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Assessing the Impact of Changes and their Knock-on Effects in Manufacturing Systems

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Abstract

Manufacturing systems are subject to frequent changes caused by technology and product innovation, varying demand, shifted product mix, continuous improvement initiatives, or regular substitutions of outworn equipment and machines. Elements within a manufacturing system are connected by a complex network of relations such as material flow, technological dependencies, infrastructure, and intangible cause-and-effect-chains. Depending on the scale of changes they may also interfere with engineering, procurement, logistics, or even manufacturing strategy. Thus, the total impact in terms of expected costs and required time for planning and implementation of those “manufacturing changes” is hard to predict. The objective of this paper is to provide a decision support for manufacturing change management and to enable a thorough analysis of changes in manufacturing systems. Although the topic of change propagation received considerable attention in product development in order to quantify the knock-on effects of engineering changes, comparable endeavors have not yet been made in the field of manufacturing science. Following a review of prevailing approaches from product development and manufacturing literature, a model-based approach for the prediction and assessment of change propagation in manufacturing systems is presented. Applied structural modeling techniques, the derived graph algorithm, and the proposed procedure of the approach are outlined. Finally, an industrial case study is presented to demonstrate the potential but also the limitations in practice.

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Keywords: Change impact, Manufacturing Change Management, Structural modeling, DSM, Engineering systems, Change propagation, Graph model

1. Introduction

1.1. Initial situation, problem statement, and objective

Manufacturing companies have to be able to handle volatile demand, product variety, and shortened product life cycles today. Quick response to changing requirements at low cost is a competitive edge for 21st century agile manufacturing companies [1]. In order to accomplish this challenge, two complementary approaches should be pursued: the efficient and effective management of engineering and manufacturing changes and the deliberate design of changeable systems – this contribution is focusing on the former. Evolving future requirements such as, e.g., changing stakeholder needs and preferences, new operating conditions, technology innovation, and market volatility [2–5] require a variety of manufacturing changes [6] which have to be implemented in manufacturing and related functions like logistics planning, product development, and procurement.

For a long time, engineering design literature has realized that changes in complex products lead to knock-on effects depending on the intensity and types of relations that constitute a product architecture [7,8]. Despite of the large body of literature that has emerged in this domain dealing with the assessment of change impact in technical products, similar endeavors are still rare in manufacturing literature. However, due to the high complexity of todays advanced manufacturing systems, the assessment of change impact represents an ever more challenging task. Especially in early conceptual phases, where decisions about a manufacturing change, project budgeting, and resource allocation have to be made, available information is sparse and the experience of system experts

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plays a vital role. But even the most experienced experts are not able to oversee and assess all possible chains of effects without appropriate supporting methods and tools [9].

This paper presents a model-based method for change impact assessment in the manufacturing domain to support the above mentioned tasks in industrial practice.

1.2. Elementary definitions

1.2.1. Engineering system

Engineering systems are an umbrella term for socio-technical systems that have been designed for a specific purpose. The term is used in various disciplines including systems engineering, product development, manufacturing, management, and social sciences. Engineering systems are defined as "*A class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society.*" [2]

1.2.2. Manufacturing and factory systems

According to Bramley et al. [10], a manufacturing system is defined as "a system that includes all procedures and facilities to transform raw materials into final products". Based on the established layer model of production systems [5], some of the authors suggested a structural definition in [11]: *Manufacturing systems comprise the spatial arrangement, relations, and properties of technology, personnel, and infrastructure in a differentiable sub-section of a manufacturing plant*, where the system boundary should be drawn technology- or product-oriented. Originally, the term "factory system" was used to emphasize the intended hierarchy in the production layer model – the system / segment level – since entities on this level commonly have been referred to as "factory objects". Within this article, however, the term manufacturing system will be used synonymously.

1.2.3. Change impact

Impact can be quantified in various forms depending on the system context, e.g., in terms of technical, organizational, legal, and ecological effects. In the domains of manufacturing and product development, impact usually refers to the objects affected and ultimately to the cost incurred by a change – either due to investments (e.g. new machines) or labor (e.g. redesign of a product component, implementation of reconfigured production layout). This understanding is also in line with the notion that changeability should be measured by the consumption of valued resources, i.e., money and time [12]. Thus, change impact is defined as *the cost incurred by a change in terms of money and time due to any activities related to its planning and implementation*.

1.3. Synopsis

The remainder of this article is structured as follows: in chapter 2 the state of the art in manufacturing (2.1) and design science (2.2) is reviewed briefly to derive the need for further research. Chapter 3 presents the developed approach for change impact simulation and assessment in manufacturing, starting from a discussion of requirements (3.1) and assumptions (3.3). The method is illustrated in chapter 4 using an industrial application example of a polymer injection molding plant before the paper concludes with chapter 5 providing an outlook for future research.

Nomenclature

a, m, b	Best case, most likely, and worst case indices
p	Path probability
p_{ij}	Direct transition likelihood between nodes i, j
$\boldsymbol{P}$	Transition probability matrix ($p_{ij} \in \boldsymbol{P}$)
c_a, c_m, c_b	Cost estimates
t_a, t_m, t_b	Working time estimates
$\boldsymbol{C_a}, \boldsymbol{C_m}, \boldsymbol{C_b}$	Investment / cost estimate matrices
$\boldsymbol{T_a}, \boldsymbol{T_m}, \boldsymbol{T_b}$	Effective working time estimate matrices
$\hat{\mu}, \hat{\sigma}$	Estimated mean and variance
α, β	Beta distribution form parameters
$\boldsymbol{\alpha}, \boldsymbol{\beta}$	Beta distribution form parameter matrices
u	Uniformly distributed random variable
c_t	Hourly rate for labor cost

2. Literature review

2.1. Manufacturing change domain

In manufacturing literature, change impact has been dealt with in the context of reconfiguration planning. Cisek presents a procedure for the comparison of alternative manufacturing layouts, triggered by varying production volume and product mix [13]. Nofen describes a process for identifying cause-and-effect chains due to manufacturing changes as a sub-method of change planning for modular factory systems [14].

A procedure for the evaluation of impacts of new products and manufacturing technologies on factories is proposed by Wulf [15]. The approach aims at the collaborative design of product, technology, and factory structure to mitigate unwanted effects of adaptations.

Based on a prediction of external change drivers, Klemke evaluates the changeability of factories depending on whether expected changes can be implemented in due time or not. Change impact is analyzed with respect to manufacturing cost, implementation time, and product quality [16].

Pohl develops a method for the identification, conception, and assessment of manufacturing structure adaptations taking product, technology, and manufacturing resource life cycles into account. His approach aims at the identification of beneficial time windows for the implementation of manufacturing system adaptations [17].

More recently, Karl & Reinhart suggested a similar approach on the manufacturing cell and workstation level using structural models in order to plan and evaluate alternative manufacturing resource reconfigurations [18].

As a means to cope with volatile markets, Richter et al. propose an approach for structural modeling of production systems to enable a faster redesign of plant structures [19]. The authors state that prevailing methods for factory modeling do not provide sufficient detail to map the variety of relations between structural elements within a manufacturing plant.

Aurich et al. propose an approach for the management of multiple engineering changes and the assessment of their impact using a virtual reality environment, where the manufacturing system is modeled using UML [20]. A similar approach is followed by Schady to support factory planning and change management [21]. Malak et al. refine the approach of Aurich et al. with respect to the procedure for planning and analyzing engineering changes supported by digital factory models. Their objective is to reduce costly production downtime due to engineering changes. Change impact is analyzed with respect to layout, process chain, harmful machine interaction, and interrupted material flow [22,23].

2.2. Engineering change domain

Since the early 2000s, product development and engineering design research is dealing with change propagation analysis on the parameter and component level using structural modeling techniques. One of the first engineering change propagation algorithms is C-FAR by Cohen et al. [24]. It aims at the qualitative evaluation of engineering change impacts caused by changing the attributes of an initiating entity on the attributes of a target entity (e.g., a component).

Another algorithm that is based on qualitative product models is RedesignIT by Ollinger & Stahovich [25]. The approach is focusing on physical quantities (e.g. the volume of a cylinder) and their causal relationships to automatically identify the parts which will be affected by a planned engineering change.

One of the most established methods for change prediction and the analysis of change propagation in Engineering Change Management (ECM) is the Change Prediction Method (CPM) by Clarkson et al. [8]. Using component level Design Structure Matrices (DSMs), a product is broken down to capture component-component dependencies. It is assumed that change only propagates along the linkages of a product's network model. Change risk is calculated using the so-called Forward CPM algorithm that computes all direct and indirect paths leading from all potentially initiating to all potentially affected components. Required information (i.e., direct change likelihood and redesign effort) is elicited from senior engineers.

Within the last decade, various extensions and amendments of the CPM have been developed using different modeling techniques and computation algorithms. Notably, the function-behavior-structure linkage ontology by Hamraz, which provides additional explanatory power and insights into change mechanisms and their propagation effects [7,26].

Due to spatial restrictions, a thorough presentation of the ECM stream of literate cannot be provided here. The interested reader is referred to [27] for an extensive review.

2.3. Discussion

The state of the art reveals that approaches suggested in manufacturing literature have a rather process-oriented character in contrast to the mostly model-based methods of ECM. Although, the existence of change propagation effects in manufacturing systems is acknowledged by some researchers [cf. 19,23], no methodological support for their analysis is provided yet.

As mentioned above, the CPM is considered as the most established tool for change impact analysis in ECM [28] and a multitude of extensions has been developed over the last decade. However, the method is focused on component-component relationships and does not provide any guidelines for modeling manufacturing systems where a variety of relation types do occur. Furthermore, the simultaneous analysis of multiple initiating changes within the system and processing of cyclic network structures is not possible up to now.

Note, that also in the domains of requirements and software engineering propagation effects have been investigated. Further analogies are, e.g., information propagation in social networks, epidemics, and technology diffusion. As these contagion phenomena are determined by very different mechanisms, they are not in the scope of this article.

3. Method for change impact analysis

In order to tackle current deficits systematically, the conceptual design of the proposed method starts with a specification of requirements, which have been derived from an extensive literature study (not reported on here) and case study experience. Furthermore, the underlying assumptions are stated in section 3.3 to specify the range of validity and formal limitations of the approach.

3.1. Requirements specification

3.1.1. General requirements

This section states substantive requirements of the method, i.e., aspects pertaining to its "functions". Firstly, the structural modeling approach needs to enhance system understanding of involved stakeholders (R1) also considering cross-domain effects (R2). Secondly, even the most knowledgeable experts will experience uncertainty when asked to quantitatively assess interdependency within a complex system; and also change propagation itself is inherently uncertain. Hence, these types of uncertainty need to be incorporated (R3). Obviously, the approach shall be designed to account for change propagation (R4) and ultimately needs to provide useful decision support for manufacturing change managers (R5).

3.1.2. Model requirements

Besides the substantive aspects listed in the previous section, also normative requirements have to be met, which aim at formal conditions for the model and the model building process. In order to achieve a justifiable benefit-to-cost ratio, a low model building effort is strived for (R6) – i.e., a trade-off between model precision and model granularity has to be made. The benefit of structural models is further enhanced, when they are designed flexible and reusable as systems evolve over time (R7). Trustworthy decision support can only be achieved by transparency, i.e., the procedure leading to numerical results has to be intelligible to the intended user (R8). In order to resolve current deficits, also synchronous processing of multiple changes and cyclic system structures have to be allowed for, as they usually do occur in industrial practice (R9).

3.2. Targeted use case scenarios

The method developed here is designed to support engineers taking part in all activities which are related to changes in manufacturing companies. Particularly, this includes the following functions: change management, simultaneous engineering, product development, technology management, plant design, and manufacturing strategy.

Targeted use case scenarios and objectives are, e.g., to increase system understanding, to support stakeholder communication, to compare alternative change options, to plan change projects with respect to resource allocation, to lower future change costs by effectively embedding changeability in manufacturing systems, and finally, to support strategic potential and feasibility studies.

3.3. Assumptions

A characteristic property of models is that they abstract from the complexity of real-world systems to be able to formally analyze phenomena of interest. This process includes simplifications which have to be weighed up carefully against a loss of information during model generation so that insights gained from model-based analysis do not lose their explanatory power. In the following, important assumptions are listed: Similar to [7] and [8], we assume that (A1) graph and matrix based models are suitable representation for the purpose at hand and that (A2) change propagation is bound to the relations of a system. With respect to required expert judgment, our experience supports the assumption that (A3) experts are capable of estimating direct transition probabilities and impacts (cost and time) between every pair of adjacent nodes in the model [8,29]. These estimates are (A4) assumed to be beta distributed [30]. If the structural system model has the form of a multi-graph (multiple edges between two nodes), (A5) experts presumably aggregate multiple edges within their mental model of the system for a specific change scenario. This synthesis is required to reduce the effort of model population. In addition, (A6) relation- and object-related impact estimates need to be summarized using a single estimate corresponding to the respective edge of the graph model. Last but not least, (A7) changes, activities, and incidents are assumed stochastically independent [8].

3.4. Conceptual design

3.4.1. Step 1: Specifying the system of inquiry

In every use case scenario, the first step of the approach is a thorough specification of the system of inquiry. The system boundary needs to be drawn according to the purpose and scope of the analysis, comparing the risk of leaving out important subsystems, system domains, or elements with the increased complexity and effort accompanied by their inclusion. System thinking in manufacturing suggests functional, hierarchical, and structural reasoning to gain a complete understanding [31]. This process can be amended by a listing of general internal and external influences that are believed to affect the magnitude of impact with respect to the change to be analyzed. Within the first step, it is also recommended to clarify significant problem domains using logic trees or similar problem structuring techniques. The list of influences as well as the structured impact domains will further be used during expert elicitation (step 3) to improve the quality of background knowledge available to system experts and therefore the quality of their estimates.

3.4.2. Step 2: Modeling the baseline manufacturing system

The starting point of system modeling is to capture the real-world manufacturing system in a domain specific multi-graph model. As a guideline for system modeling, metamodels for objects and relations within manufacturing systems have been developed and described in [11] as a formalized ontology of relevant entities and interdependencies [32]. This work has been carried out using the established "Ontology Development Guide" by Noy & McGuinness [33].

Providing metamodels has several advantages. Some of these are that they document and support language evolution over time, foster creation of well-formed models, support model-transformations, and formal checking of model properties [34]. Furthermore, metamodels determine the aspired level of abstraction and, thus, the granularity of later models [35], which provides guidelines for the construction of structural models. That way, the approach can be tailored to system specifics or requirements of additional depth with respect to selected entity or relation classes.

In order to allow for more flexibility with respect to manufacturing-external interactions, also general cause-and-

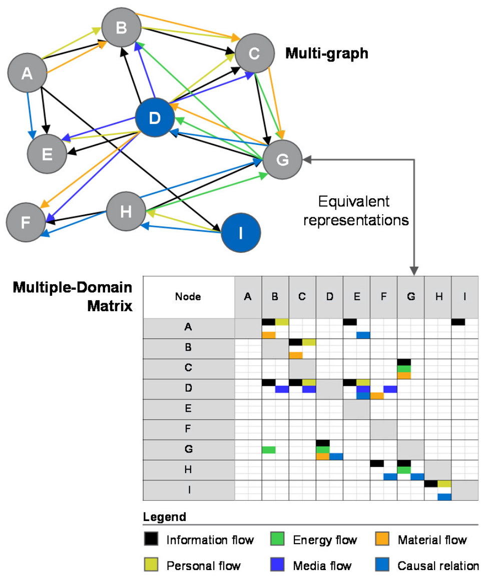

Fig. 1. Multi-graph and Engineering Systems Multiple-Domain Matrix

effect relations need to be considered. Although the metamodels in [11] are designed highly adaptable, these types of relations are not part of them, but are captured using modified Fuzzy Cognitive Maps (FCM) [36]. Extensive case study experience may provide insights into which types of general relations or entities should be added to the metamodels. However, as no sufficient categorization is attainable at

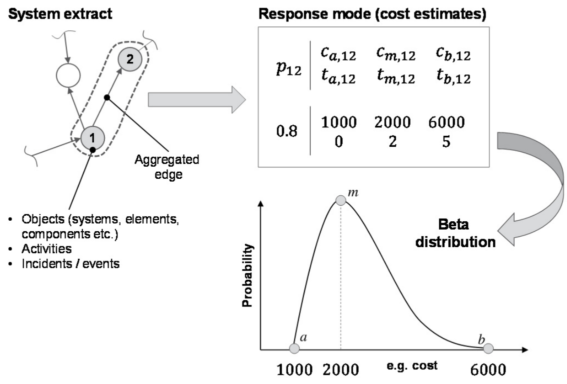

Fig. 2. Response modes required during expert elicitation.

present, a highly flexible solution as provided by FCMs is deemed favorable for the status quo.

Combining structural manufacturing system and knowledge based cause-and-effect models, that are also able to capture knock-on effects of activities or relevant incidents within the system environment, a systematic and comprehensive identification of change impact due to desired initial system changes is enabled [21]. Evidently, the resulting models may cover various socio-technical domains on different levels of abstraction. In accordance with the definition cited in section 1.2.1, the resulting representation is termed Engineering Systems Multiple-Domain Matrix (ES-MDM) (cf. Fig. 1). This conceptual modeling framework was first introduced by Bartolomei et al. [37,38] to provide a "methodology for engineers to tag and organize systems information in ways that allow for better collection, processing, and analysis of systems engineering data." [38]

3.4.3. Step 3: Expert elicitation

An expert can be defined as "a very skillful person who had much training and has knowledge in some special field. The expert is the provider of an opinion in the process of expert-opinion elicitation. Someone can become an expert in some special field by having the training and knowledge to a publicized level that would make him or her recognized by others as such." [39]

Due to the complexity of interactions within larger systems, change impact cannot be predicted without appropriate methodological support. As Clarkson et al. [8] point out, complex systems are usually not governed by a single engineer. While a chief engineer might have a high-level overview of the interplay of subsystems, subsystem experts should be interviewed to elicit detailed knowledge about their internal structure.

One way to support the process of accurately capturing knowledge about the interactions within a system is to provide experts with a model of the system they are asked to analyze to "gauge the overall understanding of the engineers and prompt them to think about possible connections between sub-systems" [8]. The process of expert elicitation is improved by providing suitable models of the system to support human memory and, thus, more complete assessments of mental models [40,41].

The edges of the original multi-graph or the corresponding entries in the ES-MDM are implicitly synthesized during the elicitation process. This aggregation of edges depends on the judgment of system experts, which relation types play a vital role for the analysis of specific changes and their propagation within the system. This step is required to reduce the complexity of the structural model in order to diminish the effort of model building to a reasonable level. Hence, during the phase of parameter estimation the resulting explicit mental model of experts could be represented by a simple graph or adjacency matrix – the "reduced graph model".

The objective of the elicitation procedure is to capture tacit expert knowledge (mental models of system experts) explicitly and to formalize this information about the system's structure. The approach proposed here is based on well-established system dynamics conceptual and formal model building procedures, in particular those of Richardson & Pugh [42], Vennix et al. [43], and Ford & Sterman [40]. The following three-phase elicitation procedure is suggested for a team consisting of facilitator (moderator) and modeler:

- *Positioning (system definition)*. In this phase, the facilitator clarifies the purpose of model building and presents the whole method for a shared understanding. The system boundary, relevant problem domains, and the changes to be analyzed are defined.
- *Conceptualization (model building)*. The second phase is usually carried out as a structured workshop with the objective of eliciting a paper based multi-graph system model. It is recommended to determine a suitable level of aggregation and to list relevant subsystems, activities, and elements in advance.
- *Discussion (formalization)*. Finally, estimates for transition probabilities and direct cost and time need to be elicited. As the experts might lack sufficient normative expertise with the response modes required, they have to be explained thoroughly in advance (cf. Fig. 2). Furthermore, experts should be briefed on subjective assessment biases that are likely to occur (e.g., availability and anchoring) and how they can be countered effectively [44,45].

3.4.4. Step 4: Formal knowledge representation

Since expert estimates are usually given without complete information and because the true outcome of the considered change process may be affected by unknown influences, it is reasonable to refer to the full range of possibilities rather than a single average value. In order to account for this expert uncertainty, three-point-estimations are elicited in step 3 for the parameterization of beta distributions for every edge of the reduced graph model.

Estimates for direct change transition probability, cost, and working time are required. For cost and time, best (a), worst (b), and most likely (m) scenarios are requested. A suitable means for processing this information to model uncertainty – both, with respect to the estimates and possible actual outcomes of change impact – are probability distributions.

The approach followed here is motivated by the Program Evaluation and Review Technique (PERT), which applies beta distributions to model uncertain activity durations [46]. According to Malcolm et al. [46] the estimated mean $\hat{\mu}$ and variance $\hat{\sigma}$ are given as:

$$\hat{\mu} = \frac{a + 4m + b}{6}, \qquad \hat{\sigma}^2 = \frac{(b-a)^2}{36} \qquad (1, 2)$$

In total, three distributions are constructed for each edge of the experts' (shared) reduced mental model. Variables c_a, c_m, c_b denote best, likely, and worst case estimates for cost (or invest) and t_a, t_m, t_b estimates for working time required for planning and implementation. Working time is multiplied by an hourly rate c_t to compute total cost per propagated change as

$$c_{total,k} = c_k + c_{t,k} \cdot t_k \ \ with\ k \in \{a, m, b\} \qquad (3)$$

The $n \times n$ transition probability matrix $\boldsymbol{P}$ contains all direct change likelihoods p_{ij} between each pair of adjacent nodes i and j. It reflects the structure of the reduced graph model:

$$P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{pmatrix} \qquad (4)$$

The cost estimate matrices $\boldsymbol{C_a}, \boldsymbol{C_m}, \boldsymbol{C_b}$ and the working time estimate matrices $\boldsymbol{T_a}, \boldsymbol{T_m}, \boldsymbol{T_b}$ have the same structure as $\boldsymbol{P}$ and contain corresponding estimates. For every edge of the model, shifted and scaled beta distributions for cost and time can be parameterized using the elicited three-point-estimates to calculate the form parameters α and β using equations (5) and (6).

$$\alpha = \left(\frac{\hat{\mu} - a}{b - a}\right)\left[\frac{(\hat{\mu} - a)(b - \hat{\mu})}{\hat{\sigma}^2} - 1\right] \qquad (5)$$

$$\beta = \left(\frac{b - \hat{\mu}}{b - a}\right)\left[\frac{(\hat{\mu} - a)(b - \hat{\mu})}{\hat{\sigma}^2} - 1\right] \qquad (6)$$

Thus, the form parameter matrices $\boldsymbol{\alpha_c}, \boldsymbol{\alpha_t}$ and $\boldsymbol{\beta_c}, \boldsymbol{\beta_t}$ are introduced to store all required data for distribution parameterization. A detailed explanation of how to derive (5) and (6) using (1) and (2) is provided by Davis [47].

3.4.5. Step 5: Change impact simulation (CIS)

In order to simulate the propagation effects of an initial change within the system, a Breadth-First Search (BFS) algorithm [48] is combined with Monte-Carlo Simulation (MCS). Theory of change propagation implies that changes propagate along the interdependencies of a system, i.e., along the relations that constitute its structure. Here, this structure is modeled using adjacency matrices. Initial changes correspond with the entries s_k of a root node vector $\boldsymbol{s}$. Thus, multiple changes can be processed simultaneously by breadth-first graph traversal. While basic BFS visits all nodes within the neighborhood of a root node s, change propagation is probabilistic with respect to the likelihood of change transition from one entity of the system to another as well as regarding the impact it generates in terms of cost and implementation effort. As mentioned earlier, the latter uncertainty is modeled using beta distributions for all edges of the reduced model.

Uncertain change transition can be modeled by means of MCS combined with BFS: the direct transition likelihood p_{ij} from node i to node j is compared with a uniformly distributed random variable $u_{ij} \sim U(0,1)$, similar to a coin toss. If $u_{ij} < p_{ij}$, which is true in p_{ij}% of cases, the change is assumed to propagate, else BFS terminates. By running a large number of simulation trials, impact distributions for cost, total cost, and working time can be computed.

3.4.6. Step 6: Decision analysis

For quantitative decision analysis, the CIS yields the total cost and working time due to initial changes, which are presented as histograms. That way, also the spread of results can be taken into account as an indicator for risk. Total cost is modeled as the sum of investments and labor cost, which is effective time multiplied with an hourly rate (cf. equation 3).

It is important to note that the CIS does only account for one-time cost. Hence, it simulates the magnitude of the initial expenses that have to be weighed up against long-term benefits both, monetary and non-monetary, as well as against recurring costs within the time horizon considered. For this purpose, Net Present Value (NPV) calculation is suitable.

4. Application example

4.1. Design tool Soley Studio

The application example was modelled in Soley Studio, which is based on the work of Helms on object-oriented graph grammars [49] and GrGen.NET, a programming productivity tool for graph transformations [50].

4.2. Case description – polymer injection molding plant

A medium-sized medical technology manufacturer wants to assess the consequences of changing the drives of a polymer injection molding tool. The manufacturing system consists of an assembly station, the machine, the tool itself, robots, and measurement and control technology (MCT). Due to previous experiences with surprisingly costly and time consuming change projects, the company asked for an assessment of expected costs, working-hours, and the associated risk for the desired change. Commercially sensitive data has been omitted or obscured. The expert group consisted of a senior engineer and a factory manager.

4.3. Structural modeling and parameter elicitation

Following the elicitation procedure proposed in section 3.4.3, the multi-graph model was captured using two joint flip chart papers. In advance of the conceptualization workshop the modeler prepared a preliminary model based on information acquired during the kick-off meeting. That way, the start of model building was significantly facilitated. After the conceptualization phase, the multi-graph model was computerized using Soley Studio. An MS Excel® template was used to import the graph data and to automatically generate the ES-MDM depicted in Fig. 3. The initial change is named “Drives (tool)”.

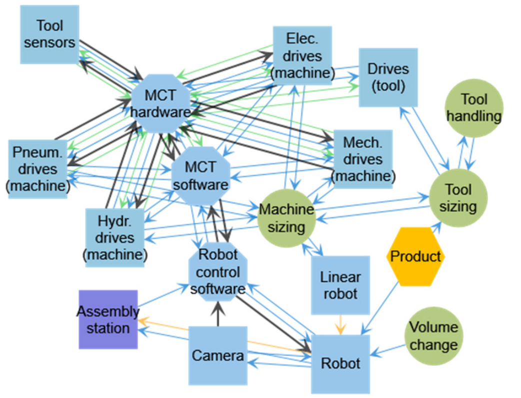

Fig. 3. Multi-graph generated using Soley Studio.

For the formalization phase, the ES-MDM and the computerized multi-graph model were prepared in addition to the paper-based model. The ES-MDM was used to focus on specific dependencies. Relation types that are deemed insignificant for the change analysis can be collapsed easily. Transition probabilities as well as the cost and time estimates were captured using the paper-based model and the notation shown in Fig. 2 presented earlier in this article.

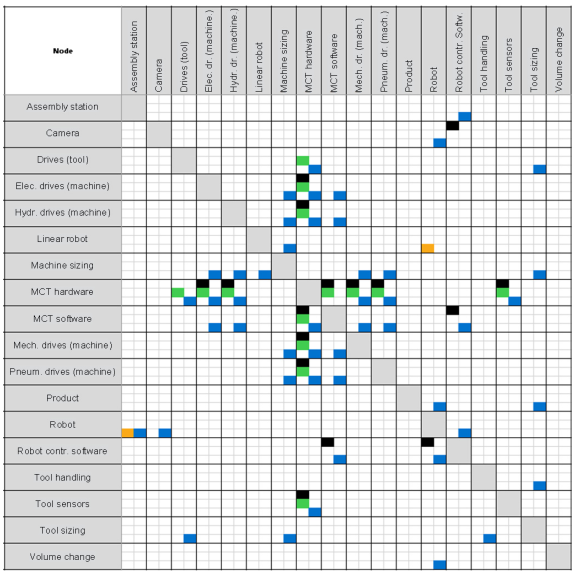

Fig. 4. ES-MDM of the injection molding manufacturing system.

4.4. Results

The CIS yields € 183’650 as mean value of total cost. However, the 90 % percentile of € 432’826 and the right tailed distribution of simulation results indicate a significant risk of excessive cost (cf. Fig. 5). In total, 282 person-hours are expected for planning and implementation with the 90 % percentile being 669 hours (histogram not shown).

Four structured workshops were conducted for this project including a kick-off meeting (6 hours) as well as the positioning (4 hours), conceptualization (6 hours), and formalization workshops (6 hours). Since no changes in recurring costs were expected and no alternative change options were available, only the one-time costs were analyzed.

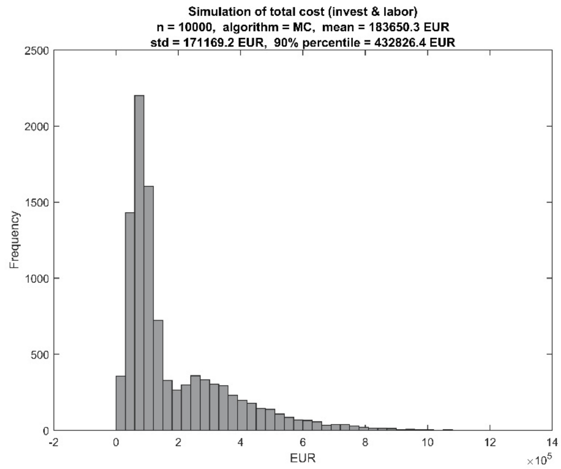

Fig. 5. Change impact simulation results: total cost distribution.

5. Conclusion

In this paper a model-based method for change impact assessment has been described. Its application was illustrated briefly by means of a real-world industrial case application. Future research needs to be carried out to evaluate the approach through further case studies. Besides, limitations of the approach, such as the current inability to process conditional probabilities, should be investigated.

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References

[1] Gunasekaran A, (Ed.) (2001) *Agile manufacturing: the 21st century competitive strategy*. Elsevier, Oxford, New York.

[2] de Weck OL, Roos D, Magee CL (2011) *Engineering Systems: Meeting Human Needs in a Complex Technological World*. MIT Press, Cambridge, MA.

[3] de Neufville R, Scholtes S (2011) *Flexibility in Engineering Design*. MIT Press, Cambridge, MA.

[4] ElMaraghy HA, (Ed.) (2009) *Changeable and reconfigurable manufacturing systems*. Springer, London.

[5] Wiendahl H, ElMaraghy HA, Nyhuis P, Zäh MF, Wiendahl H, Duffie N, Brieke M (2007) Changeable Manufacturing - Classification, Design and Operation. *CIRP Annals - Manufacturing Technology* 56(2):pp. 783–809.

[6] Koch J, Michels N, Reinhart G (2015) Context model design for a process-oriented Manufacturing Change Management. *Procedia CIRP - 48th CIRP Conference on Manufacturing Systems (CMS)*.

[7] Hamraz B, Caldwell NHM, Ridgman TW, Clarkson PJ (2015) FBS Linkage ontology and technique to support engineering change management. *Research in Engineering Design* 26:3–35.

[8] Clarkson PJ, Simons C, Eckert CM (2004) Predicting Change Propagation in Complex Design. *Journal of Mechanical Design* 126(5):788–97.

[9] Sterman JD (2002) *System Dynamics: Systems Thinking and Modeling for a Complex World*, Cambridge, MA.

[10] Bramley A, Knight W, Laperrière L, O'Donnel G, Reinhart G, (Eds.) (2011) *CIRP Dictionary of Production Engineering.* 1st ed. Springer, Heidelberg et al.

[11] Plehn C, Stein F, Reinhart G (2015) Modeling Factory Systems Using Graphs: Ontology-based Design of a Domain Specific Modeling Approach. *International Conference on Engineering Design (ICED 2015)*.

[12] Ross AM, Rhodes DH, Hastings DE (2008) Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining System Lifecycle Value. *Systems Engineering* 11(3):246–62.

[13] Cisek R (2005) Planung und Bewertung von Rekonfigurationsprozessen in Produktionssystemen: (Translation: Planning and assessment of reconfiguration processes in manufacturing systems), PhD dissertation, TUM, iwb.

[14] Nofen D (2006) Regelkreisbasierte Wandlungsprozesse der modularen Fabrik: (Translation: Control-loop-based transformation processes of the modular factory), PhD dissertation, Universität Hannover, IFA.

[15] Wulf S (2011) Bewertung des Einflusses von Produkt- und Technologieveränderungen auf die Fabrik: (Translation: Assessing the influence of product and technology changes on the factory), Dissertation, Universität Hannover, IFA.

[16] Klemke T (2014) Planung der systemischen Wandlungsfähigkeit von Fabriken: (Translation: Planning of the systemic transformability of factories), PhD dissertation, Universität Hannover, IFA.

[17] Pohl J (2013) Adaption von Produktionsstrukturen unter Berücksichtigung von Lebenszyklen: (Translation: Adaptation of manufacturing structures under consideration of life cycles), PhD dissertation, TUM, iwb.

[18] Karl F, Reinhart G (2015) Reconfigurations on manufacturing resources: identification of needs and planning. *Prod. Eng. Res. Devel.*:1–12.

[19] Richter L, Lübkemann J, Nyhuis P (2014) Development of a Model for the Redesign of Plant Structures. *International Journal of Social, Education, Economics and Management Engineering* 8(11):3295–8.

[20] Aurich JC, Rößing M (2007) Engineering Change Impact Analysis in Production Using VR. in Cunha PF, Maropoulos PG, (Eds.). *Digital Enterprise Technology: Perspectives and Future Challenges*. Springer. New York, NY, pp. 75–82.

[21] Schady R (2008) Methode und Anwendungen einer wissensorientierten Fabrikmodellierung: (Translation: Method and application of knowledge-based factory modeling), PhD dissertation, Magdeburg, Otto-von-Guericke Universität Magdeburg.

[22] Malak RC, Yang X, Aurich JC (2011) Analysing and Planning of Engineering Changes in Manufacturing Systems. *Proceedings of 44th CIRP International Conference on Manufacturing Systems*.

[23] Malak RC, Aurich JC (2013) Software tool for planning and analyzing engineering changes in manufacturing systems. *Proceedings of the 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering*:348–53.

[24] Cohen T, Navathe SB, Fulton RE (2000) C-FAR, change favorable representation. *Computer-Aided Design* 32:321–38.

[25] Ollinger GA, Stahovich TF (2004) RedesignIT -- A Model-Based Tool for Managing Design Changes. *Journal of Mechanical Design* 126(2):208–16.

[26] Hamraz B, Clarkson PJ (2015) Industrial evaluation of FBS Linkage – a method to support engineering change management. *Journal of Engineering Design* 26(1-3):24–47.

[27] Hamraz B, Caldwell NHM, Clarkson PJ (2013) A Holistic Categorization Framework for Literature on Engineering Change Management. *Systems Engineering* 16:473–505.

[28] Hamraz B, Caldwell NHM, Wynn DC, Clarkson PJ (2013) Requirements-based development of an improved engineering change management method. *Journal of Engineering Design* 24(11):765–93.

[29] Lindemann U, Maurer M, Braun T (2009) *Structural Complexity Management: An Approach for the Field of Product Design*. Springer, Berlin.

[30] Keefer DL, Verdini WA (1993) Better Estimation of PERT Activity Time Parameters. *Management Science* 39(9):1086–91.

[31] Ropohl G (1999) *Allgemeine Technologie: Eine Systemtheorie der Technik*. (Translation: General technology - A system theory of technology). 2nd ed. Hanser, Munich, Vienna.

[32] Gruber TR (1993) A Translation Approach to Portable Ontology Specifications. *Knowledge Acquisition* 5(2):199–220.

[33] Noy NF, McGuinness DL (2001) *Ontology Development 101: A guide to creating your first ontology*.

[34] Paige RF, Kolovos DS, Polack FAC (2014) A tutorial on metamodelling for grammar researchers. *Science of Computer Programming* 96(1):396–416.

[35] Henderson-Sellers B, Gonzalez-Perez C (2010) Granularity in Conceptual Modelling: Application to Metamodels. in Parsons J, Saeki M, Shoval P, Woo C, Wand Y, (Eds.). *Conceptual Modeling - ER 2010*. Springer. Berlin Heidelberg, pp. 219–232.

[36] Kosko B (1986) Fuzzy cognitive maps. *Int. J. of Man-Machine Studies* 24:65–75.

[37] Bartolomei JE (2007) Qualitative Knowledge Construction for Engineering Systems: Extending the Design Structure Matrix Methodology in Scope and Procedure, PhD dissertation, MIT, ESD.

[38] Bartolomei JE, Hastings DE, de Neufville R, Rhodes DH (2012) Engineering Systems Multiple-Domain Matrix: An Organizing Framework for Modeling Large-Scale Complex Systems. *Systems Engineering* 15:41–61.

[39] Ayyub BM (2001) *Elicitation of Expert Opinions for Uncertainty and Risks*. CRC Press, London, New York.

[40] Ford DN, Sterman JD (1998) Expert knowledge elicitation to improve formal and mental models. *System Dynamics Review* 14(4):309–40.

[41] Norman DA (1983) Some Observations on Mental Models. in Gentner D, Stevens AL, (Eds.). *Mental Models*. Taylor & Francis Group. New York, NY, pp. 7–14.

[42] Richardson GP, Pugh A (1981) *Introduction of System Dynamics Modeling with DYNAMO*. MIT Press, Cambridge, MA.

[43] Vennix JAM, Gubbels JW, Post D, Poppen HJ (1990) A structured approach to knowledge elicitation in conceptual model building. *System Dynamics Review* 6(2):194–208.

[44] Meyer MA, Booker JM (2001) *Eliciting and Analyzing Expert Judgment: A Practical Guide*. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA.

[45] Tversky A, Kahneman D (1974) Judgment under Uncertainty: Heuristics and Biases. *Science* 185(4157):1124–31.

[46] Malcolm DG, Roseboom JH, Clark CE, Fazar W (1959) Application of a Technique for Research and Development Program Evaluation. *Operations Research* 7(5):646–69.

[47] Davis R (2008) Teaching Project Simulation in Excel Using PERT-Beta Distributions. *INFORMS Transactions on Education* 8(3):139–48.

[48] Moore EF (1959) The shortest path through a maze. *Proceedings of the International Symposium on Theory of Switching (Part II)*. Harvard University Press. Cambridge, MA, pp. 285–292.

[49] Helms B (2013) Object-Oriented Graph Grammars for Computational Design Synthesis, Dissertation, TUM.

[50] Goos G. *GrGen.NET: transformations of structures made easy*. http://www.info.uni-karlsruhe.de/software/grgen/ (accessed on Dec 2015).