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Evaluation of Engineering Changes Based on Variations from the Model of PGE - Product Generation Engineering in an Automotive Wiring Harness

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Abstract

Engineering change management is a central part of the product development process. This paper investigates how variations from the PGE - Product Generation Engineering can improve the evaluation of engineering changes from the wiring harness. Engineering changes that occur in an automotive wiring harness development process are analysed in a case study, evaluated in expert interviews with regard to the risk and effort connected to the implementation and compared to the types of variations. Additional influencing factors are discussed. The variations provide an indication on risk and effort.

Keywords: engineering change, change management, design evaluation, automotive wiring harness, product generation engineering (PGE)

1. Introduction

Engineering changes are a central part of the product development process. They ensure the improvement of products and systems by eliminating errors, reducing costs, increasing quality and meeting customer requirements (Jarratt *et al.*, 2011). However, managing and dealing with engineering changes is resource intensive. This is especially the case for the automotive wiring harness. This system is very complex, has a lot of variants because of its customisability and is subjected to many engineering changes. Dealing with engineering changes in the development of the automotive wiring harnesses requires more effort than for other systems (Kuhn and Nguyen, 2019; Langer *et al.*, 2012). Academia and the industry are focussing on the improvement of engineering change management. One strategy is to deal with less engineering changes earlier, more efficiently, more effective in a better way (Fricke *et al.*, 2000; Altner *et al.*, 2021). That matches with factors from the automotive wiring harness. The reduction of manual effort, improvement of data quality and evaluation of changes are important issues (Altner *et al.*, 2021). Therefore, identifying the effort and risk that go along with the implementation of engineering changes is important. It addresses the points mentioned before. The similarities between engineering change management and product development allow the use of methods in both environments (Albers *et al.*, 2016b; Gemmerich, 1995). The PGE - Product Generation Engineering is particularly interesting. Classifying variations of technical systems is used to evaluate risk and effort (Rapp *et al.*, 2020). This paper studies how well this works for the automotive wiring harness. Engineering changes from a development process are assessed, based on structured expert interviews and classified as either carry-over, attribute or principle variations. The extent to which types of variations allow a prediction considering risk and effort connected to the implementation of engineering changes is investigated. Factors that might help a further evaluation are discussed. This paper investigates how the PGE - Product Generation Engineering improves engineering change management.

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2. State of the art

The engineering change management in the automotive harness development provides the framework for this research and the case study. The PGE - Product Generation Engineering model as well as expert interviews are used to analyse the engineering changes. The state of the art is introduced in this chapter.

2.1. Engineering change management

Engineering change management focuses on organising, handling and dealing with engineering changes in the product development process. The process can be divided into the pre-, in- and post-change stages (Hamraz *et al.*, 2013). Engineering changes are defined as

> *"changes and/or modifications to released structure behaviour, function, or the relations between functions and behaviour, or behaviour and structure of a technical artefact" (Hamraz et al., 2013).*

The role that engineering change management plays was highlighted by a study across different industries. It found that engineers spend around 25 % of their time on engineering changes (Langer *et al.*, 2012). Dealing with less changes, earlier, effective, efficient and better are principles that have been proposed and are referred to multiple times in order to improve engineering change management (Fricke *et al.*, 2000). A key aspect is identifying the effects that each engineering change has. This is difficult because parts, components and systems are often highly inter-connected which makes it difficult to assess the impact and propagation of an engineering change. This makes the entire change process challenging and requires a lot of effort and time. A common approach is based on the Design Structure Matrix (DSM) that analyses the structure of systems in order to tackle this challenge (Hamraz *et al.*, 2013; Clarkson *et al.*, 2004).

2.2. Automotive wiring harness

The wiring harness is the nervous system and backbone of the electrical system (E/E architecture) in a vehicle. It ensures the distribution of energy and information in any modern automobile. The wiring harness, as defined by Reif, provides the connection and interlinkage of all electrical components in a vehicle. It consists of electrical wires, components as well as mechanical components (Reif, 2012).
The wiring harness can have over 1200 components, a combined wire length of up to 5.000m and weighs over 50kg. The manufacturing of the wiring harness is done mostly manually. That makes it one of the most expensive systems in a car (Spilok, 2021; König, 2016; Trommnau *et al.*, 2020). A development version of the wiring harness from the case study is depicted in Figure 1.

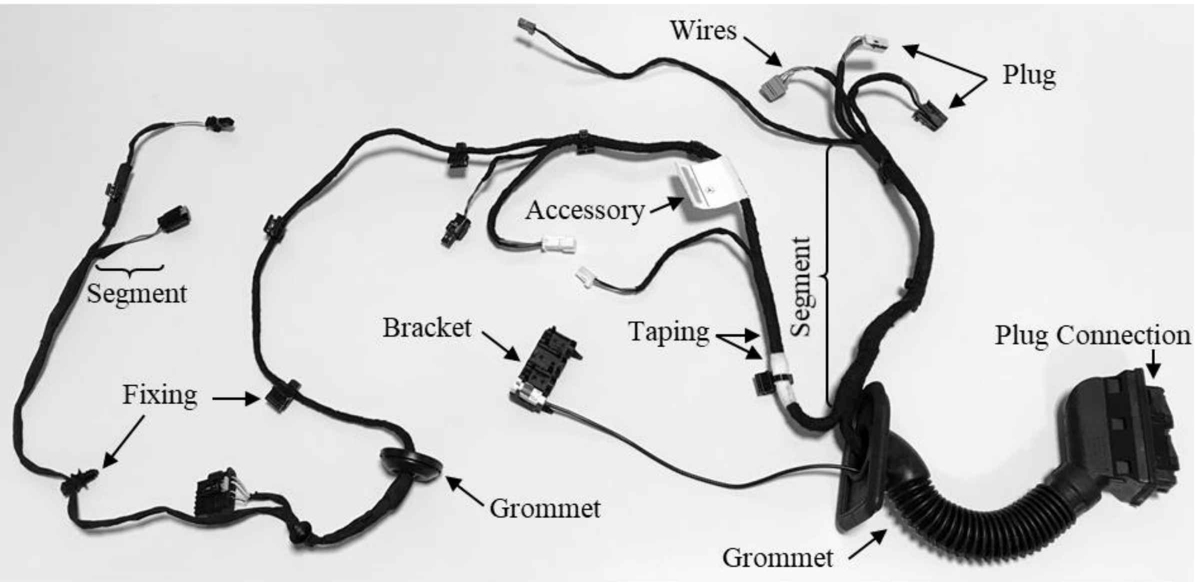

Figure 1. Development prototype of the automotive wiring harness analysed in the case study

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To produce a light, cost optimized and robust wiring harness each harness is configured according to the customisation of the vehicle. The customisation of the wiring harness is enabled by about 2.000 combinable modules. An analysis of variants shows that 20% of wiring harnesses produced for a single model are unique whereas the most common wiring harness accounts for only 1,2% percent of the total production (König, 2016). The development process deals with this by working with a master that contains a 150% extent of a wiring harness that includes the variants of a specific carline and steering type (Neckenich *et al.*, 2016). Due to the variance, wiring harnesses have to be treated as just-in-sequence parts. This affects the logistic and production processes, which in turn leads to design freezes that are earlier compared to other systems. Engineering changes in other systems lead to engineering changes of the wiring harness (Eder *et al.*, 2021). The combination of the above mentioned factors results in approximately 1.000 changes per month. Engineers have to spend 80% of their time to deal with engineering changes (Kuhn and Nguyen, 2019). This is about three times more than in other fields.

2.3. Model of PGE - Product Generation Engineering

The PGE - Product Generation Engineering is a model that helps to describe the development process of products (Albers *et al.*, 2015). According to the model, each development process is based on reference system and the reference system elements that are varied and combined to form a new product generation. This applies to the product generations and engineering generations in the product development process (Albers *et al.*, 2016a). The variations can be divided into three types: carry-over variations, attribute variations and principle variations. This paper uses the term attribute variation instead of embodiment variation due to its broader understanding that is helpful for changes of electrical and electronic systems (Albers *et al.*, 2020). Variations from the model of PGE - Product Generation Engineering will be simply referred to as variations in the paper to improve the readability.

The variations are always defined with respect to the reference system element. The characteristics of the different variations are illustrated in in Figure 2. Carry-over variations pertain not a change of a reference system element but of the connectors to other system elements. Attribute variations retain the basic structure in comparison to the reference system element and only change attributes or characteristics. Principle variations have an effect on the working principle that changes with regard to the reference system element. Therefore, the principle variation has a different inner structure.

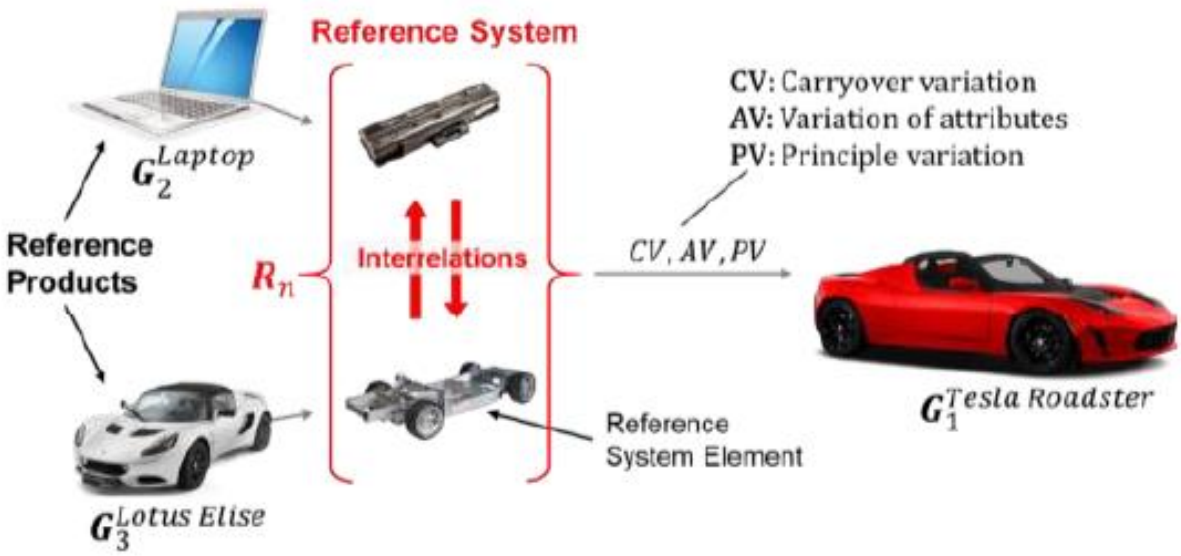

Figure 2. Schematic representation of the PGE - Product Generation Engineering (Albers *et al.*, 2019; Pfaff *et al.*, 2021)

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3. Research questions

Dealing with engineering changes and altering a product or system is a key challenge in product development as well as one of the main drivers of progress (Clarkson and Eckert, 2005; Jarratt *et al.*, 2011). This is especially true for the development of wiring harnesses where engineering change management takes up most of the engineer's time (Kuhn and Nguyen, 2019). In order to improve engineering change management in the context of the automotive wiring harness the previously mentioned strategies translate to a reduction of manual effort and the early evaluation of engineering changes. The evaluation of effort and risk with regard to the implementation of engineering changes in the design processes is a key aspect (Altner *et al.*, 2021). The high number of modules and configurations makes it difficult and to use a DSM to analyse the systems structure to evaluate the change propagation. This research draws from the field of product development that can be used to improve engineering change management in order to influence the amount of effort and the evaluation positively (Gemmerich, 1995). The PGE-Product Generation Engineering, a method successfully used in product development provides a link between engineering changes and risks & costs (Albers *et al.*, 2017) which creates the basis for an effective risk assessment method (Rapp *et al.*, 2020). This research investigates to which extent this approach can be used in the field of engineering change for wiring harness development projects. It is based on a case study where engineering changes that occurred during the development of a wiring harness were analysed. The focus lies on the classification of engineering changes into types of variatio, the evaluation of the effort and the risk of the implementation of engineering changes during the development process and the connection between those two aspects. The following questions provide the foundation for the research in this paper.

- Which types of engineering changes arise in the development of the automotive wiring harness?
- To which extent do the PGE variation classifications predict the risk and the effort associated with the implementation of engineering changes?
- Which factors influence the risk evaluation of individual engineering changes that are analysed?

This research primarily focuses on the in-change stage and the impact analysis of engineering changes, which is the area with the highest research interest (Hamraz *et al.*, 2013).

4. Research methodology

This research is divided in four stages as depicted in Figure 3. It follows the design research methodology (Blessing and Chakrabarti, 2009). The first stage includes the selection of the case-study environment and literature research. The second stage starts with the identification and documentation of engineering changes. Those engineering changes were classified according to the PGE - Product Generation Engineering and evaluated through expert interviews. The third stage includes the comparison of the results and identification of additional factors. The results are discussed in the fourth stage.

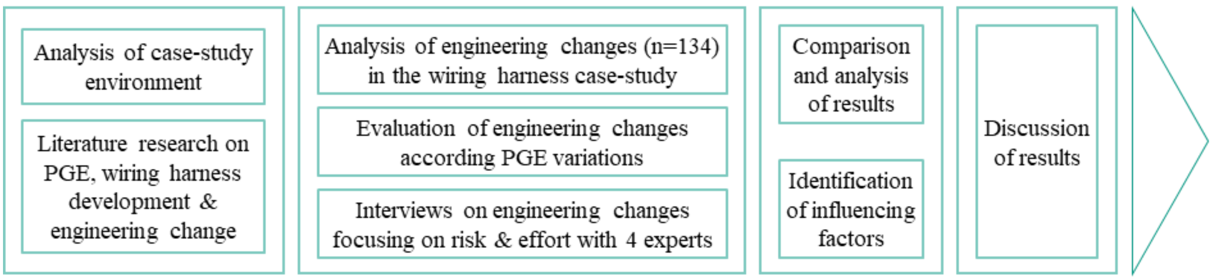

Figure 3. Methodological approach

The case study is based on the door module of an automotive wiring harness. This harness is used with variations in several derivatives of the same mid class platform. It was selected so that it is representative in its size and functions and that it contains engineering changes that occur all over a wiring harness. The observed period of the development process starts with the first physical prototype and the respective released documents of this design freeze. It ends one development generation after the start-

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of-production. The engineering changes that were analysed in this study are recorded at three different points in the development process. During the internal development and specification of the engineering change idea, the first communication with the suppliers and at the point where final decision to implement the engineering change is made. The latest point of documentation in the process with the highest maturity level and data quality was preferentially used for the classification, the interviews and evaluation. Duplicates in the evaluation were eliminated at that point. The information is transformed using a standardised change description. This description with additional information provides the basis for the classification of the variations and the interviews. The classification was based on the existing literature that contains rules as well as examples of variations in development projects (Wäschle *et al.*, 2020; Albers *et al.*, 2015; Albers *et al.*, 2016a) The reference system elements come from either the previous development generation or another variant of the product from a parallel development process. The evaluation of the engineering changes was done through structured interviews with all product experts for this harness. All four experts were asked six predefined questions on each engineering change in separate interviews. Two multiple-choice questions aimed at an evaluation of the effort and risks. More precisely the risk and effort that arise in the implementation of engineering changes in the design and the development process. The open questions were on the type of risk, reasons for conducting the engineering change, the effects of the engineering change and the time needed for an implementation. The experts were provided with definitions of the terms in the questions. All experts are directly involved in the development and change process of the wiring harness, with up to over 25 years of wiring harness specific experience. They all had previous experiences in different parts of the harness development process. The results are depicted in the following chapter. The factors that were identified are based on the information from the open questions in the interviews.

5. Results

The following chapter contains the results from the case study in the first sub chapter. The results of the classification according to the variations of the PGE - Product Generation Engineering in combination with the risk and effort assessment are shown in the second part. The additional factors are discussed in the third sub chapter.

5.1. Engineering changes classification and evaluation

The case study consists of 134 engineering changes. A possible subdivision that provides an overview on the engineering changes is shown in Figure 4. The different types of change are shown on the left side. The type of the parts in the wiring harness that were subject to change are illustrated on the right side. Sixty four percent of the engineering changes concern certain attributes of the parts that are changed. Examples for that are changes in length, colour or diameter of a wire or a variation in the position of a certain part. The type "replace" is closely related to the type "change". However, the focus is not the change of attributes but the change of the part itself that can include a change of attributes.

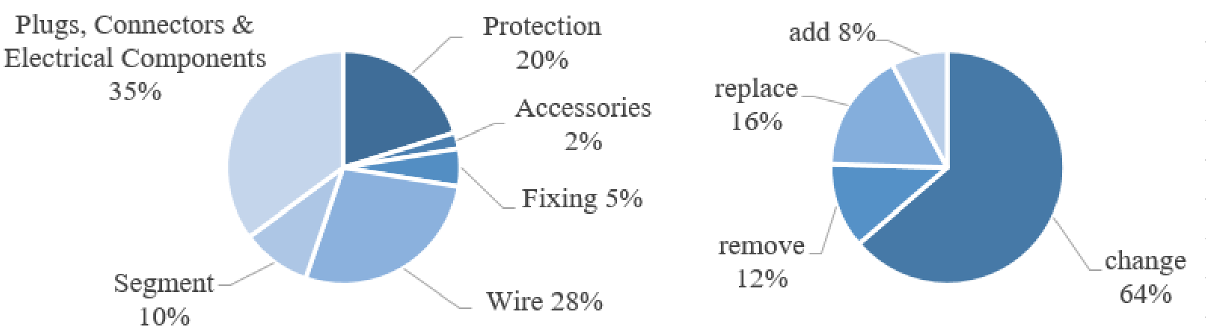

Figure 4. Objects affected by changes (left) and types of changes objects (right)

The objects that are most often affected are individual wires 28% and segments 10%, which are a combination of several wires and their overstocks. The group revered to as plugs connectors and electrical components is the biggest group and concerns the direct connection of electrical components.

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5.2. Comparison of variations with effort & risk

The results of the analysis and the interviews as well as the interrelation between different factors are presented in this section. The engineering changes, their classification according to the types of variations and the evaluation of the risk and effort is depicted in Figure 5. Each of the two graphs shows the distribution of all changes according to the type of variation and evaluation with regard to effort and risk respectively. We see that attribute variations contribute with 53%, carry-over variations the second biggest share with 28,4% and principle variations hold the smallest share with 18,6%. The differences of the percentages in the graphs are due to rounding errors. Carry-over variations are most often linked to low risk and medium to low effort. Attribute variations are also often connected to low and medium risk and effort while having a higher proportion of high risk and effort.

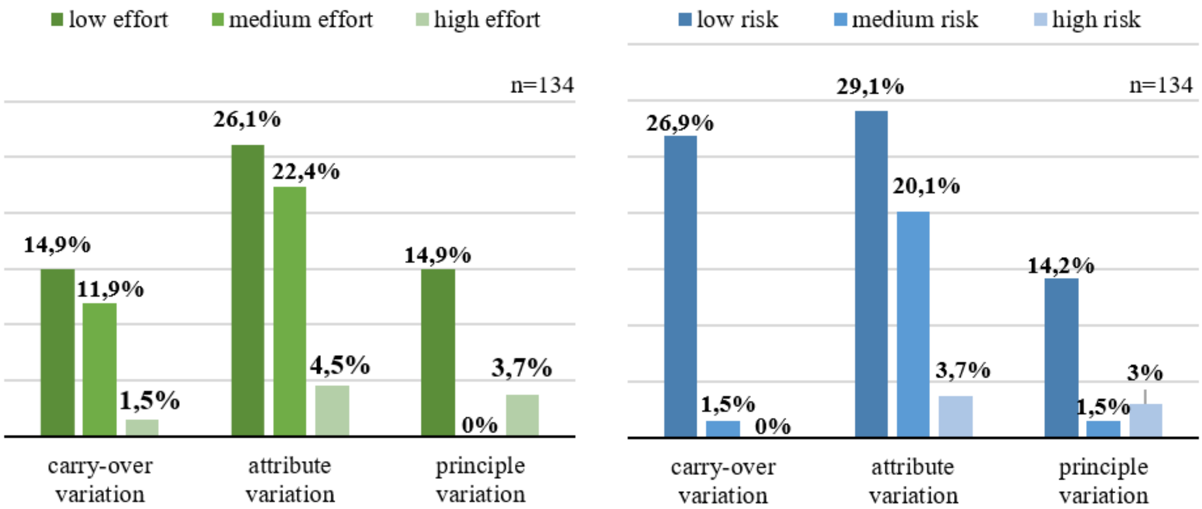

Figure 5. Share of engineering changes according to variation and effort (left) or risk (right)

Principle variations either have a low or high connection to risk and effort while having the highest proportion of high risk and effort. The different proportions of risk and effort connected to the types of variations are depicted in Figure 6. The occurrence of low, medium and high factors is normalised in reference to the total number of engineering changes from each form of variation.

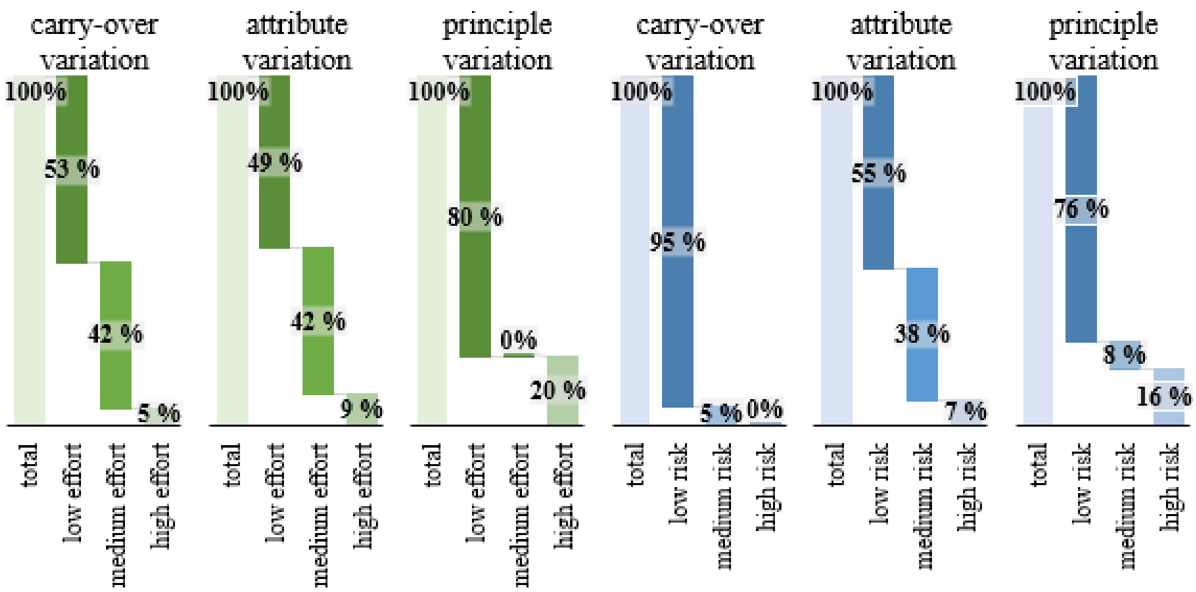

Figure 6. Percentage variation types associated with different levels of risk and effort

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5.3. Additional factors

The answers to the open questions from the expert interviews provide additional factors that help to assess the risk and effort of implementing engineering changes.

Factors that are associated with high risk or effort are the complexity of the part or system that is changed or high coordination effort that is based on the number of stakeholders involved. The number of parts involved is one of the measures that contributes to the complexity, the degree of interdependences and number of relevant boundary conditions. This includes internal teams and divisions as well as the depth of the involved supply chain from direct suppliers called "Tier 1" to indirect suppliers "Tier 3".

In addition, uncertainty concerning buildability and functionality increases the risk and effort. The factor of functionality is especially important for core functions and safety. The experts emphasized the effort and extra care connected to all engineering changes that have a close proximity to safety relevant functions. The possibility of strong negative effects from the engineering change leads to high-risk evaluations. Unclear or unknown boundary conditions and the potential of change propagation were listed as reasons for high risks and effort. Engineering changes that are classified as principle variations and are based on the removal of parts or functions were linked to low risk and effort. Engineering changes that had already been implemented in other projects were also evaluated as low risk. Good communication between the people responsible is a factor that lowers the risk of an engineering change.

6. Discussion

The results and its implications are discussed in this chapter. The structure follows the three research questions.

6.1. Which types of engineering changes arise in the development of the automotive wiring harness?

The engineering changes were sorted according to the objects that were changed, the types of changes and the classification according to the type of variation. Figure 4, Figure 5 and Figure 6 show what changes arose in the development process. The different ways of sorting engineering changes are beneficial from different perspectives. They provide an overview on where the change happens and to some degree on the functions that the object facilitates.

When looking at the objects the case study furthermore shows that most of them (73%) are directly aimed at enabling core function of the system, which is to connect the different electrical components. The rest of the objects that are changed ensure the proper placement, protection and assembly of the wiring harness. The types of activities add a layer of information by providing some more details on the nature of the engineering change and the task necessary to conduct it. Most engineering changes (64%) are adjustments to existing objects, which is not surprising considering that the changes take place during the series development where the system has a relative high product maturity. The structure is altered by 18,6% of engineering changes. Either these changes are due to better knowledge about the structures that require additional or less fixing points, protection of certain parts or they are due to changes in functions and modules that are added or removed. The variation types according to the PGE - Product Generation Engineering provide additional information on the nature of engineering changes. This is done by linking the technical nature of the change to the reference system. This provides an assessment on the novelty and degree of availability of information.

It was possible to classify all engineering changes from the case study according to the PGE - Product Generation Engineering. Principle variations are the least common form of variations; embodiment variations are the most common form of variations; Carry-over variations account for a third of the changes without including the parts that remain the same when compared with the reference system.

6.2. To which extent do the PGE variation classifications predict the risk and the effort associated with the implementation of engineering changes?

The initial evaluation of changes according to the variations gives a good idea of the effort and risk connected with the implementation of an engineering change. Carry-over variations indicate a low risk and effort. The risk and effort increase when the engineering change is classified as an attribute or

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principle variation. However, the variation does not provide the engineer with an explicit value in every individual case but allows a good prediction.
Carry-over variations tend to carry lower risks than embodiment variations and principle variations. This is underlined by the fact that 95% of all carry-over variations are related to low risks, only 5% to medium risks and none to high risks. About 55% of all attribute variations are related to low, 38% to medium and 7% to high risks. This type of variation has a high spread of risks. Engineers should be aware of this and should try to gather additional information. Principle variations have the highest proportion of high-risk evaluations. Extra scrutiny is advised when it comes to those changes. The proportional distribution between the variations and the effort of implementation differs from the connection to the risk of implementation.
Carry-over and attribute variations are similar in regards to the effort that is most often low or medium. It requires a higher effort to implement attribute variations. Principle variations are more often associated with either high or low effort while there are no changes with medium effort but many engineering changes evaluated as low effort concerning the implementation.

6.3. Which factors influence the risk evaluation of individual engineering changes that are analysed?

The factors identified help engineers to be more precise in their first evaluation when simulations or prototypes are not available. The factors are related to additional information about the environment of the change or requirements that are connected to it. The information is based on and therefore limited by the answers from the interviews. The factors can therefore be seen as a start and basis but cannot be viewed as conclusive. Further interviews and research can expand on the factors that were identified.

6.4. Validation

The results show that the variations provide an indication for the risk and effort of an engineering change in the case study presented in this paper that concurs with the expert evaluation. The harness was selected so that it is representative for the rest of the vehicle. The results are therefore also applicable to other parts of the automotive wiring harness. Carry-over variations are most often associated with low risks while attribute variations and especially principle variations lead to medium and high risk and effort more often. This validates the assumptions of the PGE - Product Generation Engineering model as well as the selection of this model in the engineering change management of an automotive wiring harness.
Furthermore, all engineering changes could be classified as variation types based on a standardised description. This shows the applicability of this approach. However, creating a standardised automatic classification or classifying the changes requires well-grounded knowledge of the PGE - Product Generation Engineering model. The prediction that is based on the types of variations together with the identified additional factors provides help to engineers. They get a first idea of the level of risk or effort that might go along with a certain engineering change. This helps engineers who have to deal with engineering changes in development projects where they face uncertainty.

7. Summary

This paper provides an evaluation of engineering changes that helps to assess risks and effort early in the development project. It allows engineers to initiate necessary activities early in the development process. Hence, avoiding errors and modifications in later stages. This reduces time and resources and thereby costs. The findings are based on the analysis of a case study from a development project of an automotive wiring harness. The analysis is based on two pillars. The first is a classification of variation types following the PGE - Product Generation Engineering model. The second one is based on expert interviews that identify the level of risk and effort when implementing engineering changes as well as additional factors. Combining the two pillars or aspects in the study shows that all changes can be classified as one of the three variations in the PGE. The variations also provide an early estimation for the levels of effort or risk when it comes to the implementation of the engineering changes that is predicted by the model. Principle variations tend to be associated with higher levels of effort and risk.

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Carry-over variations have the highest share of low effort and low risk changes. Attribute variations have average shares of low, medium and high risk and effort engineering changes. The research shows that model of PGE - Product Generation Engineering works well in the area of engineering change management and the development of the automotive wiring harness. The quantitative results match the qualitative results from previous research. Thereby supporting the model and the generalisability of the findings. Additional factors that were identified allow a further assessment of engineering changes when additional information are available.

8. Outlook

The assumptions from the PGE - Product Generation Engineering were confirmed and the application of it in the field of engineering change management in the development of wiring harnesses was successful. Engineering changes of other parts of the wiring harness should be analysed to aggregate additional information. This would help to confirm the findings and to add factors and rules in order to support engineers in the wiring harness development. The authors believe that the findings from the case study of the wiring harness development can be transferred. Development projects that focus on other systems should be analysed to investigate the applicability to those systems and compare the results with this study. Further studies should investigate this hypothesis.

An automated evaluation of engineering changes that is based on a standardised description would improve the development process. A standardised description was used as the basis for the evaluation and classification of engineering changes. Automating the process of evaluating engineering changes based on the standardised description would reduce the effort and time needed for the assessment. It would make the process efficient and more effective and engineers could use their time more effectively. It could also help to front-load a part of the development activities by allowing earlier assessments of engineering changes. Further studies should focus and investigate this possible approach.

The paper shows that the variations of the PGE provide a metric that helps to evaluate changes at an early stage. The findings could be used to investigate how the classification according to the PGE could be used to obtain a better evaluation of change propagation in products. It could therefore also be used to predict change propagation at early phases in the product development process. Improving the engineering change management by using the model of PGE - Product Generation Engineering remains an interesting research area.

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