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MODELLING DESIGN PROCESSES TO IMPROVE ROBUSTNESS

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1 Introduction

The success of any manufacturing company depends ultimately on the effectiveness and efficiency of its product development. However, "*few development projects fully deliver on their early promises*" [REP-01] as "*much can and does go wrong during development*" [WHE-92]. Although new technologies, new project management tools and information and knowledge management systems all facilitate better execution of big projects, they are still far from being able to eliminate uncertainty inherent in such projects. Uncertainty prevails as evident from an invariably high number of big engineering projects that fail to come in on time and on budget ([ELT-98], [EVA-05], [FOR-03], [MAT-03]). The situation is exacerbated by the fact that the ramifications of a project's failure are not only financial; demoralization of employees who have succeeded in delivering their share of the work can also be detrimental to the company's future projects [MAT-03].

Engineering design exemplifies a complex process where humans, technology, art and science interact with each other very closely and where the influence of uncertainty is particularly strong. Consequently, reducing the degree of uncertainty in the engineering design process has the potential to increase the probability of success of the entire new product development project. However, mitigating the influence of uncertainty without sacrificing process performance is a challenging and complex task. Different approaches have been proposed to achieve this goal, with significantly different foci. Such approaches include, for example, Taguchi methods, Risk Management methods or Failure Mode and Effect Analysis (FMEA). In this paper, we discuss design process modelling as a route to improving process robustness, i.e. the capability to deliver expected results in the presence of unexpected adverse factors.

The paper is structured in the following way. First, a discussion about the multidimensionality of process robustness is presented. Then, modelling approaches appropriate for robustness analysis are considered and their application to a simple mechanical component design process is evaluated. Finally, we discuss the appropriateness of design process modelling as a route to improving process robustness as well as some possible avenues for further research in this filed.

2 Multidimensionality of process robustness

The concept of robustness has been extensively studied in many engineering fields. Robustness analysis is common in many industries, most notably in software and manufacturing. However, as there is no precise definition of robustness, it is often used to denote very different meanings and encompass very different attributes, such as reliability or flexibility. In addition, due to a multifaceted character of robustness, there is a great deal of confusion as to the proper use of this term.

In this paper, we define process robustness as the capability of a process to bring expected results, such as on-time and on-budget delivery of fully detailed manufacturing instructions for quality products, regardless of unexpected adverse factors, such as a funding cut, changes in product requirements or variations in available development resources.

2.1 Process – product interdependencies

Although many of the well-established methods of dealing with uncertainty lend themselves to the incorporation of product requirements into process robustness analysis, none of them explicitly considers interdependencies between the design process and the resulting product. However, exclusion of such interdependencies in the analysis of process robustness renders this analysis incomplete. To illustrate this point, consider a robust design process in which mitigation of the influence of uncertainties is achieved by compromising product performance or quality. Despite significant short-term benefits that might be accrued in this way (project delivered on time and within budget), a company's long-term reputation can be severely affected.

Incorporation of interdependencies between the design process and product into process robustness analysis can be realised by treating the emerging product's attributes as one of the measures of process performance. Those attributes can be included in subsequent robustness analyses in two ways. First, they can be treated as variables exogenous to the model that pose constraints on the process. Second, they can represent main process performance variables. In this situation, the focus of robustness analysis is on reduction in the level of their variability and process robustness can be seen as a measure of insensitivity of required product attributes to various project-level factors such as budget instabilities (cf. [WEI-04]).

2.2 Cost of robustness

Robustness of a process can be generally achieved at the expense of some deterioration in performance, or of extra outlay of resources [ROS-80]. In both these cases, an improvement in robustness should be compared to the cost of the improvement; a significant loss in performance or a great amount of extra resources spent will be difficult to justify when only a slight improvement in robustness is obtained.

It is also important to note that a measure of the cost of robustness should incorporate both objective and subjective criteria. For example, managers might opt for increased project robustness at the expense of process performance or resources in order to enhance their employees' morale that has been weakened by a high failure rate of previous projects Improving process robustness.

There are two ways of deploying extra resources required to improve design process robustness. The first, most obvious one is through an outlay of new development resources, both human and technological. The second is through spending resources on process improvement.

By the deployment of more designers to a certain task, the probability of successful execution of this task may be increased. Introduction of more powerful hardware or software can have a similar effect. This method can be called, after Repenning and Sterman [REP-01], the *work harder loop* (see Figure 1). Although in precise terms an outlay of new development resources does not necessarily imply harder work from the designers, drawing a comparison between this method and the *work harder loop* is justified from a project manager's point of view. In a similar fashion to designers who need to put more energy to work longer hours, project managers need to put more resources if they wish to enhance the capabilities of the existing process.

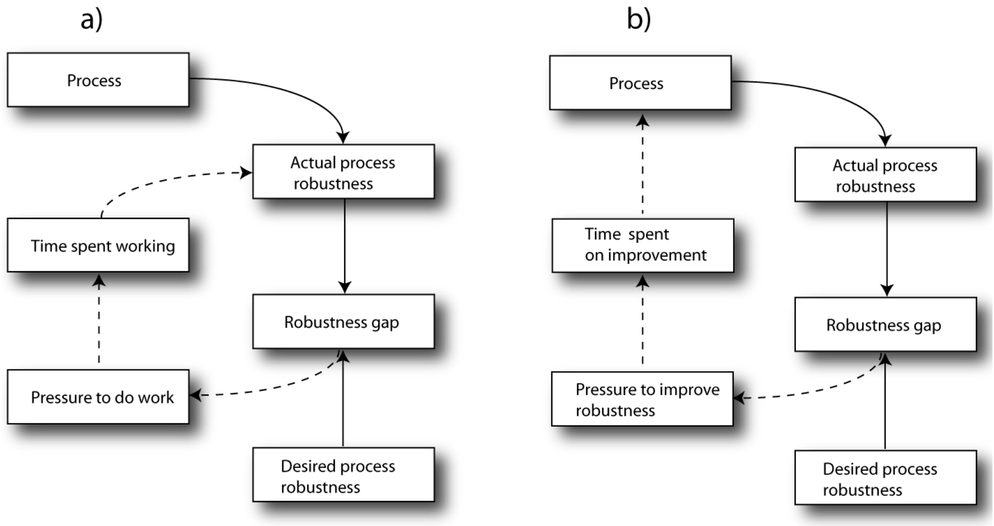

Figure 1. Improving process robustness: a) the *work harder loop* (dotted lines), b) the *work smarter loop* (dotted lines); based on [REP-01])

The second way of deploying extra resources is what Repenning and Sterman [REP-01] call the *work smarter loop* (Figure 1b). Investing more time and resources on process improvement is the only cost-effective means to enhance process performance, such as robustness, in the long run. Although finding ways of working smarter can be expensive and/or time-intensive, once such ways are found, process robustness can be significantly improved without additional cost (Figure 2b).

It is noteworthy that the aim of finding new ways of working does not have to be a direct improvement in process robustness. As illustrated in Figure 2c, a smarter way of designing can result in a new more favourable functional relationship between cost and the chosen measure of process robustness. This means that by organisational improvement of the process, a reduction in the cost of robustness can be achieved, which provides leverage for further more efficient improvement in process robustness (moving along the steeper cost-robustness curve in Figure 2c).

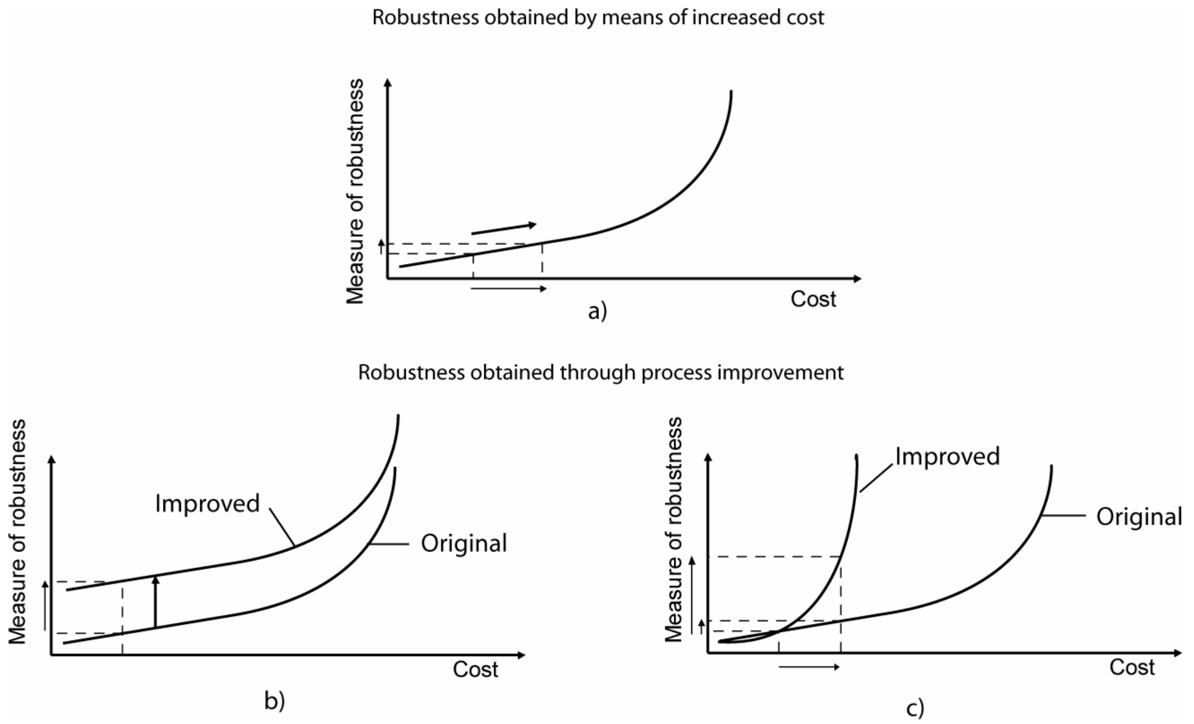

Figure 2. Improved process robustness vs. cost: a) robustness obtained by means of increased cost, b) and c) robustness obtained through process improvement

2.3 Process robustness and organisation

Improving process robustness is a complex and difficult undertaking, not least because of the social context of this task. Business psychology and organisational behaviour play an important role in all process improvement activities. For instance, looked at from an organisational point of view, efforts spent on making a process more robust can be difficult to justify once the process has delivered the expected result. This is because the successful outcome of the process can be attributed not to the improvement measures that have been implemented, but to the inherent process capability or to some extemporary measures taken during process execution. The focus of many organisations on *fighting fires* instead of preventing them makes this situation even more likely. For that reason, a shift from an approach where "*the hero is the one who puts out the biggest fire'*" [BOH-00] to one where *the hero is the one who prevents the biggest fires* can be seen as a prerequisite for successful process improvement in general, and for improved process robustness in particular.

2.4 Process robustness and modelling

Apart from contextual difficulties of implementing process improvement methods, there are several challenges more technical in nature. For example, Bohn [BOH-00] reminds that "*haphazardly introduced changes can easily create new problems elsewhere in the process*". Similarly, Ford and Sterman [FOR-03] point out that we take actions "*that make sense from our short-term and local perspectives, but, due to our imperfect appreciation of complexity, often feed back to hurt us in the long run*". It is understandable therefore, that prior to any attempt at improving process robustness problem complexity has to be carefully studied with our cognitive limitations taken into account. One way of doing this is through modelling design processes, which is the focus of the remainder of this paper.

3 Modelling approaches

Improving process robustness by means of modelling and simulation can be realised in several ways. In parallel to improving technical and organisational aspects of tasks execution, for example by utilising new hardware or software, or assigning more experienced designers to a particular task, the search for better design processes can include finding ways of more efficient interaction among the outputs of design activities.

3.1 The variables only approach

One can explore the search space for variance reduction in process performance by changing the values of various variables in a model.. Those changes can include both *work harder* and *work smarter* methods of deploying new resources (Figure 1). For instance, the indiscriminate expenditure of extra resources on the process exemplifies the *work harder loop* in improving process robustness. On the contrary, deployment of extra resources on the identification of tasks that contribute most to the variability of process performance and subsequent redistribution of development resources represents the *work smarter loop*. In both cases, the measure of success, i.e. a degree of variance reduction can be easily calculated by comparing the simulation results before and after process improvement.

3.2 Process restructuring

The search for variance reduction in process performance can be also extended to include investigation of different process structures. Compared to the *variables only approach*, this kind of analysis requires a much better understanding of process behaviour. What makes this method attractive is the fact that it offers much greater scope for improvement.

Depending on the level of restructuring the process, two approaches can be distinguished: tasks reordering and remodelling process behaviour. The former includes both simple reordering of independent tasks and the analysis of overlapping and concurrency of interdependent tasks. In the latter, issues such as outsourcing of activities or inclusion of new tasks in the model can be explored.

3.3 An example

Given that process robustness is a multidimensional measure, several aspects of process performance should be simultaneously taken into account in order to ensure comprehensiveness of robustness analysis. However, due to the limitations of the modelling framework used as well as modelling complexity itself, in this paper only one measure of process performance, namely process duration, is investigated. For the same reasons, the following example illustrates only the simplest approach to improve process robustness, i.e. the *variables only approach*.

12-task model of mechanical design

To illustrate the *variables only approach* in process robustness analysis, we have studied a simple mechanical component design process. Such design, in simplistic terms, can be described as [CLA-00]: "*the definition of a geometry to carry a given set of loads subject to constraints on the allowable bulk stress within the component and on local stress concentrations*". In this paper, in order to represent and analyse such a process we use a 12-task model built within the Applied Signposting Model (ASM) framework (interested readers are referred to [WYN-06] for a detailed description of the framework). The process is assumed to include the following tasks: *Sketch geometry, Refine geometry, Finalise geometry, Estimate loads, Analyse loads, Simulate loads, Visual check, St. Venant's, Initial FE analysis, Initial check, Stress analysis, Final FE analysis* [CLA-00]. Process behaviour is simulated using a software implementation of ASM, which uses a discrete event algorithm based on the Petri net approach to modelling information flow (see [WYN-06] for a description of the tool).

All task durations in the model are assumed to have a triangular probabilistic distribution. For simplicity of analysis, only one loop of rework is included in the model and the number of iterations in the loop is controlled by the probability of rework defined as an attribute of *Initial FE analysis*.

The *variables only approach* is summarised in Table 1, which compares the original process and its five variations. Changes in four model variables were considered to illustrate different process behaviour with regard to robustness. One variable – *Initial FE analysis: probability of rework* – was used to control the number of iterations in the loop, and by doing so to show the influence of rework on process robustness. The intent of the three remaining variables was to show the sensitivity of process performance to changes in task durations within (*St.Venant's: duration*) and outside (*Final FE analysis: duration* and *Finalise geometry: duration*) the iteration loop. In all the analysed cases, characteristics of the remaining eight tasks were unchanged. 5000 simulation runs for each process variations were carried out, which proved sufficient to identify and exclude from analysis purely random effects in process behaviour.

Process variation / Variable	a (original)	b	c	d	e	f
St. Venant's: duration (min; exp; max)	5; 6; 7	**3; 4; 5**	**1; 2; 3**	5; 6; 7	**1; 2; 3**	5; 6; 7
Initial FE analysis: probability of rework	40%	40%	40%	**10%**	**10%**	40%
Final FE analysis: duration (min; exp; max)	3; 4; 5	3; 4; 5	3; 4; 5	3; 4; 5	3; 4; 5	**1; 2; 3**
Finalise geometry: duration (min; exp; max)	3; 4; 5	3; 4; 5	3; 4; 5	3; 4; 5	3; 4; 5	**1; 2; 3**

Table 1. The application of the *variables only approach* to a mechanical component design process

Figure 3 shows simulation results of process duration for the process variations described in Table 1. It is noteworthy that in all the frequency distributions effects of triangular distribution of tasks durations can be easily discerned. Nevertheless, the primary cause of total variance in process duration is rework, as evident from several iteration peaks in each of the distributions. Accordingly, reducing the probability of rework has the most significant effect on improving the robustness of the modelled process (Figure 3d).

Reducing the expected duration of a task can also have a positive effect on process robustness. However, this is the case within the iteration loop only (Figure 3c); changing task durations outside the rework cycle has a bearing only on a mean value of process duration (Figure 3f).

Discussion

Despite the simplicity of the investigated design process and the fact that all the variables in the model have arbitrary values chosen to best capture changes in process behaviour with regard to robustness, several insights can be gleaned from the above example. First, by illustrating how process robustness can be improved by controlling certain tasks attributes, the 12-task model of mechanical design provides initial evidence of the validity of the *variables only approach* in process robustness analysis. Second, it has been demonstrated that the identification of key control variables in the process prior to any outlay of extra resources can greatly facilitate improvement in process robustness. Finally, by showing that central to improving process robustness is reducing the scope and probability of rework, the results of this study corroborate the findings of similar research (e.g. [FLA-05]).

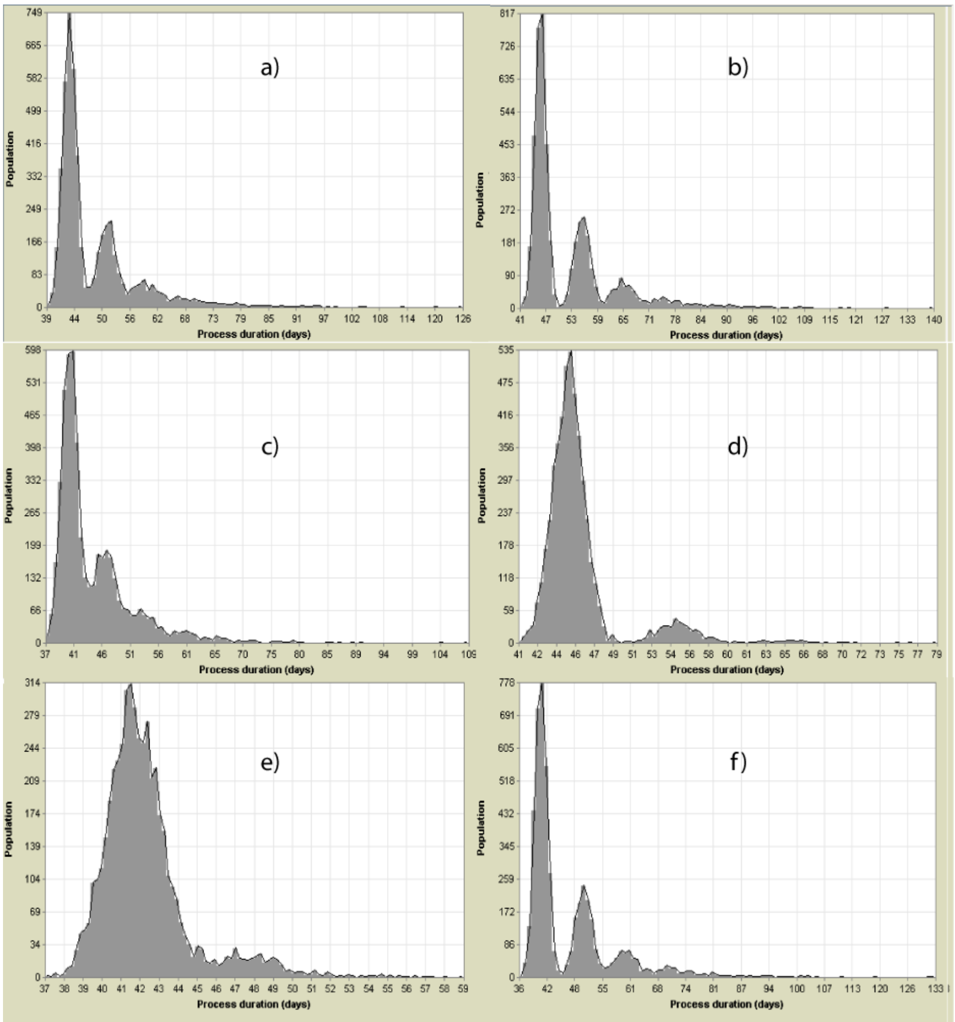

Figure 3. P3 simulation results of a mechanical component design process: a) original process b)-f) process variations (see Table 1 for details)

4 Conclusion

Due to the multitude of adverse uncertainty-driven factors, different aspects of robustness of the same process can be analysed. Similarly, because different objectives might be used in evaluating the performance of design processes, finding a robust process should be perceived as a multivariate problem with inherent trade-offs.

Modelling design processes can provide valuable insights into the nature of process robustness. For example, key tasks/attributes can be identified and their influence on process robustness can be readily evaluated using simulation. This may help a project manager find most effective ways of spending development resources.

In this paper, a 12-task mechanical component design process is studied and its robustness with regard to process duration is analysed to illustrate the appropriateness of modelling as a route to improving process robustness. The next steps in our research will be to investigate more complex design processes and to include in the analysis various trade-offs between measures of process performance.

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