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Estimating the effects of Engineering Changes in early stage product development

Lucia Becerril[1], Michael Sauer[2], Udo Lindemann[1]

[1]Chair of Product Development, Technical University of Munich
[2]Motius GmbH

Abstract: Constantly changing requirements pose a major challenge for industry, especially in the early phases of product development where there is little information available. One of the main reasons for that are the effects of change propagation. Several tools and methods address how Engineering Changes affect further product components, however how these changes affect the project cost and time has not been sufficiently addressed so far. We propose a method that aims to estimate the additional effort and impact on project time of implementing a change, providing an additional decision support whether or at what cost to implement a requirement or an engineering change.

Keywords: Engineering Change Management, Change Prediction, Project Modelling

1 Introduction

Mechatronic products are constantly affected by change to improve functionality, adapt to customer needs and regulatory standards and remove mistakes. The importance of Engineering Changes (ECs) has even increased over the last years due to the need for product individualization, shorter development cycles and carry-over parts (Hamraz, 2013).

Often these ECs may have negative consequences such as higher costs and deadline overruns (Hamraz, 2013). In order to retain market competitiveness, the importance of a company’s ability to handle ECs properly increased even further (Nichols, 1990).

Although literature covers a wide field of different research on ECs including case studies and methods supporting the Engineering Change Management (ECM) process, it still poses a major challenge for industry. One of the main reasons for that are the effects of change propagation. A change initiated to one element of a system can result in changes of other elements of the system by propagating through connections between them. These knock-on effects are often difficult to estimate and even the whole system can be affected (Hamraz, 2013).

In fast paced environments, such as our industry partner situation, the decision whether to implement a change has to be made quickly. How well informed these decisions are can be a decisive factor for the project.

There are a number of tools and methods, such as the ones proposed by Clarkson et al. (2004) or Grantham-Lough et al. (2006), to support decisions in the EC process. Promising methods in the area of change prediction help to understand how initial changes spread through a system affecting other parts and systems. However, how these changes affect the project has not been sufficiently addressed so far.

In highly dynamic contexts, the classical approaches of process modelling and analysis often reach their limits, since the depicted elements and relations are usually assumed to be static (Kasperek et al. 2014). Thus, the impact of changes is hard to predict (Kasperek et al. 2014). System Dynamics is a method to model and simulate the dynamics of systems that enables to analyze the dynamic behavior of a system – in this case the development project.

In this paper we enhance existing methods for change management decision support with elements of modelling the dynamics of projects. The approach proposed supports the estimation of the effect of changes on the project in early stage product development. The aim is to provide support for decisions under high time pressure and few information and expertise in regard of the assessment of engineering changes, especially changes triggered by stakeholders, e.g. the customers.

2 Background

In this section, two main topics are addressed. Firstly, an introduction to the possible impacts of engineering changes on projects is provided, as well as an overview on current tools and methods for assessing these effects. Then, an existing approach on simulating projects is introduced, which is discussed later in section 5.

2.1 Engineering Change Management

A broad variety of definitions of "Engineering Change" exist, however in this paper we use the definition proposed by Hamraz et al. (2013, p. 475), where Engineering Changes *"are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials etc.), behavior (stability, strength, corrosion etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behavior (design principles), or behavior and structure (physical laws) of a technical artefact."* In this definition an artefact is a representative term, which may refer to a component, a system or a whole product. Engineering Change Management (ECM) is the organizing, controlling and execution of the process of Engineering Changes (Jarratt et al., 2010).

While several ECM processes have been proposed by different authors, the process by Jarratt et al. (2004) is shown in Figure 1.

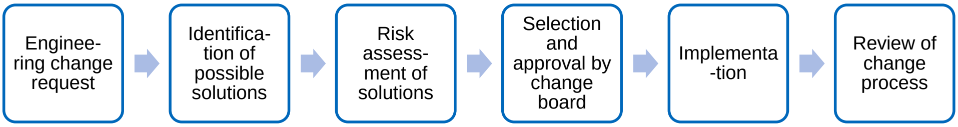


Figure 1: Engineering Change Management process, adapted from Jarrat et al. (2004)

The effects of implementing a change have been covered broadly in literature by several authors. According to Nichols (1990), ECs impact all determinants of competitive advantage of products, namely cost, quality and time-to-market. Costs and be further split down. Hamraz (2013) divides the costs resulting from ECs into direct costs and indirect costs. Direct costs include for example costs for (1) design, (2) changes in prototype tools and (3) changes in production tools (Terwiesch and Loch, 1999). Indirect costs include fines, loss of profit due to delays and costs related to damage to a company's reputation. Additionally, change propagation influences all processes throughout the value chain of a product, the number of changes and their outcomes highly influence the magnitude of time delays and project overruns (Hamraz, 2013).

Furthermore, in most cases, a change does not only affect the initial component or part, but propagates through the system. It is similar to a chain reaction, when one change causes another change, which then causes further changes. Therefore a change can spread to other parts or components of the product and even to other products (due to common platforms, processes and businesses). Terwiesch and Loch (1999) identified three key couplings that may lead to propagation: (1) Between components and manufacturing, (2) Between the components within the same subsystem and (3) Between components in different subsystems.

In order to cope with ECs, many supporting tools and methods have been developed. Jarratt et al. (2010) divide these models into two groups: those that help manage the process (documentation or work flow) and those that support engineers in making decisions during the engineering change process. The focus of this paper relays on the second group of tools and methods, which is introduced in this subsection.

According to Ahmad et al. (2011) models that support decision making through estimating the effects of changes can be differentiated between single-domain methods and cross-domain methods. Single-domain methods focus on mainly on a single product domain (e.g. components) while cross-domain methods aim on multiple domains (e.g. functions and components) and also include change propagation between domains. The method presented in this paper belongs to the cross-domain ones.

Moreover, following two methods are the base of the method described in section 4.

The Change Prediction Method by Clarkson et al. (2004), which is a single-domain method, illustrates the overall risk of changes propagating through a system, if one component is changed. The main structure of the model is the DSM, where products are modelled as linked components. These linked components are associated with a risk term, which is the product of the likelihood of the change occurring and the impact of the change. This matrix is then used to analyze new product requirements to decide on redesign plans.

Using the Information Structure Framework (ISF), Ahmad et al. (2010) add to the component layer of the CPM the further domains requirements, functions and the detailed design process. A change in requirements leads to certain changes in functions, which leads to changes of those components that are supposed to implement the respective functions. Within the components layer, a change of one component can propagate to other components, which is considered by using the CPM approach. Changes in components finally lead to changes of the detailed design process and their respective design parameters. Main downside of this model is the applicability only for stable product architectures and design processes.

2.2 Simulating project dynamics

System Dynamics is a mathematical modeling technique for framing and understanding complex issues and problems (Kasperek and Maurer 2013). Over the last 20 years, these models have been used on management of projects, including planning the determining measurement and reward systems, evaluating risks, and learning from past projects (Lyneis and Cooper 2001). One of the main elements of modelling projects is the rework cycle. A rework cycle can represent a project, a phase or a task that can be divided in further activities. Many variants of this structure exist, the one used in this paper is described below.

Here, all activities are stored in the “Work to be done” stock at the beginning of the project. Depending on the people available and their productivity, these activities flow into the “Work really done” stock. However, errors occur depending on the quality of the work. These activities do not flow into the work done but instead into the stock “Undiscovered rework”. When these errors are discovered – which can be hours, days or even years later – the work becomes “Known rework”. This “rework” gets eventually done. (Lyneis and Cooper 2001)

3 Methodology

The research approach of this work follows the Design Research Methodology (DRM) introduced by Blessing and Chakrabarti (2009), which comprises following four main stages: Research clarification, Descriptive study I (DS I), Prescriptive study (PS), Descriptive study II (DS II).

First, an overview of the current situation was obtained by a literature survey and the observation of development projects at the industry partner (DSI). Then requirements of early stage development were acquired and both from industry partner and literature sources. These requirements (not in this paper) were used to assess current ECM methods and choose the most promising method. In the Prescriptive Study, the most promising methods – the CPM by Clarkson et al. (2004) and the Information Structure Framework (ISF) by Ahmad et al. (2010) – were then extended and enhanced by the dynamic simulation approach based on Kasperek et al. (2014) and implemented as a software prototype. An initial evaluation of the proposed method was then carried out within the DS II stage (c.f. section 4.4).

4 Method for estimating the impact of engineering changes

As illustrated in Figure 1, the ECM process comprises six steps: The method for estimating the impact of engineering changes supports mainly step three, which consists of assessing each solution to the Engineering Change Request in regard of the risk of implementing it, including factors such as impact on design and production schedules.

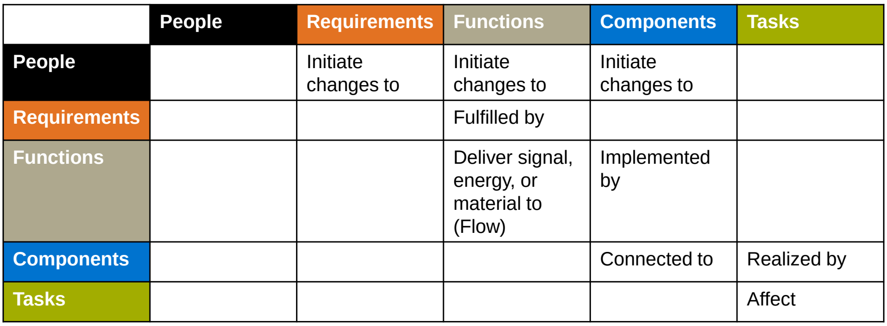
As shown in section 2.1 several tools and methods exist that support the decision-making within engineering change management. However, existing methods are not well suitable to early stage product development. Most ECM methods are designed for changes on already existing products. These changes for example cover improvements, error removal and individualization of existing products. Nevertheless, in the early stages of the development process, when a product is developed from scratch, new challenges occur. Thus, a suitable decision making support has to fulfil requirements that address following challenges:

- **No complete product model:** Projects in early stage developments mostly start with no or little knowledge about the product to be implemented. Therefore, only a basic product model exists at the beginning. Consequently, it is important that the underlying product model is easy to extend during the project.

- **High amount of changes:** The uncertain environment of early stage development results in many changes.
- **Changes often arise from stakeholders**: To steer the product development in the right direction, stakeholders are closely integrated in the development process.
- **Customers with no technical background**: A suitable method needs to deliver easy understandable output and serve as a communication platform

Additionally, further challenges derive from the situation of the industry partner, which was founded only few years ago and where the majority of the workforce consists in students, PhD candidates and young engineers. Thus, easy usage of a suitable method is important. Moreover, no or only little existing information can be reused for building the product model.

In order address these challenges, new domains are added to the existing domain "components" of the CPM building on the Information Structure Framework (ISF) (Ahmad et al. 2010). These new domains include people for stakeholder centricity, tasks to establish an interface with project management, and requirements and functions to improve product understanding and communication. The domains and their relationships among the domains described are illustrated in the MDM in Figure 2.



	People	**Requirements**	**Functions**	**Components**	**Tasks**
People		Initiate changes to	Initiate changes to	Initiate changes to	
Requirements			Fulfilled by		
Functions			Deliver signal, energy, or material to (Flow)	Implemented by	
Components				Connected to	Realized by
Tasks					Affect

Figure 2: MDM as an overview of the supported domains and their relationships

The methodology proposed in this paper comprises four stages as shown in Figure 3. In the first stage the necessary information about the system to develop and the planed tasks is acquired. The second stage uses existing CPM algorithms to compute the risk of change propagation within the system. Then, the dynamic model is built based on the information acquired and generated in stages 1 and 2. Finally, the system dynamics model is simulated and the results are used in the decision making regarding the analyzed change or changes.

Figure 3: Four stages of the estimation of changes' effects during the early phases

The following sections (4.1 – 4.4) provide a detailed description and an exemplary application of each of the stages, as well as their application with the corresponding software tools.

4.1 Information acquisition

The first step is to acquire the information about the system to develop and the project plan that is necessary to build the models in stages 2 and 3. For this purpose a MDM containing the relationships among the system's elements (requirements, functions, components and tasks) and its corresponding graph is developed. Figure 4 illustrate an example of a subsystem that fulfills exactly one requirement. This subsystem was chosen as an example due to its low complexity in order to exemplify the methodology.

Firstly, the relationships among the system elements are documented with information from product models and drawings. Figure 4 depicts the sub-systems' architecture and the corresponding tasks in form of a graph.

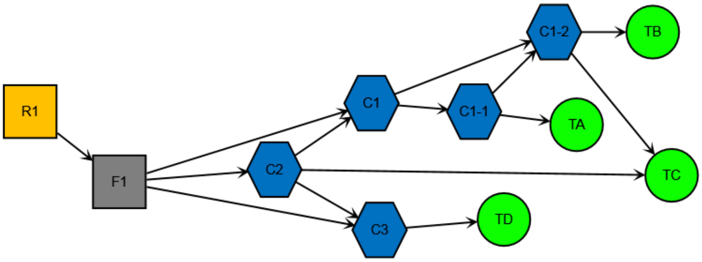


Figure 4: Relationships among requirement (R), function (F), components (C), and tasks (T)

Afterwards, the likelihood and impact values of changes are quantified trough deeper information search and expert interviews, similarly as in Clarkson et al. (2004). Moreover, for easy and quick model building, only the values 0, 0.3, 0.5, 0.7 and 1 are used for evaluating the likelihood and the impact of a change propagation. Although that limits the level of detail, it is sufficient for the purpose of this method. As described in section 2.1, risk is defined as "likelihood x impact". Here, the project structure (i.e. the Tasks DSM) is not included since this information flows directly into the project modelling (Stage 3).

4.2 Change propagation computing

When an engineering change is triggered by a stakeholder at a requirement, function or component level the risk of propagation is calculated up to the risk of changes on tasks.

Two cases are distinguished, Engineering Changes can trigger a new task or cause rework in an existing task. In this paper we focus on the second case, where Engineering Changes cause rework within an existing task. In order to calculate the combined risk, the CPM algorithms (c.f. Clarkson et al. 2004) are applied to the Risk-MDM (Figure 5). For an easier application, these algorithms were implemented in the graph processing software *Soley*.

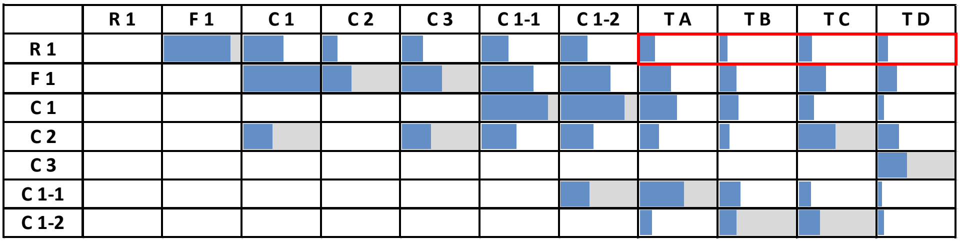


Figure 5: Computed risks of change propagation, with especial interest on propagation of requirement changes into the tasks (framed red)

In this case, the computed risks of change propagation from the requirement R1 into the tasks A through D (red in Figure 5) are especially interesting, since they represent the total risk for a change in the requirement affecting these tasks. Thus, based on these values we can estimate how much more effort (in average) would it be required to fulfill a change in R1. These calculated risk values are then transferred to the systems dynamics model. This approach is described in detail in the next sections (4.3 and 4.4).

4.3 Model building

The system dynamics model represents the project's dynamics as a series of interconnected tasks. Each task is modelled as a rework cycle, which is the basis of many dynamic models of projects (Lyneis and Cooper 2001). The tasks' dependencies that are derived from the project plan define how the "Work done" in one task influence the "progress rate" in the downstream task. Similarly as in (Kasperek 2014), the system dynamics model is developed based on the project structure documented in a DSM. The rework cycle for Task A and Task B are depicted in Figure 6.

In the next step, the changes that are caused by changes in other tasks are modelled (orange in Figure 6). For this purpose, we suggest an additional flow of activities parallel to the "normal" work, so the additional effort due to the change can be traced. The modelled risk is also estimated based on the formula "likelihood x impact".

Moreover, the changes caused by the propagation of the requirements change through the system structure are modelled separately (Green in Figure 6). The risks computed in the second stage directly affect the "change rate" together with the variable "requirements change", which is the user input of the model, in this case a step function.

The change rate of a task is then calculated through the combination of changes that propagate through the systems' architecture and the changes triggered by changes in an upstream task. Following formula provides a detailed example:

$$\text{Change rate B} = \text{Changes A} * \text{Risk BA} + \text{Changes R1} * \text{Risk R1A}$$

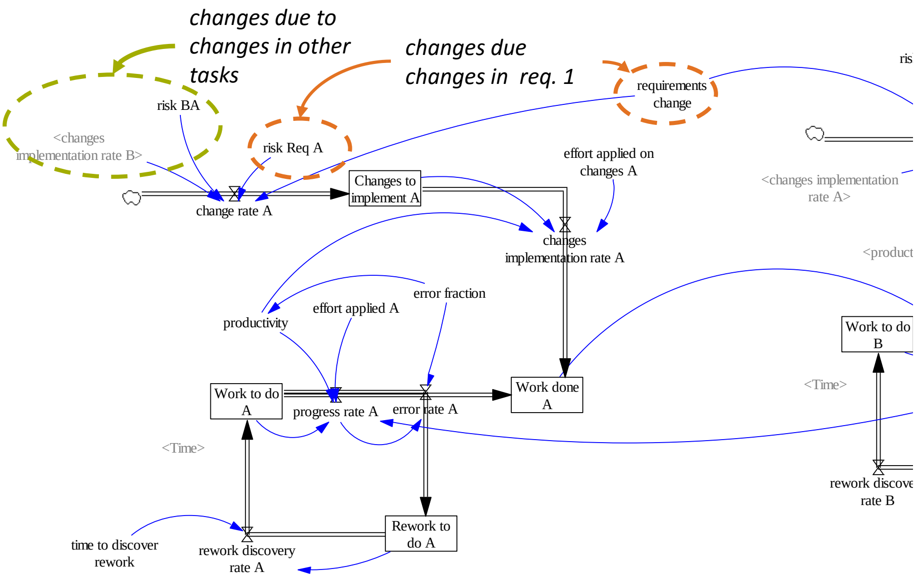


Figure 6: simplified System Dynamics Model (Task A)

4.4 Dynamic simulation

The last stage comprises the dynamic simulation of the model build in stage 3. Figure 8 shows the progress and the effort curves for all four tasks with (red/grey) and without changes (blue/green). With help of these curves, the additional effort to implement the requested requirement change can be visualized and estimated.

4.5 Evaluation

The approach developed is only beneficial as a supporting tool if it provides reliable data and information. A user should be able to identify critical elements and the effects of a change. Moreover, the accuracy of change prediction is difficult to assess and there is no right and wrong, as illustrated by Ahmad et al. (2012). Thus, the first two stages[1] of the approach were evaluated in regard of:

- The identification of critical elements: Users can identify critical elements with a high likelihood of change and is supposed to be used in the overall project planning and sprint planning.
- Identification of the effects of a change: Users can identify the elements with a high effort of implementing a certain change. This information is enhanced by the results in stage four.

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[1] The evaluation of stages three and four will take place in future research.

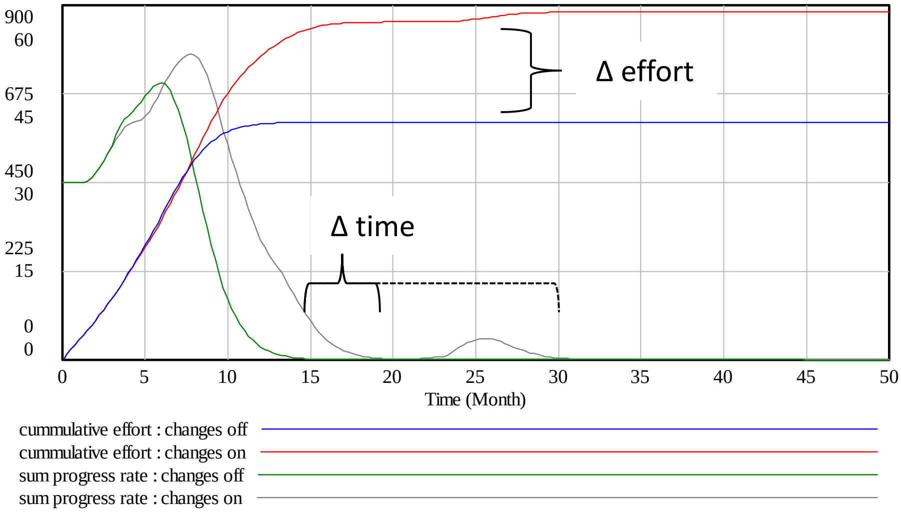

Figure 7: Simulated progress rate and cumulative effort

Two participants took part in the evaluation. Both of them had a technical background however no previous knowledge of the product nor the method. First, the participants had to identify critical elements that have a high change likelihood. Secondly, three different initiating change elements were given and the participants had to identify elements with high risk and assign them valued for the expected effort the effort. These valued were between 1 (little effort) and 6 (high effort). The time the participants needed for each task – alternating between with and without the support presented in this paper – was measured and the outcome of each task was documented.

The evaluation shows that the participant with the support was able to conduct both tasks quicker for each change and mostly performs better. Nevertheless, it has to be considered that both participants had problems with estimating the effort of implementing a change. Future evaluations should test if the system dynamics model provide a richer support for this task.

5 Conclusion and outlook

This paper presents a decision making support method for assessing the effects of engineering changes on the project's costs and time. Overall research goal namely an improved CP for early stage development was achieved. However some limitations emerged, firstly the quality of the estimation depends highly on the quality of the product model. Another important limitation is that the results depend on the initial estimations of impact and likelihood. Further research could provide additional support to form a base for these estimations.

On the other hand, thanks to the implementation of the CPM in *Soley*, the underlying DSM is not static anymore. Thus this system model organically together with the information generation process during the early phases of development; fulfilling the one of the main requirements.

Moreover, the method proposed enables an interactive assessment with the stakeholders in the ECM process. The results from stages 2 and 4 deliver visual communication documents to engage with the costumers. Finally, the dynamic simulation gives a valuable support to estimate the efforts that derivate from changing requirements.

Future work would include a comprehensive evaluation in more industrial case studies and the development of an interface between the *Soley* model and the system dynamics simulation.

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Contact: Lucia Becerril, Technical University of Munich (TUM), Institute of Product Development, Boltzmannstraße 15, 85748, Garching, Germany, +49 89 289 15124, becerril@pe.mw.tum.de

About the Authors:

Lucia Becerril, Technical University of Munich – Lucia Becerril is a PhD candidate at the Chair of Product Development at the TUM. Her current research focuses on Engineering Change Management and mechatronic product development processes. She has a master's degree in mechanical engineering and has gathered experience in research, industry and consulting in USA, Mexico and Germany.

Michael Sauer, Motius GmbH (e-mail) **–** Michael Sauer is master's student at the Technical University of Munich and Business Development Director of Motius GmbH, a Munich-based R&D Company.

Professor Udo Lindemann, Technical University of Munich - Professor Lindemann is the head of the Chair of Product Development at the TUM. His research area is systematic product development. This encompasses broad areas of systems engineering as well as various interfaces to other disciplines. He received his doctorate at TUM and assumed the Chair of Product Development after more than 15 years of experience in industry.