World Academy of Science, Engineering and Technology
International Journal of Industrial and Manufacturing Engineering
Vol:15, No:9, 2021

An Approach to Capture, Evaluate and Handle Complexity of Engineering Change Occurrences in New Product Development

Mohammad Rostami Mehr, Seyed Arya Mir Rashed, Arndt Lueder, Magdalena Mißler-Behr

***Abstract*—**This paper represents the conception that complex problems do not necessary need similar complex solutions in order to cope with the complexity. Furthermore, a simple solution based on established methods can provide a sufficient way dealing with the complexity. To verify this conception, the presented paper focuses on the field of change management as a part of new product development process in automotive sector. In the field of complexity management, dealing with increasing complexity is essential, while, only non-flexible rigid processes that are not designed to handle complexity are available. The basic methodology of this paper can be divided in four main sections: 1) analyzing the complexity of the change management, 2) literature review in order to identify potential solutions and methods, 3) capturing and implementing expertise of experts from change management filed of an automobile manufacturing company and 4) systematical comparison of the identified methods from literature and connecting these with defined requirements of the complexity of the change management in order to develop a solution. As a practical outcome, this paper provides a method to capture the complexity of engineering changes (EC) and includes it within the EC evaluation process, following case-related process guidance to cope with the complexity. Furthermore, this approach supports the conception that dealing with complexity is possible while utilizing rather simple and established methods by combining them in to a powerful tool.

***Keywords*—**Complexity management, new product development, engineering change management, flexibility.

I. Introduction

THE increase of complexity in business environment implies more complex internal transactions in every section of a company. High complexity affects the decision behavior in a negative way and leads to inefficiency. This is mainly reasoned by the mangle of traditional management approaches focusing on problems in an isolated and a linear way. Considering the research focus of this paper, two main issues appear while dealing with complexity in EC:

(1) There are many established methods and recourses in companies that represent useful tools but are not suitable in the conventional and isolated way of use in order to cope with the increasing complexity or including it to the decision-making specially in the EC process.
(2) The EC process is rigid and therefore is not matching complexity and its features.

This paper offers a rational linkage of established methods and recourses considering their usefulness within the scope of complexity management, following the fundamental philosophy by solving complex problems with relatively simple solutions and efficient use of available recourses. In order to solve these two issues, following requirements can be deduced for the solution approach. First, the necessity regarding EC from a system point of view will be evaluated. The systemic perspective provides the main framework for complexity management. Secondly, the EC process has to be framed more flexible to be able to cope with the complexity. Later in this paper, the requirements will be defined.

Complexity is often described as a systems attribute, thus a host of different system components (variety), which are related to each other (connectivity) and can alter over time. The main issue of complex systems is the enormous non-transparency and the consequential unknown causes and effects [1]. Dealing with complexity successfully means ensuring sufficient transparency and flexibility in order to handle the existing complexity.

Proceeding this paper, the authors analyzed the usage of system thinking in the automotive industry focused on the New Product Development (NPD) Process [2]. In this context the system consists of new products, processes and resources needed to produce a new product. In common NPD processes, a product is developed concurrently by emerging processes and resources based on engineering processes, Fig. 1. Although engineering processes may differ in different organizations, engineering change management (ECM) is indispensable as one of the most important elements of these processes. Also, from a system point of view, ECM can be considered as a sub-system of NPD. ECM is a highly complex process [3] and covers adjustments and modifications during NPD and afterwards, meaning a new replacement technical condition called EC [4]. Hamraz et al. [5] give a literature overview of 427 publications addressing EC as well as ECM and categorize these within the following three main topics:

- Pre-Change Stage - Publications in this topic focus on people, process or product-oriented research to reduce the impact of EC.
- In-Change Stage – Publications in this topic focus on organizational issues, strategic guidelines or tools & methods to ease the handling of EC.
- Post-Change Stage – Publications in this topic focus on temporal, qualitative or cost-oriented impacts of EC for

M. Rostami Mehr is with Volkswagen AG, Germany (e-mail: m.rostamimehr@yahoo.com):

future learning.

Thus, it appears that ECM and EC are a highly explored topic, but this has rarely been in the context of complexity. Li has investigated ECM in NPD in the context of complexity management to provide an answer to the question of how the resources of NPD can be allocated to ECM in an optimal way [6]. Störm has studied EC in order to improve the lead time of information transfer and analyze the impact of lean product development for the improvement of EC [7]. Also, Eger et al. explore the interaction of design engineering and other involved parts in order to reduce the cost of changes in product [8]. Reddi et al. have analyzed the interaction between NPD and ECM to understand which parameters and actors are involved when this occurs. It is shown that there are no methods or tools provided in order to deal with complexity in NPD and form an efficient ECM process [9]. Although researchers such as Leng et al. or Subrahmanian et al. have studied ECM in complex NPD situations [10], [11], the ECM processes − such as basic reference processes e.g., the German Association of the Automotive Industry [12] – do not imply complexity either and are relatively rigid in design. Therefore, it is not clear how to form flexible ECM processes for complex NPD where engineers are able to select an EC process based on the current condition of an NPD project, in order to adapt the evolved processes and resources for changes in product. Aside from flexible EC processes, a tool for assigning priority in implementing EC is also missing. Kocar and Akgunduz introduced a priority index for comparing changes with each other, but there remains no method or tool for assigning priority in evaluating the processes of change [13].

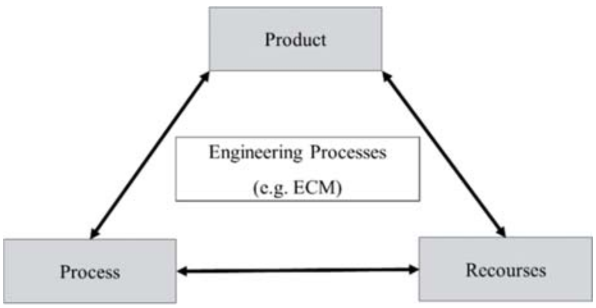

Fig. 1 ECM in the context of the PPR-Process

Ignoring complexity leads to a missed opportunity in terms of the potential competitive factor. Additionally, the negligence may result in extra costs, diminished quality or loss of time. In other words, negative impacts on basic business criteria such as time-to-market or profitability are anticipated. This conception assumes complexity as a comprehensive effect which occurs at and affects different levels of a system, see Fig. 2. This paper ties in with this perspective regarding the necessity of including complexity as an essential factor for the estimation of EC. Therefore, in the following chapters, some fundamental information about NPD and ECM is provided. These two complex systems will form a basis to approach a solution, which will be established incrementally, step by step. First of all, the relevant requirements of the approach will be deduced and further explained. Based on this, the main solution approach will be realized in 3 correlated components:

(1) Evaluation of complexity – Systematic gathering of the system components and potential interactions (system thinking) as well as successive dedication of these in the main cluster (complexity catalogue).
(2) Evaluation process – Selection of a suitable method for evaluation of the complexity catalogue in order to estimate every EC by means of its potential complexity.
(3) Case related process guidance – Defining different strategies to effectively and flexibly handle the estimated complexity of each EC.

The presented approach can be classified as a tool to ease the handling of EC in the change stage [5]. The added value lies in the explicit aspect of complexity within EC and its inclusion in the solution.

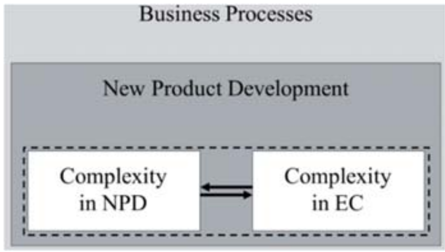

Fig. 2 Hierarchically structured perspective of the system and complexity of EC

II. Complexity in NPD

NPD processes are sequences of activities and steps that an enterprise applies to conceptualize, construct, and commercialize a product. These steps and activities are mostly mental and organizational rather than physical [14]. If NPD processes are considered as a system which has a product as an output by response to demand from a market, the nature of dependencies within this system is a significant driver of complexity [15]. This is a significant part of the car-manufacturing process and includes the organizational units of product development, production, purchasing, sales and marketing, and finance, Fig. 3. Overall processes include high-level hierarchical processes, such as strategy etc. IT systems consist of all IT hardware and software such as PLC (Product Life Cycle) management systems, data banks, servers, etc. Under every organizational unit, the corresponding processes and their interrelations in the context of system engineering can be applied; in fact, the number of processes in some cases, such as in automobile industries, can exceed 1,000 [1]. This interrelation, especially in large projects in the automobile industry, results in enormous information flow. In addition to the high number of processes and interdependencies, product complexity can be categorized under NPD processes. In the industrialization era, most products comprise a high number of connected parts or elements that undergo rapid changes [16]. Products are characterized by a large number of variants due to the mass-customization paradigm. Another feature of NPD processes in recent decades is uncertainty regarding the time-to-market, market demand, fluctuation of demand, available technology, speed of development of new technologies, and the required resources such as human resources and capital [17]. With the presence of features such as uncertainty and a high number of involved, interrelated processes and dynamics, NPD processes can be categorized as a complex part of an enterprise.

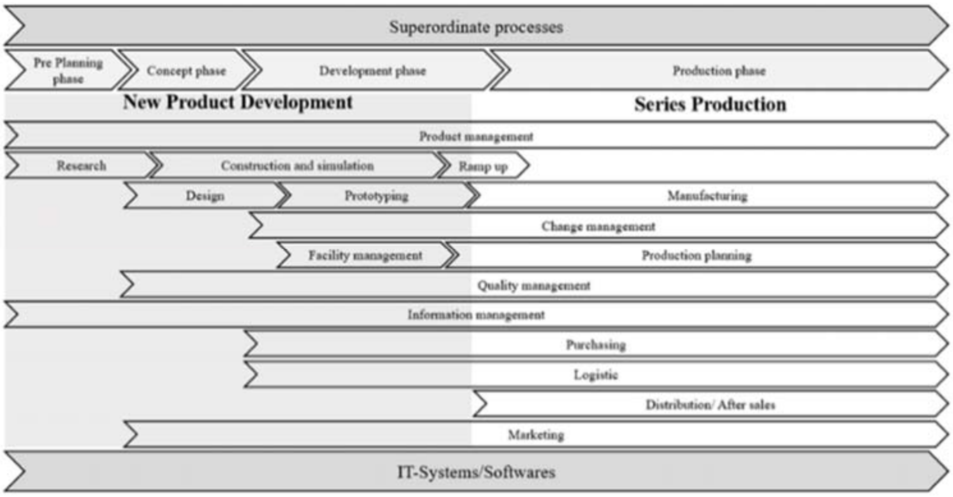

Fig. 3 Business processes of a car manufacturing company (derived from [18])

From another perspective, business processes of car manufacturing include two main interrelated blocks (in other words, there are two main components in the context of system engineering): product development and production development, Fig. 3. In the traditional engineering approach of Taylorism, the successor process can start only when its predecessor is completed. In this approach, the production planner receives considerably complete information regarding the product from the product developer and transfers the complete planning information to the next block after completing their own activities—this prolongs the development time and consequently the time-to-market. To keep competitiveness alive, it is vital to reduce the time-to-market. Recently, the approach of simultaneous engineering (SE) or cross enterprise engineering (CEE) has been introduced in the context of NPD [19]. Parallelism, distribution, and connection of product and production starts in the early phase of development. On the one hand, these approaches support the enterprise in reaching the goal of reducing the time-to-market while decreasing the cost of development [20]. On the other hand, they drastically increase the information flow and uncertainty, due to the mutual dependencies between the organizational units that are responsible for the development of products and production, even though the involvement of production development in the NPD project, and accordingly the mutual dependencies, starts in the early phase of NPD.

In the early phase, product engineers design, construct and build the first prototype, at the same time as production engineers plan production facilities. By product release, the production planner releases the planned facility and a supplier constructs and builds the production plant. After the product-release milestone, prototyping and testing of product will occur. From one side, if design engineers found a problem or an opportunity for product optimization at this stage, the product change would take place. As an example: the reinforcement of a car body to optimize crash test behavior can be mentioned. In some cases, this optimization will require adding a new component or new joining elements in the car body. From another side, if the supplier of production planning found a problem regarding manufacturability or optimization possibilities, the request for product change could be issued. For instance, if a supplier discovered a problem with manufacturing tools colliding with the product or having accessibility issues in joining components, the request for product change may be issued.

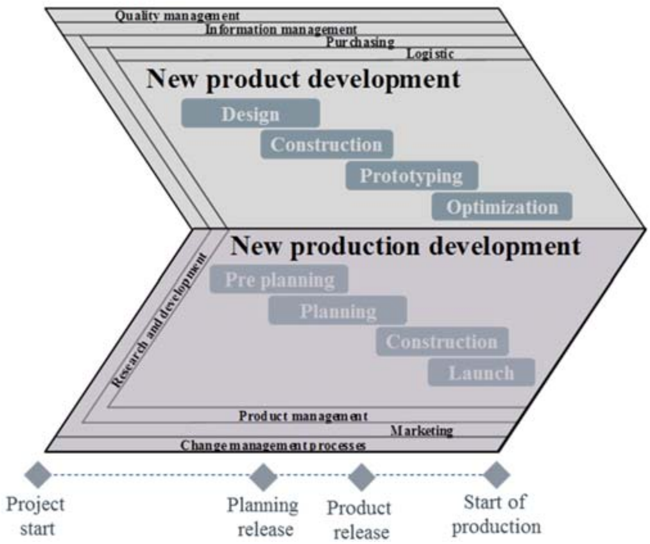

Fig. 4 Product and production processes of a car manufacturing company

In the development processes of a car different organizational units are involved in internal interaction while, due to the nature of product, within the organizational units themselves there are several tailored divisions such as press shop, body shop and assembly shop engaged in development processes. This makes NPD and change management processes in the automobile industry much more sophisticated than in other industries.

III. Complexity in ECM

As mentioned in the previous section, changes are a significant part of the product lifecycle. Thus, coping with changes to product or product-related processes is conditionally essential for the success of the company [23]. Changes in NPD in particular are often illustrated as a sub process, while Fricke et al. [21] describe NPD in its entirety as a continual change management. More specifically, in an industrial context, EC comprises adjustments or modifications of the structure (e.g., shape or pattern), behavior (e.g., stability) or functionality (e.g., performance) [21]. Engineering change process (ECP) represents the procedure and sequence of the change implication. ECM can consolidate the necessary internal company processes and organizational structure as well as external framework conditions (e.g., law, competition, innovation etc.) [5], [22]. In relation to this, Fricke et al. identify five attributes for a successful ECM [21]:

- Less (prevention of EC)
- Earlier (frontloading)
- Effective (effectiveness in the assessment)
- Efficient (efficiency in terms of optimization)
- Better (accepting and understanding changes)

In accordance with these attributes, it is necessary to comprehend the causes and effects of EC. Within the common literature different perspectives of causes of EC are given. Usually, these causes can be classified as:

- Trigger – emergent matters (product or product-oriented e.g., correcting of an error, modifying the functionality or quality and safety issues) or external matters (e.g., customers, market or competition) [23]
- Urgency – running change, emergency change and instant change
- Initiation – early, mid production or late insertion [24]
- Necessity – mandatory changes such as deficient functionality, laws and norms which have to be realized; failing to meet this necessity will affect the successful marketing of the product or go against regulations (e.g., emission regulations); optional changes such as innovation, product or cost optimizations for the purpose of customer acquisition (e.g., optimization of the emission as merchandise).

Otherwise, EC itself can affect different issues like product-process-resources (PPR) and thereby costs, quality or time [25]. However, it is necessary to point out the importance of EMC regarding EC, since aside from potential negative aspects EC can achieve positive effects as part of a continuous improvement concept e.g., optimization, innovation or higher customer satisfaction [21].

Fig. 5 VDA ECM reference process [12]

A successful ECM requires reliable processes and organization. Reference models, e.g., DIN 199 part 4, provide a common foundation of procedures and structure. In the context of this paper and the domain of industrial engineering, in particular the automotive sector, this paper refers to the VDA ECM reference process. This recommendation subdivides the ECM into five sequential phases, see Fig. 5. Usually, ECM activities initiate by identifying ideas for improvements (M1: Change Idea) triggered by the causes listed above. After gathering and assessing potential change concepts (M2: Change Potential Identification) alternate solutions will be defined and estimated on basic input quantity (M3: Potential Solution defined). Following this, the change decision is specified into a change request (M4: ECR decided). The process ends with the phases of engineering (M5: EC released) and manufacturing implementation (M6: Manufacturing change released) [12]. The approach presented in this paper specifies the process phase M3, which will be detailed in the next chapter.

IV. Objectives and Requirements of Complexity Management in EC

As explained in the introduction, NPD is considered to be a complex and dynamic process. Depending on the project phase, technical changes (EC) are happening to develop the new product. In literature and in praxis there are very well-established ECM processes, including the six phases detailed above [12], [21], [23]. However, the EC process is rigid, inflexible and not suitable for complex NPD. From a holistic point of view under different project circumstances there must be different change management processes to bring flexibility for managing complexity. These form the main objectives of the presented approach. Therefore, the first step is the evaluation of changes with consideration of project complexity, aiming to ensure sufficient transparency; (what should be evaluated). To evaluate changes in a systematic way the complexity management catalogue is suggested as a building basis for further analysis. As NPD is very dynamic and several changes can happen simultaneously or under time pressure, the evaluation of changes must be accelerated. Considering this, the complexity catalogue must support engineers by evaluating and sorting the changes, preferably in a quick and simple way. For this purpose, a suitable method of evaluation must be contemplated. The result of evaluation is the categorized changes (how, when and by whom changes should happen). The next step is assigning a corresponding ECM process for categorized changes. Here, the current ECM process provided from VDA is selected as the basis. Depending on the category of the changes, adjustment of ECM process is suggested. Adjustment of the ECM process forms a flexible change management process and provides agility (how to proceed with complexity).

V. Capturing Complexity of EC

The first step of the approach is to ensure sufficient transparency. In a complex environment it is essential to obtain an overview of the scale and connections through a holistic approach, see Fig. 6. Therefore, ECM and NPD are considered as related systems, since EC might affect not only the ECM but also the next superordinate system NPD. The reason behind using the system point of view is the vast potential of an EC. A simple technical change may trigger non-technical effects on different attributes like process, time or organization. Reflection on the total potential impact of EC allows a rational statement to be made about the existing complexity.

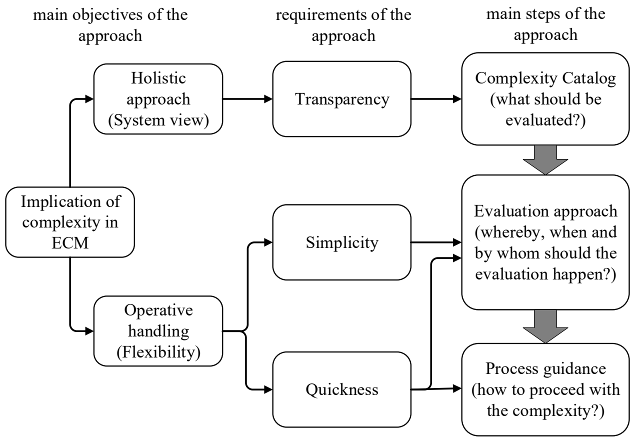

Fig. 6 Proceeding of paper

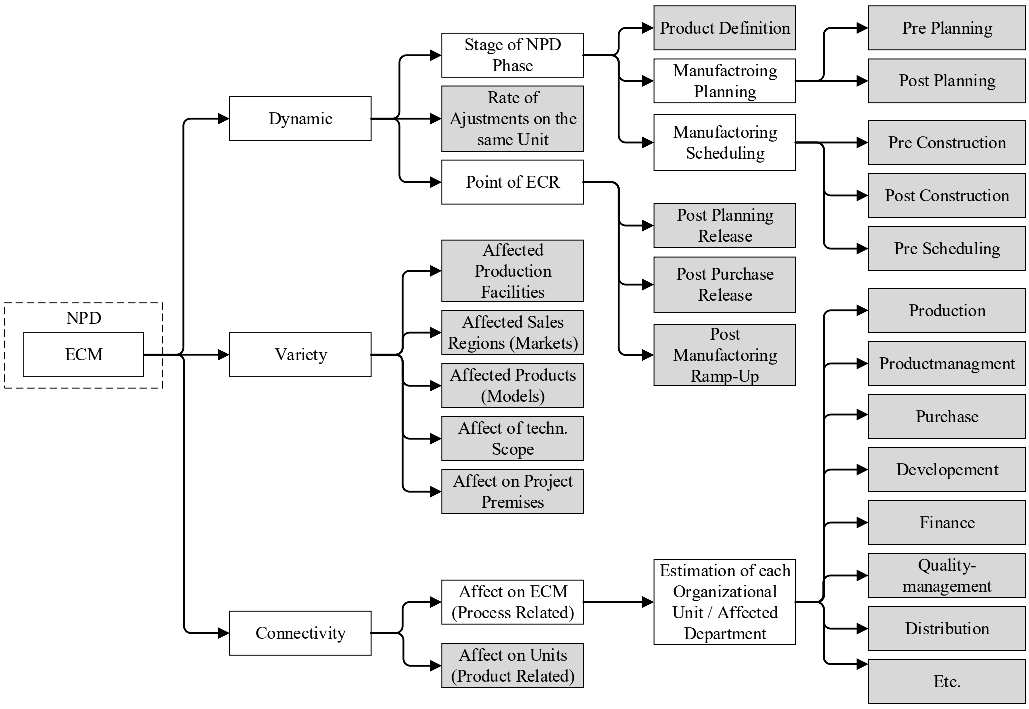

Fig. 7 Complexity catalogue

In order to gather all potential effects, a literature review has been performed. Various information could be deduced from a variety of definitions, illustrations and studies. Additionally, document and process analyses, as well as expert discussions within a major OEM, have been realized. Obtaining a more precise insight into procedures and coherences is important for a better understanding of the system. Furthermore, empirical knowledge could be collected and included. The vast spectrum of gathered information was clustered and successively assigned to the main complexity attributes (variety, connectivity and dynamic) represented in the common literature [1]. Finally, the evaluation and assignment of the cluster results in the complexity catalogue see Fig. 7.

Starting with the ECM and NPD systems, the recorded topics are hierarchically ordered. Assuming EC as the main trigger, each topic represents a cluster of potential qualitative, quantitative or temporal effects on other parts of the system. The final evaluation of the effect happens in the last tier of the path (color-coded).

The dynamic complexity attribute consolidates primary temporal effects relating to the phase of NPD (e.g., project-related changes in the planning, scheduling or construction phase) and/or the point of the Engineering Change Request (ECR), e.g., product related changes such as releases. Likewise, the total amount of changes on the same unit over time is evaluated. The variety attribute focuses on quantitative effects (e.g., affected models, facilities and sales regions) as well as technical consequences (e.g., the scope of the change or alteration of the project premises). Finally, the connectivity attribute considers effects on other units (e.g., intra- or inter-product related unit adjustment) and/or effects on the ECM process itself. Those processual effects are recorded over affected organizational units or departments. All the evaluated potential effects represented in the complexity catalogue have to be considered in the estimation process of each EC. If not, the EC can result in unexpected additional negative cost, time or resource consumptions.

VI. Determination of Systematics for Change Evaluation

Considering the complexity catalogue explained in last section, the aim of this section is to determine an appropriate evaluation method for comprehensive analysis and classifying of changes in NPD. The methods which can classify and set priorities are deliberated.

- FMEA – "Failure mode and effects analysis" is a powerful method that systematically defines and classifies potential risks of failure and accordingly sets priorities for action. This is a bottom-up method, considering all systems from a small component of a process or product up to high levels of a system being impacted from lower hierarchical levels [26]. Although FMEA provides a systematic way to identify the risk priority number (RPN), it does not support identification of the interaction of system components and its possible failure in a systematic way. For the purpose of classification, specifically classification of changes in NPD, the detailed bottom-up analysis provides precise information to categorize changes. However, it also postulates methodical knowledge and is highly time-consuming. Although it supports engineers to have a detailed overview of changes and their impacts, the lack of information in the early stages of ECM means it may not assist engineers expediently.
- ABC method – Based on the Pareto principle (also known as the law of the vital few), a useful method is to divide and categorize items in three classes according to specific criteria; A (very important), B (intermediate) and C (least important). The ABC method provides a simple and swift systematic procedure to identify and classify items with regard to the significance of their impact on the outcome of the system. The results provide a solid structure for further decision making and focusing specially on key aspects. Regarding the evaluation of changes in NPD, this method provides quick results in a simple way by analyzing available information at an early stage of the change request.
- Eisenhower Matrix – The Eisenhower Matrix is a tool for efficient and productive decision making. Based on the criteria 'important/not-important' and 'urgent/not-urgent', tasks or items can be classified into four different ranks of significance. This method has been used widely in the field of management because of its simplicity and efficiency. As with the ABC method, it provides a quick result in respect of EC evaluation in NPD.
- AHP – Analytic Hierarchy Process (also known as the Saaty method) is a quantitative technique from the scientific field of decision making and primarily serves to structure and analyze complex situations. Based on three sequenced phases the user evaluates necessary information, defines hierarchies and establishes priorities [27]. This approach allows a choice between multiple alternatives based on the highest value. Similar to FMEA, it can help engineers involved in ECM more explicitly in later steps when the information is completed. Although it matches the complexity requirement of ECM in NPD, it demands high methodical knowledge and could be a time-consuming approach.
- Delphi – The Delphi method is a qualitative approach to collect and evaluate the opinions of a panel of experts selected for their qualifications, in order to approach a consensus opinion on the selected topic. Delphi is mainly used for problems where quantitative analysis cannot be practiced. Delphi is an interactive process beginning with the collection of the opinions of each expert on the same topic [28]. Afterwards the results (all opinions) are presented to all experts with the opportunity to adjust their own previously submitted argument. In order to densify the results, this process is repeated up to three times. Gaining an appropriate result regarding the evaluation of changes in ECM demands time-consuming and well-organized discussions. Similar to AHP and FMEA, it can provide precise evaluation once sufficient information is available.

In order to identify the optimal method for the presented approach, a systematic comparison is necessary. Cost-Utility-Analysis (CUA) is a simple concept to select between different alternatives. By defining overall criteria and measures the user is able to evaluate the alternatives on the same basis. Each measurement criterion can be weighted by the user's preference, resulting in a highly qualitative approach that is highly practical at the same time. The CUA is performed in sequenced steps:

- Select the relevant alternatives for estimation
- Define and weight the evaluation criteria
- Evaluate and take the alternative with the highest value

To achieve the objectives of the approaches introduced in this paper, simplicity, quickness and precision are defined as the criteria for CUA.

- Simplicity is picked because in the dynamic phase of NPD, saving time through a simple decision-making process is gaining importance. Simplicity is becoming a leading design principle in developing new product [29]. Therefore, this principle must also be transferred to the evaluation approach of CUA used in this paper. Simplicity can be obtained by eliminating the redundant elements of processes or the replacement of interfaces. In other words, removing unnecessary elements of the process can provide ease of use. This follows the suggestion of Cunha and Rego for facilitating complexity though simple rules [30].
- Quickness is a criterion that has a strong relationship with simplicity. In fact, simplicity provides quickness, as expressed by Jack Welch: ''we found in the 1980s that becoming faster is tied to becoming simpler… If we are not simple we cannot be fast ... and if we were not fast we cannot win'' [30]. Quickness in responding to changes in product is one of the most important factors reducing the cost of product development and time-to-market. For

instance, if a change happens before product release and the process of change evaluation allows engineers to consider the change quickly and before product release, the change should be cost effective to implement [8]. The longer the evaluation process affecting the implementation of changes, the more expensive the changes could be.

- Precision means that although making a precise decision regarding the type of changes in product is an important factor, in comparison to the other two factors it gains less attended. Indeed, in a dynamic NPD, a rough estimation for change categorization causes a lower risk compared to the factor of quickness. Specifically considering ECM processes, providing precision at the beginning has no relevance because only the change request and possible solution are identified, see Fig. 8.

The five methods introduced above have been analyzed based on these three criteria. According to the requirement of ECM in NPD, quickness and simplicity are high weighting in comparison to precision. Analysis of CUA is completed by gathering information from a group of experts with sufficient experience in the field of change management in praxis. For ranking, the Likert scale has been used, with scaling from one to five; where one is "not matching" and five is "completely matching".

TABLE I
COST-UTILITY ANALYSIS

	precision	simplicity	Quickness	Quantity
Weighting	0.1	0.4	0.5	1.0
Eisenhower	1	4	4	3.7
ABC Analyses	2	5	5	4.7
FMEA	5	3	1	2.2
AHP	3	1	2	1.7

This analysis shows that ABC is the highest-ranking method. Accordingly, it is selected as the optimal evaluation method for the presented approach. Determination of the ABC method as an optimal evaluation method is therefore the response to the necessity for an appropriate system to provide flexibility to the ECM. When and by whom the evaluation must take place are the next concerns that need to be answered, see Fig. 6.

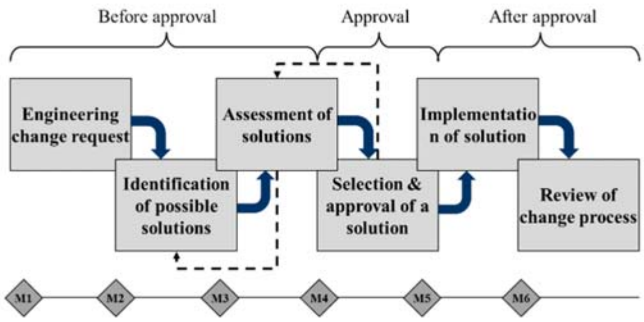

Fig. 8 ECM processes (adopted from [23])

As depicted in Fig. 8, in the second step of ECM a team including experts from different departments define possible solutions to the change request. This is the earliest step at which relatively sufficient information is available to evaluate the change. Therefore, the recommendation of the presented approach is implementation of ABC-Analysis in the second step of ECM, where the team of experts are gathered together.

To assign A, B or C for a change in NPD, all 24 items (see Fig. 7) from the complexity catalogue have to be separately evaluated and assigned as A, B or C. Determination of the category of each item is based on experiences of experts with process responsibilities. The items can be sorted in different categories with differing weights depending on the type of company in question. For instance, for automotive companies with diverse manufacturing penetration, the weighting of changes on e.g., production or purchasing can be variable. Even the weighting of items within the same company can vary in different projects based on project premises. Therefore, the weights for items are considered as a variable parameter which has to be defined in the early phase of the project. The weight of items is defined by w_i, and the category of items by x_i where i is the item and x can be "A", "B" or "C". For example, the Likert scale can be used for weighting. A change is assigned with an index calculated by

$$\sum_{i=1}^{24} w_i x_i \quad (1)$$

The index includes all three categories (A, B or C). The calculated result (highest number) defines the category of EC. In the case of an identical number of categories, final determination of A, B or C rating depends on the opinion of the concerned parties.

VII. Defining Case-Related Process Guidance

While the previous subchapter dealt with the issues of complexity content and the evaluation method, the final step of the approach is a response to the question of how to proceed with the results. After evaluating the complexity catalogue via ABC-Analysis, each EC can result in a differing complexity intensity, e.g. A for high complexity intensity, B for medium complexity intensity and C for low complexity intensity. In order to grant maximum flexibility, this approach suggests three different procedures depending on the complexity intensity, see Fig. 9. A quick and adequate response is an important factor when handling complex systems. The sooner the existing complexity and its potential impact are assessed, the better the chance to prevent negative effects.

ECs with a low complexity intensity are considered as having a low effect on the viewed system (ECM and NPD). These are rated via ABC-Analysis as C and visualized with the green traffic light, meaning proceeding with the existing standard processes (ECP) without any further changes is adequate, e.g., reference process by VDA. Because of the low intensity no further significant negative impacts are likely to be expected.

B-rated ECs are considered to have a medium complexity intensity (yellow traffic light). It must be assumed that these ECs will have an impact on the viewed system (ECM and NPD) resulting in possible negative cost, quality, technical or temporal effects. In order to respond quickly to the potential extra effort hidden in these ECs, an adjustment of the standard process is necessary. By-pass processes are suitable for such cases because they are based on the principle of shortening or compressing of the existing processes. This can be achieved by reshaping the standard process via elimination of process/ milestones or redefining the process flow/structure [31], as shown in Fig. 9. In daily business, by-pass processes for B-rated ECs have to be prioritized, treated with higher attention or estimated by different premises than C-rated ECs in order to achieve a more time efficient procedure (see Fig. 9, new t_B).

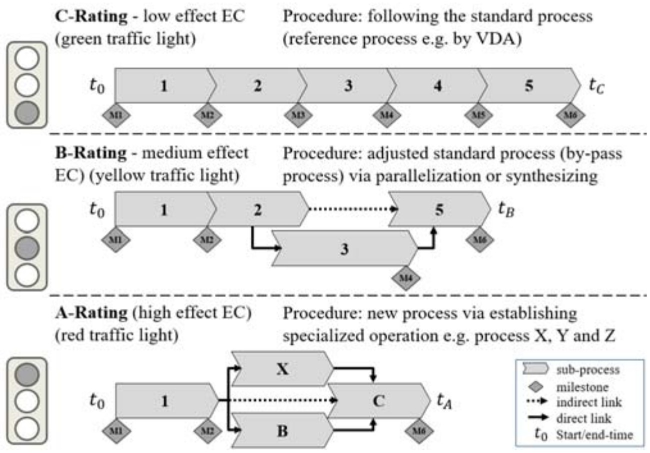

Fig. 9 Process guidance overview for different EC category

ECs with an A-rating have a high complexity intensity (red traffic light). These are particularly critical changes and anticipated to have highly potential negative impacts on the other parts of the system e.g., unintentional harmful consequences. After identifying change potential via the ABC-Analysis in milestone M2, this approach suggests a radical deviation of the procedure, since the standard process or the by-pass process is no longer considered to be sufficient. ECs with such high effects need to be treated separately, and therefore new specialized ECM processes have to be defined and implemented (see Fig. 9, new specialized operations X, Y and Z). In daily business, for example task forces can be formed by a team of experts. These task forces are responsible solely for A-rated ECs. Other necessary adjustments include defining fitting estimation premises, quick decision making and continuous auditing. Therefore, a minimum in loss of time can be provided.

VIII. Discussion

The literature research exposed that on one hand a comprehensive analysis of EC process in a system of NPD, its causes and impacts are missing. And on the other hand, EC process is formed as a not flexible procedure. The approach presented in this paper responding these two points by the three following steps; complexity capturing, identification of evaluation methodic and defining corresponding process guidance. Introduction of traffic light systematic to the change process enables the organization to improve communication within EC. Once change occurs and the request of change is issued, the team of experts from different organizational units discusses and rates the changes. Rating the changes appends very necessary composed information to the process with two significant functions. The first preliminary function is defining which process should be selected to proceed the change request. Selecting a proper process increases the efficiency of ECM by providing commensurate reaction to the changes. The second function is providing transparency which makes necessary information more evident. Assigning red, yellow or green sign to the change simplifies the transfer of information in very quick way within (procedural view) and as well between (organizational view) department units.

Presented approach contributes to ease knowledge management in ECM. For rating a change parallel to the common change evaluation, required information is collected by team of experts. Gathered information supports to categorize a change request in A, B or C-Rating categories. In fact, a correlation between the collected information and rated changes is formed. Considering this information as experience of experts, building of this correlation is a systemic approach to manage knowledge in ECM. Strictly speaking, collected information from previous EC is transferred to knowledge supporting new EC with appropriate anticipation regarding changes. Eventually, the contributions of introduced approach will provide flexibility in ECM by facilitating communication and stablishing a systematics to knowledge management. This will increase efficiency of ECM by e.g., reduction of change costs, enabling an organization by better resource allocation and appropriate reaction on changes.

IX. Conclusion and Outlook

The initial purpose of the presented approach is to provide transparency and flexibility to manage the complexity of EC in NPD. The first step of most complexity management methods introduced in research papers comprises analysis of the system, the connectivity of its elements and the impact of status changes of elements providing transparency [32], [33] meaning that capturing complexity is an essential factor in the presented concept. The complexity catalogue demonstrated in this research yields a systematic comprehensive evaluation method to provide transparency in ECM. It supports experts in classifying EC in different categories. Clustering, and consequently assigning, the changes is a fundamental step towards providing flexibility in ECM. Indeed, the final result of the approach is to provide several ECM processes matching the features of defined change categories. Based on the category of EC, experts have the option of selecting various procedures. Strictly speaking, according to the law of requisite variety [34] providing variety in ECM processes is the key to managing their complexity. Another aspect considered in this paper is the time intensity of new product development in the automobile industry which is an important complexity driver. Due to time pressure, a quick decision regarding the type of EC is a necessary factor. The quickness of the method used to evaluate EC is ensured by using a proper evaluation tool. In fact, quickness helps to reduce time intensity and increase flexibility again. Generally, a group of experts evaluates and clusters EC based on know-how, which could be considered as a subjective evaluation. To intensify the quickness of evaluation and decrease the subjectivity, the authors recommend the extension of the presented approach with data-mining methods as a suggestion for future work. With proper data mining methods, information gathered from previous projects could be sorted into different categories. A change request in a project can be immediately matched with a determined category and suitable change process can be assigned. Consequently, a transition from qualitative to quantitative evaluation would be achieved. Furthermore, a completely automated precise evaluation of complexity by means of machine learning could be available.

REFERENCES

[1] Kirchhof R. „Ganzheitliches Komplexitätsmanagement“. Wiesbaden: Springer Fachmedien Wiesbaden GmbH. 2003.
[2] MirRashed S. A., Rostami-Mehr M., Mißler-Behr M. and Lüder A. “Analyzing the causes and effects of complexity on different levels of automobile manufacturing systems”. IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA). 2016.
[3] Huang G.Q., Yee W.Y. and Mak K.L. “Current Practices of Engineering Change Management in Hong Kong Manufacturing Industries.” Journal of Modern African Studies 2003, 13.139: 481-487.
[4] Deutsches Institut für Normung 1990. “DIN 6789-3. Teil 3.
[5] Hamraz B., Caldwell N. H. M. and Clarkson P. J. “A Holistic Categorization Framework for Literature on Engineering Change Management”. System Engineering, 2013, Vol. 16 No. 4: 473-505.
[6] Li W. and Moon Y. B. “Modelling and managing engineering changes in a complex product development process”. Proceedings of the 2011 Winter Simulation Conference S. Jain, R.R. Creasey, J. Himmelspach, K.P. White, and M. Fu, eds, 2011.
[7] Ström M. “Redesign of the engineering change process of a supplier in the automotive industry”. Göteborg: 2nd Nordic Conference on Product Lifecycle Management – 2009, NordPLM’09. p. 28-29.
[8] Eger T., Eckert C. M. and Clarkson P. L. “Engineering change analysis during ongoing product development”. Paris: International conference on engineering design, Paris, France, 2007.
[9] Reddi, K. R. and Moon, Y. B. "Modelling Engineering Change Management in a New Product Development Supply Chain". Mechanical and Aerospace Engineering 16, 2013.
[10] S. Leng, L. Wang, G. Chen and D. Tang. 2015. “Engineering Change information propagation in aviation industrial manufacturing execution processes”, Int. J. Adv. Manuf. Technol. p. 1–11.
[11] Subrahmanian; E., Lee, C., Granger, H., “Managing and supporting product life cycle through Engineering Change Management for a complex product”, Res. Eng., 2015. Des. 26. p. 1–29.
[12] VDA Verband der Automobilindustrie. „ECM Recommendation: Part 0 (ECM)”. 2010., Darmstadt: SASIG VDA 4965, Part 3.0
[13] Kocar, V. and Akgunduz, A. “ADVICE: A virtual environment for Engineering Change Management”, 2010, Computers in Industry 61. p. 15–28.
[14] Oyama, K.; Learmonth, G.; Chao, R. “Analyzing complexity science to new product development” Modelling considerations, extensions, Journal of Engineering and Technology Management, 2015, No.35, P.1-24.
[15] Ulrich, K. T. Eppinger, S. D. “Product design and development”, fifth edition, 2008.
[16] Vogel, W. “Complexity management approach for resource planning in variant-rich product development”, Springer Fachmedien Wiesbaden GmbH, 2017.
[17] Grussenmeyer, R; Blecker, T. “Requirement for the design of a complexity management method in new product development of internal and modular products”, international journal of engineering, science and technology, 2013, Vol.5, No. 2, P. 132-149.
[18] Porter, M. E. „Wettbewerbsstrategie: Spitzenleistungen erreichen und behaupten“, Campus Verlag Frankfurt Main, 1986.
[19] Kerga, E.; Taisch, M.; Terzi, S. “Manufacturing process planning in Set-Based concurrent engineering paradigm, International federation for information processing”, 2012, IFIP AICT 388, P. 158- 169.
[20] Wannenwetsch, H. „Integrierte Materialwirtschaft, Logistik und Beschaffung“ (German), fifth edition, Springer Vieweg, Berlin, 2014.
[21] Fricke E., Gebhard B., Negele H. and Igenbergs E. “Coping with Changes: Causes, Findings and Strategies”. System Engineering, 2000. Vol.3 No. 4: 169-179.
[22] Hollauer C., Wickel M. and Lindemann U. “Learning from Past Changes: Towards a Learning-oriented Engineering Change Management”. Proceedings of the 2014 IEEE IEEM: 1081-1085.
[23] Ullah I., Tang D. and Yin L. “Engineering product and process design changes: A literature overview”. Procedia CIRP 56:. 25-33.
[24] Jarratt T. A. W., Eckert C. M. and Caldwell N. H. M. 2011. “Engineering change: an overview and perspective on the literature”. 2016, Res Eng Design 22: 103-124.
[25] Köhler C. „Technische Produktänderungen: Analyse und Beurteilung von Lösungsmöglichkeiten auf Basis einer Erweiterung des CPM/PDD-Ansatzes”. Saarbrücken: Schriftenreihe Produktionstechnik Band 45, 2009.
[26] Peeters, J.F.W., Basten, R.J.I. and Tinga, T. “Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner”, Reliability Engineering and System Safety, 2018.
[27] Brunelli, M. “Introduction to the Analytic Hierarchy Process”. Springer, London, 2014.
[28] Young, S.J. and Jamieson, L.M. “Delivery methodology of the Delphi: A comparison of two approaches”. Journal of Park and Recreation Administration. 2001. 19(1), p. 42-58.
[29] Eytama, E., Tractinsky, N., Lowengart, O. “The paradox of simplicity: Effects of role on the preference and choice of product visual simplicity level”, International Journal of Human – Computer Studies, 2017, 105. p. 43–55
[30] Cunha, M. And Rego, A. “Complexity, simplicity, simplexity”. European Management Journal, 2010, 28. p. 85– 94.
[31] Lindemann U. and Reichwald R. „Integriertes Änderungsmanagement“. Springer, 2013.
[32] Asan S. “A Methodology Based on Theory of Constraints’ Thinking Processes for Managing Complexity in the Supply Chain”. Dissertation, 2009.
[33] Kluth, A., Jäger, J., Schatz, A. and Bauernhansl, T. „Method for a Systematic Evaluation of advanced Complexity Management Maturity”, Robust Manufacturing Conference (RoMaC), 2014.
[34] Ashby W.R. “Requisite variety and its implications for the control of complex systems”, Cybernetica, 1958. 1:2, p. 83-99.