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A Retrospective Analysis of Engineering Change Orders to Identify Potential for Future Improvements

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Abstract
A serious part of development capacity in industry is needed for implementing Engineering Changes (EC) in order to improve or adapt products. Companies usually apply workflow-management systems to administrate and document these ECs. Within this paper typically available data which arise within Engineering Change Management (ECM) processes were established based on a real data base with approximately 53,000 Engineering Change Orders (ECO) and a literature review. Subsequently, strategies for coping with ECs were examined in detail in order to derive indicators. These indicators signal which EC strategy should be selected. Resultant patterns of EC data were established, which in retrospect indicate that a change could have been identified earlier in the design process (front-loading), could have been prevented, or could have been implemented more efficiently or more effectively. These patterns shall aid Engineering Change Managers to identify the right strategy and activities for coping with ECs.

Keywords: engineering change management, knowledge discovery in databases, learning

1 Introduction

Engineering changes (EC) have always been a necessary part of engineering design. They are used to improve and adapt products or to reach a defined status of the product that has not been met because of a problem [1]. But ECs also tie up 30–50 % and sometimes up to 70 % of the development capacity in industry [2, 3]. This shows the necessity to manage ECs with the purpose not to kill it with changes or to miss the chance of a successful product. Based on a case study, Fricke et al. [4] identified five strategies for coping with ECs: prevention, front-loading, effectiveness, efficiency and learning. However, EC Managers lack knowledge about mechanisms or patterns within the company to pursue the strategies effectively. For example, to perform ECs more efficiently, company specific mechanisms of those past ECs with a long lead time have to be known. Such mechanisms or patterns could be, for example, ECs which involve more than five departments and occur shortly after a Design Freeze that often have a very long lead time. These patterns do not normally exist within companies and so the chosen actions often do not lead to wanting of improvement of the ECM.

On the other hand, data and information in the form of, for example, Engineering Change Requests (ECR) or Engineering Change Orders (ECO) is stored when dealing with ECs in industry. The use of workflow-management-systems and the documentation requirement for

ECs even reinforce this trend. This data of previous ECs is often not considered within companies and is rarely applied for extracting knowledge[5, 6].

Within this paper, a large data set of past ECOs from a car manufacturer is analyzed. The aim is to identify previous ECs within the data base which could have been addressed by the five named strategies in order to analyze the EC data and to learn from them for an improvement of the ECM.

2 Methodology

This paper is based on Design Research Methodology (DRM) according to Blessing and Chakrabarti [7] and started with a Research Clarification (RC). The following main research question is a result of the RC phase:

How can available data of past ECs be used to determine that the strategies of effectiveness, efficiency, avoidance, front-loading or learning would have been beneficial for them?

Within this paper a dataset of approximately 53,000 previous ECOs generated within one company from 2005 till 2009 is used together with literature to build up the Descriptive Study I (DS I). In a three-step approach the Prescriptive Study (PS) is prepared. In the first step, it is examined which data of ECs is available according to literature, and which data is stored in the data base of a company. The result of this step is generally available in EC data. In a next step the ECM strategies are examined in detail and in different literature in order to find detailed explanations of which strategy should be applied in which EC case. Hence indicators for ECs are derived which point to the ECM strategies. The third step is based on the results of step one and two. Herein the bridge between EC data and ECM strategies is built by connecting EC data with the derived indicators for the ECM strategies: whether possible single attributes of an EC were related directly to indicators. Otherwise several attributes of EC data are combined or several attributes of EC data plus sequences and frequencies of the ECs are combined to relate them to indicators.

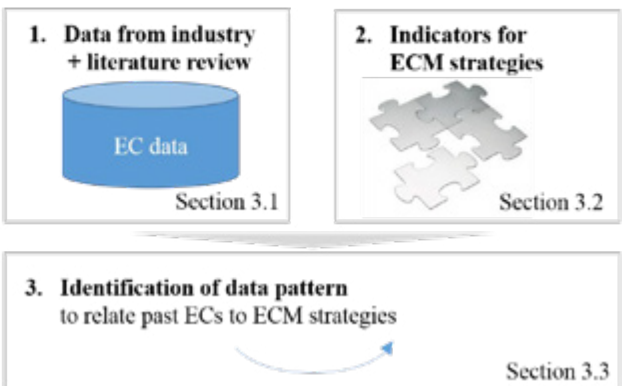

Figure 1 Structure of the paper and methodical procedure

3 ECM improvement by using EC data

ECs involve modifications of parts, drawings and software that have already been released and are part of every development process [8]. An ECM process is characterized as complex [8], extensive regarding administrative document management [9] and with high collaborative effort (due to cross functional and multi-disciplinary teamwork) [10]. Furthermore, a high product complexity can induce several downstream changes and additionally increase the process complexity Because of this, workflow management systems are commonly used in industry to support the handling and efficient processing of ECs. Workflow-based systems enable employees to issue and approve engineering change requests, track the change status and manage the related documents [11]. A formal ECM process normally consists of six phases [12]:

1. Engineering change order issued
2. Identification of possible solutions(s) to change order
3. Risk/impact assessment of solution(s)
4. Selection and approval of a solution by change board
5. Implementation of solution
6. Review of particular change process

Within the process phases much data is generated and stored, but this data is considered less for use in further improvements of the ECM [5, 6].

3.1 Data of Engineering Changes

The approach represented in this paper has the aim to improve the ECM by using the potential of previous EC data. The approach shall be explicitly based on typically available EC data, in order to use available data instead of generating new data with additional effort. Typically available EC data from literature was determined within a literature review for this. Since the use of previous EC data is considered less, there is a moderate amount of literature which describes EC data. The tracking of the existing data base of approximately 53,000 previous ECOs generated within one company, over a five year period is presented. The examination of EC data from literature and EC data from industry shows that there is no difference in the content of EC data. Therefore the data of the used case (see section 3.1.6) could be included as generally available EC data in this paper.

3.1.1 EC data according to Giffin et al. [13]

Giffin et al. [13] examined a large data set of change requests from industry in order to understand how and why changes propagate. They named the following data of ECs: ID number, date (created and last updated), status, stage originated, defect reason and severity of the EC, number of affected areas, change magnitude (categorization of the anticipated impact), associated change request, individuals involved (submitter, assignees, associated individuals).

3.1.2 EC data according to Sharafi [6]

Sharafi [6] modeled EC orders in a UML class diagram which contains classes, their relations and their attributes. Central class is the ECO, the involved activities, affected assemblies, parts and documents (with usage and affiliation to a development project) and process dates. Each class contains approximately ten to twenty attributes. The activities can be classified to inform, to check or to approve an ECO.

3.1.3 EC data according to Mehta [14]

Mehta [14] uses previous EC data in his systematic knowledge-based approach for determining whether a proposed EC effect has high expected cost impact. For this he identified a large number of possible EC attributes (in the magnitude of hundreds) for determining the relevance for his application. In Figure 2 the root EC attributes belonging to a change are depicted. The attributes characterize the change itself (id, type, priority, reason, and requesting department) and objects which are affected by the change (assemblies, parts and involved downstream processes).

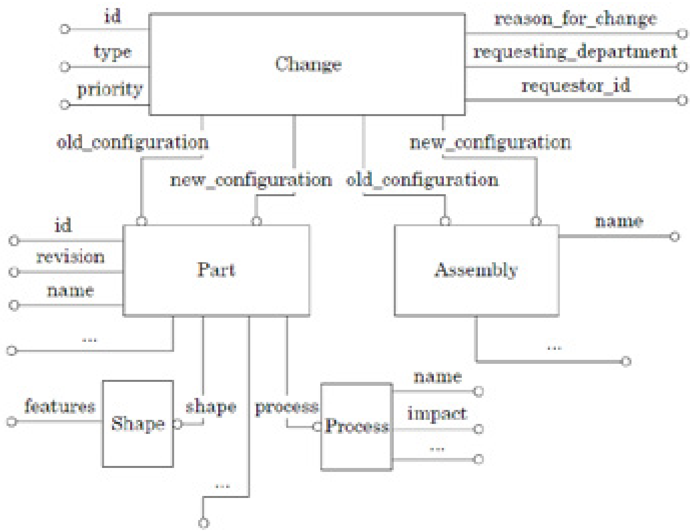

Figure 2 A data model to capture the attributes of ECs [14]

3.1.4 EC data according to Lindemann and Reichwald [3]

Lindemann and Reichwald [3] classified ECM data in order to analyze them in:

- EC master data (EC number and short description);
- Trigger of ECs (description of the deviation, classification of the EC trigger, i.e. change of requirements, department and activity within the need of an EC was detected, date);
- Cause of the EC (description, classification, responsible department, activity in which the failure occurred, phase within the design process, possibility to avoid the change);
- Effects of ECs (departments involved, activity which is needed, necessary time for the activity, further effort, i.e. material and tooling cost, and non-quantifiable effort);

Additionally they name the schedule and dates as relevant EC data.

3.1.5 Classification of knowledge in Knowledge Intensive Processes according to Eppler et al. [15]

Eppler et al. [15] classified the knowledge within Knowledge Intensive Processes. This classification can also be used for data and is introduced in order to be clearer in the large amount of EC data. Consequentially data is classified into:

- *Data about the process:* What are the phases of the process? What are the responsibilities? Which resources are necessary for the process (time and involved persons or departments)?
- *Data within the process:* What are the data inputs and outputs of the phases? What are possible decision points in the phases?
- *Data from the process:* Which processes were successful? Are there critical factors?

3.1.6 EC data of a use case

The existing data base analyzed in this paper consists of approximately 53,000 previous ECOs which were generated within a five year period. This data base was already applied by Elezi et al. [5] for extracting causes of iterations. For this they used only some fields of the ECO, especially text fields with a description of the EC by the change initiator. In contrast, within this paper the focus is set on structured data which arise during the ECM process or which describe the process. In Figure 3 the available structured EC data is depicted in relation to the phases of the ECM process of the company.

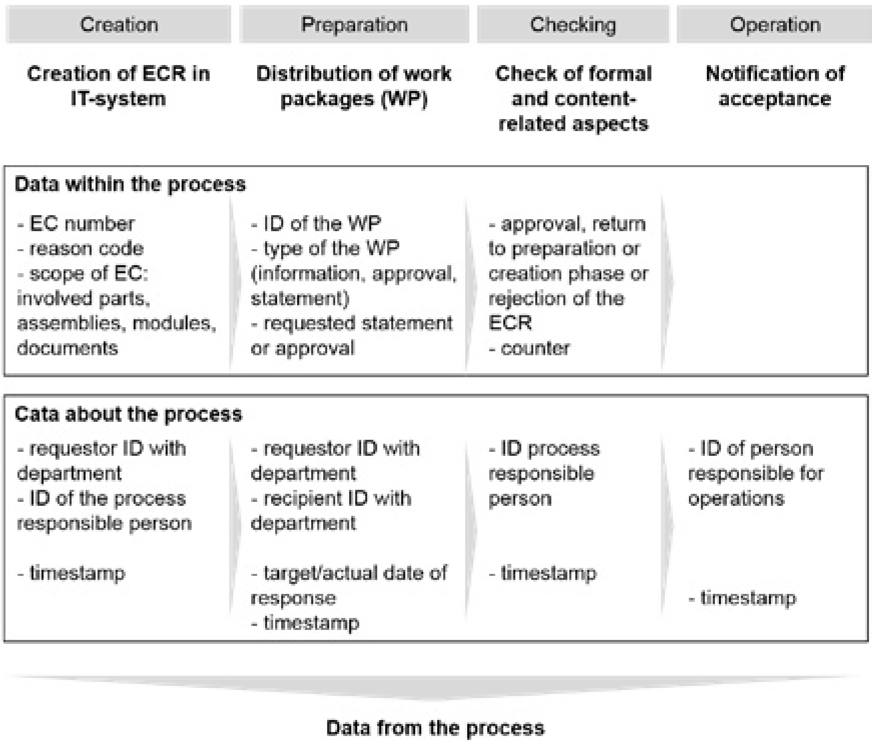

Figure 3 Data of ECs in relation to phases of an ECM process and data types

Due to the fact that the phases of the company differ from the formal ECM process typically found in literature the phases are roughly explained in the following:

The creation phase is simply the entry of a new ECR in the company specific IT-system, a workflow-management system. The need for an EC as well as the proposal of how to implement the EC was previously determined. The EC gets a unique ID number, a reason code and the scope of the EC is stated. The IT-system provides approximately 30 different reasons, i.e. change in requirements or corrections. The scope is set by referring all parts, assemblies, modules and documents involved in the EC. In addition, further information and data within the company, such as a bill of material, affected development project, can be drawn by relational data bases. Also involved persons or departments are recorded, such as the requestor of the EC or the person/dept. responsible for the future process. In the following preparation phase a detailed assessment of the ECR takes place. In the form of work packages (WP), different persons or departments are either (1) informed about the EC, (2) a statement is requested about an expected cost impact of the EC, for example, or (3) an approval is necessary from a particular person or department. The WPs (2) and (3) are limited in time and there will be a reminder when a response is delayed. This information will also be tracked by the system. In the next phase, the responsible person for the ECM process checks the formalities of the ECR as well as the responses of the persons or departments from the preparation phase. The responsible person for the process then decides about the EC. When the decision is positive, the ECR becomes an ECO within the IT-system. In case of a refusal, the ECR can be returned to preparation or the creation phase to be reworked or be completely canceled. Here the system counts the number of returns and records the further WP for each iteration. The operational phase is explained as "just do it", so everyone involved in the ECM process receives the notification of acceptance and is engaged to implement the ECs according to the ECO. Then the official ECM process is closed. Over the whole process the time is tracked by a timestamp. Besides the analysis of individual EC data, it is possible to consider a set of ECs. Then further data are assessable, such as typical sequences or frequencies of EC within the company or a development project.

3.2 Engineering Change Management Strategies

In literature many authors suggest strategies for coping with ECs. The most comprehensive and widely accepted list is from Fricke et al. [4]. They identified strategies based on five attributes to implement better management of ECs: Less, earlier, effective, efficient and better. Within this section indicators of EC are derived for each strategy. The indicators shall point (retrospectively) to which strategy should be applied to which EC.

In the following each strategy is first examined in detail according to different literature. Here the focus is on the description of ECs which should be addressed by the particular strategies. Subsequently, the description of ECs based on literature is further condensed to indicators. This was done by the authors very closely to the original description in literature.

3.2.1 Prevention

This strategy is intended to prevent ECs so that the total number of ECs within a company can be reduced. According to Clark and Fujimoto [9], it is possible to prevent two-thirds of all ECs by improving communication and discipline in the decision-making process. There is no agreement in literature as to which ECs shall be prevented. Jarratt et al. [12] name especially "emergent changes" which occur unplanned within the engineering process as the focus of this strategy. In contrast Fricke et al. [4] aim to prevent "avoidable" ECs and prioritize ECs in the later phases because of an expected higher impact. However the term "avoidable" is not further clarified by them. Lindemann and Reichwald [3] aim within this strategy to avoid failures, or at least to avoid the repetition of failures, and propose methods like Quality Function Deployment (QFD) or Design Review. Knowledge about the occurrence of ECs in the context of the design processes is necessary in order to prevent ECs in the future [4], especially what kind of change occurs at what point in the design process and which costs arise due to the EC. Additionally, it must be clear what kind of change should be addressed and avoided.

Indicators of the strategy prevention: ECs in late phases, emergent ECs, avoidable ECs and ECs due to failures.

3.2.2 Front-Loading

Within the front-loading strategy, an earlier detection and implementation of ECs is pursued in order to have a lower general impact and lower costs for the ECs (e.g. [4, 9, 16]). The rationale behind this is the Rule of Ten, which indicates the relationship 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 by approximately a factor of ten with every phase of the design process [9]. Fricke et al. [4] highlight the parameter "point of time of the change", which has to be manipulated and transferred to an earlier point using this strategy. Literature provides several approaches to detect changes earlier, for instance by simulations or methods such as Failure Mode Effect Analysis (FMEA), "Design for manufacture and assembly" or risk management.

Indicators of the front-loading strategy: ECs due to failures, EC with high impact, ECs detectable earlier by simulations

3.2.3 Effectiveness

Literature concurs that the aim of this strategy is to assess the usefulness of an EC by analyzing the "ratio of effort to benefit" for each proposed EC [4]. Not all ECs are urgent or technically necessary [12]; according to a study of Fricke et al. [4] only 40%-60% of ECs were mandatory. Therefore, companies have the possibility to decide on approximately 50% of all ECs and thereby identify and reject uneconomic ECs. Some changes seem to be beneficial at first glance but finally lead to minor cost savings that do not compensate for the negative impact of the EC [8].

Indicators of the effectiveness strategy: EC with negative ratio of effort to benefit, not necessary changes

3.2.4 Efficiency

This strategy concentrates on the implementation of necessary ECs by an optimal use of resources. According to Fricke et al. [4], the decision to change should only be made with a direct implementation of an EC because with a time delay the risk increases, so that the basis for the evaluation might itself change. The communication of an EC, which should be forced as soon as possible and include affected people and sections [12], also plays an essential role. Speeding up the EC process is also one of the four principles of change management from Terwiesch and Loch [8]. The efficiency in general can be measured in the form of time and cost of the change [4]. Huang et al. [17] propose "calendar time taken to deal with an EC" and "cost or effort (in person hours)" needed to implement an EC.

Indicators of the efficiency strategy: No direct communication and implementation of the EC, time and cost of the EC

3.2.5 Learning

The aim of this strategy is to support the already named strategies (prevention, front-loading, effectiveness and efficiency) by learning from previously performed EC processes. Fricke et al. [4] set the focus especially on the effectiveness and efficiency strategies By reviewing and critiquing ECs, information about typical failures or repetitions of failures on product and process can be generated and used to improve the ECM [3]. Jarratt et al. [12] especially name the design of a product, the product design process and the engineering change process which can be improved. The parameter quality shall be increased with this[4]. Lindemann and Reichwald [3] propose analysis of previous EC data: Master data of ECs can be used to identify the EC; further data such as trigger, causes and costs, affected parts, assemblies as well as persons or departments, can be used for the analysis. In addition, the dates of the individual activities are relevant particularly in regard to the processing time.

Indicators of the learning strategy: typical failures and repetitions, typical ECs

3.3 Data patterns to relate past ECs to ECM strategy

In order to relate past ECs to strategies, an approach was established which relates typically available data of past ECs (see Section 3.1) to indicators for strategies (see Section 3.2). Due to the fact, that for each indicator a one-to-one relationship to an attribute of the EC data is not possible, we derive a data pattern of EC data. Within that data pattern, several attributes of the EC data and, if necessary, a sequence or frequency or both is combined. Furthermore, we made some assumptions because of unavailable direct data. So the number of involved departments or persons, the scope of the EC (expressed by the involved parts, assemblies, documents, modules) and the affected development projects is used to indicate the effort for an EC. The more parties that are involved, the more complex the EC is and the higher the effort to coordinate and implement the EC. At the same time, the risk increases for implementation of the EC due to an increasing failure probability. In Table 1 the connection between the five strategies for coping with ECs and the EC data pattern are presented.

Table 1 Connection between strategies, indicators of the strategies and EC data pattern

Strategy	**Indicators of strategies**	**Data pattern of ECs**
Prevention	ECs in late phases emergent ECs (unplanned ECs) avoidable ECs ECs due to failures	- phase of the development project (indirect available via relation database) - comparison of sequences and frequencies of EC reasons in a set of development processes to identify untypical ECs - comparison of sequences and frequencies of EC reasons in a set of development processes - code of EC reason (direct)
Front-loading	ECs due to failures EC with high impact detectable by simulations	- code of EC reason (direct) - number of involved departments - number of involved parts, assemblies, documents (scope of the EC) - number of involved development projects - code of EC reason (direct)
Effective-ness	ratio of effort to benefit unnecessary changes	- requested statements (to determine necessity of the EC) - number of involved departments - number of involved parts, assemblies, documents (scope of the EC) - number of involved development projects - code of EC reason (to identify optional ECs)
Efficiency	direct communication and implementation of the EC time and cost of the EC	- lead time of the EC - idle time - overrun of target date (reminder) - lead time - number of involved persons etc.
Learning	Typical failures and repetitions Typical ECs	- frequency of failures in a single project - frequency of failures in different projects - sequence and frequency of EC reasons, involved parts or assemblies, as well as departments, in different development projects

4 Conclusion & discussion

This paper presents patterns of EC data which indicate retrospectively that a change could have been identified earlier in the design process (front-loading), could have been prevented, or could have been implemented more efficiently or more effectively. These patterns are based on typically available EC data within companies so that no further effort for generating additional data is necessary. The patterns involve sequences and frequencies and a combination of different attributes of EC data in order to retrospectively determine the right strategy for an EC. The patterns established within this paper have already been applied in an initial verification study to a portion of the data base which was provided by a company. Hereby subsets of ECs could have been generated for each strategy. The results of the EC subsets are promising, but still have to be evaluated in detail using further data from the company and discussions with experts as well.

This approach depends strongly on the data quality, thus incorrect data will lead to false conclusions and a false selection of a strategy. Furthermore, the approach is based on several assumptions in order to compensate for EC data which was not readily available. These simplifications can also distort the result. To make a conclusion using the established data pattern, it is possible to relate past ECs to strategies in order to improve the ECM, but there have to be more analysis made in order to evaluate how accurate and reliable the approach is working.

5 Outlook

The building of subsets of past ECs with potential of improvement, according to the particular ECM strategies, is the first step of a Knowledge Discovery in Database (KDD) process. The aim of the KDD process is to identify the mechanisms of those insufficient and past ECs by applying the EC data base. Using the knowledge about interrelations and mechanisms of those insufficient ECs and processes in the past, the ECM can be improved more effectively by initiating specific measures which override these mechanisms.

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References

[1] Eckert, C., Clarkson, P.J., Zanker, W., "Change and customisation in complex engineering domains". *Research in Engineering Design*, Vol.15, No.1, p. 1-21, 2004.

[2] Langer, S., Maier, A., Wilberg, J., Münch, T., Lindemann, U., "Exploring differences between average and critical engineering changes: Survey results from Denmark", in *International Design Conference DESIGN*. Dubrovnik, Coratia, 2012.

[3] Lindemann, U. & Reichwald, R., "Integriertes Änderungsmanagement". Springer Berlin, 1998.

[4] Fricke, E., Gebhard, B., Negele, H., Igenbergs, E., "Coping with changes: causes, findings, and strategies". *Systems Engineering*, Vol.3, No.4, p. 169-179, 2000.

[5] Elezi, F., Sharafi, A., Mirson, A., Wolf, P., Krcmar, H., Lindemann, U., "A Knowledge Discovery in Databases (KDD) Approach for Extracting Causes of Iterations in Engineering Change Orders". ASME, 2011.

[6] Sharafi, A., "Knowledge Discovery in Databases". Springer, 2013.

[7] Blessing, L.T. & Chakrabarti, A., "DRM, a design research methodology". Springer, 2009.
[8] Terwiesch, C. & Loch, C.H., "Managing the process of engineering change orders: the case of the climate control system in automobile development". *Journal of Product Innovation Management*, Vol.16, No.2, p. 160-172, 1999.
[9] Clark, K.B. & Fujimoto, T., "Product development performance: Strategy, organization, and management in the world auto industry". Harvard Business School Press (Boston, Mass.), 1991.
[10] Huang, G., Yee, W., Mak, K., "Development of a web-based system for engineering change management". *Robotics and Computer-Integrated Manufacturing*, Vol.17, No.3, p. 255-267, 2001.
[11] Lee, H.J., Ahn, H.J., Kim, J.W., Park, S.J., "Capturing and reusing knowledge in engineering change management: A case of automobile development". *Information Systems Frontiers*, Vol.8, No.5, p. 375-394, 2006.
[12] Jarratt, T.A.W., Eckert, C.M., Caldwell, N.H.M., Clarkson, P.J., "Engineering change: an overview and perspective on the literature". *Research in Engineering Design*, Vol.22, No.2, p. 103-124, 2010.
[13] Giffin, M., de Weck, O., Bounova, G., Keller, R., Eckert, C., Clarkson, P.J., "Change propagation analysis in complex technical systems". *Journal of Mechanical Design*, Vol.131, p. 081001, 2009.
[14] Mehta, C.R., "Knowledge-based methods for evaluation of engineering changes", Dissertation in *Mechanical Engineering*. The University of Michigan, 2010.
[15] Eppler, M.J., Seifried, P., Röpnack, A., "Improving Knowledge Intensive Processes through an Enterprise Knowledge Medium (1999)", in *Kommunikationsmanagement im Wandel*. Springer, 2008.
[16] Rouibah, K. & Caskey, K.R., "Change management in concurrent engineering from a parameter perspective". *Computers in Industry*, Vol.50, No.1, p. 15-34, 2003.
[17] Huang, G.Q., Yee, W.Y., Mak, K.L., "Current practice of engineering change management in Hong Kong manufacturing industries". *Journal of Materials Processing Technology*, Vol.139, No.1-3, p. 481-487, 2003.