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APPROACHES TO MITIGATE THE IMPACT OF UNCERTAINTY IN DEVELOPMENT PROCESSES

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ABSTRACT

The inherent complexity of Product Development (PD) processes, coupled with competitive pressures to deliver products *cheaper, faster better*, has been a significant source of difficulties in planning and executing many large-scale PD projects. This is evident from the large number of projects that have failed to deliver on their original time or cost expectations.

Given the potentially severe consequences of PD process delays, mitigating the impact of uncertainty sources that may affect PD process duration has been a popular research topic. Concepts such as reliability, flexibility, versatility and robustness have been used in the literature to denote process insensitivity to various types and sources of uncertainty. This paper interprets these four related concepts as different types of process insensitivity to uncertainty and thereby contributes to clarifying their meaning in the context of PD processes. We focus on those approaches which aim to mitigate the likely impact of process risks on project performance without removing the sources of these risks.

Keywords: Product Development (PD) process, uncertainty, robustness, reliability, flexibility, versatility

1 INTRODUCTION

Although the introduction of state-of-the-art technologies, new project management tools and information and knowledge management systems has greatly facilitated better execution of big engineering projects, project managers are still far from being able to effectively mitigate the influence of multiple sources of uncertainty inherent in such projects [1]. In short, uncertainty prevails. This is demonstrated by many high-profile projects that have failed to deliver on their early promises and is supported by numerous other studies (e.g. [2],[3]).

On the one hand, at the heart of these difficulties lies the very nature of current PD, in which the designing of an artefact has been separated from its realisation process [4]. This has led to increased difficulties in planning and executing development projects in which off-nominal behaviours may dominate [5], because "*much can and does go wrong*" [6]. On the other hand, these difficulties have been driven by competitive pressures to develop products *cheaper, better, faster*. Therefore, it is important to effectively manage uncertainty in PD processes as this may improve the likelihood of PD project success.

This paper reviews, discusses and relates several approaches to mitigate uncertainty in PD processes. The paper proceeds as follows. Section 2 discusses the motivation for the research and thereby provides background for the subsequent analysis. In Section 3, different sources of process uncertainty are discussed to illustrate the scope of difficulties faced in managing PD process uncertainty. In Section 4, we define the concept of process insensitivity through discussion of process operating domains. Section 5 presents different approaches to improve this insensitivity and in Section 6 the relationships between the approaches to protect the system are discussed. Section 7 illustrates how the abstract concept of process insensitivity to uncertainty can provide concrete insights by presenting a process simulation example. Section 8 presents discussion and, finally, conclusions are given in Section 9.

2 BACKGROUND

Existing literature on uncertainty in PD processes falls into two main categories. Firstly, some studies focus on understanding uncertainty in PD (e.g. [7]-[9]). Secondly, other studies explore approaches to manage this uncertainty. Examples include studies on flexibility (e.g. [10]-[13]), reliability (e.g. [14], [15]) and, most recently, robustness (e.g. [16], [14], [17]). However, with the increasing number of publications on uncertainty and ways of managing it, there is also growing confusion as to the proper use of many concepts associated with uncertainty mitigation – different concepts are often used to convey the same meaning or, alternatively, the same concept is often used to denote very different meanings. There is therefore a need to clarify the various concepts and their relationships. Drawing on the work of [18], whose framework is one of the most comprehensive attempts to clarify different concepts related to managing uncertainty in PD, this paper aims to undertake such investigation, further developing those concepts that relate to protecting the system against the influence of uncertainty.

The paper discusses 'process insensitivity to uncertainty'–henceforth referred to simply as 'insensitivity'–as a high-level term which encompasses a number of different definitions. A conceptual framework is presented which distinguishes between types of insensitivity and between the different approaches which can be employed to improve insensitivity. The framework is intended to clarify the relationships between different uncertainty mitigation concepts and does not provide direct guidance for approaching uncertainty mitigation in practice. Interpretation of our framework in a concrete context is illustrated with an example: the development of insights which can be used to support the design of processes to be more robust to delays in individual tasks.

3 UNCERTAINTY IN THE PRODUCT DEVELOPMENT PROCESS

The sources of difficulties in delivering timely PD projects are often represented and discussed through different sources of uncertainty (e.g. [19], [20], [9]). Uncertainty–"*the inability to determine the true state of affairs of a system*" [21, p. 238] or "*things that are not known, or known only imprecisely*" [18, p.3]–has been a popular topic in the literature of PD; many different views and numerous classifications of uncertainty have been proposed. An exhaustive review is outside the scope of this paper (an extensive analysis of different perspectives and classifications of uncertainty can be found e.g. in [22] and [23]).

In general, however, project managers have to manage two types of 'process uncertainty' which can be defined as the uncertainty associated with executing a process, i.e. with coordinating people and other resources to follow the plan [24]. The first type can be called exogenous (external) process uncertainty, as it relates to the unknowns in the process environment, and the second endogenous (internal) process uncertainty, as it is driven by the novelty of the process itself (Figure 1). The following sub-sections briefly outline these two main types of uncertainty as related to PD processes. This helps to clarify the objectives of the mitigation strategies discussed later.

3.1 Exogenous (external) process uncertainty

Exogenous process uncertainty is used to describe uncertainty in the process environment and can arise from organisational change, the instability or unpredictability of markets, changes in user expectations, or the evolution of the political and cultural contexts of the company [25], [9]. While PD companies control the corporate context of their design processes and can, to some degree, influence the user context, most of them have little influence over other elements of the design process environment (Figure 1).

3.1 Endogenous (internal) process uncertainty

There are two main dimensions to internal process uncertainty: the technology novelty dimension and the process complexity dimension. The first has two components: uncertainty associated with product technology novelty and uncertainty associated with process technology novelty; the second reflects the difficulty of the process objectives, the newness of those objectives to the company, and the degree of interdependence among product elements. Both the difficulty and newness of process objectives derive from the broad goal of competitiveness within a complex and competitive environment and compliance with various stakeholders' and regulatory bodies' complex and changing requirements. Since the process required to develop a more complex product is normally a process of greater complexity than that undertaken for a simpler product [27], the degree of interdependence among aspects of a design process is a derivative of structural and functional product complexity.

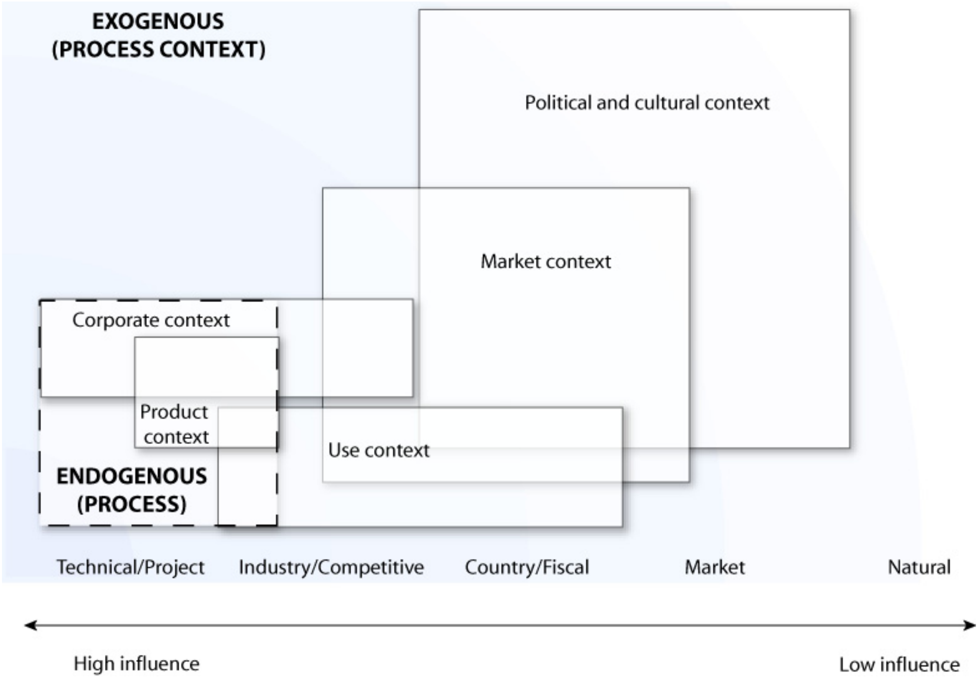

Figure 1. Contexts of uncertainty and its layers (based on [9] and [26]).

4 DEFINING INSENSITIVITY

This section begins to develop the conceptual framework by discussing how insensitivity of PD processes to uncertainty can be conceptualized. An approach is outlined to distinguish between different types of insensitivity through consideration of different operating domains of the PD process.

Processes which are insensitive to the influence of uncertainty are often described as having low variability (e.g. [14]). In PD process execution, variability can stem from a number of factors. For example, since there may be several ways of pursuing a particular goal within the process, execution may follow a different route according to how participants choose to organise their work. In the context of turbine blade conceptual design, Bell et al. [28] illustrate this by discussing a situation in which a choice has to be made between two types of analysis: a fast and efficient method yielding limited design insight, and a more detailed but time-consuming and expensive method. Bell et al. argue that different routes of process execution will result from different choices regarding which type of analysis is chosen at each point in the process.

Defining insensitivity to uncertainty in terms of minimising variability is justified in manufacturing situations, where the objective function is typically of the form: ‘*nominal-is-better*’ (e.g. the dimensions of manufactured parts should be as close to the specifications as possible). However, application of this view to the design process may not always be appropriate. This is because the objective function for optimising project execution includes not only predictability, but also performance expressed as ‘*less-is-better*’ (e.g. lower cost or shorter duration). In other words, variability alone does not sufficiently describe a PD process’ insensitivity to uncertainty in a way which could be useful to help companies improve profitability.

A more suitable perspective may be gained by considering the four domains of the system operational environment discussed by [29]:

- **Standard Domain (SD)**–the set of all operational conditions for which the system meets its specification.
- **Anticipated Exceptional Domain (AED)**–the set of all operational conditions for which the system delivers correct exception outcomes – i.e. meets its exceptional specification.
- **Failure Domain (FD)**–the set of all operational conditions for which the behaviour of the system contradicts the specification or exceptional specification.
- **Unanticipated Domain (UD)**–the set of all operational conditions which are not included in the system specification.

Using a design process example, these concepts can be graphically illustrated by linking the four domains to the probability density function (PDF) of the expected process duration (Figure 2). In this representation, Standard Domain refers to all those acceptable process durations that represent process execution within the planned timeframe (although this may include some responsive re-planning and fire-fighting); Anticipated Exceptional Domain will cover those acceptable process durations that reflect some exceptional but anticipated situations; Failure Domain will denote unacceptable process durations; and Unanticipated Domain will signify all those possible process durations that result from process execution in the presence of unanticipated events, such as unplanned iteration.

In the following sections, we argue that the four operating domains are a useful way of positioning different approaches to improving PD process insensitivity and show that different approaches can be distinguished on the basis of which domain(s) are considered. Furthermore, it is possible to distinguish different approaches according to what types or sources of uncertainty are represented by the domain(s) they consider.

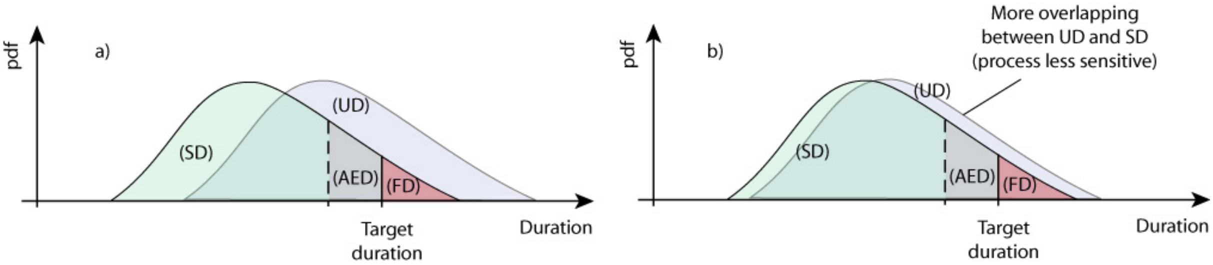

Figure 2. Variance-based evaluation of process insensitivity: a) original process b) process with improved insensitivity.

5 APPROACHES TO IMPROVE INSENSITIVITY

5.1 Strategies for dealing with uncertainty

Various concepts have been used to convey the meaning of process insensitivity to uncertainties. Managing process uncertainty starts with choosing the overall strategy for dealing with uncertainty. Such strategies include:

1. The existence of process uncertainty can be reduced by lowering the difficulty of process objectives. Setting more realistic time targets is one example of this approach. Although in principle contradictory to the need to reduce time-to-market, this approach may nevertheless be viable as some studies suggest that less ambitious time targets do not necessarily lead to lower profitability (e.g. [30, p. 2539].
2. Uncertainty mitigation strategies aimed at minimising the probability of occurrence of undesired events can be employed. Examples of these approaches include accessing and developing knowledge of unknowns (e.g. [31]) and Risk Management techniques (e.g. [21]).
3. The process can be designed to be less sensitive to various unknowns. This amounts to mitigating not the *existence*, but the ultimate *impact* of the uncertainty.

To facilitate discussion about which of the above strategies can or should be used in a particular situation, it is useful to consider the different responses to uncertainty which they represent. In general, two such responses can be identified ([7], [32]):

1. **Reducing the uncertainty**. Uncertainty reduction methods aim to increase knowledge about the system and its environment. Examples of such methods include collecting more data, performing additional analyses or partitioning the system into more manageable and easier-to-understand subsystems.
2. **Protecting the system**. There are two basic ways of protecting systems against the influence of uncertainty: active and passive:
   a. **Active protection**. Protecting a system in an active way is to ensure, by design, that the system is capable of adapting itself to effectively deal with unknowns. Ensuring that a system is flexible, i.e. that it is capable of adapting itself to deliver acceptable results despite changes in the results themselves, is one example of an active way of protecting the system.
   b. **Passive protection**. Protecting a system in a passive way is to ensure, by design, that the system is capable of withstanding the influence of uncertainty without the need to change its structure or basic mode of operation during operation.

Ignoring uncertainty is an equally valid response, but the implications of that approach are not discussed here. Likewise, dealing with consequences of uncertainty only when it has materialised as an adverse event can be seen as another possible response. However, as one does not have to deal with unknowns in such a scenario, this response is also not considered in this paper.

While protecting a system is presented here as an alternative to reducing uncertainty, it is important to note that protection also involves some uncertainty reduction. This is because knowledge of uncertainties against which the system is being defended is required in order to design the system against them. Such uncertainty-uncovering is one form of gaining knowledge and hence also a method of uncertainty reduction.

While the choice of strategy for dealing with process uncertainty will be influenced by the attitudes of process stakeholders with regard to risk (e.g. risk seeking managers will be inclined to start a project even if there is a significant amount of uncertainty), the choice of response will primarily depend on the type of uncertainty being addressed.

The concept of insensitivity, as discussed in subsequent sections of this paper, covers protecting the design process against all types of uncertainty. However, since different methods are required to handle different types of uncertainty, different approaches may be taken depending on the class, or classes, of uncertainty which are of primary concern. In the following sub-section we therefore discuss types of uncertainty in more detail to draw clear boundaries for our subsequent analysis.

5.2 Uncertainty types

One of the most common ways of classifying uncertainty is to distinguish three dimensions–aleatory uncertainty, epistemic uncertainty and errors:

1. **Aleatory (irreducible) uncertainty** (from the Latin *aleator*–dice thrower) refers to the inherent randomness or unpredictability of the system [33]. In its pure form it does not contain any uncertainty which is due to a lack of knowledge ([21], p. 239-240). Aleatory uncertainty is usually quantifiable, and thus is best represented in stochastic terms and can be reasoned about using probability theory [33]. Aleatory uncertainty is sometimes equated with variability.
2. **Epistemic (reducible) uncertainty** (from the Greek *episteme*–knowledge) stems from lack of knowledge and as such, is sometimes called imprecision or subjective uncertainty. According to [33], this type of uncertainty is best represented in terms of intervals. When building a model, epistemic uncertainty reflects how well the model represents the target system's significant behaviour. It can be introduced through the model's topology, its parameters, and the data collection and processing techniques [21], p. 233). Accordingly, it can manifest itself in incorrect models, missing variables, and wrong assumptions and abstractions [22]. The distinction between aleatory and epistemic uncertainties sometimes reflects the distinctions between the terms 'risk' and 'uncertainty' [34], [21p. 53].
3. **Errors** take place due to practical constraints (e.g. limitations of experimental approaches or approximation methods used) and are not associated with lack of knowledge [35]. As such, errors are also sometimes viewed as a subclass of reducible uncertainty [22]. Error is sometimes referred to as numerical uncertainty.

This three-dimensional classification of uncertainty highlights two reasons for aiming to protect a PD process against uncertainty, rather than aiming to reduce uncertainty. Firstly, since aleatory uncertainty is essentially irreducible, protecting the system against its influence is the only possible response. Secondly, since reducing some constraints or accessing knowledge to reduce epistemic uncertainty and errors may prove too expensive or too time-consuming, protecting the system against the influence of these difficult to reduce constraints and this difficult-to-access knowledge may be the only practical response.

6 PROTECTING AGAINST THE INFLUENCE OF UNCERTAINTY

Building upon the discussion of uncertainty types and insensitivity strategies, this section outlines some of the key approaches to protecting a system against the influence of uncertainty. The approaches are differentiated in terms of the process operating domains and types of uncertainty considered, according to the definitions given in previous sections.

6.1 Process reliability

Reliability can be defined as the "*Probability that the system will do the job it was asked to do (i.e. will work)*" [18, p.7]. The division of a process into different operational domains, as discussed in previous sections, allows full reliability to be defined as the property of systems with FD =[]. In other words, a fully-reliable system behaves exactly as specified in its specification and exceptional specification.

6.2 Process robustness

The essence of reliability and that of robustness are fundamentally the same: both concepts refer to the ability of a system do the job it was asked to do. However, while the concept of reliability usually concentrates on the probability of achieving the goal under a specific set of circumstances, robustness refers to achieving the same goal in the presence of uncertainty. More formally, full robustness is the property of systems in which FD =[] and UD=[] [29]. According to this definition, increasing process reliability requires Failure Domain to be reduced and increasing process robustness requires more overlapping between Unanticipated Domain and Standard Domain.

Considering all four domains of process operational environment as one distribution (hereafter referred to as the Process Operating Domain) can also be useful for clarifying differences between process robustness and process reliability. If a set of all process outcomes that are not acceptable is represented by Extended Failure Domain (EFD), as shown in Figure 3, then improving process robustness is equivalent to reducing EFD. Conceptually, this can be achieved in two ways: by redesigning the process such that there is more overlapping between Unanticipated Domain (UD) and Standard Domain (SD) (Figure 3a) or by reducing Failure Domain (FD), i.e. by improving reliability (Figure 3b). A process which is more robust therefore also usually implies greater reliability.

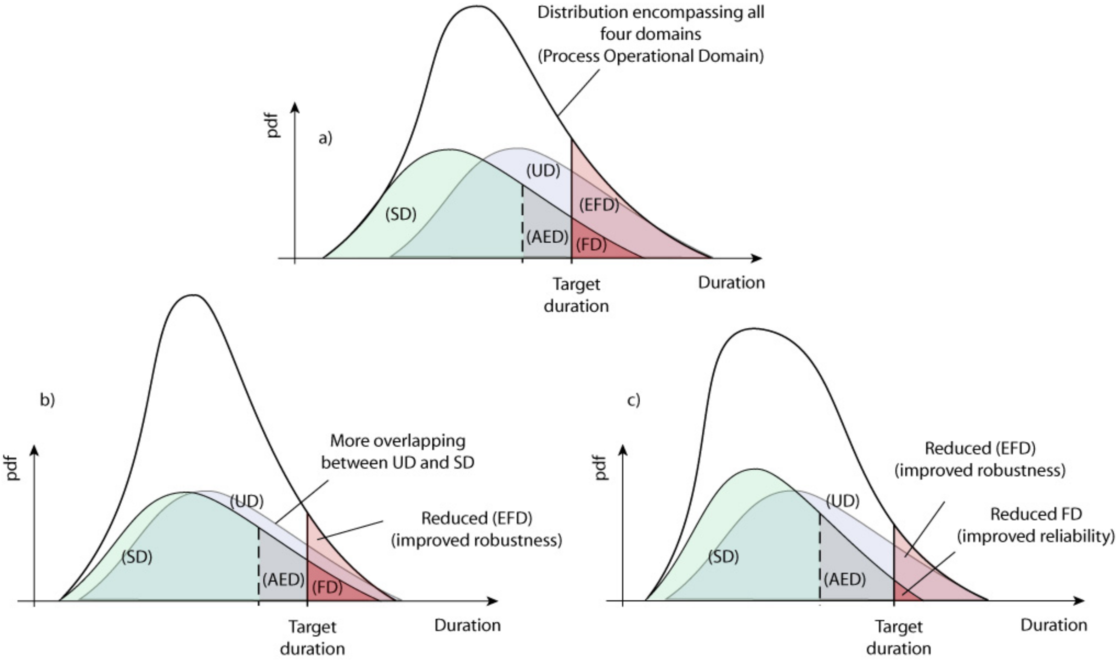

Figure 3. Improving process insensitivity through reduction of Extended Failure Domain (EFD): a) original process, b) improved robustness due to more overlapping between UD and SD, c) improved robustness due to reduced FD (improved reliability).

6.3 Process flexibility

Flexibility, which has been defined as "*room for manoeuvring*" [36, p.67], is arguably one of the terms that have been most frequently used in relation to process robustness. Nevertheless, two fundamental differences between the two concepts have been typically recognised. The first difference is that flexibility, in contrast to robustness, exemplifies an active way of protecting the system. To illustrate the second difference it is convenient to represent the two concepts as a function of the system's objectives and environment. Both robustness and flexibility refer to a characteristic of a system that operates in a changing and/or unknown environment. However, whereas robustness involves satisfying a fixed set of objectives, flexibility denotes the ability to meet changing objectives [11] or, in other words, “to do jobs not originally included in the requirements definition” [18, p.7].

It is important to realise that the distinction between flexibility and robustness, based on the above definitions, is often blurred when applied to the PD process. This arises for two reasons. Firstly, it is often difficult to classify actions during process execution as being either passive or active responses to uncertainty (e.g. exercising a built-in option could be classified either way). Secondly, the *basic job* of many design processes is defined only by some high-level product characteristics (e.g. to meet fuel efficiency requirements for vehicles), which leaves a considerable degree of freedom for the interpretation of the system’s *basic job* and for actual process execution. As a result, changes in product requirements that are introduced during process execution but which do not require modifying key product characteristics, i.e. which do not require changing the system’s high-level objectives, can be seen as falling within the domain of process robustness. Accordingly, while responding to major changes in product architecture (see e.g. [37; 38]) will most likely be outside the scope of robustness analysis, responding to changes in secondary product characteristics or to small deviations in the main product specifications will most likely lie within the scope of this analysis.

As with reliability and robustness, flexibility and robustness are thus inherently related to each other. For instance, the robustness of a design process might in theory be improved by means of flexibility in decision-making or by designing flexible product architectures that enable design changes to be readily absorbed.

6.4 Process versatility

The fourth and final uncertainty protection approach we consider is the concept of process versatility. Versatility had been defined as the “*Ability of the system, as built/designed, to do jobs not originally included in the requirements definition, and/or to do a variety of required jobs well*” [18, p.7]. The similarity between versatility and robustness lies in the fact that both concepts, as highlighted in the first part of the above definition, exemplify the passive way of protecting the system against the influence of uncertainty. However, there is one fundamental difference between the two concepts: while robustness applies to systems with fixed objectives, the concept of versatility, similar to flexibility, implies meeting objectives not originally included in the requirements.

6.5 Summary

The relationships between the four concepts discussed above are summarised in Figure 4. It is important to note that the above list is not fully comprehensive. It comprises concepts that have been most widely studied in the literature of PD and which, therefore, are considered most important to this research.

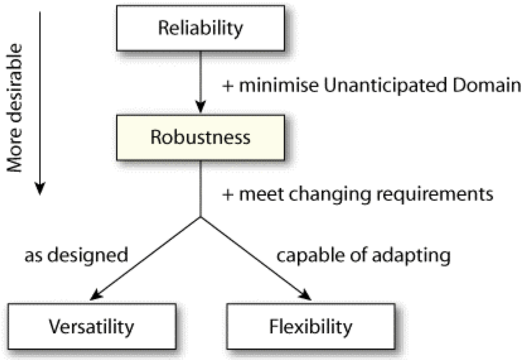

Figure 4. Relationships between process robustness and the associated concepts.

7 CASE STUDY: IMPROVING INSENSITIVITY THROUGH ROBUST PROCESS DESIGN

This section describes a case study that shows how process insensitivity can be improved in practice. The study is outlined here to illustrate one way in which the abstract concepts discussed in this paper can be operationalised to study more concrete problems; it is reported in full detail in [39].

7.1 Using simulation experiments to explore Process Operating Domain

One way to understand and improve PD process insensitivity is to construct a simulation model of the process under consideration. Such models incorporate sources of uncertainty explicitly, for instance in the duration of individual tasks. Simulation then reveals an approximation of the operational domains. It is then possible to conduct experiments in which the models are modified to explore the impact on the operating domains and evaluate proposed improvements (e.g. [40], [14]). However, coupled with the difficulty of interpreting simulation results, the high cost of designing and conducting simulation modelling experiments means that in most real-life applications, regardless of the fidelity of the model and design of the simulation experiment, the Process Operating Domain will be difficult to state with confidence (Figure 5a).

One way to avoid this problem is to design simulation experiments that do not aim to emulate the behaviour of a particular real-life system through a specific and potentially very complex model, but rather to explore the mapping from particular model characteristics to the conclusions which could be drawn about processes which exhibit those characteristics. The essence of this approach is to explore characteristics of the unknown Process Operating Domain by sampling from the search space of possible process configurations. For instance, experiments of this type could aim to understand how process robustness varies with different process structures or different modelling assumptions. This second approach is shown in Figure 5b and illustrated below through an example application.

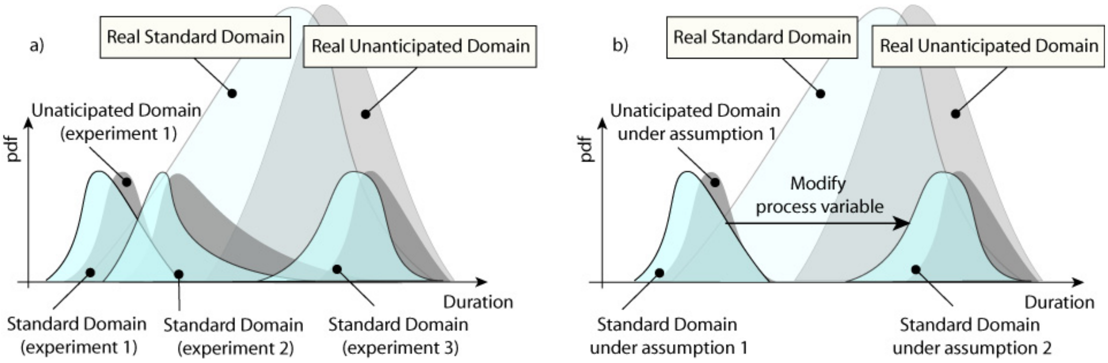

Figure 5. An illustration of the experimentally derived process operating domains that do not match the real Standard and Unanticipated Domains: a) traditional process experiments, b) simplified process experiments.

7.2 Overview of an example simulation experiment

In the example experiment using this approach, discrete-event simulation was used to examine the factors which impact upon robustness of engineering design processes–more specifically, to explore what determines how delays in completing individual tasks lead to greater or lesser delays in the overall process. The experiment was based around simulating large numbers of hypothetical 'process fragments' comprising 3, 4, 5 and 6 tasks (the search space of possible process configurations). We modelled the fragments using a task-based simulation framework, which allows process duration (process operating domains) to be calculated from the properties of individual tasks (model's parameters) and the structure of information flows between tasks (process variable). The rationale of the experiment was that by modifying task properties and by changing the density of information flows a better understanding of the scope and the characteristics of the unknown Process Operating Domain could be developed as indicated in Figure 5b.

The simulation modelling framework we used–the Applied Signposting Model (ASM)–is described in full by [41]. In short, the ASM simulation is based on the following assumptions:

- The order of attempting tasks is governed by information flows, such that a task is attempted immediately that all its predecessors are completed.
- Tasks may be possible to execute concurrently given the information flow constraints. However, this may be limited by resource availability – if two tasks are ready to start but both compete for the same resource, then one must be selected and attempted first. When that task is completed, the resource is released and the second may be attempted.
- Task selection policies govern which task is attempted when more than one task is possible to start but they cannot be executed in parallel due to resource limitations.

Given these modelling assumptions, the effect of a delay within any cluster of tasks upon the cluster's total duration is determined by the following variables:

- the number of tasks in the cluster;
- the duration of each task;
- the information flows which constrain the order in which tasks can be attempted;
- the resource constraints which can prevent tasks from being executed concurrently;
- the task selection policy;
- the task(s) whose completions are delayed;
- the duration(s) of the delays.

For the purposes of this example we concentrated on evaluating the impacts of information flow density and resource constraints upon the robustness of a cluster's duration to delays in constituent tasks. We treated all other factors as uncertain variables whose values are uniformly distributed within given ranges. This allowed the impact of information flow density and resource constraints on process robustness to be studied independently of other factors in the model. This was achieved by generating all possible combinations of information flows by which 3, 4, 5 and 6-task clusters can be interconnected, then assigning a range of values for the duration of each task in each such variant. Each variant was then simulated to calculate its response to a delay introduced to each task in turn, relative to the baseline case of no delays in that variant.

The results of these experiments were presented in a form which highlights the impact of task connectivity degree and resource constraints upon the ability of the cluster to absorb delays, independent of other variables which influence process behaviour. Analysis of these results suggested that reorganising a process to reduce the number of dependencies can decrease the likelihood of a task delay propagating to delay the entire process, and that reducing the number of resource constraints (e.g. by cross-training personnel) can have a similar effect. These findings are aligned with expectations from critical path theory. Our experiments, reported in detail in [39], provide additional insights by quantifying the degree of improvement to be expected, on average, if more resources are made available. Detailed insights are discussed in [39].

7.3 Summary

This example shows how simulation methods can be applied to explore the determinants of design process robustness and produce suggestions for improvement without requiring high-fidelity simulation models of specific processes–which can be difficult to obtain in practice. The example therefore illustrates one way in which epistemic uncertainty can be accounted for when devising approaches to design processes for insensitivity.

8 DISCUSSION

The analysis in this paper has focused on clarifying the different approaches that can be taken to make a PD process less sensitive to the influence of uncertainty. However, uncertain events are, fundamentally, value neutral–they can lead to opportunities as well as risks [18]. Accordingly, the likelihood of discrepancies between the actual and planned process durations is also fundamentally value-neutral–the nature of the discrepancies can be such that the actual process duration is shorter than planned (Figure 6). However, despite the possibility of such a favourable outcome, and despite the fact that a growing number of authors have been stressing the importance of exploiting opportunities in addition to mitigating risks (e.g. [7; 8; 32]), the focus of this work has been on the investigation of methods of mitigating risks–negative manifestations of uncertainty.

The rationale behind restricting the focus to risks only is twofold. First, according to [18], opportunities can often be more easily exploited than risks can be mitigated–if this argument is accepted, there are greater benefits from risk mitigation. Second, a great deal of uncertainty in managing PD stems from lack of knowledge about the fundamental relationships among elements of PD processes, e.g. about information flows among tasks. Since it is reasonable to assume that due to lack of such knowledge risks are more likely than opportunities (e.g. it is more likely that due to unknown dependencies a task will take longer than expected rather than less than expected, more rather than fewer design incompatibilities will emerge, and more rather than less rework will be needed), mitigating risks is also a task that project managers are more likely to face than exploiting unexpected opportunities.

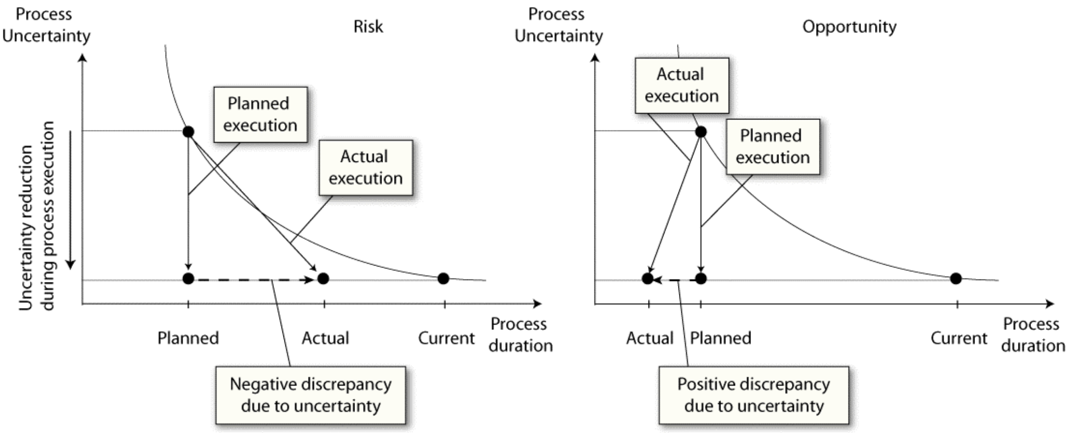

Figure 6. An illustration of two manifestations of uncertainty: risk and opportunity.

Narrowing our focus in this way has one important consequence for the validity of the argument in this paper. By reducing the risk associated with certain uncertainties, it is inevitable that some opportunities will be lost. This is well-understood in financial derivatives markets, another domain concerned with managing risk and uncertainty. For example, buying a commodity at a price specified in advance removes the risk of paying more should the price increase but, at the same time, creates the potential for loss in the event that the market price later drops.

9 CONCLUSIONS

Uncertainty is ubiquitous in product development processes, and can lead to risks to project performance. Companies could therefore benefit from a better understanding of uncertainty, how it impacts upon their projects, and how processes could be made less sensitive to the effects of uncertain events. This paper has introduced a conceptual framework which aims to clarify the relationships between different approaches to mitigating the influence of uncertainty in PD projects. The framework is based on the system operating domains and types of uncertainty which are considered by each mitigation approach. We have also shown one way in which these quite abstract concepts can be operationalised, using simulation experiments to give useful insights to improve PD processes in practice. Future work may include investigating other concepts associated with process insensitivity, in particular, exploring such concepts as process agility, process dependability or process resilience.

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