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WHEN TO CHECK FOR DEVIATIONS IN THE DESIGN PROCESS – AN APPROACH TO DETERMINE A SYSTEMATIC CHECKPOINT SCHEDULE

Martina Carolina WICKEL, Florian BEHNCKE, Lindemann UDO
Technical University of Munich, Germany

ABSTRACT

Changes in engineering design are a necessary and inevitable part of the design process, be it to improve products or to cope with occurring problems. Changes, however, are often connected with high effort which furthermore grows exponentially the later in the design process those changes ocurr. Therefore strategies for identifying the need for changes in the early phases of the product development have been established. These activities themselves imply high effort, though, and are many times not efficient due to unavailable or inaccurate data in the early stages.

This leads to the conclusion that an optimal point of time can be determined within the design process in terms of the ratio of cost for changes vs. effort for change identification. In this paper an approach is presented, that supports the determination of optimal checkpoints to detect deviations from the planned development progress. Relevant aspects that have to be taken into account to determine the optimal time were deduced as a theoretical foundation.

Keywords: engineering change, product development, change management, engineering change management

Contact:
Martina Carolina Wickel
Technical University of Munich
Products Development
Garching
85748
Germany
wickel@pe.mw.tum.de

1 INTRODUCTION

1.1 Motivation

Changes have always been a necessary part of engineering design because they are used to improve and adapt products or reach a defined status of the product, which has not been met because of a problem (Eckert et al., 2004). In the literature, there are different definitions of engineering change (EC). The main differences are related to the object of modification and the release status in which the object has to be. Objects of modifications can be merely components of a product (Wright, 1997), products and components (Huang and Mak, 1999) or parts, drawings and software (Terwiesch and Loch, 1999). Regarding the release status of the objects of modifications, the literature differentiates between "released" without any further details [(Huang and Mak, 1999), (Terwiesch and Loch, 1999)] and the condition that the product is already in production when the EC occurs (Wright, 1997). This paper will use the definition of Terwiesch and Loch (1999) because of its less restrictive understanding of objects and focus on the release status of ECs in product development.

Changes have a different and strong impact on costs. Changes arising in the late phases of the product design process are often accompanied by high costs (Conrat Niemerg, 1997) and development project delays and therefore by high risks. The "rule of ten" indicates the relation between the phase of the design process in which an EC is implemented and the cost impact regarding an EC. According to the "rule of ten", the cost impact for the EC increases approximately by a factor of ten with every phase of the design process.

New product development (NPD) projects, in particular - which differ strongly from previous projects regarding products and processes - are difficult to plan for companies and lead to many changes in the late phases of development. Five strategies are suggested for coping with the situation of late changes among front-loading (Fricke et al., 2000). Within the front-loading strategy, the point of EC is transferred to an earlier one in order to have a lower general impact and lower costs for the ECs (as explained above). This means that the need for an EC has to be identified earlier in the design process and thus the deviation between a nominal and an actual state. According to Herberg et al. (2010), the deviation conforms to a trigger of changes and can be subdivided into different types. Figure 1 depicts two exemplary types of deviation: a "non-achieved nominal state" (left side), in which the actual state does not match the pursued nominal state, and a "changed nominal state" (right side), which indicates that a nominal state is perfectly matched by the actual state, but the nominal state changed during process execution.

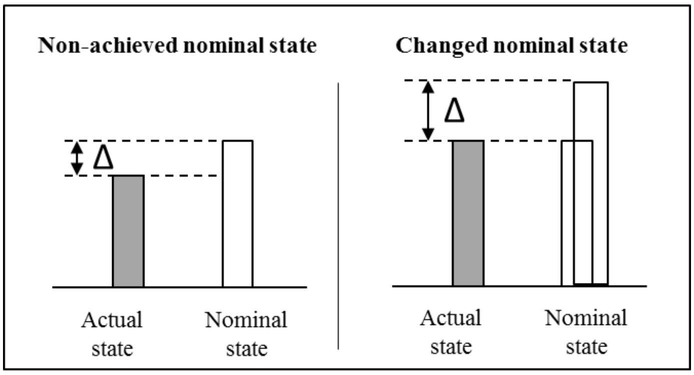

Figure 1: Two types of deviations between actual and nominal state: Non-achieved nominal state and changed nominal state (Herberg et al., 2010)

Front-loading involves not only benefits but additional work and expenses for companies. For example, employee capacity is bound to identify the need for ECs in an earlier phase in the design process, which could otherwise be used within the design process and contribute to development. Also, data has to be collected and consolidated. Furthermore, the coordination of the activities for detecting deviations requires more effort for project coordination. Apart from that, not every activity for identifying deviations between nominal and actual state is possible during every phase or point in the design process. Also, the effort for finding the deviation can differ within the design phases.

In the early phases of the design process only fuzzy data is generally available, which can be applied for detecting deviations. For this reason, it is difficult to get clear statements if, for example, a nominal state has been reached or not. In the course of the design process, data become less fuzzy. The assumption for using the front-loading strategy is that, in sum, less effort is needed. But an analysis of cycles in development processes revealed that an optimized scheduling of checking deviation leads to higher overall process efficiency (Langer et al., 2011).
Thus, this paper presents a more differentiated approach to support the selection of the right methods so deviations can be identified at the right time in order to have an efficient change management.

1.2 Research questions

The following research questions arose with regard to the challenges within the field of research:

- Which activities can be done within the design process to check if the actual state reaches the planned nominal state in order to have an effective change management?
- When is the most appropriate time for companies to engage in deviation-detecting activities under the aspect of efficiency?

Two more questions result from this and they must be taken into account to answer the two main questions:

- Which aspects and data have to be considered so these research questions can be answered?
- Which aspects determine the sequence of activities to detect deviations?

In this context, efficiency and effectiveness mean: Doing the **right activities** for detecting deviations (effectiveness) and doing them **at the right time** within the design process (efficiency). The research questions lead to an approach that supports the selection and scheduling of the right activities for checking deviations under the condition of efficiency and effectiveness in the design process.

1.3 Research background

The development of complex products is characterized and influenced by a number of cycles can be both internal (i.e. occurring within the company) and external. The Collaborative Research Centre (SFB 768) – 'Managing cycles in innovation processes – Integrated development of product-service systems based on technical products' focuses on these cycles, which are reoccurring patterns (temporal and structural) and are classified by phases. Due to their reoccurrence, engineering changes occur specifically in development cycles, which are focused within the SFB 768 by a subproject on the cycle-oriented planning and coordination of development processes. For cycle planning and coordination, cycle triggers play an essential role within the development process. Triggers are deviations that arise during the development process; their detection can be planned.

2 METHODOLOGY

Based on a literature review and a discussion within the "Workgroup: Engineering Change Management", the initial need for an approach arose to support the scheduling of activities for detecting deviations within the development process and achieve more efficient change management. The "Workgroup: Engineering Change Management" was founded in 2012 by the Institute for Product Development at the Technical University of Munich and meets three times a year. Generally, five to ten change, project or process managers of different companies attend the workgroup meetings and discuss current challenges within ECM.
The methodology used in this paper follows the design research methodology according to Blessing and Chakrabarti (2009). This work focuses on the Research Clarification (RC) and an initial Descriptive Study I (DS-I). The article first clarified and defined the research aim. Therefore, literature was reviewed and approaches to the scope of the research field were analyzed. Then the research questions were formulated. Afterwards, an approach was established in order to answer the research questions. The last step of this paper was a theoretical evaluation to check whether the aims were achieved, followed by steps to evaluate the case for possible use.

3 LITERATURE REVIEW

3.1 Methods for identifying deviations of product and process properties within design processes

The literature describes various methods for measuring the actual state of parts, drawings as well as software and process properties. Together with the nominal state, these methods can be used for identifying deviations during the design process. An initial literature review of these methods was restricted to standard literature and established books in the field of product development methods (Albers and Nowicki, 2003; Ehrlenspiel, 2007; Ehrlenspiel et al., 2007; Kipfmüller, 2009; Lindemann, 2009; Pahl et al., 2007; Ponn and Lindemann, 2008; Schwankl, 2002; Spur and Krause, 1997). The literature review is intended to give an insight into this field of literature. Figure 2 depicts the results of the literature review presented within a DMM (Domain Mapping Matrix). Methods are listed in rows and literature in columns. The “x” in the cells indicates which method was found in which literature.

	Lindemann, 2009	Schwankl, 2002	Albers and Nowicki, 2003	Ehrlenspiel, 2007	Spur and Krause, 1997	Kipfmüller, 2009	Pahl et al., 2007	Ponn and Lindemann, 2008	Ehrlenspiel et al., 2007
Discussion / consideration		x		x					x
FMEA	x	x		x	x		x	x	x
Fault-tree analysis	x			x			x	x	
Risk and damage analysis	x			x				x	
Failure analysis				x					
Estimation with comparison	x	x						x	
Comparison	x								
Comparison in pairs	x								
Advantage-disadvantage-comparison	x								
Dimensioning- / rough Calculation	x	x		x	x				x
Recalculation	x	x		x				x	x
Optimazition				x	x				x
Multibody simulation						x			
FEM	x	x	x	x	x	x			
BEM					x				
Numeric simulation	x	x						x	x
Topology Optimization			x						
CAE, CAD					x				
Rapid Prototyping					x		x		x
Exploratory analysis with functional models									
Testing and testing with prototypes	x	x	x	x	x			x	
Hardware-in-the-Loop	x		x						
in-situ test	x	x							

Figure 2: Methods for detecting deviations within the design process

The literature review points out the variety of established methods available for detecting deviations. These methods are manifold and applicable to different phases of the design process. They are also different regarding the properties that can be measured. Therefore, further preparation and categorization is useful for selecting the right methods.

3.2 Effects of changes

The literature distinguishes between different kinds of changes and their effects. While Eckert et al. (2004) differentiate between initiated and emergent changes, Langer et al. (2012) refer to average and critical changes. For Eckert et al. (2004), changes as emergent when they arise during the design process due to problems. The initiated changes are more or less accepted and occur because of new requirements emerging from within the company or customers. Langer et al. (2012), in contrast, differentiates between average and critical changes. Critical are EC that endanger the start of production or the whole project whereas average changes are all non-critical (Langer et al., 2012).

Changes become necessary during the design process when an actual state does not achieve a planned nominal state. This can lead to rework, which according to (Wynn et al., 2007) is a form of iteration in the design process. The effect of a deviation depends mainly on the amount of rework needed. Eckert et al. (2004) depicts possible returns within the process to previous design stages in order to

compensate for the deviation. The more advanced the design process, the larger the return to a previous point in the project can be and the more cost-intensive changes can become. Also, the process becomes more critical and the product more integrated (Eckert et al., 2004). Changes which occur late in the design process often affect more people than changes which occur early in the process (Jarratt et al., 2010).
Prediction of change effects is very difficult due to indirect changes which can result from multi changes to be taken into account (Eckert et al., 2006). Eckert et al. (2006) mention also the probabilistic prediction of the effects of changes and the visualization of change propagation for supporting designers. For analyzing the risk, the likelihood of the change occurring is needed too. Clarkson et al. (2001) have established possibilities for predicting such risks (Clarkson et al., 2001).

4 AN APPROACH FOR SCHEDULING EFFICIENT CHECKPOINTS SO DEVIATIONS OF PRODUCT PROPERTIES CAN BE IDENTIFIED

Within this approach, the scheduling of checkpoints for identifying deviations should be supported. The approach addresses such deviations resulting from a non-achieved nominal state. Therefore, methods for detecting deviations have to be identified (see section 4.1).
Furthermore, these methods have to be scheduled within the design process. The approach assumes that there is an appropriate checkpoint date for particular deviations regarding benefit and effort. Comparatively speaking, the front-loading strategy generally indicates that deviation should be detected early in the design process while this approach says as early as beneficial. This paper discloses a way of how the optimal time for detecting changes can be found.

4.1 Methods for identifying deviations

This section describes a procedure supporting the selection of the most appropriate method for identifying deviations within the design process, especially with regard to an efficient one. Therefore, the developer should filter possible methods regarding the boundary conditions to select all relevant methods for his specific case. A second step evaluates the methods regarding the best cost to benefit ratio. The second step is also needed for scheduling the application of the methods.

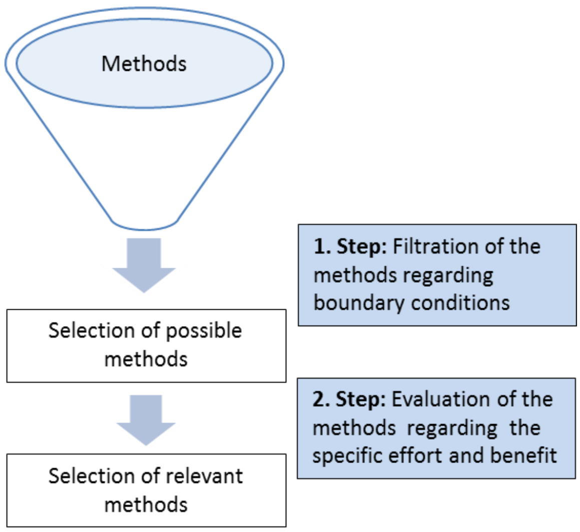

Figure 3. Procedure for selecting the relevant methods for identifying deviations

In preparation for the **first step**, the methods have to be analyzed and categorized. The aim of the categorizations is to reduce the number of possible methods. This will be helpful for selecting the right methods for a specific case. The following categorizations regarding the boundary conditions were addressed:

- Design process phase (this phase answers the question when the application of the method will be possible in the design process)
- Property of the product or process (the property answers the question of which actual state can be measured)

A **second step** evaluates the methods that should take place regarding the benefit and effort of the methods. Therefore, the information about expected effort and benefit has to be determined for every method.

4.1.1 Categorization of methods

According to the literature, the methods were related to **phases in the design** process. Figure 4 shows the DMM with the relation of methods to phases. The "x" once again indicates the correlation of methods within the rows to phases within the columns.

	Phases in the design process					
	concept	draft	detail	prototype	testing	production
Discussion / consideration	x	x	x	x	x	x
FMEA	x	x	x	x	x	x
Fault-tree analysis	x	x	x	x	x	x
Risk and damage analysis	x	x	x	x	x	x
Failure analysis	x	x				x
Estimation with comparison	x	x	x	x	x	x
Comparison	x	x	x	x	x	x
Comparison in pairs	x	x	x	x	x	x
Advantage-disadvantage-comparison	x	x	x	x	x	x
Dimensioning- / rough Calculation	x	x	x			x
Recalculation	x	x	x			x
Optimization	x	x	x			x
Multibody simulation	x	x	x	x	x	x
FEM (finite elements method)	x	x	x	x	x	x
BEM (boundary element method)	x	x	x	x	x	x
Numeric Simulation	x	x	x	x	x	
Topology Optimization	x	x				
CAE, CAD	x	x	x	x	x	x
Rapid Prototyping	x	x	x	x	x	x
Exploratory analysis with functional models	x	x	x	x	x	x
Testing and testing with prototypes	x	x	x	x	x	x
Hardware-in-the-Loop				x	x	
In-situ test					x	x

Figure 4. Methods and their relations to phases in the design process

Figure 4 was created with the aim to find applicable methods for a specific phase of the design process. The DMM depicts also the variety of methods which can be used in different phases in the design process. However, there is no hint on when the methods should be used in the design process to achieve the best result according to the necessary effort.

A subsequent step expands the categorization of methods to the properties, which can be measured with the method. This is a crucial factor for selecting the right method. The literature review identified ten categories of properties: Mechanics, materials, technical requirements, layout, function, production and assembly, application, man-machine interaction, environment and costs.

Figure 5 exemplarily depicts the properties and methods within a DMM. The categorization supports the finding of the right method and depicts the possibility that one method can be used for various properties.

The fact that one method can be used for measuring different properties also leads to the consideration that the overall effort can be reduced by using the same methods for different properties or during different phases within the design process. The assumption is that the effort for the first application of the methods could be higher than for following applications.

4.1.2 Evaluation of methods regarding effort and benefit

The literature contained no precise information about the effort necessary to implement the method. A reason might be that the effort depends strongly on the specific situation and is very difficult to predict in general. The same applies to the benefit of a method. For example, less effort is needed for a FEM (finite elements method) when there is already a complete CAD model available and the designer himself has the FEM software and the capability to execute the FEM. The benefit of the FEM depends also on the database available and on users' skills. To sum up, a method's information about effort and benefit depends on the specific situation and has to be taken into account to get an adequate statement. An approach could provide a rough prediction of effort and benefit in an ideal case but a company-specific adjustment must be made in any case.

	Mechanics							Technical requirements							
	Kinematic	Statics	Kinetics	Fluid flow	Eigenmode	Eigenfrequency	Vibration	Life-cycle	Abrasion	Availability	Corrosion	Stability	Thermal behavior	Quality, reliability	Energy, effort
Discussion / consideration	x	x	x	x				x	x						x
FMEA	x	x	x	x				x	x					x	x
Fault-tree analysis	x	x	x	x				x	x						x
Risk and damage analysis	x	x	x	x				x	x						x
Failure analysis	x	x	x	x				x	x						x
Recalculation	x	x	x	x			x	x	x			x	x		x
Optimization	x	x	x	x			x	x	x						x
Multibody simulation			x												
FEM (finite elements method)	x	x	x		x	x	x					x	x		x
Topology Optimization					x		x	x							

Figure 5. Exemplary categorization of methods regarding the artifact of measurement

4.2 Scheduling activities for identifying deviations

4.2.1 Aspects for scheduling activities for detecting deviations efficiently

This approach schedules activities with the aim of achieving an efficient process. That means that the goal is to find within the design process the checkpoints for detecting deviations which lead to an overall minimal effort. Therefore, the effort for detecting deviations and for compensating deviation (plus possibly the impact of the compensation on the product or process) is relevant. The efforts additionally depend on the point of execution and occurrence in design process and on the probability of occurrence (Clarkson et al., 2001). Furthermore, the accuracy of the expected effort plays a role for the evaluation of activities. Figure 6 gives an overview of the main aspects and an exemplary course over time:

As described by the "rule of ten", the effort for compensating failures (deviations) v_C increases strongly over time (see Figure 6, bottom). On the other hand, the effort for detecting deviations v_D decreases over time. This depends mainly on the availability of necessary data, which either already exists or which has to be established with additional effort. Because of the situation of the directly opposed courses, a point with minimal effort is supposed to exist. This point is not necessarily the first possible point when the method is applied. For example, the minimal total effort can be reached in Figure 6 after the method is applied for the first time.

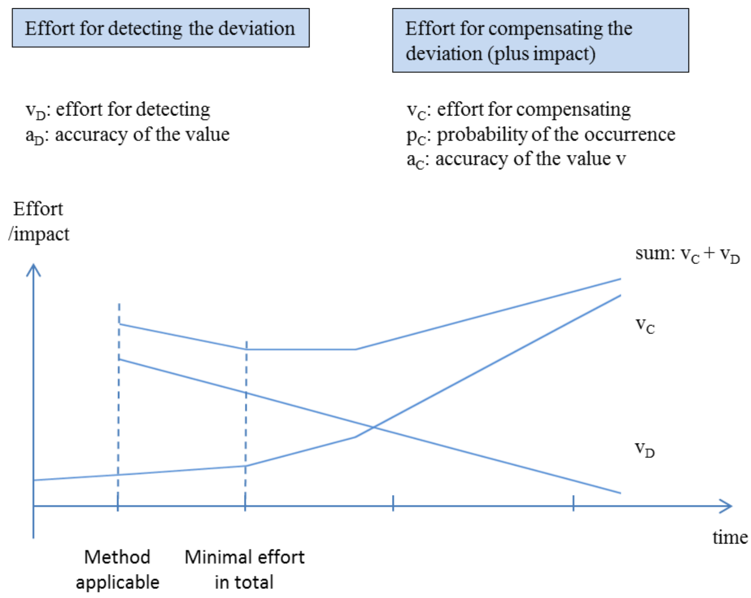

Figure 6. Exemplary course of effort for detecting and compensating deviations

4.2.2 Accomplishment of relevant aspects for scheduling deviations efficiently

In section 4.2.1, the main aspects for scheduling activities were collected and their interdependences explained. This section now describes how the information has to be accomplished regarding the main aspects and the available appropriate methods (see section 4.1). Scheduling of activities is again connected with effort, which leads to the consideration that it's not efficient to find the optimal point for every activity. Only the activities with a high effort-saving potential seem to be selected far better. The matrix in figure 7 supports the selection and depicts the relation between the effort for compensating and detecting deviations to three possible strategies:

- **Front-loading:** When high effort for compensating deviations is necessary and low effort for detecting the deviation. The activity for identifying deviations should be done as soon as possible.
- **Scheduling of activities:** When the effort for compensating and detecting of deviations is more or less on the same level, scheduling of activities can lead to a more efficient process.
- **No activity necessary:** When there is a high effort necessary for detecting deviations but only a low expected effort for compensating them, front-loading or scheduling the activities for identifying deviations is not beneficial.

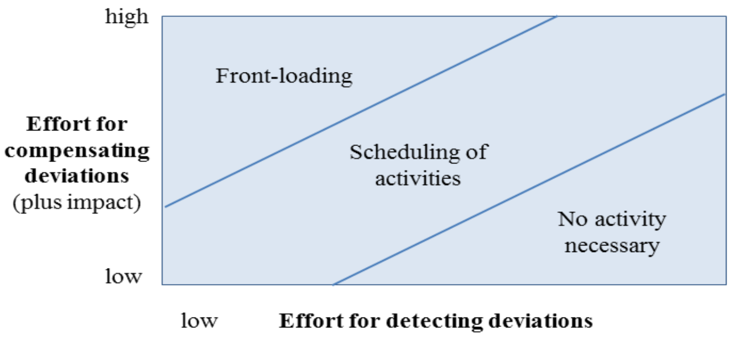

Figure 7. Three-strategy matrix

If several methods are appropriate for detecting deviations in the specific case, all of them have to be evaluated regarding the three-strategy matrix.

When the recommended strategy is scheduling of activities according to the categorization within the matrix, the efforts have to be calculated in detail. There are two main ways for identifying checkpoints with minimal effort:

- Calculation of the efforts (effort for detecting deviations and effort for compensating the deviation) for a range of possible checkpoints and selecting the point with minimal effort
- Establishing the charts for the efforts (efforts for detecting and compensating the deviation) and identifying the point with minimal effort within the chart

Thus, establishing the charts is supposed to be very complex because this approach entails the calculation of efforts for different checkpoints. The checkpoints should be selected to cover relevant points within the development process regarding the effort of changes. Examples for checkpoints are the "design freeze", the start of supply process of tools or prototypes or start of production. The effort for changes generally leads to a strong cost increase when detected after these checkpoints.

Table 2 displays the procedure of the calculation for different points within the design process.

Table 2. Calculation of total efforts

	Checkpoint t_1	Checkpoint t_2	Checkpoint t_3	Checkpoint t_4
Effort for detecting the deviation E_D	$E_D(t_1)$	$E_D(t_2)$	$E_D(t_3)$	$E_D(t_4)$
Effort for compensating the deviation E_C · probability p	$E_C(t_1)\cdot p$	$E_C(t_2)\cdot p$	$E_C(t_3)\cdot p$	$E_C(t_4)\cdot p$
Sum	$= E_D(t_1) + E_C(t_1)\cdot p$	$= E_D(t_2) + E_C(t_2)\cdot p$	$=E_D(t_3) + E_C(t_3)\cdot p$	$=E_D(t_4)+E_C(t_4)\cdot p$

The checkpoint with the lowest value can be selected for reaching the lowest effort regarding the activity.

5 CONCLUSION AND OUTLOOK

5.1 Conclusion

The motivation of this contribution arises from the challenge of managing engineering changes effectively and efficiently in the design process. The approach presented in this paper depicts a way of how the activities for identifying deviations could be scheduled under the aspect of high benefit-effort relation of activities. Aspects determining the most efficient point within the process were analyzed. The approach can be applied to predictable deviations with assessable consequences or effects. The approach closely follows project risk management but does not explicitly include unforeseen occurrences. Moreover, the intention is to find the right checkpoints for activities already planned within the design process to achieve more efficiency. Currently, the approach provides an overview of aspects which should be taken into account and a rough strategy of how to decide about the right point of time when deviations should be checked.

5.2 Outlook

The approach for scheduling checkpoints within a design process will be elaborated further in subsequent research and executed as well as evaluated within different use cases. Therefore, companies of the “Workgroup Engineering Change Management” will provide the necessary data. Then, the approach will also be evaluated regarding the applicability within an industrial environment and the benefit regarding its efficiency in engineering change management.

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