INTERNATIONAL DESIGN CONFERENCE - DESIGN 2012
Dubrovnik - Croatia, May 21 - 24, 2012.

EXPLORING DIFFERENCES BETWEEN AVERAGE AND CRITICAL ENGINEERING CHANGES: SURVEY RESULTS FROM DENMARK

S. Langer, A. M. Maier, J. Wilberg, T. J. Münch and U. Lindemann

Keywords: engineering change management, change management, engineering change, design change, change cause, change effect

1. Introduction

Change or modification has always been a fundamental part of engineering design. Changes to a design are the rule and not the exception [Clark and Fujimoto 1991]. Engineering changes (ECs), as Jarratt et al. [Jarratt et al. 2005] describe, are alterations made to parts, drawings or software that have already been released during the design process. Over the past decades, engineering change management has gained prominence in engineering design and product development literature, with a number of in-depth case studies (e.g. [Clarkson et al. 2004], [Fricke et al. 2000], [Giffin et al. 2009], [Jarratt et al. 2010], [Lindemann and Reichwald 1998], [Loch and Terwiesch 1999], [Vianello and Ahmed-Kristensen 2011]), industry surveys (e.g. [Deubzer et al. 2005], [Huang and Mak 1999], [Huang et al. 2003]), and reviews (e.g. [Ahmad et al. 2011], [Jarratt et al. 2010], [Wright 1997]).
Researchers describe and analyse a number of aspects of changes, such as characterisations of changes, causes, initiators, objectives, effects, and potential strategies, and software support to anticipate and handle changes. Studying characterisations of changes, some investigate late engineering changes (e.g. [Coughlan 1992]), others describe strategies to detect avoidable and to cope with unavoidable changes [Fricke et al. 2000], yet others characterise initiated design changes and the associated emergent modifications according to their development over time and potential effects on implementation within the allotted amount of time forming ripple, blossom, or avalanche patterns [Eckert et al. 2004].
Whilst differing in terms of focus and research design what all studies have in common is differentiating between engineering changes for better understanding of patterns of change, ultimately better to manage engineering changes. In this paper, we aim to continue this line of investigation and

- *examine differences between average and critical changes according to results from a survey with industry participants, and thereby*
- *explore as to what makes changes critical.*

In this paper, we focus our description on results from an industry survey. With this in mind, the remainder of the paper is structured as follows: Section 2 describes in brief what motivated criticality of engineering changes as the research focus of this paper and outlines the data acquisition and analysis procedure. We present results of this study in Section 3. Section 4 summarises contributions and concludes with suggestions for further work.

2. Methods: Towards average and critical changes, data acquisition, and analysis

2.1 Towards differentiating between average and critical engineering changes

This research is situated within a wider research programme on cycles in innovation processes. One of the focus areas is 'critical incidents' [Flanagan 1954] within innovation projects, whereby critical incidents are described as project situations and tasks which influence the quality or the outcome and success [Wastian et al. 2009]. Having conducted expert interviews in industry on critical situations in innovation processes, we then identified engineering changes as one type of such critical situations. However, when looking more closely into the elicited incidents and comparing them to results from mining engineering change databases of our industry partners, we saw that a major proportion of changes in the database address what we might consider as more straightforward and average modifications of the product, with only few people being involved over a short implementation time.

Our working assumption from these two research activities was therefore that there might be a difference between average and critical engineering changes as far as relevancy of overall manageability and project success is concerned. Criticality of project situations in engineering design in general is, for example, discussed by Badke-Schaub and Frankenberger [Badke-Schaub and Frankenberger 1999]. When considering engineering change literature in specific, we find a number of characterisations of engineering changes (e.g. by [Eckert et al. 2004]) and aspects of criticality in combination with topics such as schedule risk [Browning and Eppinger 2002] or change impact analysis [Kilpinen 2008], yet, with scope for studies specifically focusing on criticality. Consequently, we aim to explore differences between average and critical engineering changes through an industry survey. Therefore, we provided the following definition of critical engineering changes within the survey:

A critical EC endangers the start of production or the whole project
in terms of cost, time, resource-involvement, or feasibility
(e.g. changing customer requirements, changes for a massive cost reduction).

2.2 Development and distribution of electronic survey

Following pilot-testing with three academic staff members in engineering faculties, two mechanical engineering students, and six engineering change experts from different industry sectors, the survey was subsequently distributed per electronic mail to engineering companies of all sizes and industry sectors in Denmark. The survey was requested to be forwarded to the responsible for engineering changes in the respective company, e.g. the R&D director, innovation director, engineering change lead. Ninety-three usable questionnaires were returned within the response time of four weeks, with 22 questionnaires being fully completed.

2.3 Description of study sample

Over 90 firms in Denmark participated in the survey on engineering change management practice. Survey participants have on average 20 years of industry experience, and most of them are in leading engineering and technology positions. Participants represent firms of different sizes, customers (B2B, B2C, Wholesale), and types of production (individual, small series, series production) from industry sectors such as aerospace, automotive, building services engineering, chemical, construction, consulting, electronics, energy, general mechanical engineering, healthcare/pharmaceuticals, telecommunications, transportation, software, synthetic materials industry, and packaging.

2.4 Data analysis procedure

Results are analysed and presented following the same pattern: Firstly, a short description of the background of the analysis is given by alluding to literature underlying the survey. Secondly, an initial analysis of the result overall is provided. Thirdly, the results are analysed by comparing average and critical changes. Fourthly, as and when applicable and possible, we differentiate between companies with fewer critical changes (<= 25 %) and companies with more critical changes (> 25 %). This comparison is based on the estimation of participants on the average amount of critical changes in their overall changes. Finally, a short discussion of the findings is provided. Not all questions were answered by all respondents (N=93). Therefore, when displaying results in what follows, the statistical basis (n) of the number of respondents for the respective questions is provided.

3. Results

3.1 Occurrence and relevance of engineering changes in development

3.1.1 Occurrence of changes mostly in later phases of product development

Results from our survey show that most of the changes occur in the later phases of the product development process. Within the sample surveyed, almost 60% of the changes mostly occur whilst the product is already in production or released to market. Only 3% of the respondents see changes as never occurring in production or in the field (n=68).

3.1.2 Capacity of R&D used for engineering changes and amount of critical changes

Responses show that engineering change management consumes almost one third of the total R&D capacity of manufacturing companies in Denmark (30,81%; SD 25,18; n=27). It can further be said that survey participants estimated one third of all engineering changes are critical changes (33,48%; SD=22,97; n=29) as depicted in the top part of Figure 1.

Results in this study correspond with findings from a survey of German engineering businesses that found that approximately 30% of all work effort was due to engineering changes [Fricke et al. 2000] - this included rework as well as adding of functionality to a product. [Terwiesch and Loch 1999] report that engineering changes consumed between a third and a half of the engineering capacity at the firm they examined, along with 20–50% of tooling costs [Jarratt et al. 2005].

3.1.3 Differentiating between companies with a higher and lower amount of critical changes

When differentiating between companies with a higher and lower amount of critical changes, Figure 1 shows that for companies with more critical changes (48%), the R&D capacity used for changes increases to 39%, whereas companies with fewer critical changes (12%) use only 16% of their total R&D capacity on engineering changes.

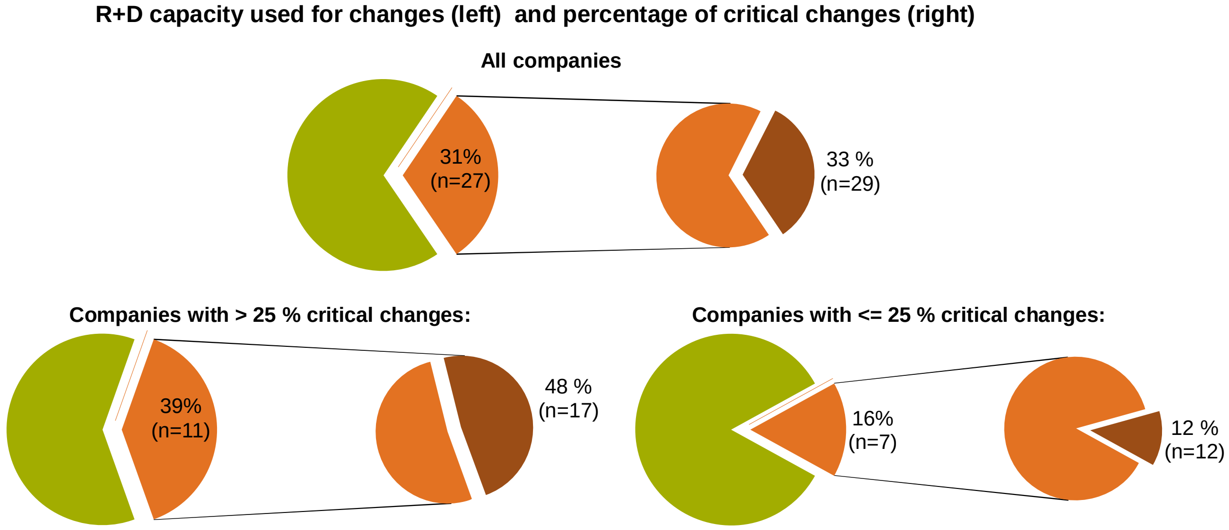


Figure 1. R&D capacity used for engineering changes (left side of each diagram) and percentage of critical changes (right side of each diagram)

With such a high proportion of occurrence of late changes and amount of total R&D capacity used, one may say that critical changes are of high relevance and successful management is of importance.

The next sections investigate similarities and differences between objectives, initiators, and causes of average and critical engineering changes.

3.2 Objectives, initiators, and causes of engineering changes

3.2.1 Background of the analysis

Different definitions and associated factors are used in literature to describe objectives, initiators, and causes of engineering changes. Based on literature [Deubzer et al. 2005], [Eckert et al. 2004], [Fricke et al. 2000], [Huang et al. 2003], [Jarratt et al. 2010], [Pikosz and Malmqvist 1998], [Terwiesch and Loch 1999], [Vianello and Ahmed-Kristensen 2011], we distinguish between objectives that support the decision of implementing engineering changes of engineering changes, the ‘source’ of an engineering change by asking for initiators, and the actual root cause.

3.2.2 Objectives of engineering changes

Survey results show in specific that major objectives underlying average engineering changes are to improve deficiencies of the product, to integrate new technologies and innovative solutions, and thirdly to develop alternative products or variants (Figure 2).

Rank	Average changes (n=31)	Critical changes (n=27)
1	Improving deficiencies of the product	Improving deficiencies of the product
2	Integration of innovations, new technologies or trends	Integration of innovations, new technologies or trends
3	Developing alternative products or variants	Change necessity due to other changes

Figure 2. Ranking of top 3 objectives of average and critical changes

For critical changes, this picture changes, with almost 50% of change necessity stemming from change propagation. Interestingly, in companies with more critical changes, change propagation is listed as the second highest objective, following reducing deficiencies of the product. This may mean that critical changes have a higher affiliation to change propagation, both in terms of what causes them but also in their effects (see also 4.3).

3.2.3 Initiators of engineering changes

Despite a discussion in industry as to who is considered company-external and –internal, we draw the line between the organisation and the supply-chain. With respect to initiators, results of this survey show that there are similarities for average and critical changes. Within the organisation, Research and Development, Marketing and Sales, and Manufacturing are major internal initiators of engineering changes. External initiators number one are customers, end-users and market trends, with laws and regulations following suit.

Rank	Average changes (n=30)	Critical changes (n=26)
1	Customers, end users, market trends	Customers, end users, market trends
2	Development, R&D	Development, R&D
3	Marketing, Sales	Laws, regulation, certification

Figure 3. Ranking of top 3 initiators of average and critical changes

Further, results show that customers, end users, and market trends are most frequent initiators of engineering changes. This is interesting when seen in connection with responses on the objectives of engineering changes, which show that one of the major reasons for engineering changes is the integration of innovations and new technologies (Figure 2). With R&D being one of the top initiators, we might conclude that there is a possibility for actively influencing this field of initiators.

Implications of this might be further research on approaches for proactively reducing or avoiding unnecessary changes.

3.2.4 Causes of engineering changes

Having examined initiators, this section presents survey results on causes of engineering changes. Major causes for both average and critical engineering changes are first and foremost insufficient clarification of requirements, followed by human error in process execution. For average changes, the third major cause is insufficient external communication (e.g. with suppliers and customers) and for critical engineering changes inadequate processes, methods or tools are listed (Figure 4).

Rank	Average changes (n=26)	Critical changes (n=25)
1	Insufficient clarification of requirements	Insufficient clarification of requirements
2	Human error in process execution	Human error in process execution
3	Insufficient external communication (with suppliers or customers)	Inadequate processes, methods or tool support

Figure 4. Ranking of top 3 causes of average and critical changes

While these findings do not allow for identifying specific causes of critical changes, they indicate the most relevant issues leading to engineering changes. For example, insufficient clarification of requirements might point towards a need for a transparent definition of goals and objectives as well as towards the need for communication support.

3.3 Effects of engineering changes

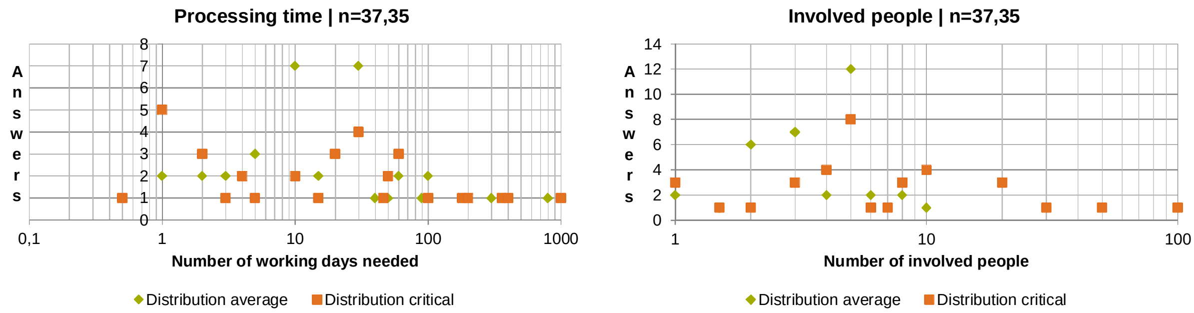
Having investigated objectives, initiators, and causes of engineering changes, this section aims to find out whether criticality of engineering changes might be attributed to implications changes have on the organisation and across the value-chain.

3.3.1 Background of the analysis

Effects are firstly investigated by asking for an estimation of the efforts for both average and critical changes with respect to processing time and personnel involved. Secondly, we identified a large set of factors which a number of authors describe as effects of ECs (e.g. [Browning et al. 2006]). These factors were grouped into effects on the product, the process, people, and cost. Each 'domain' of effects was assessed with respect to a possible positive, negative, or neutral impact, measured on a 5-point Likert scale.

3.3.2 Estimation of processing time and number of personnel involved

Results show both a higher processing time and a higher number of involved people for critical changes (see Figure 5). Yet, as can be seen in Figure 5 overleaf, standard deviations show both processing time and the number of involved personnel is subject to high variation. This is not surprising as changes during the design process are discussed as being of high individual nature due to the variety of products, companies, markets etc. [Jarratt et al. 2005]. Nevertheless, results point towards a tendency that critical changes tend to show higher resource consumption in terms of processing time and involved personnel (see Figure 5 overleaf).
Further investigation into more detailed effects on the product, process, people, and cost within and across the value-chain for both for average and critical changes is necessary and will be discussed in the following sections.



	Average changes (n=37)	Critical changes (n=35)
Mean processing time	60,6	80,2
Standard deviation	140,1	185,5
Mean involved people	7,4	11,1
Standard deviation	16,3	18,2

Figure 5. Estimation of processing time and involved personnel

3.3.3 Effects on the product

When looking at effects of engineering changes on the product (Figure 6), we see that new or alternative product solutions, satisfaction of customer requirements, product functionality and product quality are clearly estimated as increasing both for average as well as for critical changes.

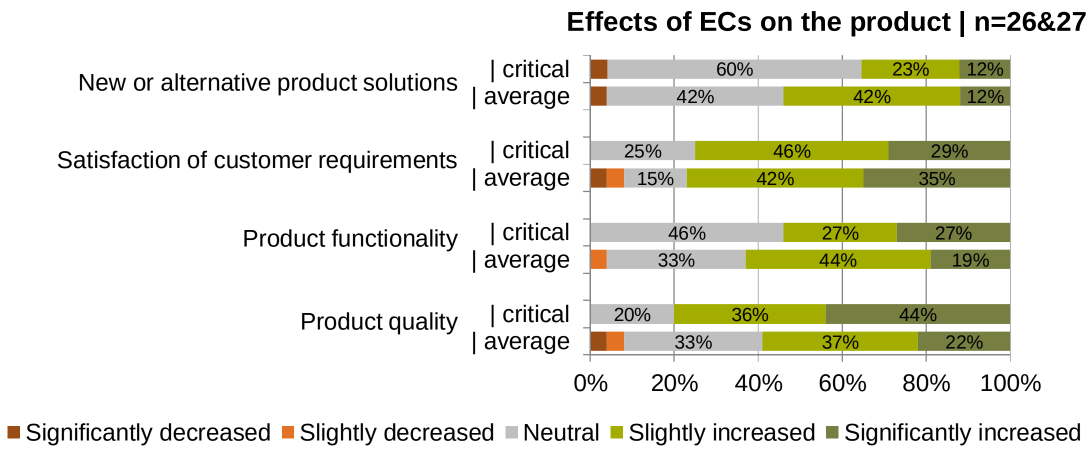


Figure 6. Effects of critical and average ECs on the product

When examining the differences between the effects of average and critical changes, we notice that there is an increase of over 50% in new or alternative product solutions for average changes, whereas this is not as strong for critical changes. Critical changes seem to be less used for developing new or alternative product solutions. We further notice that there is a significant increase in product quality for both critical and average engineering changes, with a strong increase and improvement for critical changes. Results point towards the conclusion that the intention behind critical changes is more on improving higher deficiencies of products.

3.3.4 Effects on people

With respect to the effects of engineering changes on people involved, again, respondents´ answers point to effects estimated as being mostly positive (Figure 7) both for average and critical changes, with a relatively low proportion of negative effects.

When comparing average with critical changes, reputation with customers shows interesting results. On the one hand, critical changes are seen as having slightly more negative effects, yet, the amount of companies estimating a significant increase in reputation with the customer is more than twice the

amount compared to average changes. This might suggest that the effects of critical changes are somewhat heterogeneous, yet, might offer possibilities for higher customer satisfaction.
Reputation with suppliers is seen as remaining neutral, both for average and critical changes. The main difference here is seen in a higher proportion of positive effects, pointing to similar possibilities for increasing reputation as seen above for customer satisfaction.
As far as change effects on the experience of employees are concerned, more than 70% of all surveyed companies see slight or significant increases. A major difference here can be seen when comparing average and critical changes: While for average changes, no respondent chose ‘significant increase’, for critical changes significant increase in experience amounts to 17%.
With respect to change effects on morale and motivation of employees, for average changes, no significant increase is seen at all, yet a noteworthy slight and significant decrease can be noticed. For critical changes, however, 50% of the survey participants see a slight or significant increase in morale and motivation.

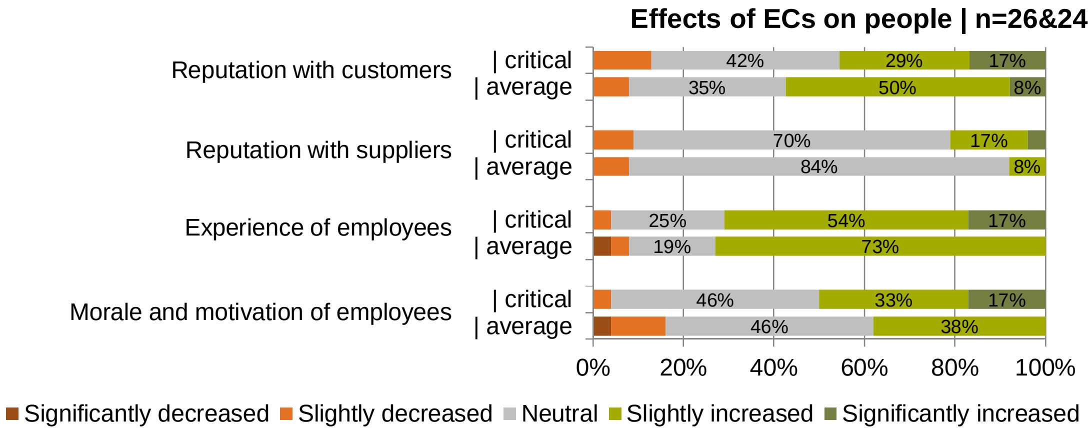


Figure 7. Effects of critical and average ECs on people

Despite the mainly positive effects on product and people involved in engineering changes, positive or negative effects have to be analysed in more detail, e.g. by considering the effects engineering changes have on the process and costs. This is discussed in the following sections and depicted in Figure 8.

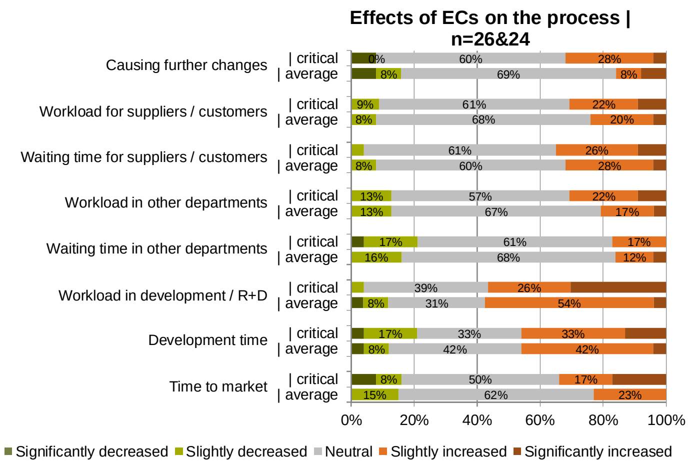


Figure 8. Effects of critical and average ECs on the process

3.3.5 Effects on the process

Results on change effects on the process show that there are a proportionally high number of responses pointing to a neutral or balanced effect between a positive and negative impact on process management (Figure 8). Exceptions to this are particularly the aspects of workload in R+D as well as the development time, which are seen rather negatively.

Comparing critical and average changes with respect to their effects on process execution leads to several interesting findings. Firstly, results show that critical changes lead to more additional changes compared to average changes. In other words, the likelihood of change propagation is higher for critical changes (see also causes earlier). Secondly, there is a substantially higher proportion of significant increase in workload for the R&D department. This applies as well for the workload in other departments as well for external stakeholders, such as suppliers and customers. Thirdly, both development time and time to market show a substantially higher proportion of a significant increase (e.g. a significant increase of time to market is seen by 17% of the participants). Surprisingly, for average changes, only 23% see time to market as slightly increased which could point to the fact that engineering change management is already planned into the product development process.

3.3.6 Effects on cost

The analysis of change effects on company-internal and -external costs shows a comparable picture as the analysis of effects on processes. Yet, what is interesting in this regard is that cost effects for change implementation are seen rather negatively both for average and critical changes, while internal mid- and long-term costs as well as company-external costs show a heterogeneous picture for both positive and negative effects (Figure 9). Given a variety of changes and their objectives (see e.g. Figure 2), this suggests that change implementation is in most of the cases connected with an increase in short-term costs, yet, such changes might offer potential for mid- and long-term cost reductions.

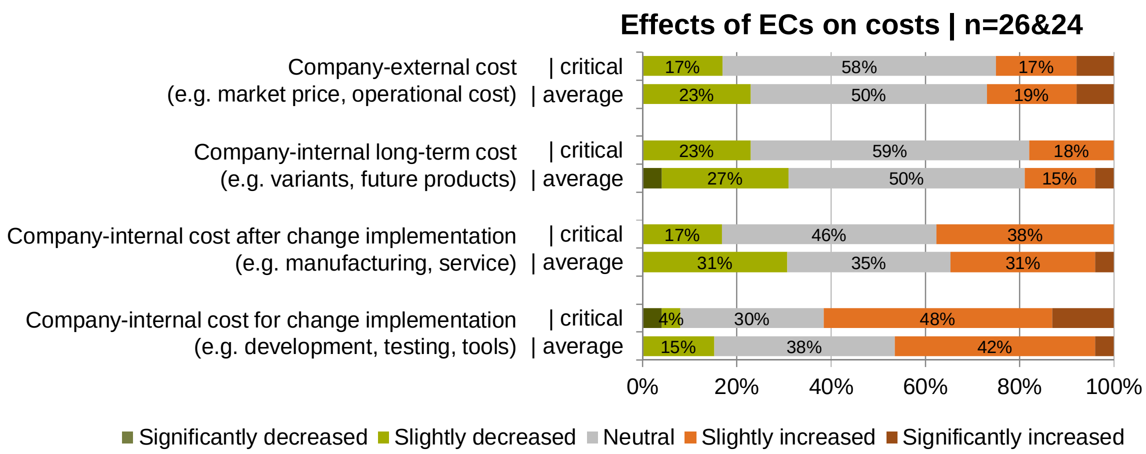


Figure 9. Effects of critical and average ECs on costs

Comparing average with critical changes is particularly interesting with regard to internal change implementation costs and internal costs after implementation. For critical changes, change implementation costs are more frequently assessed as slightly and significantly increasing, this amounts to more than 60% of all answers. The potential for reducing internal and external costs is seen by fewer participants. This suggests that critical changes are connected with higher costs and are not as often used for reducing internal and external mid- and long-term costs.

4. Contribution and further work

This paper presents results from a survey conducted among more than 90 manufacturing companies in Denmark and complements existing studies on engineering change management in three ways: Firstly, it explores differences between average and critical engineering changes in industry; secondly, it focuses on how engineering changes affect the whole organisation, and thirdly, it provides data on engineering change management in Denmark.

The overall aim of this research was to examine differences between average and critical changes through a survey with industry participants and thereby explore as to what makes changes critical. Results may be summarised as follows:

Firstly, our analysis on occurrence of and the capacity used for average and critical changes showed that critical changes can play a decisive role both for change management as such as well as for the

R&D capacity used. Results show that companies with a higher amount of critical changes tend to also expand higher percentage of R&D for engineering changes. Results underpin the relevance of addressing the specific aspect of critical changes.

Secondly, we analysed factors leading to engineering changes by differentiating between objectives, initiators and causes of changes. For each of these aspects, a clearer picture could be derived which factors are of highest relevance in leading to engineering changes (see Figures 2 – 4). This suggests focus areas for supporting change management and related research. With respect to the difference between average and critical changes, results depict a similar picture in terms of major initiators, objectives, and causes. There seems to be a slightly stronger emphasis on inadequate processes, methods and tool support as causes for critical changes. Further analyses are needed to investigate the link between objectives and the effect.

Thirdly, we addressed potential effects of changes from the perspectives of products, people, processes and costs. Here, effects on products and people were evaluated as surprisingly positive by the survey participants in the sense that changes can also be regarded as an opportunity, while process and cost effects were seen more negatively. Comparison of average and critical changes shows higher extremes in the effects of critical changes, both positively and negatively. For example, potential product quality improvements are seen significantly higher for critical changes, while at the same time potential workload increases are considered also as being significantly higher. In other words, results suggest that one of the main differences between average and critical changes can be found in the workload and the additional time necessary for change implementation. In combination with findings on factors leading to changes, a proposition may be formulated that criticality of changes stems predominantly from the characteristics of their effects. Yet, no one specific factor stands out as characterising critical changes – rather a multitude of factors seem to describe criticality of engineering changes.

While initial tendencies of differences between average and critical changes can be derived from our results, results also indicate that the role of changes as well as their criticality might vary depending on company context. Further analyses on the influence of the customer base and the business model, the position in value-chain, or the size of the company are therefore necessary. Taking results in this paper as starting point, avenues for further research are also seen in discussing appropriate strategies of coping with engineering changes. In particular, focusing on exploiting the positive effects and reducing the negative effects of critical changes – as derived from the survey – is an avenue for future research activities. In summary, the need for supporting engineering change management, especially considering critical cases, can be underpinned. In the words of a survey participant:

“[...] most people still plan as if no serious changes will occur - but they do all the time and are an integrated part of normal project management to day as I see it.”

Acknowledgement

We thank the German Research Foundation (Deutsche Forschungsgemeinschaft – DFG) for funding this project as part of the collaborative research centre ‘Sonderforschungsbereich 768 – Managing cycles in innovation processes – Integrated development of product-service-systems based on technical products’.

References

Ahmad, N., Wynn, D. C., Clarkson, P. J., "Information models used to manage engineering change: a review of the literature 2005-2010", 2011, pp 538-549.

Badke-Schaub, P., Frankenberger, E., "Analysis of design projects", Design Studies, Vol. 20, No. 5, 1999, pp 465-480.

Browning, T. R., Eppinger, S. D., "Modeling impacts of process architecture on cost and schedule risk in product development", Engineering Management, IEEE Transactions on, Vol. 49, No. 4, 2002, pp 428-442.

Browning, T. R., Fricke, E., Negele, H., "Key concepts in modeling product development processes", Systems Engineering, Vol. 9, No. 2, 2006, pp 104-128.

Clark, K. B., Fujimoto, T., "Product development performance: Strategy, organization, and management in the world auto industry", Harvard Business Press, 1991.

Clarkson, P. J., Simons, C., Eckert, C., "Predicting change propagation in complex design", Journal of Mechanical Design, Vol. 126, 2004, p 788.

Coughlan, P. D., "Engineering change and manufacturing engineering deployment in new product development", Integrating Design and Manufacturing for Competitive Advantage, New York, 1992, pp 157-177.

Deubzer, F., Kreimeyer, M., Rock, B., Junior, T., "Der Änderungsmanagement Report 2005", CiDaD Working Paper Series, 2005.

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

Flanagan, J. C., "The critical incident technique", Psychological bulletin, Vol. 51, No. 4, 1954, p 327.

Fricke, E., Gebhard, B., Negele, H., Igenbergs, E., "Coping with changes: Causes, findings, and strategies", Systems Engineering, Vol. 3, No. 4, 2000, pp 169-179.

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, 2009, p 081001.

Huang, G. Q., Mak, K. L., "Current practices of engineering change management in UK manufacturing industries", International Journal of Operations & Production Management, Vol. 19, No. 1, 1999, pp 21-37.

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, 2003, pp 481-487.

Jarratt, T., Clarkson, J., Eckert, C., "Engineering change", Design process improvement, 2005, pp 262-285.

Jarratt, T., Eckert, C., Caldwell, N., Clarkson, P., "Engineering change: an overview and perspective on the literature", Research in Engineering Design, 2010, pp 1-22.

Kilpinen, M. S., "The emergence of change at the systems engineering and software design interface: an investigation of impact analysis", 2008.

Lindemann, U., Reichwald, R., "Integriertes Änderungsmanagement", Springer Berlin, 1998.

Loch, C. H., Terwiesch, C., "Accelerating the process of engineering change orders: capacity and congestion effects", Journal of Product Innovation Management, Vol. 16, No. 2, 1999, pp 145-159.

Pikosz, P., Malmqvist, J., "A comparative study of engineering change management in three Swedish engineering companies", 1998.

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, 1999, pp 160-172.

Vianello, G., Ahmed-Kristensen, S., "A comparative study of changes across the lifecycle of complex products in a variant and a customised industry", Journal of Engineering Design, 2011.

Wastian, M., Schneider, M., Klendauer, R., Gunkel, J., " Time line Job Analysis (TJA) – setting the stage for a process-focused, flexible human resource management in innovation projects", Proceedings of the 14th European Congress of Work and Organizational Psychology, Santiago de Compostela, 2009.

Wright, I. C., "A review of research into engineering change management: implications for product design", Design Studies, Vol. 18, No. 1, 1997, pp 33-42.

Stefan Langer, Dipl.-Ing.
Scientific assistant
TU München, Institute of Product Development
Boltzmannstraße 15, 85748 Garching, Germany
Telephone: +49.89.289.15137
Telefax: +49.89.289.15144
Email: stefan.langer@pe.mw.tum.de
URL: http:// www.pe.mw.tum.de