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Approaching the Reduction of Uncertainty in Production System Design through Discrete-Event Simulation

Untersuchung der Reduktion von Unsicherheit im Produktionssystem-Design durch ereignisdiskrete Simulation

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Abstract: The presence of uncertainties associated to the introduction of novelty and significant change challenge manufacturing competitiveness. Addressing this issue, the purpose of this qualitative case study is to examine the uncertainties reduced by Discrete-Event Simulation (DES) use during the design of a production system when significant changes are introduced at a manufacturing company. The results of this paper, based on empirical findings from a Swedish manufacturing company, reveal the presence of eight different uncertainties affecting the design of a production system including state, technical, environmental, system, temporal, structural, epistemic, and definition. Empirical results also show how DES contributed to reducing technical, structural, epistemic, and definition uncertainties. This paper contributes to existing knowledge by proposing a model that aids decision makers anticipate the type of uncertainty faced and the suitability of DES use as an uncertainty reducing activity during significant change introduction.

1 Introduction

Modern day manufacturing companies can no longer rely on the use of everyday practices to secure a strong market position (Michalos et al. 2010). Instead, manufacturing firms are increasingly required to introduce significant changes in a production system to gain a competitive advantage (O'Connor and Rice 2013). To achieve this, literature has proposed the use of both production system design (Pisano and Shih 2009) and DES (Law 2015). However, past studies reveal that when significant changes are introduced the presence of uncertainties challenge the characterization of a production system during its design. In this context uncertainty arises from the changes in requirements, products, challenges, or expectations that are different from what currently exists (Bellgran and Säfsten 2010). Thus, DES theory recommends that uncertainty be reduced to increase knowledge during modelling and diminish potential inaccuracies (Oberkampf et al. 2002).

Nonetheless, results from past DES studies underscore what seems to be a tenuous understanding of uncertainty reduction when significant changes are introduced during production system design. A key limitation of current DES publications is that these have approached the reduction of uncertainty by focusing on the selection of values of design parameters and not on issues that arise when such parameters must first be identified (Wynn et al. 2011). For example, Gien and Jacqmart (2005) investigated the presence of uncertainty as incorrect of inaccurate data inputs for DES models, and Kleijnen et al. (2011) found which uncertain parameters in a DES model lead to an uncertain design. This shows that, regardless of establishing what mechanisms facilitate the reduction of uncertainty once DES model parameters have been chosen, it remains important to determine how uncertainties challenge the production system characterization will be dealt with prior to model development. This issue is significant as good theory must specify both what and how an issue occurs (Karlsson 2010). Furthermore, addressing this gap would help establish which of the presently known types of uncertainty may be resolved through DES use, and thereby determine the appropriateness of a DES based analysis in conditions of high uncertainty (Carrillo and Gaimon 2002; Haveman and Bonnema 2015).

Accordingly, the purpose of this paper is to examine the uncertainties reduced through DES use during the design of a production system when significant changes are introduced at a manufacturing company. This paper contributes to existing knowledge by presenting a model that informs decision makers about the type of uncertainty faced during significant change introduction and suggest whether DES use is a suitable alternative to the reduction of these uncertainties during production system design. Empirically, data is collected from a real-time case study at a Swedish manufacturing company where a multi-product assembly system was developed under conditions of significant change and high uncertainty. The structure of the paper is the following. Section 2 presents a frame of reference. The method through which research was performed is described in Section 3. The empirical findings and analysis are presented in sections 4 and 5 respectively. Finally, conclusions and future research venues are presented in Section 6.

2 Frame of Reference

2.1 Production System Design

According to recent findings, manufacturing companies can only sustain a competitive advantage by developing the ability to introduce significant changes in both products and production system (Frishammar et al. 2012). These significant changes include novel production and organizational processes as well as component technologies that are different from and new to a manufacturing company´s current capabilities (Holweg 2008). Production system design includes the conception and planning of the overall set of elements and events constituting a production system, together with rules for their relationship in space and time (Chisholm 1990). Hence, production system design has been regarded as a problem-solving activity where significant changes can be introduced into the production system. This is achieved by selecting equipment, information flow, work procedures and related decisions in accordance to the desired objectives (Bellgran and Säfsten

2010). However, a growing body of literature suggests that the introductions of significant changes leads to uncertainties that challenge a manufacturing company´s characterisation of a production system (Parida et al. 2016).

Uncertainty has been defined as the gap between the information that designers need for formulating a proper decision and the information that they actually have (Galbraith 1973). In a context of significant change introduction uncertainty arises form an inherent lack of information related to inclusion of new elements into a production system (O'Connor and Rice 2013). Paradoxically, even though companies face high levels of uncertainty when introducing significant changes, a poor management of information is noted. This lack of information has been attributed to deficient information gathering, communication and usage (Bruch and Bellgran 2013). Accordingly, the reduction of uncertainty is desirable and includes generating agreement on what there is uncertainty about and acquiring additional information about agreed upon issues (Koufteros et al. 2005).

Reducing uncertainty requires first creating awareness of the different types of uncertainties and then selecting a suitable approach that leads to a state of increased information (Carrillo and Gaimon 2002). From a production systems perspective, uncertainties have been originally grouped into environmental or system based on the whether these develop beyond or within the boundaries of a production system respectively (Ho 1989). However, further research has revealed a diversity of uncertainty types that go beyond this classification, these are presented in Table 1.

Table 1: *Types of uncertainty*

Author	Type	Description
Milliken (1987)	State	Limited understanding of changes in environment
	Effect	Inability predicting the consequences of changes
	Response	Lack of knowledge of available response options
Gerwin (1988)	Technical	Unknown precision and reliability of processes
	Financial	Inability to determine the return on investment
	Social	Questions concerning the required support system
Rowe (1994)	Temporal	Absence of information about future or past states
	Structural	Uncertainty due to system complexity
	Metrical	Doubtful and variable measurement process
	Translational	Difficulties explaining results across the company
McManus and Hastings (2005)	Epistemic	Facts that are not known or known imprecisely
	Definition	System has not been decided/specified
Lane and Maxfield (2005)	Truth	Inability to prove if an alternative is true or not
	Semantic	Doubts on what the meaning of an alternative is
	Ontological	Actors' ontology based uncertainty
Clarkson and Eckert (2010)	Known	Variability in past cases seen as a distribution
	Unknown	Unexpected internal and/or external uncertainties

2.2 Discrete-Event Simulation

DES has been used extensively in multiple sectors of manufacturing (Jahangirian et al. 2010). The use of DES in the analysis of a production system originates from the selection of relevant information and development of understanding necessary to establish causal relations between elements in a such a system without disrupting its operation (Law 2015). Two distinct approaches to the reduction of uncertainty through DES use emerge from current literature.

First, DES use as confirmation of a selected alternative including all major decisions that indicate what a production system will look like and how will a production system operate, as shown by Jagstam and Klingstam (2002). Here the use of DES in late stage of production system design exists as a contingency to poor input data that may lead to a weak simulation results (Robinson 2002). Thus, DES contributions to the reduction of uncertainty focus on a sufficiently narrow selection of parameters and hence conditions of low uncertainty.

Opposite to this perspective, literature suggests the use of DES early in production system design. Here limited commitment to the characteristics of a production system exist and uncertainty is high. Consequently, this approach assumes a continuous use of DES as a way of gradually reducing uncertainty as suggested by Oberkampf et al. (2002) and Jagstam and Klingstam (2002). This approach is underpinned non-exclusive strategies which have been extensively addressed in literature. Such approaches include and are not limited to modelling a production system while incurring in assumptions and simplifications (Robinson 2014), accounting for uncertainty as an experimental factor through sensitivity analysis (Durieux and Pierreval 2004; Kleijnen et al. 2011) or fuzzy data intervals (Gien and Jacqmart 2005).

3 Research Methodology

To achieve the purpose of this paper, a real-time case study was conducted at a Swedish manufacturing company. A case study method was chosen to provide understanding of a real world context when a lack of control over events was anticipated (Yin 2013), and contribute with empirical evidence to current understanding (Voss et al. 2002; Eisenhardt and Graebner 2007). Because uncertainty was expected to change over time as a result of design, a real-time approach was selected to investigate the same phenomena at multiple points (Karlsson 2010). Thus, data was collected longitudinally as events took place (Eisenhardt and Graebner 2007). Case study data was collected between February and May 2016. Multiple sources of evidence were used including company documents describing the design of the production system. Data was also acquired through participatory observation in ten one hour meetings and three full day workshops. Participatory observations focused on identifying uncertainty and its reduction while a cross-functional team characterized the production system during its design. Also, data was collected during the development of six different DES models. DES model development followed the steps in a simulation study suggested by (Law 2015). Input data used for DES model development was based on a combination of historical, anecdotal and observational data (Chung 2003). Data collected for the development of DES models included assembly times per station, operator quantity, shifts, capacities, production demand, and disturbances. A whitebox validation technique was employed to verify the DES models (Robinson 1997) while verification included face validation and black box testing (Balci 1994). Uncertainty identification was underpinned by type and definition of uncertainties presented in the frame of reference. Data was scanned for issues that revealed a lack of information necessary for production system characterization during design. Then, activities that contributed to the acquisition of information were pinpointed. All steps in a simulation study including problem formulation, data collection, model definition, validation, verification, experimental design, runs, analysis, documentation, presentation, and implementation were inspected for the presence of uncertainty and its reduction. Data were analysed iteratively following the stages of data condensation, data display, and conclusion drawing (Miles et al. 2013). Analytic generalization was prioritized to address concerns about generalizability of research results (Yin 2013). First a theoretical framework was developed to gain a basic logic about uncertainty and its reduction. This general logic was compared with data drawn from an empirical context. To address concerns about validity of research, key concepts about uncertainty types were identified to establish a chain of evidence based on multiple sources of data (Maxwell 2012). Theory was used to gain an understanding on uncertainty reduction through DES use. This was examined in relation to case findings to understand occurrences and rule out rival explanations.

4 Empirical Findings

A real-time case study was conducted at a Swedish manufacturing company from the heavy vehicle industry. The case study followed a production system design project where substantial modification to an existing production system were conceived. Here the manufacturing company decided to change its product specific assembly system to a multi-product assembly one where three distinct product families and 600 different variants could be assembled. These significant changes to the assembly systems were seen as means for the company to increase its competitive advantage by shortening lead time to customers, reducing manufacturing footprint, and providing a common architecture for its products.

4.1 Case Study Findings

Case study documents show the limited experience on the design and operation of a multi-product assembly system at the manufacturing site. Site visits and participatory observation revealed that no major modifications had taken place in the existing production system since its implementation. Collected data shows that the transition from single product assembly lines to mixed model assembly one meant an unavoidable increase in variation in the multi-product assembly system. This included diverse assembly operations, increased number of products and an increment in the difference between assembly times within each assembly station. Furthermore, empirical data stemming from documents, site visits, workshops and DES model development show the presence of uncertainties affecting a complete characterization of the designed assembly system. These uncertainties were distinguished by a lack of information that came as a consequence of the introduction of changes necessary to implement a multi-product assembly line. Targeting the increased variation and acknowledging the limited insight into the consequence of introducing a multi-product assembly system, six different DES models were developed during production system design. Following different purposes, the models were divided into three different phases. In the first phase the current production system was simulated (Model 0), serving as a basis for comparison with the production system under design according to performance measures i. e. total production and lead time. In the second phase, Model 0 was compared against the future multi-product assembly line (Model 1). The aim of this phase was to verify whether the multi-product assembly line would be able to meet the current demand requirements, using the same input data as the previous model. The third phase, consisting on the four different models (Model 2 to Model 5), simulated and analysed different future state design decisions proposed by the company. From Model 2 onwards, which aimed to simulate the future state according to the company specifications, the subsequent scenarios were cumulatively modelled, meaning that Model 3 was an enhancement of Model 2, and so on. The buffer analysis simulated in the Model 3 unveiled a trade-off in form of an increase of 1 % in the total production for an increase of 15 % in the lead time. Through Models 4 and 5, the production system modelled proofed to be resilient enough to handle variation in both demand and product mix, with a minor decrease in the total output.

5 Analysis and Discussion

Based on the frame of reference, a model showcasing the relation between uncertainty and DES is proposed. This model displays the uncertainty types observed when introducing significant changes into the production system, and based on the empirical finding of the case study, suggests which of these uncertainties are reduced via DES. From the 19 uncertainty types defined in the frame of reference, eight of them were addressed through DES use in the case study. This eight uncertainty types include state, technical, environmental, system, temporal, structural, epistemic and definition. Table 2 summarizes the uncertainty types in the empirical study.

Table 2: *Types of uncertainties observed during the production system design*

Type	Uncertainties observed
State	Unknown future demand, new product introduction and competitors.
Technical	Unclear if the new production system will meet the requirements.
Environmental	Unknown product demand variation, model and production mix, product design changes and new product introduction.
System	Lack of knowledge about production process related to significant change introduction.
Temporal	Unclear future state and poor historical documentation.
Structural	Complex product assembly, numerous parts and customer options.
Epistemic	Poor information about the current system and inexperience performing production system design.
Definition	Objectives, common visions and requirements not clearly defined.

Based on these results, Figure 1 shows a model describing how the uncertainties above are reduced when using DES. In this model, identified uncertainties are grouped based on Ho (1989), including external (environmental) and internal (system) uncertainties, here temporal uncertainty affects both classifications.

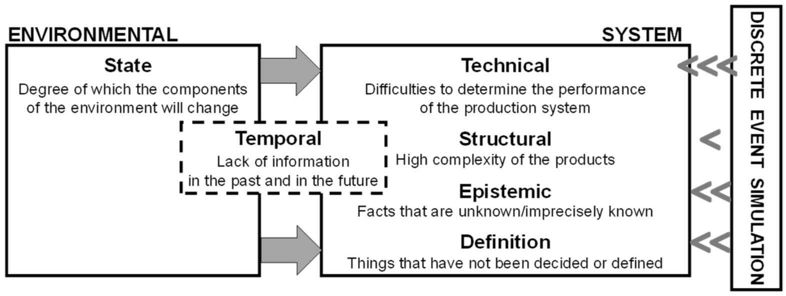

Figure 1: *Model showing reduction of uncertainties through DES use*

The model shows that, the information provided by the simulation study to reduce uncertainty in production system design can be divided into two different categories: the output of the models in form of key performance indicators (KPIs) and the simulation modelling process itself. On the one hand, in line with previous studies (Durieux and Pierreval 2004), the empirical study not only revealed that the design alternatives were viable, but it also predicted a 3 % of increase in the total production compared to the current situation. Besides, relevance of factors such as seasonality and disturbances previously not considered in the early stages of the design was found out. In fact, Model 1 showed a decrease of 6.6 % of the total production attributed to the two discoveries. Model 3, whose aim was to overcome these factors, revealed a potential 1 % total production further increase by using stock buffers. All in all, the KPIs provided information about the behaviour of the system, and thus reducing the technical and epistemic uncertainties in high degree (Gerwin 1988; McManus and Hastings 2005). Empirical evidence suggests that the modelling process also brought a decrease in the uncertainty level. Discrepancies between management and operational level among capacity and disturbance behaviour was solved by involving cross-functional team member backgrounds in the project, where steps like the problem formulation or data gathering decreased in a high degree the definition uncertainty (McManus and Hastings 2005). In line with the findings of Kang et al. (2015), the visual aspects of DES made easier to present information and results to different backgrounds, ensuring a common vision towards the uncertainties affecting the production system in the project team and thus, decreasing definition uncertainty and improving the communication across the company (Bruch and Bellgran 2013). Concerning the conceptual model building, the simplifications of the system and subsystems made the overall introduction of significant changes more understandable and accessible to the different levels of the organization, decreasing in a lower degree the structural uncertainty (Rowe 1994). Environmental uncertainties were not reduced through DES, but their consequences understood. Nevertheless, DES helped understand the effects that changes in demand and new product introductions would have on the production system, and thereby reduce temporal (Rowe 1994) and effect uncertainties (Milliken 1987).

6 Conclusions and Future Research Venues

The purpose of this paper was to examine the uncertainties reduced by DES use during the design of a production system when significant changes are introduced at a manufacturing company. Based on the result from a real-time case study, this paper presented a model identifying the uncertainties present during significant change introduction, where uncertainties of technical, structural, epistemic, and definition type were reduced during the design of a production system through DES use. This model contributes to existing knowledge focusing on the early use of DES during production system design in conditions of high uncertainty described in the frame of reference. Results suggest that as far as identification of uncertainty is concerned, theory driven categories of uncertainty are meaningful to understand the difficulties of characterization during significant change introduction. Further, revealing which of these uncertainties are accounted for by DES complements current understanding about the mechanisms that facilitate the reduction of uncertainty once DES parameters have been chosen. Also, the results of this paper show the usefulness of DES in the acquisition of information relevant to production system design, situation achieved by predicting the future system performance and behaviour and aiding in the communication through the organization with the visual aspects. Managerial implications of this paper strongly focus on the contingency of uncertainties that stem from introducing significant production system changes. Thus, the presented model serves as a guideline for decision makers to anticipate the types of uncertainty and the applicability that DES use for their reduction. Future research includes confirmation of results based on additional cases and industries that strengthen the insight provided by this single case study. Research results indicate the importance of production system design and DES use when addressing uncertainty reduction. Future research could describe the necessary conditions that facilitate this. Finally, the results of this paper suggest that different levels of uncertainty reduction occur when DES is used. Thus, future research could illuminate how and why this occurs.

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