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Data-Based Method for the Implementation Planning of Engineering Changes in the Automotive Industry

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Abstract

Each year, automotive OEMs implement a variety of Engineering Changes (ECs) in their production. In the timing of ECs, different KPIs are often in conflict with one another or even unknown to the OEMs. Therefore, OEMs struggle to identify the optimal date to implement an EC. This paper presents a method to determine the cost-optimal implementation date for each EC, considering time, cost, and quality KPIs based on a new EC classification rule-set. To evaluate the presented method, case-studies at a German automotive OEM were performed, two of which are discussed.

Keywords: engineering change, change management, cost management, implementation planning

1. Introduction

Engineering Changes (ECs) in the product development process are inevitable (Meissner, 2021) and represent *"a rule more than an exception"* (Clark and Fuijmoto, 1991). Changing customer requirements, new regulations and emergent quality issues lead to changes in the product throughout its whole lifecycle (Stekolschick, 2016). This implies high efforts and costs for manufacturing companies. Therefore, the adequate management of these changes, Engineering Change Management (ECM), is a key factor for companies to remain competitive (Schuh et al., 2018). Once an EC has been designed and approved, an adequate implementation is essential to guarantee the success of a product development project (Meissner, 2021) and has been highlighted by Hamraz (2013) as a research opportunity. Especially in industries such as the automotive industry, the implementation of ECs in the production implies high complexity and coordination efforts. On one hand, due to the high degree of connectivity of vehicle components, the dependencies between ECs have to be taken into account in the implementation (Oh and Hong, 2017). On the other hand, in automotive Original Equipment Manufacturers (OEMs) around 85% of the value creation has been delegated to suppliers (Wong, 2017). As a consequence, a global network of stakeholders needs to be coordinated in the implementation of an EC. In addition, vehicles must comply with stringent security and quality regulations (Singer, 2018) and OEMs must be able to trace back all changes and have control of the part numbers built into each vehicle. Within the implementation phase, this paper focuses on its timing aspect, specifically, the selection of an implementation date. In the automotive industry it is especially challenging for two main reasons. In the first place, a wide variety of ECs with different characteristics and priorities needs to be individually managed. Secondly, especially in the series production, it is difficult to identify all the relevant costs and other Key Performance Indicators (KPIs) involved. Because the automotive industry is a mass production system, the number of cars that include an EC and the associated costs are very sensitive to the selected implementation date. Therefore, the objective of this paper is to develop a method to support OEMs in the timing of ECs within the implementation phase. The paper is structured as follows. Section 2 presents the basic definitions on which this paper builds upon. Section 3 reviews the state of the art on EC characterization frameworks and methods for the timing of ECs in the implementation and identifies a research gap. Section 4 develops a data-based method for the implementation planning of ECs to fill the research gap. The method is evaluated at a German automotive OEM and two case studies are described in Section 5. Finally, the conclusions and outlook are presented in Section 6.

2. Basic definitions

The implementation planning is responsible for the determination of the implementation date for each EC and the organization of all related primary activities (Jin and Tang, 2013). According to Balcerak and Dale (1992), the implementation date can be interpreted in various manners. In this paper, it is the date when the first product with the new parts is assembled. Authors like Jin and Tang (2013), Barzizza et al. (2001), Shiau and Li (2009) and Balakrishnan and Chakravarty (1996) have proposed different strategies to determine this date. (1) *"As soon as possible"* strategy: implementation of the EC as soon as it is technically possible. It is used for very urgent ECs like issues that affect passenger security. (2) *"Pre-defined date"* strategy: it is mandatory to implement the EC on a given date that depends on external factors to the EC itself, for example a new regulation. (3) Optimization strategy: implementation of the EC on the date that results from an optimization problem that includes time, cost and quality KPIs. This procedure is called *"use-up technique"* in the literature, since only scrapping costs are considered.

In addition, the implementation of ECs in groups or batches is a strategy proposed by Oh and Hong (2017) to deal with changes in complex products with multiple sub-systems and high probabilities of change. The batching of ECs for coordination reasons is inspired in the software industry strategy known as *"sync-and-stabilize"*, where different teams work on different software modules that are tested together on a periodical basis throughout the development process (Cusumano and Selby, 1998). Analogously, in the automotive development process different teams work on different vehicle modules that are integrated into pre-scheduled construction phases. ECs are then accumulated and implemented as a batch in the next release or product version (Wänström and Jonsson, 2006). However, this can also be done during the series production, since ECs can also be implemented in batches on a periodical basis within a certain product version (Bhuiyan et al., 2006). This reduces coordination efforts and simplifies the traceability of ECs.

3. State of the art

Following the framework for literature reviewing proposed by Vom Brocke et al. (2009), 392 results were obtained from a keyword literature search in *Scopus* and *Web of Science*. Through a progressive analysis of the titles, abstracts and full texts, and a backward and forward search, nine works related to either the classification of ECs or the implementation planning have been filtered. Four of them, Stekolschik (2016), Wänström et al. (2006), Balcerak and Dale (1992) and Pimentel Barroso (2019), focus on the determination of categories of ECs depending on their characteristics. These, however, aim to determine process-related aspects such as the number of steps to follow or the number of people to involve, and do not address the timing aspect of the implementation phase. For example, Stekolshick (2016) characterizes changes according to the implementation effort (high or low) and to the change impact on manufacturing and supply chain (local or global). Depending on these characteristics, the number of process steps to be followed varies. None of the four methods proposes a characterization that allows to determine an implementation strategy or date. The remaining publications present different implementation strategies, but they either do not focus on the timing aspect, or do so in a qualitative manner, as in the works of Jin and Tang (2013), Schuh et al. (2013) and Bhuiyan et al. (2006). Balakrishnan and Chakravarty (1996) do present an optimization model to find the optimal date to release a new product. However, in this model all product changes are implemented on the same date, the release date, and it is not possible to individually optimize each EC that arises during the product lifecycle. Barzizza et al. (2001) distinguish three categories of ECs to manage in the implementation phase: scrap (when the introduction of the change leads to a scrapping of the pre-change parts), rework

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(when the pre-change parts can be reworked to include the new characteristic) or *"use-as-is"* (when the pre-change parts and EC parts are interchangeable). This last category can take place with or without a cost reduction for the new parts in comparison with the old. The categories scrap and rework should be implemented as soon as possible. The ECs categorized as *"use-as-is"* should be implemented at minimal costs. These costs include scrapping costs and cost reductions. However, the three categories do not cover all the cases that the automotive industry handles, such as regulations or change propagation, and the optimization model lacks important cost elements of this industry, like warranty or complexity costs. To summarize, none of the EC characterization frameworks covers the wide scope of ECs managed in the automotive industry, and a structured representation of the KPIs that are relevant for the timing of ECs at an automotive OEM has either been found. To address the identified shortcomings, a data-based method for the implementation planning of ECs in the automotive industry is developed in this paper.

4. A data-based method for the implementation planning of ECs

The development of this method has been guided by the CRISP-DM (Cross Industry Standard Process for Data Mining) methodology. In the initial phase, the business understanding, the aim was to identify the relevant change attributes that define the categories of ECs managed in the automotive industry, the possible implementation strategies at an OEM and the relevant KPIs for the implementation phase. Based on the literature and nine semi-structured interviews with change management experts of a German automotive OEM, the main goal of this paper is to support automotive OEMs in the implementation planning of ECs, in order to increase effectiveness and efficiency and contribute to the overall profit of the company. To successfully achieve this goal, the following objectives for the method have been defined:

- Support the timing of ECs by selecting the adequate implementation strategy and optimal implementation date.
- Identify the different categories of ECs managed at an automotive OEM.
- Increase transparency by considering all relevant time, cost and quality KPIs.

The method developed to address these objectives consists of two main steps which are represented in Figure 1 and are further explained in this section.

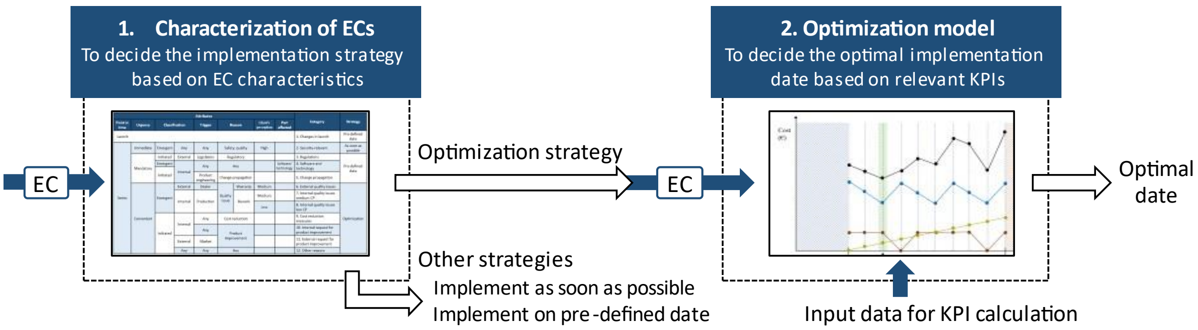

Figure 1. Overview of the method

4.1. Characterization of ECs

Not all ECs that are approved should be implemented in the same way. The adequate implementation strategy depends on the characteristics of the EC. A characterization of ECs is an essential step to achieve the ultimate objective for which an EC was approved. To develop a framework for the characterization of ECs, a list of 21 attributes from the literature and the industrial practice was presented to nine experts belonging to the divisions involved in the ECM process: development, production, and procurement. The interviewees rated the importance of each attribute as high, medium, low or irrelevant for the implementation planning from their perspective of the process. As a result of these ratings, six relevant change attributes were determined: point in time (launch or series production), urgency (immediate, mandatory or convenient), trigger (e.g. customers, legislators), reason (e.g. quality issue, cost reduction), the client's perception of a quality issue, and the part affected by the EC. The urgency

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attribute is understood according to the EC classification by Diprima (1982). In the next step, the six attributes have been combined to define twelve categories of ECs and the adequate implementation strategy for each (Table 1). The classification of emergent/initiated ECs and external/internal triggers, widely present in the literature (Jarratt et al., 2011), has supported the categorization.

Table 1. EC attributes, categories and strategies

Attributes: Point in time	Urgency	Classification	Classification	Trigger	Reason	Reason	Client's perception	Part affected	Category	Strategy
Launch									1. Launch	Pre-defined date
Series	Immediate	Emergent	Any	Any	Safety issue		High		2. Security-relevant	As soon as possible
	Mandatory	Initiated	External	Legislators	Regulation				3. Regulations	Pre-defined date
			Internal	Any	Any			Software/ technology	4. Software and technology	
		Emergent		Product engineering	Change propagation				5. Change propagation	
	Convenient	Emergent	External	Dealer	Quality issue	Warranty	Medium		6. External quality issues	Optimization
			Internal	Production		Rework	Medium		7. Internal quality issues medium client perception	
							Low		8. Internal quality issues low client perception	
		Initiated	Internal	Any	Cost reduction				9. Cost reduction measures	
				Any	Product improvement				10. Internal request for product improvement	
			External	Market					11. External request for product improvement	
			Any	Any	Any				12. Other reasons	

The ECs that follow the *"pre-defined date"* strategy are those that belong to categories 1, 3, 4 or 5. ECs during the launch phase of a product must be implemented on the dates where a prototype build is planned, whereas ECs associated to legislative topics must be applied on the date defined by the regulation. Due to the degree of connectivity, software and technology-related ECs and change propagation topics are also implemented simultaneously on pre-defined dates. The *"as soon as possible"* strategy is followed by ECs that arise to solve an urgent security-relevant issue (category 2). Finally, all remaining categories (6-12) are candidates for the optimization strategy and are considered for the second step of the method where several KPIs are taken into account.

4.2. Identification of relevant KPIs

The ECs that have no particular characteristics that lead to an implementation as soon as possible or on a specific date, need further analysis in order to find an optimal implementation date that takes time, cost and quality aspects into account. An overview of the considered KPIs in each dimension, obtained from the literature and expert interviews, is presented in Figure 2.

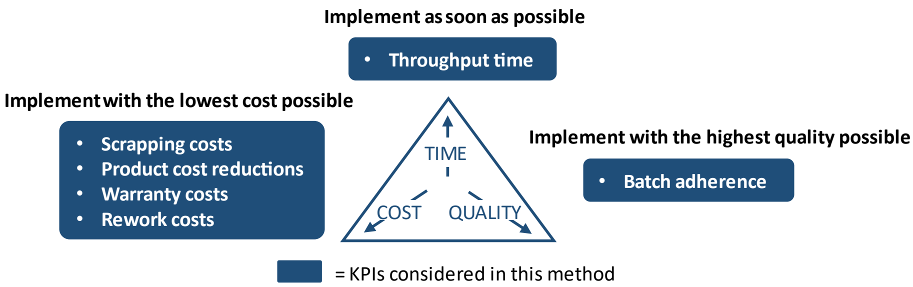

Figure 2. Relevant time, cost and quality KPIs

The time dimension is optimized by minimizing the throughput time (TT) between EC approval and EC implementation in the first vehicle. For the selection of cost-related KPIs an important criterion is the

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date-dependency. For example, tool costs associated to an EC are not considered, since they remain constant if a change is implemented one week earlier or later. On the contrary, costs like scrapping costs (SC) experience daily variations, since they are directly proportional to the inventory level. Warranty costs (WC) and rework costs (RC) both increase proportionally to the number of vehicles assembled. The later an EC is implemented, the more vehicles with the defect are produced and the higher the WC and RC are. Finally, product cost reductions (PCR) are meant to introduce cost savings from the moment the EC is implemented. For each delivery of old parts without the EC, the benefits of the cost reduction are not being realized, resulting in opportunity costs for the OEM. The graphical representation of the cost-related KPIs is presented in Figure 3 (left).

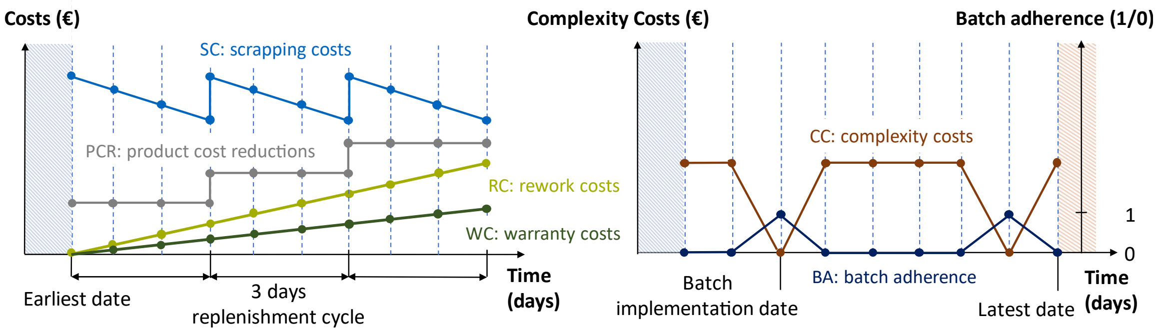

Figure 3. Graphical representation of the KPIs

The automotive industry is characterized by a high complexity due to the high number of possible vehicle variants and coordination required (Jania, 2004). Moreover, OEMs must be able to trace back what version of each part has been implemented in each vehicle. As presented in Section 2, an option to both reduce complexity and facilitate traceability is the EC batch implementation on a periodical basis (Bhuiyan et al., 2006). The batch adherence (BA) is a binary KPI that is 1 when an EC is implemented on the dates when a batch is planned, and 0 otherwise. In this paper it is considered an indicator of the quality in the implementation. Since the BA is a measure of the ability of a company to minimize its complexity costs (CC), the CC can be derived from the BA by assigning a monetary cost or fine to the *"non-batch adherence"*. This cost includes the extra coordination and documentation efforts that arise from implementing an EC individually outside a batch. As a guide, the monetary value of implementing inside a batch could be seen as the amount of money for which a manager is willing to accept the implementation of an EC outside its corresponding batch. The BA and CC are represented in Figure 3 (right). Finally, depending on the category an EC belongs to, the relative importance of time, cost and quality KPIs differs. Table 2 shows the KPIs that are relevant for each of the twelve EC categories.

Table 2. EC categories and relevant KPIs

Category		KPIs: Cost				Time	Quality	Implementation strategy
		SC	PCR	WC	RC	TT	BA/CC	
1.	Launch						x	Pre-defined date
2.	Security-relevant					x		As soon as possible
3.	Regulations						x	Pre-defined date
4.	Software and technology						x	
5.	Change propagation						x	
6.	External quality issues	x		x	x	x	x	Optimization
7.	Internal quality issues with medium client perception	x			x	x	x	
8.	Internal quality issues with low client perception	x			x		x	
9.	Cost reduction measures	x	x				x	
10.	Internal request for product improvement	x					x	
11.	External request for product improvement	x				x	x	
12.	Other reasons	x					x	

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4.3. Optimization model

For the categories where more than one KPI is relevant (categories 6-12), an optimization problem is formulated. The decision variable is the time variable (measured in days, *d*), since an implementation date is what is aimed to be determined. The objective function is a cost function to be minimized. This cost function is measured in monetary units and is the sum of all cost-related KPIs that apply in each case: SC, PCR, WC, RC or CC. The total costs have to include the costs for all part numbers (*n*) and plants (*p*) affected by an EC. *N* is the set of part numbers affected and *P* is the set of plants affected. The general expression of the objective function is shown in Equation 1:

$$Min\ Total\ Costs = \sum_{p} \sum_{n} \left[SC_{p,n}(d) + PCR_{p,n}(d) + WC_{p,n}(d) + RC_{p,n}(d) + CC_{p,n}(d)\right] \quad \forall p \in P, \forall n \in N \tag{1}$$

Equations 2-6 represent the cost-related KPIs for a certain *p* and *n*, as a function of *d*:

$$SC(d) = SC\,(d-1) + \left(NPD(d) - NPA(d)\right) \cdot P_o \tag{2}$$

$$PCR(d) = PCR\,(d-1) + NPD(d) \cdot \Delta \mathrm{P} \tag{3}$$

$$WC(d) = WC\,(d-1) + NPA(d) \cdot \%\,defect\ \cdot C_w \tag{4}$$

$$RC(d) = RC\,(d-1) + NPA(d) \cdot \%\,defect\ \cdot C_r \tag{5}$$

$$CC(d) = \begin{cases} 0 & if\ d\ is\ a\ batch\ date \\ C_C & otherwise \end{cases} \tag{6}$$

Being *NPD* the number of parts delivered, *NPA* the number of parts assembled, P_o the price of the old parts, ΔP the difference in price between old and new parts, *% defect* the percentage of parts affected by the defect, C_W the cost of one warranty case, C_r the cost of reworking one part, and C_C the extra complexity costs for implementing an EC outside a batch. As a constraint, an implementation date can only be selected among the days where production takes place, leaving out weekends, holidays and production stops for maintenance. This constraint does not have to be explicitly included, since on holidays *NPD* and *NPA* are zero and the objective function remains constant. In addition, for each individual EC there is an earliest possible implementation date (EPID) before which it is technically not possible to implement the change. The three major factors that determine the EPID derived from the expert interviews are: the impact (number of parts and derivatives impacted by an EC), the logistical relevance (geographical distance between plants and supplier sites), and manufacturing relevance (change of tool at the OEM or supplier). Finally, some categories may include a latest implementation date (LID) which is considered acceptable to satisfy customer expectations. A LID sets a limit to the throughput time and is a way of considering this KPI in categories 6, 7 and 11. These two constraints are formulated in Equations 7 and 8:

$$d \geq EPID \tag{7}$$

$$d \leq LID \tag{8}$$

The decision variable, the objective function and the constraints are represented in Figure 4.

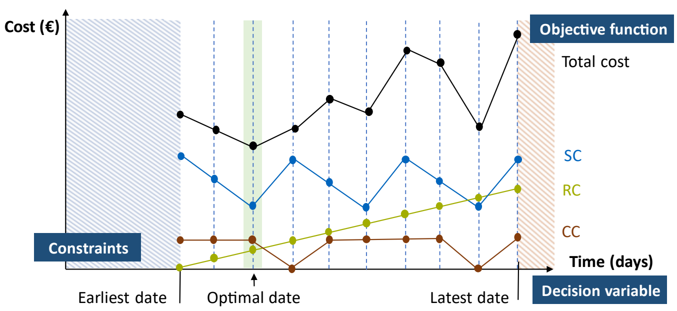

Figure 4. Graphical representation of the optimization problem

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The input data required in the different parts of the optimization model comes from three main sources: the Product Data Management (PDM) system (EC attributes, part numbers affected and plants affected), the Manufacturing Resource Planning (MRP II) system of each plant (parts consumed and delivered per day, inventory levels, price of the parts), and other IT systems depending on the company (percentage and costs of warranty and rework cases). As explained in this section, some parameters also need to be estimated by the user, such as the earliest and latest implementation dates and the complexity costs. In addition, in the contracts with the suppliers an earliest possible date to cancel a delivery could be provided. If a delivery is cancelled, the *NPD(d)* function changes. The purpose of cancelling deliveries is to bring inventories to zero as soon as possible to implement earlier and with lower costs. The optimization problem that considers this optional variable is explained in more detail in case study 2.

5. Case studies

In design research, the evaluation of the developed artefact represents a crucial step for further iterations in design. Following the CRISP-DM methodology, after the modelling of the presented optimization model, an MS Excel prototype has been developed and evaluated. This evaluation aims to assess the validity of the method in the industrial practice as a proof of concept. The selected evaluation method are case studies that make use of real ECs provided by the partner automotive OEM. Two of them are presented in this paper. As a general context, the partner OEM implements changes in batches, not on a single date, but within an interval of dates to give the suppliers and plants more flexibility for ECs that are not critical. However, the ECs in critical parts (e.g. airbags), software or technology-related changes, and change propagation cases must be implemented simultaneously on a pre-defined date within the interval. Currently, the company uses the SC and BA as the criteria to decide an implementation date.

5.1. Case study 1: small component with a quality issue

Case study 1 (Figure 5) analyzes an EC triggered by the customer and whose source is a quality issue that involves warranty (30€/car) and rework costs (1€/car). Only 0,6% of the customers claim a warranty for this specific issue. The EC belongs to category 6, external quality issue. Without using this method, the OEM would implement this EC when the SC are close to zero (planned implementation on day 45), within implementation batch 3. An earliest possible implementation on day 1 and complexity costs of 500€ have been considered in both case studies.

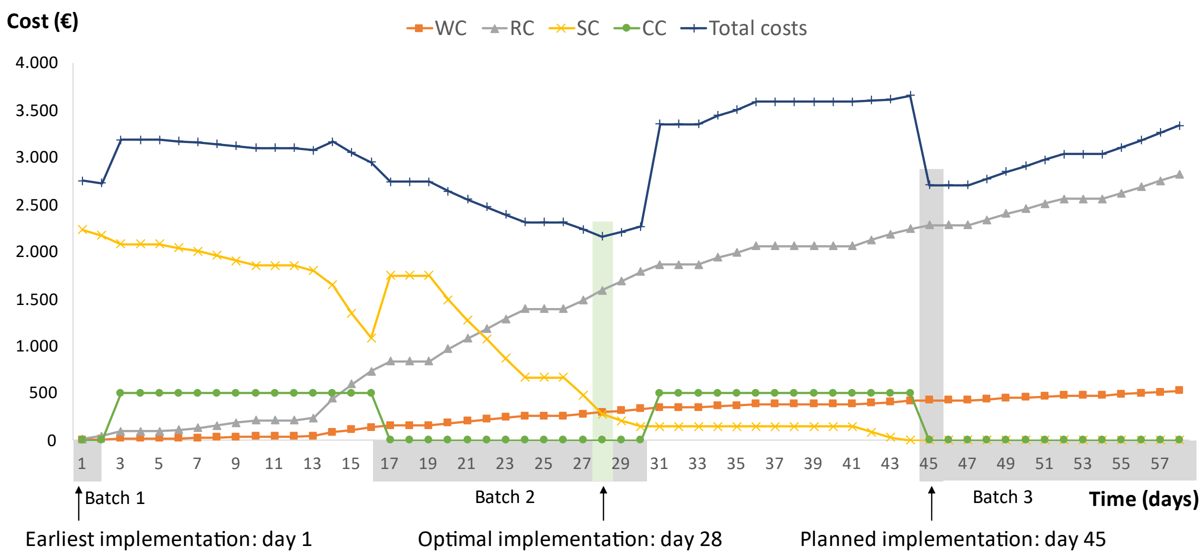

Figure 5. Results of the optimization problem in case study 1

After applying the optimization model, the optimal date is day 28, which falls inside implementation batch 2. By moving the implementation two weeks earlier, 20% of the implementation costs that are

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date-dependent can be saved. In this case, the savings come from WC and RC. CC do not affect this particular example because both dates have 0€ in CC.

5.2. Case study 2: cost reduction measure on a large component

Case study 2 deals with a cost reduction measure (category 8) triggered by the development department during the series production. The price of a part is reduced 35 cents and there are no quality issues associated with this EC. Because of the lack of urgency, this EC has been dated several months in the future (planned implementation on day 173), and the case study makes use of average delivery volumes and part consumptions. Deliveries take place every two days. Figure 6 shows that the SC are notably larger than the opportunity costs that arise from a late implementation of the PCR measure. Therefore, the minimum of the total cost function is strongly influenced by the minimum of the SC function. The SC function reaches its minimum on the planned implementation date (day 173) because no deliveries are planned on the previous two days, making the SC decrease notably.

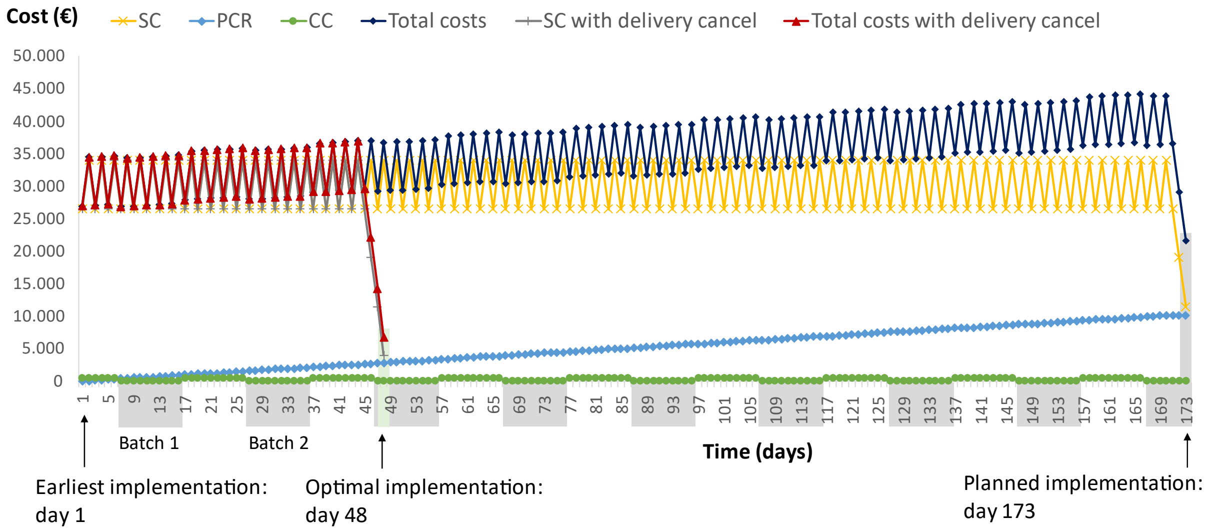

Figure 6. Results of the optimization in case study 2

In this case study, the contract with the supplier of the component affected allowed a cancellation of deliveries and the parameter *"earliest possible delivery cancel"* (EPDC) is taken into consideration. The EPDC is on day 43. The delivery cancellation date is a new decision variable that can be modified to find an optimal solution. Several scenarios have been analyzed and compared. The optimal solution is the best of all scenarios. The first scenario consists in cancelling all deliveries starting on the first possible date (day 43). The second scenario maintains the delivery on day 43 and cancels the second possible delivery (day 45). The third scenario maintains the two deliveries and cancels from day 47 onwards. For the three scenarios, the implementation takes place some days later, when the inventories are closer to zero. The summary of the three scenarios is shown in Table 3.

Table 3. Scenarios for delivery cancellation

	Scenario 1	Scenario 2 (optimal)	Scenario 3
Delivery cancellation date	Day 43	Day 45	Day 47
Implementation date	Day 46	Day 48	Day 50
SC (€) PCR (€) CC (€)	3.960 2.618 500	3.960 2.856 0	3.960 2.975 0
Total costs (€)	**7.078**	**6.816**	**6.935**

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In this example, the effect of the CC is appreciated. Generally, cancelling the first possible delivery leads to the optimal solution. However, in this case, cancelling the second possible delivery allows the OEM to meet a batch implementation interval and avoid the CC. Therefore, scenario 2 on day 48 is the optimal one, which represents a reduction of 68% of the costs compared to the original scenario without cancelling deliveries (Figure 6). The number of scenarios considered should be large enough to include the transition from non-batch to batch implementation. It can be concluded that he major contributor to cost reduction is the possibility to cancel deliveries, whereas the scenario selection will have a major or minor influence on the costs depending on the specific case.

6. Conclusions and future work

The major contribution of this model is that it provides an optimal implementation date by using data that can be found in the systems of any OEM. Implementing on the optimal date for each case is the objective of decision making in the implementation planning and achieving this means an increase in effectiveness. The case studies have shown that the integration of all relevant KPIs into one model allows the user to know what the primary driver for cost in each particular case is, which does not necessarily have to be the SC, as is being currently assumed in the practice. Furthermore, the optimal implementation date comes along with considerable cost savings in comparison to the original date planned by the OEM (20% in case study 1 and 68% in case study 2). In addition, a potential for increase in efficiency (both in time and human resources) has also been identified. With a further development of the tool in which the data integration from the different sources is automized, a large amount of time could be saved for the implementation planners, since a recommendation about the optimal target date for different scenarios could be automatically generated. The reduction of the workload for the implementation planners also means a saving in human resources. Finally, the transparency delivered by this method can also be translated into efficiency in communication and discussions.

The main limitations of this method are the lack of integrated data from the supplier network to determine the EPID with precision, as well as a qualitative approach in the estimation of the complexity costs. Also, the generalization of relevant KPIs for the automotive industry is limited by the fact that the interviews were carried out within the same OEM. Additionally, the optimization only considers individual ECs and technically dependent or connected ECs cannot be analyzed as a group with this method. A further limitation is that alternatives to scrapping have either been considered. Certain types of parts could be used as spares or replacement parts and be resold instead of scrapped.

Concluding, to achieve the goal for which an EC is initiated, all steps in the change management process have to be considered to guarantee the success of a product development project. This paper presents a method to increase effectiveness and efficiency in the implementation phase of ECM, especially relevant for complex industries like the automotive industry. Through a characterization of changes, ECs are divided into categories that require a different implementation approach. In this way, ECs are managed individually and according to their purpose and specific characteristics. Through the formulation of an optimization problem, an optimal implementation date can be found for those ECs where time, cost and quality aspects need to be balanced. This paper has developed a method to support the implementation planning of ECs and a first prototype has been tested at a major German automotive OEM. A potential for effectiveness and efficiency increase has been identified, as well as a contribution to the overall profit of the company by enabling cost savings. As future work, the precision of the optimization model should be improved. Three main fields are proposed. The first one is a study of the complexity costs in the implementation phase of ECM, especially to identify the main influence factors. The second one is the data integration from the supplier network, since currently the EPID is qualitatively estimated by the user. A data integration from the supplier and transport network would allow to quantitatively determine the minimum number of days for the supply chain to be able to deliver the new parts. The third field is the validation or extension of the relevant KPIs through an analysis of other automotive companies.

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