Design for Uncertainty[1]

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Abstract
The development of engineering systems, whether those systems be products, plant or services, is a complex activity. The systems themselves are becoming more rather than less complex. Partly this arises from the need to optimise multiple system attributes including function, cost, resource usage, and style, among others. Also, most significant engineering projects involve diverse activities (including design, risk assessment, decision making, construction, and ongoing operation), and these invariably require teams of people with different skills. In turn that diversity requires effective management and leadership. Furthermore, the addition of electronic functionality and active control systems adds functionality but also introduces complex failure modes. Currently the development of complex engineering systems is typically managed by decomposing the project according to the bodies of knowledge involved, i.e. according to engineering design, manufacturing/construction, project management, management theory, etc. Consequently, there exist separate professional bodies of knowledge that interface with each other in limited ways. In particular, design theory, risk management, decision theory, and organisational behaviour are all important factors in determining the success of an engineering system, but relate together only weakly.

This paper presents the development of a descriptive meta-model that seeks to integrate multiple separate bodies of knowledge, namely design theory, risk management, decision theory, and organisational behaviour, into one consistent epistemology. This paper presents results for a subset of the larger model. It focusses on key activities in the design process, namely how the design objectives

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(needs) are determined, how early design concepts are formed, and how uncertainties are treated during design. Results are presented for strengths and weaknesses of the constituent methodologies, and issues are identified for further study. Also, the features of a novel methodology, called DSI, for coping with design uncertainties are described and illustrated with data from a domestic dishwasher design.

Keywords: design, system model, uncertainty, decision making, manufacturing

1 Introduction

The development of engineering systems, e.g. plant or products, is a complex activity. Partly this arises from the need to optimise multiple system attributes including function, cost, resource usage, and style, among others. Also, significant engineering projects involve diverse activities, including design, risk assessment, decision making, construction, and ongoing operation. These invariably require teams of people with different skills. In turn that personnel diversity requires effective management and leadership. Furthermore, the addition of electronic functionality and active control systems to systems adds functionality but also introduces complex failure modes.

2 Problem definition

Currently the development of complex engineering systems is typically managed by decomposing the project according to the bodies of knowledge involved, i.e. according to engineering design, manufacturing/construction, project management, management theory, etc. Consequently, there exist separate professional bodies of knowledge that interface with each other in limited ways. In particular, design theory, risk management, decision theory, and organisational behaviour are all important factors in determining the success of an engineering system, but relate together only weakly.

The project hypothesis was that a descriptive meta-model could be developed to integrate the bodies of knowledge on design theory and uncertainty into a consistent epistemology. This is worth doing because it could increase understanding of the availability, strengths and weaknesses of the constituent methodologies, and identify issues for further study.

3 Other approaches

Engineering Design can be formulated as a problem of deciding on the functional structure and values for variables (stochastic uncertainty) in systems for which the behaviour is weakly understood (epistemic uncertainty). However, existing design theory tends not to take this perspective, instead describing methodologies for engineering design. Significant contributions in this area have been made by (Pahl &

Beitz, 1988), Hubka and Eder (1996), (Finger and Dixon, 1989 a, b) among others. There have been many prior graphical models of the design process, including the simple linear model (Finger and Dixon, 1989 a, b) (BS7000, 1989), functional modelling (Pahl & Beitz, 1988), design science (Hubka, 1987; Hubka & Eder, 1996), total design (Pugh, 1991) and derivatives (e.g. Raine, 1998), business environment (Hales, 1994), network (Crisp, 1986), designer's process (Candy et al, 1996), communications (Wallace, 1987), phase diagrams (Hales, 1994), project management, design structure matrix (Yassine et al, 1999; Yassine and Falkenburg, 1999), signposting (Clarkson and Hamilton, 2000), and integration definition (Pons, 2001) among others.

Design is a cognitively complex process, and the complexity arises from the incomplete nature of problem definition and the enormous number of design paths that may be taken. Generally the existing design models do not specifically include uncertainty. Some have identified the stochastic uncertainty in design, and have applied probabilistic (Vose, 1996) or fuzzy theory (Wood and Antonsson, 1989) to process this form of uncertainty. More recently, it has been identified (Ullman and D'Ambrosio, 1995; Ullman, 2001) that making decisions is another significant part of design. Decision analysis has also been applied (Clemen, 1996; Ridgman, 1996).

4 Method

The dynamic process analysis (DPA) methodology (Pons, 2004a) was used. DPA is a structured, deductive process that decomposes the process being analysed into multiple sub-activities (functions) and for each deduces initiating events, the controls that determine the extent of the outputs, the inputs required, the process mechanisms that are presumed to support the action, and the outputs.

The IDEF0 notation (e.g. FIPS, 1993; KBSI, 2000) is used, in which a box describes a function (or activity), and an arc (line arrow) describes an object. Inputs, controls, outputs, and mechanisms (ICOM) are distinguished by placement relative to the box. In most other flowchart notations arrows represent sequence of activities. However, with the present notation it is important to note that arrows should be interpreted as conveying objects to activities (blocks). An activity may begin autonomously when its required inputs are available and its constraints permit. Consequently, the notation provides that multiple activity boxes can be simultaneously active (concurrent/parallel). Sequenced activities (series) can still be readily modelled where necessary. DPA also has the capability to represent complex and uncertain relationships, and it accommodates qualitative (textual) variables.

5 Results

The purpose of the analysis was to identify and relate together the methodologies to design and develop a technical system under uncertainty. The viewpoint is that from a technical expert (e.g. design engineer, engineering manager, or risk analyst) involved in an engineering development project (e.g. product development, or project in the built environment).

5.1 Design, develop, and deploy technical system under uncertainty {DTS}

The top view of the model is shown in Figure DTS. The initiating activity is to determine the need {1} (Pons, 2004b), which leads generation of candidate solutions {2} (Pons, 2004b). This can precipitate assessment of the system technology risk {3} (Pons, 2004c) and simulation of system behaviour {4} (Pons, 2004d). Assessment of the technology risk {3} typically involves probabilistic/quantitative risk assessment (PRA, QRA) and human reliability analysis (HRA). The assessment of technology risk is usually necessary, but not always sufficient, and risk perceptions may also need to be included (Pidgeon, 1998). Both HRA and risk perception are centred on human behaviour, but HRA has been included with PRA as it aims to quantify probability of human operator error which is complementary to PRA. Thereafter a decision is made on which concept to adopt {5} (Pons, 2004e), implementation occurs (design and build) {6} (Pons, 2004b) and the system operated {7}. If system failure occurs, then such failures are analysed {8} (Pons, 2004f) and the system improved. At the end of the system life it is decommissioned {10} and recycled (more or less effectively) for other use.

This process is not necessarily sequential as described. Instead multiple activities may simultaneously be active and at different stages of completeness. The development process is therefore perceived as dynamic and concurrent.

In the background, the organisational leadership creates a culture and shapes individual behaviours {9}, one of which (among many) is the attitude towards uncertainty. It is particularly important that the existence of uncertainty be acknowledge, as otherwise there may be a tendency to adopt deterministic approaches to development, e.g. proceeding directly from {2} to {5} without traversing {3} and {4}.

5.2 Determine the need {DTS-1}

It is essential that the activity of determining the need is adequately performed during any engineering development. It is this activity that defines the specification and shapes all the subsequent activities. The activity has been decomposed into sub-activities, as shown in Figure DTS-1.

Define criteria for new system {4}
The main activity is to define the criteria for the new system (product, service) {4}, where criteria include the description of a satisfactory solution (Ullman, 2001) and the scope. However, it seems unrealistic to expect that any formal specification activity will necessarily be able to fully or even sufficiently identify quantitative constraints prior to commencement of design. Instead the constraints listed in the

specification may be partly qualitative and incomplete. They may also have different strength or degree of compulsion (Owen, 1993).

Determine customer needs {2}
The definition of system criteria is initiated by an evaluation of the quality of the current system {3} , or by determining the customer needs {2}, or a request for relaxed constraints from elsewhere in the design process. These could be downstream or concurrent engineering activities.

Customer needs and importance thereof, e.g. ranked or quantified, are important in accurately determining the system criteria. Market research mechanisms include quality function deployment (QFD) (Bergman and Klefsjö, 1994; Martin et al, 1998), voice of the customer (Gustafsson, 1996), and analytical hierarchy process (AHP) (e.g. Perego and Rangone, 1996; Gustafsson, 1996), and focus groups. The effectiveness of the activity is affected by organisational constraints, particularly the willingness of the organisation to perceive customer opinion as valuable (customer focus). Customer perceptions of product worth and key characteristics (Pons and Raine, 2004) also affect the identified customer needs.

Evaluate quality of current system {3}
The evaluation of the quality of the current system (product or service) {3} is a strategic activity undertaken by the organisation. It can result in initiation of new product development, and the allocation of finance (capital rationing), and prescription of constraints on the development. Initial concepts at if any, might include competitive products (market pressure), bench marking against related products, and customer feedback. These are used to produce specifications for the user interface (styling) and engineering product function.

5.3 Generate early design concepts {DTS-2}

The generation of early design concepts (Figure DTS-2) is essential to innovative design. It is suggested that the main activities are to generate concepts {1}, and refine them {2} to produce conceptual solutions for subsequent evaluation.

Generate concepts {1}
The first activity is to generate concepts. If the design is an incremental improvement on an existing design, then a well-defined input concept may exist. In the more general case of innovative design there may be no existing concept and the solution must be created from scratch. A variety of inventive mechanisms exist. The human inventive mechanisms include personal experience, proven solution elsewhere, natural analogy, and brainstorming. The structured inventive mechanisms include functional decomposition (Pahl and Beitz, 1988), mapping, catalogue (Kersten, 1996), systematic idea generation, morphological analysis (Hague et al, 1996), and theory of inventive problem solving (TIPS/TRIZ) (Zlotin and Zusman, 1999). The artificial Intelligence inventive mechanisms include logic languages, expert systems (Cunningham and Smart, 1993), grammars (Andersson, 1994), genetic algorithms (Schmidt and Cagan, 1993), case based reasoning, and neural networks (Noguchi, 1998).

The initiators and constraints on the conceptualisation activity include prescribed inventive constraints (functional needs) originating from the specification. Organisational constraints generally exist in the form of organisational behaviour, team effectiveness, and encouragement for innovative behaviour. The activity may also be initiated by a downstream process that calls for a new solution. This might arise from identified system errors, need for remedial design, or as a consequence of a project decision to freeze some other aspect of the development.

The output is a concept. It is possible that several concepts may be considered simultaneously and be in various positions within the design activity, and several design activities in a larger system may all be active. Therefore, the activity should not be interpreted as a set of discrete state transitions but as a system of multiple simultaneously active threads.

Refine concepts {2}

The next activity is to refine the potentially vague initial concept, to produce a concept that demonstrates potential as a real solution. The refining process primarily takes into account concurrent engineering constraints from elsewhere, e.g. design and manufacturability, production capability, cost, ergonomics, material strength, component availability, etc.

Multiple candidate concepts will usually be at various stages of generation and refinement for a project. The activity might also impose concurrent engineering constraints on other processes (e.g. design, manufacturing). These may be the preliminary constraints for concurrent engineering, cf. the overlapping concept in design structure matrix (Yassine and Falkenburg, 1999). If the activity proves too difficult to achieve, it may result in a call for relaxed constraints on the specification.

Mechanisms that support the refinement activity include focus groups, system modelling, functional modelling (Hubka and Eder, 1988, Oh and Sharpe, 1996), bond graphs (Cellier, 2001), feature based modelling (Fu and De Pennington, 1994), risk assessment (Ossenbruggen, 1994), sensitivity analysis, design of experiments, loss functions (Box et al, 1988), decision analysis & belief networks (Clemen, 1996), operational research/management science (Taylor, 1999), Fuzzy theory (Wood and Antonsson, 1989), Monte Carlo analysis (Vose, 1996) and qualitative simulation (Kuipers, 1994), among others.

Retrieve past design intent and record current one {3}

Knowledge of any earlier design intent is important in the process, as this prevents the re-introduction of known failure modes or deficiencies back into the system when a design revision occurs. This is an underdeveloped area of design since it relies on some prompt, usually human memory, to initiate and sustain the activity.

5.4 Predict system behaviour {DTS-4}

The process for developing a system model is shown in Figure DTS-4. The desired output is a model of system behaviour that can identify or preferably quantify the system outcomes.

The output of activity {1} is a basic model of the system physics, which then needs to be refined {3} to include treatment for uncertainties (e.g. stochastic and epistemic) {4} and the inclusion of dynamic effects {5}. All these activities may be concurrent, repetitive and in various stages of completeness. It is then necessary to ensure robust modelling by adjusting the model to meet known data {2}. The desired output is a model that is able to show uncertainty, and accommodate the complexity of problem (completeness). Once an adequate model of the system is available, it becomes possible to predict behaviour of the system {10}. The ultimate objective is to predict anticipated system states for various input variables. For example, in an engineering design application the model might be run using the candidate concept to determine the anticipated system state(s) and the probability (or likelihood) of each state. The design would then be optimised for desired function. In turn this requires the prior collection of data {6, 7, 8} and the estimation of other variables for which data are lacking {9}.

5.5 Ensuring accurate modelling {DTS-4-2}

Once a model of system behaviour is created, it is necessary to ensure that the model is accurate. The associated activities are shown in Figure DTS-4-2.

The simplest approach is to calibrate the model to meet known data {2}, which of course requires knowledge of existing cases and how the system (or a similar system) responded. Calibration results in a model that is accurate for particular input data, assuming that those data were from a sufficiently similar system. The mechanism for achieving this is usually adjustment of a calibration constant, the value of which need not have strong theoretical justification. For further robustness it is desirable to validate (or reconcile) the model {3} so that its accuracy is known for a range of inputs. This ensures that the underlying processes (operating physics) have been adequately included. This is a typical target for many engineering analyses. However, a calibrated or validated model is only accurate for the range of input data, and may be inaccurate when extrapolated beyond that range.

An additional level of modelling integrity is to verify that the model operates correctly {4} even outside the known range of inputs (case-base). This requires a more extensive knowledge of the system, typically a complete understanding of the operating physics, and data from numerous different areas to confirm the hypothesised physics. The advantage of this type of model is that it permits accurate extrapolation beyond the range of input data. However, the required level of system knowledge is typically unavailable for problems in the 'risky' domain.

5.6 Provide treatment for uncertainties {DTS-4-4}

Any model that simulates system behaviour, especially one that explores risk, should have some ability to incorporate or show uncertainty. Purely deterministic models have limited usefulness because their output provides no information as to the robustness of the result. The means for providing treatment for uncertainties in a system model are shown in Figure DTS-4-4.

A crucial initiating activity is for the analyst to acknowledge the existence of uncertainty {1}. The present work proposes three independent dimensions of uncertainty: epistemic uncertainty, random variability, and type of variable (Pons, 2001; Pons, 2004d), as elaborated in Figure DTS-4-4-1.

Accommodating stochastic uncertainty in a model {2} requires the use of single values (worst or plausible bounds, random what-if analysis, mean values), ranges (sensitivity analysis, moment methods, PERT, fuzzy theory), or full distributions (algebra of random variables, controlled interval method, Monte Carlo) (Pons, 2001). The full distribution mechanisms are considered superior, providing that the problem is sufficiently well defined for their use (which is not always the case).

Abstraction {3} can be a major problem in model development. This is because most simulation systems in engineering use mathematical equations, and therefore require quantitative variables. However, real problems typically present qualitative variables too. Trying to assign weights or a numerical scale to qualitative variables is fraught with methodological difficulty. Some aspects of this problem, and its application to prediction of dishwasher performance, have been described by Pons and Raine (2004).

The third aspect of uncertainty that needs to be considered is epistemic uncertainty {4}. Mechanisms for including epistemic uncertainty in model formulation include explicit functions (axioms, mathematical equations), correlation (statistical regression), logic (boolean) & rules, expert opinion (conditional probability, decision theory, fuzzy theory), and novice opinion (Pons, 2001).

The three primary dimensions of uncertainty (stochastic, abstraction, and epistemic) are proposed to be independent, so that both quantitative and qualitative variable types may have stochastic (or indecision) uncertainty, and the relationships (epistemology) may also be uncertain. Consequently, combining the multiple dimensions of uncertainty in a risk model is a non-trivial task, but the existence of the uncertainties should be acknowledged.

Modelling tools are generally incapable of accommodating all three dimensions of uncertainty. Yet these uncertainties frequently arise in design studies. The design for system integrity (DSI) methodology (Pons, 2001) was developed particularly to begin to address this problem. This software system is able to model systems with:

- quantitative and qualitative variables,
- objective and subjective knowledge,
- uncertain values for variables.

What is unusual is that a single DSI model can accommodate all these forms of uncertainties in one model. The software embodiment of DSI also includes catalogue features and multiple viewpoints, as support features for the engineering design environment.

DSI was used to construct a model of a wash performance for domestic dishwashers (Pons and Raine, 2004). The model incorporated qualitative variables, such as soil type (Figure 1) among others. Under conditions of high uncertainty, the model was able to successfully predict the wash performance of a particular dishwasher (Figure 2). The figure shows the predicted and actual wash performance of a dishwasher, but instead of a single deterministic metric it provides a complete probability distribution for the output variable. This illustrates that it is possible to overcome the difficulties caused by uncertainties in model formulation. The advantages of DSI are (a) the ability to model system behaviour in situations where it was not previously possible to do so, and (b) the opportunity to be explicit as to how uncertainties were treated. The risk in the design is therefore more transparent than in a deterministic solution.

6 Discussion

The DPA method provides a descriptive and graphical model of the process under study. Its intended use is to describe and clarify the design processes. It is not primarily intended to simulate how a particular design might progress.

Predictive ability
The DTS model permits the consequences of failed processes to be identified, and these are shown as 'detriments' on the figures. For example, there is a lack of constraints on the early design process, corresponding to the difficulty of identifying specification requirements (Pons and Raine, 2004), and reliance on professional judgement and other subjective human attributes (Court et al, 1996). Alternatively, over-constraint of the design activity may occur due to conflicting specifications. Additional detriments appear on the figures.

Further developments
The ways in which organisational behaviour and personality psychology affect the design process are only beginning to be represented in the design literature. It may be noted that this DTS model includes the concept that organisational constraints affect the solution generation process. Specific factors are identified as organisational behaviour, team effectiveness, and extent of encouragement for innovative behaviour. It appears to be feasible to extend the DTS model into these areas since the DPA method excels at accommodating the qualitative variables and subjective knowledge.

Other work in progress explores risk assessment, use of expert opinion, design for robustness, decision making, risk perceptions, system operation, and failure analysis. The ability to integrate these multiple domains in one model is perceived to be highly useful in better understanding the complexities of the design processes.

Limitations of the model
The work is conceptual and descriptive and it is explicitly acknowledged that it is based on personal insight and opinion of the author, and is therefore subjective. To reduce the likelihood of error, the model was reconciled during construction with the extant body of knowledge as represented by the references.

The model provides a big-picture perspective for a system in which epistemic uncertainty is high. Consequently, the model cannot be considered definitive or final. It is possible that multiple models, from different perspectives, could all be simultaneously useful. Indeed, the concept of viewpoint is a fundamental premise of the IDEF0 modelling standard, which states that:

> '*different statements of viewpoints may be adopted that emphasize different aspects of the subject. Things that are important in one viewpoint may not even appear in a model presented from another viewpoint of the same subject*' (FIPS, 1993: p14).

The model presented here should therefore be considered one of potentially many perspectives.

Since the model is an interpretative one, its output is limited to providing explanations of the processes. In principle the diagrams could be successively detailed down to the level of providing detailed standardised prescriptive procedures, mathematical relationships, conditional probabilities, or even dynamic Monte Carlo algorithms. However, that is not attempted here, nor is it certain that it is desirable even if it is feasible. The intended value in the model is the provision of a conceptual checklist to support, rather than prescribe, the engineering design and development processes.

7 Conclusions

Using the DPA methodology a descriptive meta-model (DTS) has been developed to integrate the bodies of knowledge on design theory and uncertainty into a consistent epistemology. This provides useful insights into the availability, strengths and weaknesses of design practices.

The originality in the DTS model is (i) the development of a novel way of relating together different bodies of knowledge that affect the design processes, and (ii) the extraction of qualitative assessments of the robustness of various methods used in these processes.

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