INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

AN EMPIRICAL INVESTIGATION ON MODELLING OF SOCIO-TECHNICAL UNCERTAINTY LEVELS TO SUPPORT DESIGN PROCESS PLANNING

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Keywords: collaborative design process, uncertainty, process planning, socio-technical system, modelling and analysis

1. Introduction

Planning of engineering design processes concerns multiple aspects that are related to the whole product, the process and that of dependent organizational characteristics. Planning is always a challenging issue for managers, more than describing the process in order to understand or rationalize it, and hence being supported by practical tools that are able to predict the behaviour of the design process (DP) remains a desirable goal. The main obstacle to this goal might be the high degree of complexity and inherent uncertainty that often occur in DPs in multiple levels and therefore make it difficult to apply a single plan in different time-scales of a design project.
Uncertainty, in general, has been a wide area of study and researchers from different disciplines have proposed a broad range of approaches, tools, and models, in order to mitigate the impact of uncertainty on the planning issues (examples of review can be found in [Thunnissen 2003], [de Weck et al. 2007]). However, the major limitation to the most of the existing tools is that the social and technical aspects of uncertainties are taken into account separately. Consequently, the mutual relationships and impacts would be completely neglected. This paper considers the concept of socio-technical uncertainty in an integrated form and applies the previously developed "Actor-Based Signposting" (ABS) methodology [Hassannezhad et al. 2015] to demonstrate the mutual impact of different uncertainty levels on the DP planning. The thesis behind ABS is that the DP is a set of interconnected technical activities that are associated with a set of actors (e.g., designers) and their interactions and mutual influences can affect the overall performance of the DP [Hassannezhad et al. 2014].
This paper is concerned with the application of the ABS methodology in providing 'predictive' process planning during the DP of an automotive engine component. In terms of the research objective, unlike the previous efforts in modelling of uncertainty levels, we aim to support managers on 'locally' dealing with uncertainties (e.g., finding the right design strategy in different project time-scales), by addressing the technical (originated from the product or the process) and social (originated from the design organization) aspects of uncertainty, and consequently by providing an extensive analysis of process outcomes in response to the input changes.
Hence, we first propose a literature review on methods that dealt with uncertainty, in order to identify a research question in Section 2 and to provide a final classification of the uncertainty types in Section 3. By use of the classification of uncertainties on the one hand, and the development of advance analysis panel in the ABS simulation tool on the other hand, in Section 4, we empirically address an extensive analysis of process sensitivity in response to the changes in the model parameters (e.g., quality/data level), attributes (e.g., rework duration/likelihood), and human-factor issues (e.g., number of actors

involved in design). This section justifies that apart from the technical issues, the characteristics of the people involved in the DP (e.g., their performance, behaviour, and influences) can affect not only the execution of their corresponding activities but also the execution of other activities that are associated with the actor. Section 5 concludes the paper with some feedback and insights from the company.

2. Socio-technical uncertainty sources and their impact on the planning

2.1 Originality of the uncertainty sources

Researches from different disciplines have presented various definitions on the term uncertainty and, accordingly, they have proposed different classifications. Two streamlines therefore could be existed: based on the degree of "predictability" (concerned with the level and accuracy of information) (e.g., [Khovanov 2005], [Engelhardt et al. 2009]), and based on the "origin" (source) of uncertainty (e.g., [Huijbregts 1998], [de Weck et al. 2007]), as each of which might be associated with the qualitative and quantitative classes of uncertainties. The former has its main applications in the mathematical modelling of uncertainty while the latter can provide a broader perspective with respect to the different fields. An overview of the different sources of uncertainty is presented in Table 1, which is not limited to the only engineering design field.

In the context of engineering design, uncertainty is defined as related to Epistemic/Aleatory [Thunnissen 2003], known-unknowns/unknown-unknowns [McManus and Hastings 2005], endogenous/exogenous [de Weck et al. 2007] behaviours, or somehow a combination of them [Wynn et al. 2011] that are related to activities, rework, resources, human performance, etc.

Among these last, the least frequently addressed aspect seems to be the integrated socio-technical uncertainty type (in spite of a few efforts such as [Thunnissen 2003]), where the behaviour, performance, and the reciprocal influences between people involved in the DP can directly or indirectly affect the process planning decisions. Since each engineering DP has to come up with something unique in respect to those in the past, DPs are inherently uncertain, and understanding their dynamic behaviour therefore requires a specific attention.

2.2 Difficulty of dealing with socio-technical uncertainties

In general, three different approaches to dealing with uncertain issues are adopted: ignoring, minimizing, or coping with them. Russell and Norvig [2005] termed the first approach as an implicit approach through which you ignore what you are uncertain about, and would try to build a robust procedure in order to prevent subjective interpretation. This approach along with the second one of minimizing [Grote 2004] might work well in small-scale companies, but fail in large complex systems with the higher level of uncertainty.

The present paper instead would adopt the third approach of coping with uncertainty since it considers the DP as a collaborative socio-technical system of actors, where design activities can be affected by both human- and non-human (technical) factors. The belief is that the technical aspects of uncertainty can be influenced by the behaviour, performance, and interactions between the people (e.g., designer) involved in a DP.

Accordingly, the paper shows that effectively coping with uncertainty leads to avoid neglecting or mitigating the mutual impact of technical and organizational issues, and it instead highlights that actors are potentially the major source of uncertainty. Even, they should be given enough authority to locally handle the uncertainty, since they can act as enablers of the system and can convert uncertain issues into opportunities. The critical issue becomes to find the right actors (in terms of their performance and interactions) to perform the design activities at their highest level of quality, that means supporting both organizational and technical aspects of DP planning in an integrated form.

3. Classification of socio-technical uncertainty levels

A three-dimension classification of the sources of uncertainty is presented in this section and it will be used as a baseline for modelling and analysis of uncertainty levels in the next Section 4. These dimensions are respectively presented in the following:

Table 1. Taxonomy of uncertainty sources in the literature

Reference	Taxonomy
[Bedford and Cooke 2001]	Aleatory uncertainty; Epistemic uncertainty; Parameter uncertainty; Data uncertainty; Model uncertainty; Ambiguity; Volitional uncertainty
[Bordia et al. 2003]	Strategic uncertainty; Structural uncertainty; Job-related uncertainty
[Bradley and Drechsler 2013]	Ethical uncertainty; Option uncertainty; State-space uncertainty
[Chalupnik et al. 2009] [Oberkampf et al. 2002]	Aleatory uncertainty; Error; Epistemic uncertainty
[de Meyer et al. 2001]	Variation; Foreseen risk; Unforeseen risk; Chaos
[de Weck et al. 2007]	Endogenous uncertainty; Exogenous uncertainty
[Earl et al. 2001]	Known uncertainty; Unknown uncertainty; Uncertainty in data; Uncertainty in description
[Engelhardt et al. 2009]	Aleatoric uncertainty; Epistemic uncertainty; Prognosis uncertainty
[Huijbregts 1998]	Parameter; Model; Due to choices; Spatial variability; Temporal variability; Variability between sources and objects
[Kepecs 2013]	Decision confidence; Reward risk
[Khovanov 2005]	Interval uncertainty; Stochastic uncertainty; Bayesian uncertainty
[McManus and Hastings 2005]	Lack of knowledge; Lack of definition; Random variables; Known unknowns; Unknown unknowns
[Milliken 1987]	State; Effect; Response
[Pons and Raine 2007]	Epistemic uncertainty; Stochastic uncertainty; Abstraction uncertainty
[Rosqvist 2008]	Aleatory uncertainty; Epistemic (Model; Parameter; Data) uncertainty
[Rotmans et al. 2001]	Due to lack of knowledge (Unreliability, Structural uncertainty); Due to variability (Ignorance, Indeterminacy)
[Thunnissen 2003]	Ambiguity; Epistemic uncertainty; Aleatory uncertainty; Interaction
[Wynn et al. 2011]	Epistemic/Aleatory; Information and description; Abstraction and interpretation; Uncertainty due to Complexity
[Zimmermann 2000]	Lack of information; Abundance of information; Conflicting evidence; Ambiguity; Measurement; Belief

1. In terms of 'origin', it can be epistemic (due to the lack of information/data) or aleatory (due to the variation in parameters/elements);
2. In terms of 'environment', it can be endogenous (stem from some internal issues in an open system) or exogenous (refers to some external sources such as technology and competitors); and
3. In terms of 'object', it can stem from technical (product/process) or organizational (behavioural and interactional) issues. This latter dimension further can be further classified into multiple levels as shown in Figure 1: Parameter, Model, and Human-factor uncertainty.

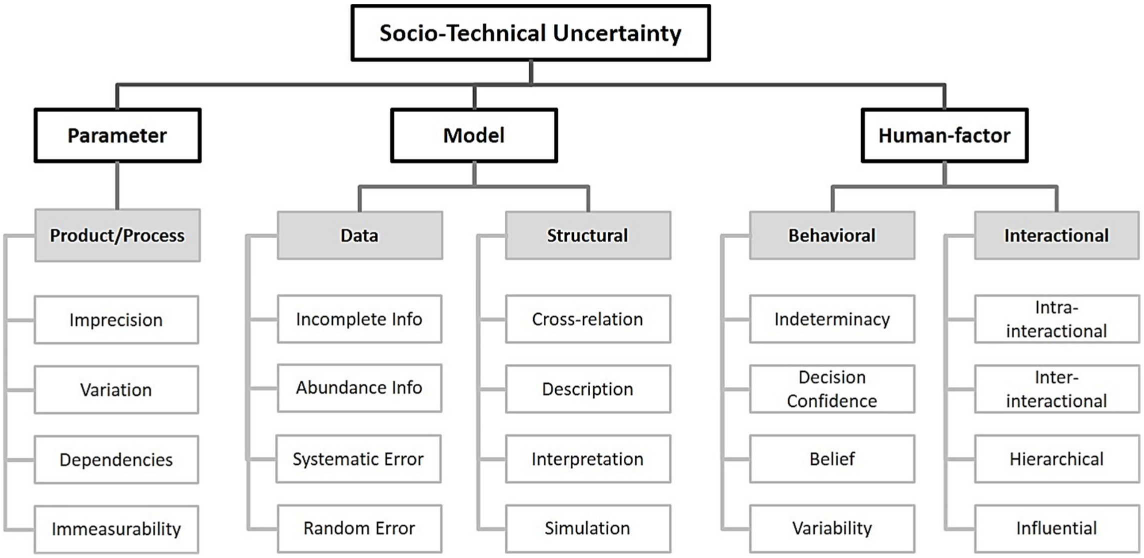

Figure 1. Classification of Socio-technical uncertainty

- 'Parameter uncertainty' refers to the product or process specifications. It can be due to the imprecision or variation in the definitions (e.g., specifications), or to the complexity of the mutual dependency of parameters, and so far to the vagueness in estimating the product specifications (e.g., customer requirements), which is known in this paper as immeasurability.
- 'Model uncertainty' refers to the amount by which the true value of a design variable differs from the value that is computed for it [Fernandes et al. 2014]. In the context of this paper, it can be related to the structural complexity of the model such as difficulty in the description or interpretation of the input/output data. In some cases, the simulation model of a DP can be determined as a major source of uncertainty.
- 'Human-factor uncertainty' is less frequently taken into account in modelling and planning of DPs than technical uncertainty. Actors in DP are unpredictable and reflective, and their behavioural attributes (such as belief, self-confidence, competences, etc.) can affect the process behaviour. Apart from the behavioural uncertainty, actors moreover often interact with each other. This occurs at multiple levels and layers of the team and organization. The own mechanisms of interaction therefore can become a source of uncertainty, e.g., as the result of negotiation or because of influencing other actors. In this paper, we follow the classification of interactional uncertainty that is presented in the reference [Hassannezhad et al. 2015]: intra-, inter-, hierarchical-, and influential-uncertainty.

4. An illustrative case study

4.1 Description of the case

A company that provides re-engineering and design services for big players of the automotive industry was chosen as a test bed for the application of the "Actor-Based Signposting" (ABS) [Hassannezhad et al. 2015] approach. The aim was to provide both a support for the internal planning of the future 'redesign processes' and to define a sort of 'add-in' to the design services the company provides so that it could develop a new business segment devoted to providing project planning in addition.

During the five months stay of the first author in the company, the method was applied, in particular to the "Oil-Pipe" development case. Being a re-engineering situation, this component was already designed the product and hence the main parameters, although not their values, were roughly determined. The design team was required to re-design the component, six concepts were generated and the most delicate step was the selection of these. Each of these solutions had different technical performances, but even more implied different costs due to the spent effort and the resources involved. So it became fundamental for the in-charge persons to be precise in the cost estimation related to the planning.

The primary design (that we started modelling with) and the final best proposal (as the decision made based on the modelling and analysis results) of the case are shown in Figure 2. Not only the client needs, i.e., the product specifications, might be changed in the future, but also attributes such as the activity durations, the number of designers or the availability of the right competences could have affected heavily the processes performances. Through an application of the ABS methodology, we simulated a range of different scenarios according to the changes on the major attributes of the case (from both technical and organizational aspects) and analysed their impact on the process outcomes such as overall process duration, cost, and the amount of rework.

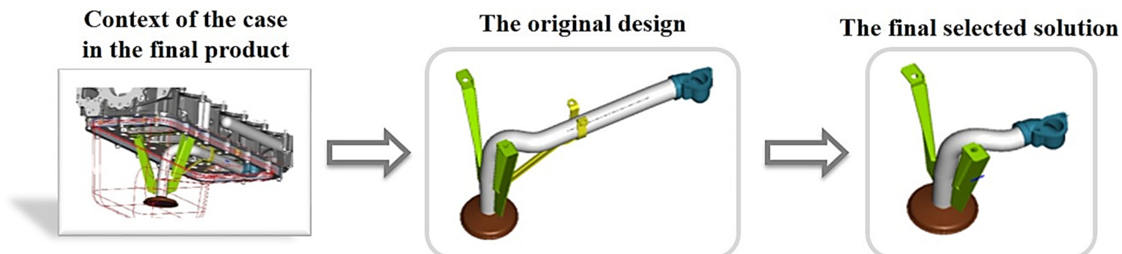

Figure 2. Context of the redesign process of an Oil-Pipe case

From a structural point of view, the DP of the case is composed of four main phases: requirement analysis, concept design, detail design, and testing. In more detail, 22 tasks identified for the process, each of which can be associated with a sort of eight technical parameters. In addition, up to four actors, including a senior and junior designer, and a senior and junior cost engineer, can accomplish the redesign process. The association matrix for this process is represented in Figure 3, along with the minimum required level of confidence for each parameter. Following the definition of the confidence in the Signposting system, each parameter is defined within the range of one (minimum) to four (maximum).

		Temperature Pressure	No. of components	Capability of the system	Maintenance Frequency	Accessability	Standardizatio n	Process Technology	Complxity of assembly
		TP01	**TP02**	**TP03**	**TP04**	**TP05**	**TP06**	**TP07**	**TP08**
Requirement analysis	**P1**								
Analysis of current Strainer	RA01	2	3	3			3		4
Requirement analysis	RA02								
Analysis of functions (e.g., pumping)	RA02-1	2		3					2
Analysis of structure (e.g., material resistance)	RA02-2	3		3	2				
Analysis of dimensions (e.g., length)	RA02-3		1			2			
Analysis of layout (e.g., encumbrance)	RA02-4					3	2		
Technical definition of the proposed specifications	RA03	3		4	4		4		
Concept design	**P2**								
Generation of all the ideas	CD01								
Analysis of possible (alternative) components	CD01-1		4	3				1	2
Analysis of possible material changes	CD01-2	3		3				3	2
Analysis of possible profile changes	CD01-3	3	2	3		1	3	3	3
Analysis of the possible solution layouts	CD01-4		2	3		2	3		3
Analysis of the impact on the production process	CD01-5		1	3			2		4
Rough cost estimation of proposed ideas	CD02								
Rough analysis of the investments	CD02-1		4				4	3	
Rough analysis of the product cost	CD02-2		4				3	4	2
Proposal of the design suggestions	CD02-3		1				1	1	
Selection of the idea (proposal = idea 5A)	CD03								
Preparation of the presentation document	CD03-1		2				1	2	2
Selection meeting with the customer	CD03-2			4	2		4	4	4
Detail design of the proposal	**P3**								
Product design	DD01								
3D modelling	DD01-1		3	3	2	3	3	2	3
2D drawing (to analyze the eg tolerance)	DD01-2		3	3	2	1	3	3	3
Testing	DD02			4	2				
Detailed cost modelling	DD03								
Detailed analysis of the product cost	DD03-1		3				2	3	1
Detailed analysis of the investments	DD03-2		3				3	2	
Selection of the final design solution	DD04			4	2		4	4	4
Testing (cost benefit analysis)	**TS01**			**4**	**2**				

Figure 3. Matrix of task-parameter associations for the Oil-Pipe design process

4.2 Application of ABS methodology for modelling the uncertainty levels

In comparison to the previous versions of the Signposting system (e.g. [O'Donovan 2004], [Wynn et al. 2006]), ABS has come up with some improvements: (1) the meaning of parameter in ABS is broader than before, since more than the product or process quality factors, the organizational factors also can be embedded into the system; (2) the outcome of the system, instead of being a sophisticated sequence of activities (to guide what to do next) would be a sophisticated fit of actors-tasks (to guide who should do what and how?); (3) the role of people involved in the DP is highlighted in the ABS, along with their mutual influences and multiple types of interactions; and finally (4) ABS is capable of capturing the technical and social aspects of uncertainties in an integrated framework, and their simultaneous impacts on the process outcomes.

In this paper, we have developed the advance analysis panel in the ABS simulation tool (to overview how ABS works, see the reference [Hassannezhad et al. 2015]) and used it to analyse the potential sources of uncertainty that can affect the overall cost of the Oil-Pipe redesign process. This includes such considerations on the DP parameters (e.g., client needs), rework policy, rework duration and cost, and the quantity and quality of actors involved in the process. The next section presents the result of simulation and analysis for a range of scenarios of changes, by using the Arena® and after 500 runs.

4.3 The result of simulation and discussion

Built on the classification of socio-technical uncertainty in Section 3, the impact of different sources of uncertainty on the process outcome (such as process duration, cost, increment in the level of quality, and amount of rework) investigated in advance, and due to the space limitation, some of them that have been recognised by the practitioner to have more influence in the Oil-Pipe process planning are presented in the following. Previously, impact of parameter and data uncertainty has been addressed in the Signposting systems (e.g. [Wynn et al. 2006]), however due to the focus on only technical characteristics of the DP, the impact of human-related factors (e.g., the number of actors involved in the process, their dependencies with the duration and probability of reworked tasks, or impact on successful completion and cost of the tasks) has not been addressed in such similar models.

(1) Parameter uncertainty: change in the probability of successful completion of the tasks

Three range of probabilities for the successful completion of the tasks are addressed: normal completion, completion 'on-time', and completion 'before the due time'. The process is assumed to be accomplished by a senior designer and a senior cost engineer. The impact on the total amount of process cost and rework is presented in Figure 4, respectively in the left-hand and right-hand sides. The results show completion of each task before the due date largely increases the reworked tasks and consequently requires more investment for the company that is largely different in comparison to the on-time situation, and hence might not be a reasonable offer to the client. On the other hand, on-time completion of the DP although requires more rework for some tasks during the requirement analysis and concept design phases, there is not much different found in the rework and the total cost of the redesign process.

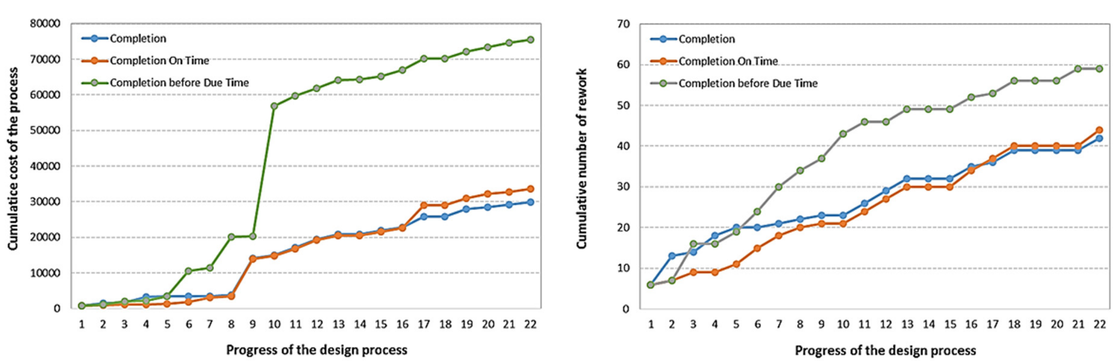

Figure 4. On the impact of parameter uncertainty, in successful completion of the tasks: on the process cost (left-hand), and on the total amount of rework (right-hand)

(2) Parameter uncertainty: change in the duration and cost of the rework tasks (learning during process)

Rework can be considered from two different aspects in the ABS analysis panel: the duration of a reworked task, and the likelihood of occurring rework, with respect to the associated actor. As an example, three different classes of the duration and cost of the reworked task is considered here: slow rework (100% of the original task), normal rework (80% of the original task), and accelerated rework (40% of the original task). The impact on the overall process duration and cost is presented in Figure 5. The results represent that the duration and cost of the use-case process follow rather a similar increasing trend; however, the slope seems to be more continuous in the case of accelerated rework duration. This achievement along with the findings in the previous part (1) can support managers to find the best policy of rework, i.e., if the goal is to complete the process on time (less than 30,000 Euro), regarding the deadlines, the goal should be to reduce the rework time (towards the accelerated form).

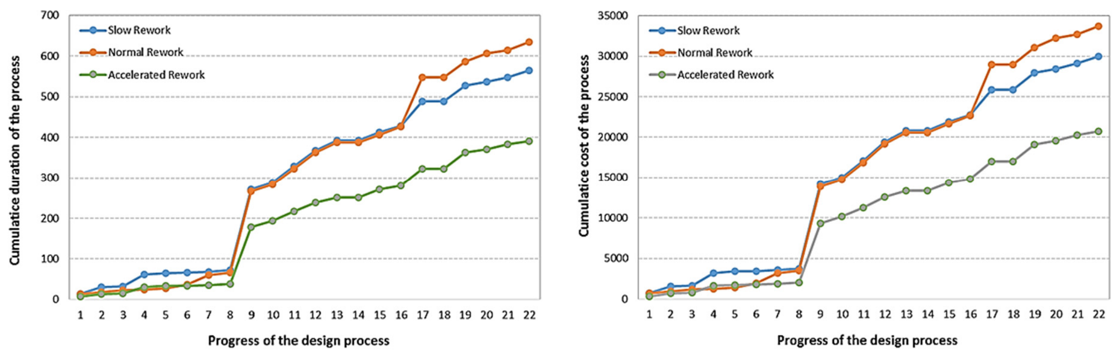

Figure 5. On the impact of parameter uncertainty, in rework duration: on the process duration (left-hand), and on the process cost (right-hand)

(3) Data uncertainty: change in the value of technical confidence levels (quality level/client needs)

Changes in the quality level of the tasks are very likely in the reality of DPs, due to for example; change in the product specifications, client needs, or due to the behavioural instability of actors. So we selected the two more important parameters that were associated with both the product and the process (Process technology, and Complexity of assembly) and changed their values in the range of -20% to +20% with the step-size of 10%. The impact on process cost and duration is presented in Figure 6 (left-hand side). Obviously, increase in confidence levels (using higher technologies with less complexity of the product assembly) facilitates the satisfaction of the minimum requirement of the quality and so, as expected before, there is not sensible variation in the level of cost and duration. On the other hand, 20% decrease in the quality levels has three times enhanced the total cost and process duration so far. This is probably due to a large amount of iteration that was required to satisfy the minimum required level in the quality parameters. However, this variation might be changed based on the importance of different parameters.

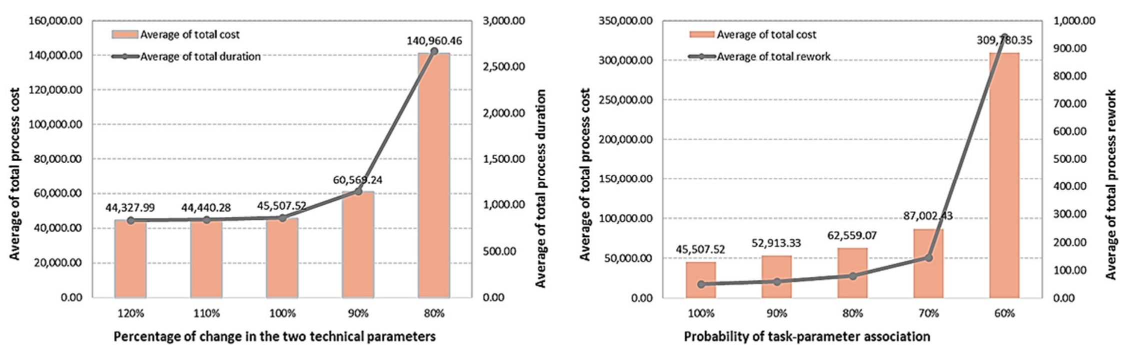

Figure 6. On the impact of data uncertainty: associated with value of technical parameters (left-hand), and associated with probability of task-parameter association (right-hand)

(4) Data uncertainty: change in the probability of task-parameter associations

Successful completion of a task is relied on the successful achievement of the associated parameters. However, what happens if a parameter could not satisfy its corresponding task at the highest level of confidence? To address this practical issue, which has not investigated before, we changed the probability that each technical parameter can affect its corresponding task, from the normal case (100%) down to 60%, and for the three parameters that were associated with respectively the product (number of product components), process (maintenance frequency), and with the both product and process (standardization). Figure 6 (right-hand) represents the impact on the overall process cost and rework.

The result shows that 'the probability of a parameter in satisfaction of a task' has less impact on the process outcomes in comparison to 'the value of a parameter in satisfaction of that task'. It is evident from the two-sides of Figure 6, where 20% decrease in parameter value has raised the cost up to the 140,000 Euro, while in a similar case for the parameter probability, this amount is around 62,560 Euro, less than a half. This sort of output information can be helpful on the effective definition of the product specifications and requirements, i.e., what kind of parameter are more influential in what phases of DP?

(5) Human-factor uncertainty: change in the number of actors involved in the DP

In the context of the Oil-Pipe case, up to two designers (a senior and a junior) and up to two cost engineers (a senior and a junior) can accomplish the redesign process. We generated two teams: once with only the two seniors (designer and cost engineer), and then involving all four actors (two seniors and two juniors). Due to the difference in the cost-per-hour of the seniors in respect to the juniors, we have expected a notable difference accordingly in the simulation analysis with respect to two teams. As an assumption, there was not any limitation on the availability of the actors.

It should be highlighted that, based on our interviews with the managers, it was not possible in reality to complete all the design tasks by using the two juniors (a designer and a cost engineer). For the purpose of comparison, the performance of the two teams is analysed in the cases of a normal process completion and on-time completion of the project. The impact on the process cost and duration is presented in Figure 7, respectively on the left-hand and right-hand sides.

Following the figure, the trend for both cost and duration of the process is rather similar in general, except during the last phase of the detail design where the difference in process behaviour is obvious. Concerning the process cost, the two teams are overlapped which means the earlier phases of the redesign process are mainly accomplished by the seniors and therefore the main difference is due to the normal or on-time completion of the work done.

In terms of process duration, inversely, the priority is based on the composition of the teams and the process including the two seniors represented a better proposal in respect to the four-member team, which can be interpreted in the same way as the former cost analysis. However, there might not be a meaningful difference between the two groups of teams in general, since the more actors involved in the DP, the better comparison should be expected from the ABS. Because the mechanism of actor's selection in the ABS works based on the reciprocal comparison of people involved in the process.

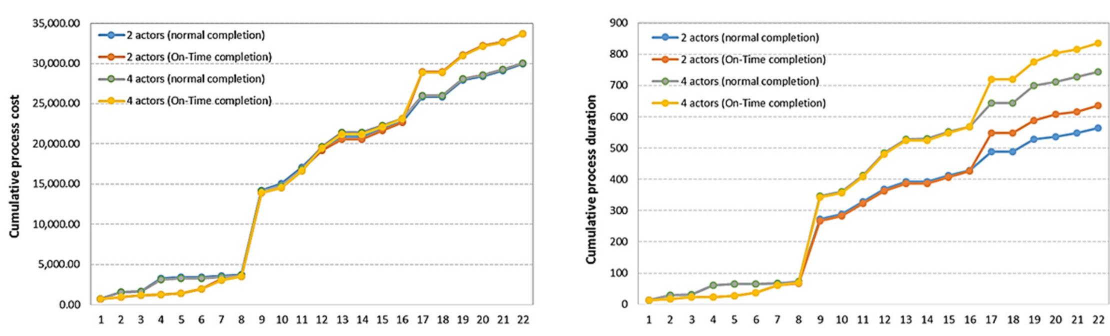

Figure 7. On the impact of human-factor uncertainty, associated with number of actors, on the process cost (left-hand), and on the duration (right-hand)

5. Feedback from practitioners and conclusive implications

In this paper, we addressed the difficulty of process planning from a broader perspective of socio-technical uncertainty modelling. To doing this, a classification of uncertainty presented and illustrated through application of Actor-Based Signposting (ABS) approach in the case of an Oil-Pipe redesign process. A range of five scenarios of uncertainty selected based on their importance in the process planning and analysed, each of which was related to a specific aspect of the proposed uncertainty classification, i.e., parameter, and data uncertainty. The conclusion from the result would be the fact that there is no absolute way to fully manage the uncertainty of complex projects, and therefore there should be a balance between the degree of uncertainty and goodness (quality) of the product.

The full set of achievements presented to the company partners and fortunately sounded very satisfactory to them. Part of the simulation analysis used to support the selection of the best alternative redesign proposal (as is shown in Figure 2), while the rest of output data was found interesting to be used in the future redesign process of the case, in collaboration with the client. Confirmed by the practitioners, the ABS methodology reflected a good ability not only on supporting the process planning issues but also acting as an integrated cost estimation and analysis tool. In addition, in comparison to the other process modelling approaches like DSM and Petri-Nets that were in use of the company, ABS reflected good capability on providing a detailed information on the unconventional process planning issues and on the optimal way that the work should be carried out, i.e., optimal tasks-parameters associations, optimal amount of learning that could be achieved during the work, identification of criticalities in relation to the more influential parameters, actors, and their associations. As a feedback, it was asked from the partners to develop the ABS methodology for a more complicated case of engine platform design.

As a conclusion, based on the simulation results, multiple sources of uncertainty reflected such a direct and indirect dependency to each other. For example, successful and ‘on-time’ completion of the tasks can be directly related to the early satisfaction of the parameters by the tasks, or the duration and likelihood of the reworked tasks. As another example, the value of confidence level (in the quality parameters) and the probability of satisfying the task's requirements can be strongly related together, since the low-quality parameter value in the high-probability parameter (in terms of satisfying the task's requirements) might have as the same impact on the process outcome as a low-quality probability parameter has in the high-quality parameter value.

In summary, predictive planning of the future DPs cannot be achieved unless we consider the multiple levels of uncertainty in an integrated perspective and try to locally handle the uncertainty sources, in order to mitigate their reciprocal impacts. Accordingly, this requires the development of such well-formulated approaches that are able to capture multiple aspects of the product, process, and the design organization in an integrated platform. ABS could effectively perform as a tool to help support modern needs of process planning and management, and above that could act as a baseline for development of such ‘integrated process modelling’ approaches that enables the user to address integrated socio-technical uncertainties, integrated product, process, and organisational factors, with respect to the integrated (typical and unconventional) process planning characteristics.

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