflicts. (Bojesson et al. 2015)
- Application of methods within the Uncertainty Mode and Effect Analysis (UMEA) Methodology during the phases of the product development process. (Engelhardt, et al. (2011))
- Introduction of a methodology is called Uncertainty Mode and Effects Analysis (UMEA): a strategic procedure to analyze uncertainties and their consequences. (Engelhardt, et al. 2011)
- Creation of framework to cover the different aspects of technology uncertainty discussed in current empirical studies. (Geissmann et al. 2015)

### Uncertainty in Product Development

- Novel integrated screening framework for flexibility analysis considering multi-domain uncertainty sources and multi-criteria for designing complex engineering systems. (Bourani et al. 2013)
- Analysis of how complexity is perceived in this industry and gives guidance to the improvement of complexity management. (Maurer & Wölfling 2013)
- Strategy identification for collecting information in the problem formulation: depth-first, breadth-first and hybrid search. (Wang 2015)

### Uncertainty in Complex Plant Engineering

- Approach on the precautionary identification of uncertainties. (Daniel Kasperek et al. 2013)

### Uncertainty in Problem Formulation

### Uncertainty in Complexity Management

### Uncertainty Identification and Classification

This section presents different uncertainty classification methods. These are introduced sequentially from more classic categorizations to newer ones. Firstly, uncertainties are classified regarding the awareness of experts. Uncertainty can be divided in two distinct broad groups: known unknowns, and unknown unknowns. This taxonomy is well known in literature, being most of the times a starting point in uncertainty classification. Special attention is dedicated to the latter group since recently a framework proposed by Ramasesh et. al (2014) to deal with unknown unknowns formulate a subdivision of this group in knowable unknown unknowns and unknowable unknown unknowns. Secondly, uncertainties are classified per context in which they arise, either in contexts present inside an engineering complex system, endogenous uncertainty, or in its environment, exogenous uncertainties. Regarding this classification two approaches are described, being the first one characterized by having a hard limit dividing what are uncertainties arising inside and outside system boundaries. The second approach is characterized by not having a hard boundary diving endogenous and exogenous uncertainties. The third uncertainty classification groups uncertainty in five layers: Nature Layer, Cause Layer, Level Layer, Manifestation Layer, Expression Layer. Lastly, it’s introduced another framework of classification presented by Wynn et al. (2011), where the authors define Imprecision, Inconsistency, Inaccuracy, Indecision, and Instability as the main uncertainties that require understanding in complex engineering design

### Known & Unknown Unknowns

Ramasesh et. al (2014) introduced a conceptual framework that approaches unknown unknowns (a.k.a. unk unks) providing specific guidance for recognizing and reducing knowable unk unks in a project. Uncertainties are primarily divided in two groups: Known unknowns and Unknown unknowns. Known unknowns are uncertainties that have the awareness of experts, i.e. project managers and system designers. Common and well
developed techniques for conventional risk and opportunity management often can be applied with high level of success. Examples of known unknowns are: costs and duration of system activities; quality of outcomes; both availability and quality of resources. These are uncertainties that can be estimated in a probabilistic way.

**Unknown unknowns** are uncertainties which the experts are not aware of. Unrecognized uncertainties that are only observable when revealed, most of the times in negative system outcomes. It is important to point out that events that were foreseen but weren't considered because were to cost demanding or to unlikely to happen are not categorized as *unknown unknowns*. Such division in *Unknown unknowns* and *Known unknowns* is well study, being the novelty related to the fact the authors divide unk unks in two separated sub-categories: *Unknowable unks* and *knowable unk unks*. The paradigm of this categorization relies on the premise that: “Just because something is currently unknown does not mean that it is unknowable”.

*Unknowable unk unks* are related to events that cannot be anticipated by experts. There is not an amount of action by designers and project managers that will be able to convert unknowable unk unks into known unknowns. Such uncertainties are tightly related with disruptive events such as earthquakes or tsunamis.

*Knowable unk unks* are Unk Unks that could be, but for some reason were not foreseen by the system's expert. This idea is supported by many retrospective studies of projects that fail or succeed poorly. These studies suggest that a considerable amount of unk unks could have been anticipated. One of this cases is described by Montealegre et al. (1996). The author describes several problems arising in an automated baggage-handling system at Denver International Airport. Those problems could, but were not anticipated. Being only identified well past project's deadline.

A more catastrophic one happen in June 4, 1996, Ariane 5 rocket was launched in French Guiana, South America. The mission from European Space Agency's centre started to have problems 37s into the launch when internal computers “decided” that rocket was 90º off course, making an automatic adjustment of the trajectory as the rocket was travelling at the speed of sound. It exploded 2 seconds later destroying everything on board, including four satellites. This was an unexpected and catastrophic outcome for a ten years’ project that cost $7,000 Million and took tens of millions of hours of human labour and expertise. This problem was only revealed in a posterior analysis that confirmed that there was a malfunction in the rocket’s guidance system software. The conclusion withdrawn was that the system was not fully analysed perhaps because the software had worked successfully with previous rock, Ariane 4.

**Endogenous / Exogenous Classification**

As pointed out, uncertainty has an unwavering presence in complex systems, being systems of different nature subject to different types of uncertainties. Depending of the system the uncertainty degree varies from higher levels, where uncertainty is more difficult to be dealt, to lower levels, where uncertainty is much easy to be tamed. One way of differentiating uncertainties is to analyse where they arise. Within the system or in the system's environment. Primarily uncertainties arise from within, being classified as Endogenous. One characteristic is that they are not directly influenced by the environment where the system inhabits, i.e. they are mainly correlated to the system itself. Uncertainty arising from within can be influenced
by system designers to a greater extent, being uncertainties out of the system boundaries only
influenced by designers to a lesser extent.
Endogenous uncertainties in complex engineering systems can be seen in a Product context or
in a Corporate context. (De Weck et al., 2007). Product context - Uncertainties are present in
each stage of the product development being more preponderant in products that exhibit some
element of novelty, from a product that has a new manufacturing process to a product that
follows new design criteria. That element of novelty inputs uncertainties in the system that are
being sorted out during the design process. De Weck et al. (2007) also points out an important
aspect. The reuse of ideas that already exist could in fact eliminate uncertainties that were
dealt with previously in the past, but introduce uncertainties that designers are not accounting
for. These uncertainties are called knowable unknown unknowns and could in fact lead to
catastrophic events such as the crash of the Ariane 5 rocket. Bottom line, products design in
slightly different contexts, to meet different demands or that were modified in subtle ways
require a revision process in order to perform uncertainty mitigation. Theories of design for
flexibility applied in engineering systems in this sense could be stretched to products and their
several components, i.e. designing product, thus their components considering the possible
future integration of versions of the product or even in different products could be a major
tool the reduce uncertainties in this context.

In the Corporate context, endogenous uncertainties can arise in the business context in which
the product is developed. If it's argued (Pierre et al., 2007) that the product must be aligned
with the corporate plan in order to achieve true potential and success the reciprocal isn't less
tue. In fact, business strategies that do not contemplate their individual products in a higher
level could miss changes when the future leads to favourable environments. One case
innumerable times described in the literature is the Daimler Chrysler’s PT Cruiser case, where
inflexibility lead to a missed opportunity and around $480 million in forgone pre-tax profits
according to estimates by Prudential (Brown, 2004). More specifically, PT Cruiser was a big
hit in the models of years of 2000 and 2001. The demand rapidly surpasses the capacity of the
plant in Mexico where it was produced. The issue was that Daimler Chrysler was not able to
shift the overflow of production to another plan in Illinois that had capacity to spare because
this plant was not able to fully accommodate the PT Cruiser since the paint shop was not tall
enough or add the sufficient flexibility to become tall enough.

Other uncertainties arise outside of a system, Exogenous Uncertainties. These kinds of
uncertainties are beyond direct control of the system's designers, being only able to be
influenced at some extent. In engineering system, exogenous uncertainties mainly arise from
the market place, the product, supply chains, stakeholders, political, cultural and
environmental contexts where the system is embedded in.

Uncertainties in the User Context are related to the usage of the product. The way a product is
going to be used by the end user and the conditions under which will operate are far from
being certain. Product life cycle uncertainties may lead to suboptimal performance or even to
failure if unmanaged (Mikaelian et al., 2007). When designing product, product designers
should consider several less likely scenarios and some incorrect ways of product usage.
Several factors may change during the operational life of the product and accounting them
and integrated them as part of the design process may lead to more robust products
introducing high capabilities and better performance.

Change in trends is a characteristic of fast moving markets. Following these trends are the
demand profiles that quickly can turn system requirements obsolete. In the Market Context,
uncertainties should not be underestimated and a thorough market analysis should be conducted leading not only to the anticipation unfavourable events but also to exploitation of advantageous circumstances. Market's sphere of influence in an engineering system is very large and has many levels. In a deeper level, market drivers can change economy having a huge impact in exchange rates that in turn have large influence on the cost of manufacturing as well as the ability to sell products abroad.

Political environment has a wide impact in engineering systems since it can affect a system in many ways. In the Political Context, several aspects must be taken into consideration when designing a system. Designer and managers should consider government policies and be aware of upcoming legislation as they can affect positively or negatively their system. Among changing regulations emissions and fuel economy legislation may require changes not only in the design of manufacturing systems and their products as well operability of existing products. Example of that changes is the position of the huge car industry in Germany after the German upper legislative chamber, in October of 2016, appealed to German government to support a phase-out of gasoline vehicles by 2030.

Cultural forces apply even more profound changes. In the Cultural Context, trends of the masses can put companies out of business or make sales of rise in a fast and unpredictable way. Sometimes governmental policies are not in related to the political context but rather to cultural context. Public opinion can pressure the governments to apply policies. One example of the public influence is the growing concern about nuclear power plants that's leading European countries to rethink their energy policies.

Layered Uncertainties

An important characteristic of engineering systems that gets more prominent has the level of complexity increases is the ill definition of its boundaries. It's not trivial and very often difficult to argue where a system ends and its environment begins. In this sense, considering that a system possesses fuzzy boundaries rather than hard boundaries allows a more realistic view of the uncertainties sphere of influence. Miller et al. (2001) introduces a representation where uncertainties in large engineering projects are stratified in layers, as can be seen in Figure 1, in order to tackle complexity and uncertainty offered in today's megaproject developments. The central layer represents the Technical/Project uncertainties, this are the uncertainties capable to be influenced by the system designers and experts at the most extent. It comprises uncertainties related with operations, technical details and management.

Recalling the previous Contexts taxonomy, this is related with the Product Context. Next is the Industry/Competitive layer, where uncertainties in the evolution of the industry, demand, growth rates or supply conditions, to name a few, arise. This layer of uncertainties is in the Corporate Context and can only be influenced at some extent by the system designers. The next outer layer is the Country/Fiscal one, where exists uncertainties that are hard to modify or out of the range of company's influence power. These are uncertainties in the Political & Cultural contexts such as terrorism, inflation, regulatory stability and intervention or legal stability. The layer that follows is the Market layer. In this context, uncertainties arise in prices of commodities, and exchange and interest rates. The most outer layer is related to natural phenomenon’s e.g. weather phenomena or geological formations.
In this layered uncertainty model one can see that the designers’ degree of influence and their ability to mitigate risks and exploit opportunities decreases from inside out. Uncertainties arising in the inner layers are related to endogenous contexts in which system designers have the ability to control the forces. Example of that are operational strategies or supply conditions. Such control does not imply that uncertainties are known or easy to tame, but in some sense, are uncertainties that are constant and have been studied for quite some time in the literature. Uncertainties in the outer layers tend to be more disruptive. Here is where most of the unknown unknowns are concentrated.

Five Layers of Uncertainty

Uncertainties arise in many levels being common practice to develop distinct models to deal with the different sets of uncertainty separately, being after merged into general framework to tame uncertainties at some extent. Kreye et al. (2011) presents a rather complete classification of uncertainties based in a comprehensive literature review. This review lead to the identification of the need of a holistic classification of uncertainty in order to accommodate different uncertainty aspects. The authors divide uncertainties into five distinct layer: Nature Layer, Cause Layer, Level Layer, Manifestation Layer, Expression Layer. Kreye et al. (2011) defines the different layers as follows:

Nature Layer - Layer regarding generalized uncertainty characteristics, i.e. if uncertainties are due system parameters inherent variability (aleatory uncertainty) or general lack of knowledge (epistemic uncertainty).

Cause Layer - Layer that defines uncertainties based on their source, for instance, lack of understanding, ambiguity and human behaviour. Example of uncertainties concerning this layer is the investigation performed by Yanagisawa & Mikami (2015), where it is stated that prior expectation alters the perception of physical variables. This hypothesis is validated conducting an experiment with subjects using the size-weigh illusion as a case of expectation effect. A simulation model, considering uncertainty, was proposed to explain expectation effect. Zhang et al. 2013 also investigates uncertainties related to human behaviour in scheduling to improve process predictability and efficiency and overcome conflicts of resources.
**Level Layer** - This layer classifies uncertainties regarding its severity, i.e. the level of information detained and the level of information that is missing in the description of a situation.

**Manifestation Layer** - Deals with the point in the process where uncertainties occur. Kreye et al. (2011) not only introduces this classification, *Five Layers of Uncertainty*, but also focus in particular on this layer, where proposes a sub classification for the manifestation layer.

**Expression Layer** - Layer that defines the treatment applied to the uncertainty. Quantitative or qualitative approaches.

**Imprecision, Inconsistency, Inaccuracy, Indecision, and Instability**

Wynn et al. (2011) defines *Imprecision, Inconsistency, Inaccuracy, Indecision, and Instability* as the main uncertainties that require understanding in complex engineering design such as the design of a manufacturing system. The first uncertainty, *Imprecision*, is associated mainly with early stage of the design process where exists an abundance of solutions and alternatives for system designers to apply. *Inconsistency* arises in the presence of information ambiguities, information contradictions or model simplifications. *Inaccuracy* arises primarily in early design stages where the lack of full knowledge or data leads to estimates that may contain errors. An iterative design approach during the various design steps its able to severely decrease this type of uncertainty. *Indecision*, is linked also with the abundance of solution and alternatives, and the tests conducted in early stages. *Instability*, may come from the lack of definition of requirements and specifications of the design process, Afshari et al. (2014). Eckert et al. (2004) gives the example of a receipt of a change request that could increase the expected instability in several design descriptions.

**UNCERTAINTY MODELING**

When modelling uncertainty two main approaches can be followed, a formal approach and a more practical one. As pointed out by De Weck et al. (2007) often methods based in more formal approaches with strong roots in probability theory are not accessible to system designers and engineers and thus cannot be incorporated in their thinking and work in progress. The authors suggest that this fact is due to obscurity and complexity of the formalisms and formulated theories that are not taught generally in engineering design. De Weck et al. (2007) states that others reasons are the harsh company environment to conceive design guidelines that take long to develop. Intensive schedule and money pressure are constants that lead to rapid generation of design methods.

**Formal Approaches**

In his book “Reasoning about Uncertainty” Halpern (2005) performs a comprehensive work about uncertainty where he presents four representations of uncertainty, all requiring numerical expression of likelihood of future events, structured and defined in De Weck et al. (2007) as follows:

*Probability*: Extent to which an event is presumable to happen. Probability theory is a branch of mathematics with ground-breaking contributions in diverse areas such as physics and philosophy, to name a few. Powerful tools based in probability use probabilistic models of natural phenomena, probabilistic intuition, powerful mathematical techniques.
Bayesian Probability: Subjective or Bayesian probability is an interpretation of probability concept under the light of the Bayesian theory. The concept is based on a strength of subjective degree of confidence in a probable outcome. Bayes’ rule can be used as a general principle for how to learn from past experience.

Dempster-Shafer Belief Functions: General framework for reasoning with uncertainty that has connections with probability, possibility and imprecise probability theories. First introduced in the context of statistical inference were later modified and turned into a framework to deal with epistemic uncertainty. This theory allows the combination of evidences from different sources to arrive at a degree of belief represent by belief functions.

Possibility: Possibility theory is an uncertainty theory intended to handle with incomplete information. It differs from probability theory since it uses a pair of dual set-functions (possibility and necessity measures) instead of only one. These dual-functions allow the capture of partial ignorance.

Practical Approaches

This section comprises two parts. The first part is dedicated to a brief introduction of classical practical approaches when modelling uncertainty. In the latter part, examples of practical approaches to model uncertainty in some aspects of the design of complex systems are introduced. For each approach an example of applicability is presented based in research articles. A step-by-step detailed exposition of the approaches is not going to be performed for sake of brevity, since the intension is to familiarize the reader with the current situation point related to modelling uncertainty in design of engineering systems.

Classical approaches

Among the standard approaches to deal with uncertainty are Diffusion models, Lattice Models and scenario planning, a model with roots in the Delphi method. Both Diffusion models and Lattice models represent uncertainty as continuous variables. Representing uncertainty as a real variable is commonly use to forecast future values in electricity prices, stock prices or raw materials prices such as oil and gas.

Diffusion and Lattice Models

Diffusion models are currently an essential approach to describe performance and statistics in decision making. (Moreno-Bote, 2010). Most used models are based on a mathematical description of Geometric Brownian Motion (GBM) (De Weck et al., 2004). GBM is a continuous time stochastic process defined by:

\[ S(t) = s_0 e^{\mu t + \sigma B(t)}, \]

where \( B(t) \) is the standard Brownian Motion, \( s_0 \) is the initial value, \( \mu \) is the drift parameter or in other words the mean trend over time, and \( \sigma \) the volatility parameter that can be estimated based on the standard deviation of past values. GBM is widely use in economics for model market prices evolution due to its simplicity. As stated, the price of a commodity such as a raw material can be estimated using Monte Carlo simulation with GBM. Let’s consider the monthly price of aluminium in the last 30 years, Figure 2, forecasts of different scenarios can be done based on the Geometric Brownian Motion. Figure 3 shows the forecast for 5 different scenarios in the price of aluminium.
As pointed out by De Weck et al., (2007) a big issue with diffusion models is the infinitude of future scenarios. As De Neufville et al. (2004) stated if there’s no will to forego prediction of future states at any intermediate time periods and resorts instead estimate future states at relatively large time intervals one may apply a lattice model to uncertainty modelling. An example of these type of models are the Binomial lattice models that are basically decision trees. This allows the calculation of expected values.

**Scenario Planning**

Scenario Planning was established more than 30 years ago, and since then several techniques and methodologies have been developed (Bradfield et al. (2005)). In Schoemaker, (1991), the author defines scenario as script-like characterization of a possible future presented in considerable detail, giving a certain emphasis on casual connections, internal consistency, and concreteness. Moreover, the author states that good scenarios present more than an end-state description and they should reflect a variety of viewpoints with the purpose of covering a broad range of possibilities. In Scenario Planning the focus is not on forecasting the future nor fully define uncertainty, but rather bound uncertainty. Scenario Planning could prove to be worth using in systems with the following type of conditions:

- Uncertainty is high, relative to the ability of experts to predict and/or adjust to it.
- Several costly events have occurred in the past similar systems.
- Inefficient generation of opportunities.
- Low quality strategy thinking (common trail of too routinized strategic planning).
- Industry has experienced, or is about to experience, significant change.
- Desire of a common Language and framework.
- Strong polar but valid opinions exist among the experts.
It’s worth to point out that scenario planning has several levels of analysis that should be considered when planning strategies.

This stratification in levels of analysis helps the translation from high levels, such macroeconomic or political, to levels that can be directly linked to an option’s consequences.

**Current Applied Approaches**

The constant increase of complexity continues to be a central challenge faced by manufacturing system today. These systems operate in an environment of change and uncertainty (ElMaraghy et al., 2012). Complexity and the associated uncertainty has manifestations across all manufacturing environment: products, manufacturing processes and company structures (Wiendahl & Scholtesse, 1994). ElMaraghy et al. (2012) defines, in their article, the drives and enablers of manufacturing complexity, these drivers are present in Figure 5.
All these drivers affect, at some extent, the several design stages of manufacturing systems. There is a close relation between uncertainty and complexity. Moreover, uncertainty is seen by some as the core of complexity (Suh, 2001). ElMaraghy et al., (2012), defines a complex system as a system consisting of a large number of members, elements or agents, which interact with one another and with the environment. From this interaction new collective functional, structural, spatial, or temporal behaviours may emerge. The difficulty to model those complex behaviours can be a source of uncertainties in complex systems. Among others, complexities that introduce uncertainty in engineering systems are: Complexity in the definition of concepts in all ranges of abstraction; Complexity of identification and quantification of all the constitutive elements of a system; Complexity of the interactions between the said elements within the system; Complexity inherent to time-variant parameters; Complexity in defining the system's boundaries, even if fuzzy, and the interaction with the surroundings. ElMaraghy et al., (2012), proceeds to add that “a complex system is an ‘open’ system, in the thermodynamics sense, involving entropy principles, as well as involving nonlinear interactions among its sub-systems which can exhibit, under certain conditions, a degree of disorderly behaviour.”

Agent-based Modelling

Agent-based models are a class of modelling approaches that views complex systems as an aggregation of autonomous and interacting agents (Macal and North, 2010). Agent-based models not only have a wide range of applications but also their applicability spreads across several scientific domains.
Multi Objective Genetic Algorithms, Petri Nets, Bayesian uncertainty representation

Konak et al. (2006) developed a robust manufacturing system design based in integrated multi objective Genetic Algorithm (GA) and Petri net based modelling framework coupled with Bayesian methods of uncertainty representation. This proposed approach was demonstrated on a manufacturing system configuration design problem in order to find the optimal number of machines in several different manufacturing cells for a multi-product producing system. Uncertainties in the processing times, equipment failure and repairs, and products demand were considered. The objective function aims at minimizing makespan, mean work in progress (WIP) and machine’s number. This framework was used to design, analyse and simulate candidate models while considering distribution model and parameter uncertainties.

Multi Objective Genetic Algorithms

Konak et al. (2006) defines Multi-objective formulations as “realistic models for many complex engineering optimization problems. In many real-life problems, objectives under consideration conflict with each other, and optimizing a particular solution with respect to a single objective can result in unacceptable results with respect to the other objectives”. In order to solve a multi-objective problem is necessary to investigate a large set of solutions, ensuring that each solution has the capacity to satisfy the all objectives with an acceptable amount of efficiency without being dominated by any other solution. In their work, Konak et al. (2006), present a complete list of another well-known multi-objective GA.

Petri Nets

Petri net is a mathematical model language design for the description of distributed systems. This logical network, as can be seen in Figure 7, is a directed bipartite graph comprised of two types of nodes: places and transitions. Places, represented by circles are the conditions and transitions, represented by bars are the events that may occur.

The connections between places and transitions are performed by arcs. The black circular marks are called tokens, and are able to move between two places (e.g. P1 and P3) in the network when a transition (e.g. T1) between the places is enabled and triggers. Each arc has a weight assigned, and the transition is allowed to fire when the amount of tokens in the input places (e.g. P1) matches the weight of the arcs connecting input and output places. Petri nets have a wide range of applications from manufacturing systems to communications protocols (Murata, 1989), or even to model design processes of automotive crankshaft and automate the interactions of concurrent activities (McMahon and Xianyi, 1996). Sharda & Banerjee (2013) develop a design for robust manufacturing systems via Petri net models that use Bayesian uncertainty representation to find performance measures to represent uncertainty.
FUTURE RESEARCH EFFORTS

The industrial context in the last decade has significantly changed. Industry is experiencing fast advancements in technologies and applications leading to the emergence of many new manufacturing concepts (Qin et al., 2016). Industrial policies that foster social and technological innovation towards the new paradigm of industry 4.0 are being implemented in companies all around the world, changing the concepts and common understanding of manufacturing systems. Qin et al. (2016) also states that the future of current manufacturing systems is most likely to evolve in the direction of cyber-physical systems with new complex challenges and broader boundaries where customers and other stakeholders are brought closer and embedded in the manufacturing system.

This new paradigm challenges designers of manufacturing systems being these challenges more prominent nowadays since there’s still a considerable gap between classic manufacturing systems and manufacturing systems intended to be implement under these new guidelines. Currently, the change in progress boosts manufacturing system designers to pursue the industry 4.0 goals and criteria when the latter are not yet well defined. This call for new and better tools for classify manage and model new types of uncertainties arising in this new environment. New ways of dealing with uncertainty such as flexible design approaches, metaheuristic approaches and machine learning aided algorithms have shown themselves to be good candidates in these new scenarios of uncertainty and complexity.

CONCLUSION

This paper summarizes methodologies to classify and model uncertainty when designing general complex systems such as manufacturing systems. First a definition of uncertainty is presented where it is pointed out that uncertainty arises in a variety of different contexts and knowledge areas. After, it’s investigate the growing role of uncertainty in design research. The transversal uncertainty study and its contemplation in design methodologies shows the concern of design researchers in terms of mitigation and exploitation of uncertainty when designing an engineering system. State of the art classification of uncertainties was developed in which it was introduced not only classic uncertainty descriptions but also more recent ones to couple with the evolution of concepts and frameworks. Lastly, theoretical and practical approaches to model uncertainty were introduced as well as some insights about future efforts in uncertainty mitigation and exploitation in a fast-changing manufacturing system’s environment.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding by Ministério da Ciência, Tecnologia e Ensino Superior, FCT, Portugal, under grant MITP-TB/PFM/0005/2013.

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