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A Review Of Data-Based Methods For The Development Of An Adaptive Engineering Change System For Automotive Body Shop

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Abstract

The automotive body shop with its high investment costs and resource intensive high automation level is not sufficiently responsive to the demands of agility and adaptivity. The coexistence of combustion engine and e-mobility platforms, but also design modifications on products during production phase, require constant and agile product adaptation in automotive structural components.

These changes to the structural car body design have different effects on production planning. However, in some cases they have a considerable influence on the equipment design, e.g., the choice of jig, fixture, and joining technology and the number of robots used. This means that investment decisions for the procurement of new equipment or even entire production systems are also determined. In particular, late introduced new requirements or engineering changes in the product development process (PDP) have a massive impact on the quality of planning and compliance with established premises at the beginning of the PDP. Measures for the holistic consideration of engineering changes and their influences require both a product-side and a production-side review of influences.

In this review paper, existing approaches for the product and production-side handling of requirements and engineering changes are analyzed by a systematic literature review. Existing data-based methods are analyzed with regard to their applicability on engineering change management (ECM) in body shop. Based on this, enabling methods are assessed concerning their suitability for the transfer to a holistic, adaptive, and data-based ECM system for the PDP of automotive car bodies.

Keywords

Requirements Management; Engineering Change Management; Change Request; Artificial Intelligence; Vehicle Production; Versatile Production; Production Intelligence

1. Motivation

Shorter product life cycles and a dynamic, interdisciplinary product development process (PDP) characterize automotive body design [1]. In fast-moving agile development of product and production, requirements management (RM) and engineering change management (ECM) are therefore becoming increasingly important. The rise of e-mobility and the associated profound alterations are reinforcing this trend. In complex product production systems (PPS), engineering changes are associated with extraordinary consequences. Engineering changes are generally considered to cause costs. In a study from 2012 with participants from industrial practice, 82% of the study participants indicated an increase in costs for change implementation [2]. One reason for this can be seen in the processing effort required, since technical changes

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take up an average of 25% of the total Research & Development (R&D) capacity [2]. Furthermore, with increasing complexity of the product, an increasing amount of subsequent changes can be expected [3].

Therefore, cost estimation of late introduced changed requirements for body shop systems has to be made. A decision is then made as to whether the change is to be absorbed by adapting the production line or whether design alternatives are to be examined [1]. Making appropriate decisions for defining and changing requirements, requires a holistic view. The scope of necessarily considered interdisciplinary requirements in the PPS extends along the entire PDP. This explicitly includes a production wise analysis, contrary to the classic product-sided understanding of requirements. The integration of production-side RM into existing, largely product-oriented processes offers opportunities to record and manage requirements in a structured manner and to incorporate them at the appropriate point in the development process as part of Concurrent Engineering [4]. This emphasizes the influence of a temporal perspective within RM, making a consideration before and after the definition of requirements necessary. Requirements must be examined a priori with regard to their consequence and evaluated a posteriori, in order to point out the consequences of selected solution mechanisms and at the same time make a priori investigations more reliable than established manual assessments [5]. Sustainable handling of requirements and engineering changes offers better planning capability with regard to time and equipment. The aim of this paper is to answer the research question:

How can existing approaches of RM and ECM in the literature be analyzed with respect to their usability in agile PDP?

2. Research Methodology

To answer the research question, an appropriate research framework is first established. The research procedure is based on the Design Research Methodology (DRM) of *Blessing et al.* [6]. Research clarification is intended to provide an overview and generate thematic understanding. Tasks of the research clarification consist in the definition of an overall research goal and in the identification of indications that support the developed assumptions. Relevant disciplines and the topic areas to be investigated need to be identified. Objectives include determining preliminary success criteria and identifying influencing factors that contribute to conceptualizing an adaptive engineering change system which enables agile PDP. A systematic literature review is then necessary to find approaches that represent the preliminary success criteria. The Research Clarification will serve as the basis for a later Descriptive Study. Factors that show the greatest influence are to be addressed for the subsequent Prescriptive Study. The results are the development of initial reference and impact models that describe the existing and the desired situation.

3. State of Research

The first step is to clarify the terms used in context with requirements and changes. In literature and in general use of language, a partly synonymous use of requirements and changes exists. Requirements and changes are therefore defined and explained in this context.

3.1 Requirements vs. Engineering Changes in PDP

A requirement is defined by the German Institute for Standardization (DIN) as "a need or expectation that is specified, usually assumed, or mandatory" [7]. The Institute of Electrical and Electronics Engineers (IEEE) characterizes a requirement as (1) a condition or capability needed by a user to solve a problem or achieve an objective. (2) A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed documents. (3) A documented representation of a condition or capability as in (1) or (2) [8]. Further definitions for requirements can be found in [9]. For the formulation of requirements, rules exist, which deal with the use of suitable units, the avoidance of inaccurate designations, compound sentences as well as abbreviations, and the definition as well as consistency of acronyms [10]. Starting with change, it is generally defined by DIN as "the agreed specification of a new state in place of the previous state" [11]. *Jarrat et al.* point out that “change is defined as an alteration made to parts, drawings or software that have already been released during the product design process and life cycle, regardless of the scale or the type of the change” [12]. *Wickel* describes engineering changes as "modifications to products, product models, as well as related components, using a defined change process, after they have been released for further development and production" [13]. The existence of a release date distinguishes an engineering change from an iteration in the development process. In practice, the implementation of engineering changes may be linked to mandatory approvals [14]. Further definitions for engineering changes can be found in [3].

Considering the highlighted terminological relationship of the requirements with engineering changes, an engineering change implies to be a reaction on non-fulfilment of requirements and/or new definition of requirements [13]. There are procedures for handling of both requirements and engineering changes using RM and ECM. In agile PDP, however, the differently named domains show strong similarities, since every change is due to new requirements. A consideration of both domains therefore seems inevitable for the development of an adaptive engineering change system.

3.2 Handling of Requirements and Changes

The tools used for RM and ECM include proprietary software, generic reference processes and industry-specific standard processes. Proprietary software used for RM offers comprehensive options for managing requirement documents. There are possibilities to track changes and the effects of changes can be examined on the basis of previously generated links [9]. From a process perspective, the handling of changes can be retraced using generic processes. With a generic high-level ECM process, *Jarrat et al.* provide an often-cited basis for ECM approaches. Triggered by a change trigger, the reference process runs through the phases before, during, and after approval of the change in six steps. The elicitation of the change request is followed by an identification of possible solutions. This is followed by an assessment of the risks and impacts of solutions. After a solution is selected and approved by a change committee, a solution is implemented. The process is completed by a review [12]. An ECM reference process has been developed by the Automotive Industry Association (VDA) in collaboration with the Strategic Automotive Data Standards Industry Group to provide guidelines for the automotive industry in dealing with engineering change. The reference process includes the phases Identification of Potential for Change, Development of Alternative Solutions, Specification of and Decision for Change, Engineering Implementation of Change and Manufacturing, and Implementation of Change [15]. In addition to the aforementioned software tools and reference processes, industry- and company-specific standard processes are also common. For the automotive industry, a standard change process has proven its worth, helping in particular with the coordination of approval and reconciling processes. Adapted processes can also be found for other industries [16].

Deficiencies of such solutions are shown by a pronounced latency. Between the definition of the requirement, its assessment, and its ultimate implementation in production, there are further time-consuming process steps which cause this latency. This represents an inefficiency and obstacle in agile PDP. Further deficits can be seen in the mostly manual linking by a requirement engineer employed to coordinate the requirements. Due to the complex PPS resulting primarily from the large number of interdependent technologies, processes and logistic chains [16], the data sets to be examined and its complexity can become enormous [17], which severely limits the manageability for manual procedures. Additional complexity arises from the different times of requirement definition and from the interdisciplinary PDP, which makes it necessary to model the interdependencies. The amount of knowledge required for this exceeds the possibilities of manual evaluation quickly.

4. Sustainable Handling Through Data-based Methods

The development towards automated, data-based methods, which rely on decision making based on data, can enable sustainable handling of requirements and engineering changes. Individual components or even the entire RM or ECM process could be implemented more effectively using data-based methods. Data mining is one of the methods for combining data into information and converting it into knowledge. „Data mining is defined as the process of discovering patterns in data. The process must be automatic or (more usually) semiautomatic. The patterns discovered must be meaningful in that they lead to some advantage, usually an economic one. The data is invariably present in substantial quantities" [18]. The application of data mining techniques in ECM is currently still quite little researched [5]. However, the data required for this is certainly available, since quality management standards used in the automotive industry, such as DIN EN ISO 9001, require the retention of documented information [19]. Nevertheless, according to expert statements, the data are not used sufficiently [13].

In this context, the application of data mining or other artificial intelligence techniques offers possibilities to make predictions already during the creation of a change request. Another example are automatically generated suggestions on how to reduce the lead time of the change [20]. As a consequence, there can be the ability to provide a prediction of the impact of changes as instant feedback for the stakeholders involved in the PDP, thus simultaneously reducing the latencies present in usual ECM processes. A strong data basing requires sufficient modeling of the structures involved *(cf. chap. 3.2)*. Again, the high complexity of automotive PPS places correspondingly high demands on modeling. Changes are inevitable in the development of a complex product [21]. In order to effectively manage changes, it is of utmost importance to understand the effects, probability and propagation paths of engineering changes and thus gain capabilities for sustainable decisions [21]. An established variant of modeling products and product development processes is based on the use of characteristics and properties. Characteristics define the product, while properties describe the behavior of the product and result from the characteristics [22].

In terms of the described DRM, an initial impact model as a deliverable of the previous explanations is to be built up. **Figure 1** refers to the "Industrie 4.0 Maturity Index" in accordance to *Schuh et al.* [23], which identifies three stages on the way to an adaptive engineering change system starting from a computerized and connected PPS. The impact model is based on the levels of visibility, transparency, and predictive capacity, as computerization and connectivity are assumed to be the starting situation.

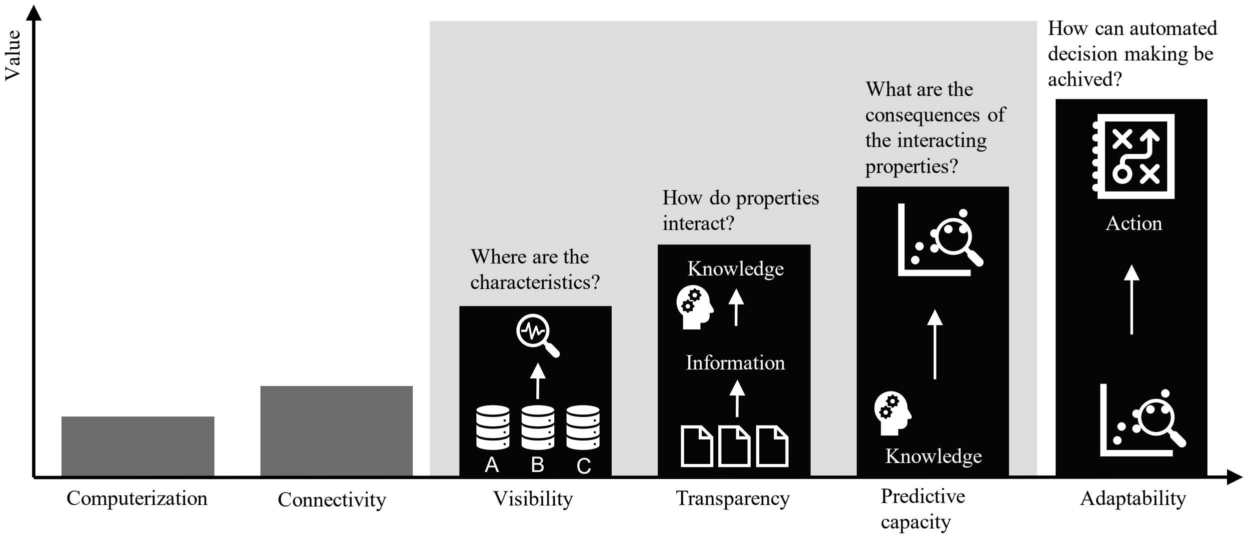

Figure 1: Integration into the Industrie 4.0 Maturity Index. According to *Schuh et al.* [23]

Within the stages, the levels of the Knowledge Pyramid can be classified. The Knowledge Pyramid places characters, data, information, knowledge, and action in a hierarchical relationship [24]. Features of the PPS must first be found in the data stored in decentralized silos. With regard to the interdisciplinary PDP, a comprehensive access must be created, and the visibility limited to individual departments must be expanded. The collected data is the basis for the step toward transparency, in which data is aggregated into information through semantic linking. This provides the opportunity to uncover interactions and thus interpret characteristics in terms of their properties, which determine the requirements through knowledge. This knowledge provides the basis for mapping the consequences of the properties and interactions. Future scenarios can be simulated through the acquired predictive capacity. Predictive capacity, in turn, is the basis for automated action and decision-making.

The model puts the topics visibility, transparency, and predictive capacity for building an adaptive engineering change system into focus. Thereupon, preliminary success criteria are now to be determined. To handle the required amounts of data, approaches characterized by a high degree of automation and *data basing* are required. To be able to justifiably make the implications of development decisions in the interdisciplinary PDP, approaches are required that take a holistic view of the PPS, including *product and production side*. In order to uncover properties and interactions in the PPS, modeling of structures is required. The *modeling of product structure and production structure* therefore represents a further criterion in the analysis of the approaches. A *consideration of interdependencies* within the PPS is necessary to link the structures on an abstracted level and to understand mutual influences. Both *a priori and a posteriori analysis* is required to ensure predictive capacity and to achieve learning effects. To consider the use case described in *chap. 1*, an approach that has already been tested for *body shop applications* is preferable.

5. Systematic Literature Review

Based on the six preliminary success criteria developed above, a systematic literature review of RM and ECM approaches was conducted.

5.1 Methodology For Literature Review

The STARLITE methodology was used to conduct the systematic literature review [25]. The STARLITE methodology provides guidelines for documenting literature searches in terms of sampling strategy, type of studies, approaches, range of years, limits, inclusions and exclusions, terms used, and electronic sources. A purposive, representative search strategy was chosen as the sampling strategy. The type of studies was limited to dissertations, papers, monographs, and articles in collective works. In addition to the structured literature search, an explorative approach based on the snowball principle was used for the initial search. The range of years was limited to entries from 2005 and until 2020. The search was limited to German and English language. Inclusions and exclusions were made by limiting the search to the technical field or mechanical engineering, as well as a target-oriented, individual adjustment of the filter categories and a focus of the search on title, keywords and abstract. In selecting the terms used, search components were determined and divided into main and secondary components. While the main components describe the thematic framework of RM and ECM, the secondary components address desired elements of the application domain, formalization, and methods. For the search, the databases Web of Science and Scopus were selected as electronic sources. In addition, the German National Bibliography, as well as SpringerLink and Hanser eLibrary were used. A search string was developed by composing the main and secondary components with AND and OR links. An example search string for Web of Science is shown below: *TS=(("Engineering Change Management" OR "Requirements Engineering“ OR “Product Changes”) AND (data* OR "Machine Learning" OR AI OR Body OR Automotive OR Manufacturing OR Production OR Development OR “Product Features” OR “Product Properties” OR “Product Characteristics” OR dependency)).* For the three last mentioned databases with limited search string functionality, a simple keyword search was used. After performing the initial search run, a large set of search results was obtained. The PRISMA Methodology was used to reduce this initial result to a manageable level [26]. After removing duplicates, the search results were reduced to 1.062 entries. 193 titles remain after selecting by title relevance. After a review of abstracts and conclusions, 71 entries were determined to be suitable for next step. These entries were further reduced after a full review, leaving 38 entries for final evaluation. An overview of the search results remaining for evaluation is shown in **figure 2.** The evaluation of the approaches is described in the following chapter.

	Criteria						Evaluation scheme		
Author	Consideration of product and production side	Consideration of the body shop	Consideration of PPS-Interdependencies	Structure modeling	Degree of data basing	A priori and a posteriori analysis	**Consideration of product and production side:** ●: both sides, ◑: production or product, ○: other **Consideration of the body shop:** ●: body shop, ◑: universal / automotive, ○: other **Consideration of PPS-Interdependencies:** ●: syst. representation, ◑: loose relations, ○: no representation **Structure modeling:** ●: syst. modeling, ◑: show possibilities, ○: no modeling **Degree of data basing:** ●: automated data-based, ◑: structured, ○: experience-based **A priori and a posteriori analysis:** ●: a priori and a posteriori, ◑: a priori or a posteriori, ○: no analysis		
							Level	Represents	Based on
Elezi 2011 [27]	●	◑	◑	◑	◑	◑	Framework	Data-based process design	KDD
Sharafi 2013 [28]	◑	◑	●	◑	●	●	Framework	Data-based process design	KDD
Jarrat 2011 [12]	●	◑	●	○	◑	●	Framework	ECM/RM process design / modeling	Engineering Change
Harms 2009 [14]	◑	◑	◑	◑	◑	◑	Framework	ECM/RM process design / modeling	Engineering Change
Wu 2014 [29]	◑	◑	○	○	◑	○	Framework	ECM/RM process design / modeling	Engineering Change
Kröger 2019 [30]	◑	◑	●	◑	○	◑	Framework	ECM/RM process design / modeling	Engineering Change
Brandl 2019 [31]	◑	◑	○	○	○	○	Framework	ECM/RM process design / modeling	Engineering Change
Basse 2019 [32]	●	●	●	◑	◑	◑	Framework	ECM/RM process design / modeling	Requirements
Meis 2017 [4]	●	◑	◑	◑	◑	●	Framework	ECM/RM process design / modeling	Requirements
Deubel 2007 [33]	●	◑	◑	●	◑	◑	Framework	Structure modeling	Characteristics
Weber 2001 [22]	●	◑	◑	●	◑	◑	Framework	Structure modeling	Characteristics
Köhler 2009 [3]	●	◑	●	●	◑	◑	Framework	Structure modeling	Characteristics
Grieco 2017 [34]	○	◑	◑	○	●	◑	Method	Clustering and searching	Automated
Kocar 2010 [35]	◑	○	●	●	●	◑	Method	Clustering and searching	Automated
Haunstetter 2010 [36]	◑	●	◑	○	●	○	Method	Clustering and searching	Automated
Wickel 2016 [13]	◑	◑	●	●	●	●	Method	Clustering and searching	Automated + Matrix
Schedl 2008 [9]	●	◑	◑	◑	◑	◑	Method	Documentation	Proprietary software
Ma 2017 [37]	◑	◑	●	◑	◑	◑	Method	Impact prediction	Graph-based
Koch 2016 [38]	◑	◑	◑	○	○	○	Method	Impact prediction	Graph-based
Wilms 2019 [39]	◑	◑	●	◑	○	◑	Method	Impact prediction	Graph-based
Plehn 2017 [40]	◑	◑	●	●	○	◑	Method	Impact prediction	Graph-based
Masmoudi 2020 [41]	◑	◑	◑	◑	○	◑	Method	Impact prediction	Graph-based
Hamraz 2013 [42]	◑	◑	●	●	◑	◑	Method	Impact prediction	Matrix-based
Hein 2018 [43]	◑	◑	●	◑	●	◑	Method	Impact prediction	Matrix-based
Leistner 2019 [44]	●	●	●	◑	◑	◑	Method	Impact prediction	Matrix-based
Bauer 2015 [45]	◑	○	●	◑	◑	◑	Method	Impact prediction	Matrix-based
Gärtner 2011 [46]	◑	◑	●	◑	◑	◑	Method	Impact prediction	Matrix-based
Tang 2018 [47]	●	◑	●	◑	◑	◑	Method	Impact prediction	Matrix-based
Kattner 2019 [48]	○	◑	◑	◑	◑	◑	Method	Impact prediction	Matrix-based
Giffin 2009 [17]	◑	◑	●	◑	◑	◑	Method	Impact prediction	Matrix-based
Ullah 2018 [49]	◑	◑	●	◑	◑	◑	Method	Impact prediction	Matrix-based
Heimes 2020 [50]	◑	◑	◑	◑	◑	◑	Method	Impact prediction	Matrix-based
Lee 2017 [51]	◑	◑	●	◑	◑	◑	Method	Impact prediction	Statistical method
Bracht 2015 [52]	◑	◑	◑	○	◑	◑	Method	Impact prediction	Statistical method
Schweitzer 2020 [20]	◑	○	○	◑	◑	◑	Method	Impact prediction	Statistical + automated
Petzelt 2009 [53]	●	◑	◑	◑	◑	○	Method	Linkage	Feature-based
Bossmann 2007 [54]	◑	◑	○	●	◑	○	Method	Linkage	Feature-based
Hirani 2005 [55]	◑	◑	○	◑	◑	○	Method	Linkage	Graph-based

Figure 2: Evaluation of the identified approaches based on the systematic literature review

5.2 Description of the Evaluation Criteria

Based on the previously defined six criteria *(cf. chap. 4)*, a three-stage evaluation scheme was introduced that describes the respective degree of fulfillment of the criteria. Based on their fulfillment of the evaluation criteria, the approaches were classified into an evaluation matrix *(cf. fig. 2)*. The degree of fulfillment is represented through the three stages by Harvey Balls (full-half-empty). A full Harvey Ball corresponds to a good match with the respective evaluation criteria. The explanation of the degrees of fulfillment of the evaluation categories is shown in a legend in the figure.

5.3 Categorization

As shown in **figure 3**, the identified approaches address different levels in terms of their solution detailing. Some approaches represent comprehensive frameworks, each addressing different previously defined criteria. While differing in terms of their focus, the objectives of frameworks generally are to classify and relate. Overarching frameworks for ECM / RM process design and modeling are available, as are frameworks for data-based process design and approaches to modeling structures. Other approaches specifically apply certain methods that deal with clustering and searching, impact prediction and linkage and thus represent different parts within identified reference processes and the developed model. A method can be described as procedure to reach goals and is aiming to a lower level of abstraction. The methods presented are to be seen as enablers for the stages visibility, transparency and predictive capacity, while the frameworks form a basis for procedures. Therefore, to establish an adaptive engineering change system, the development of a holistic framework is required, which is designed with methods from different domains.

In the collection and clustering of requirements and engineering changes, as well as searching for best practice solutions, automated data-based approaches have been applied by using technologies such as Natural Language Processing and Sequential Pattern Mining. In predicting impact and propagation of changes, matrix-based and statistical approaches have been used in particular. Of particular note is the Design Structure Matrices-based Change Prediction Method by *Clarkson et al.* [56], which has been used and extended by many authors. Graph-based and feature-based approaches were found suitable for representing linkages in simple products or PPS. In addition, there are previously described software solutions and complementary research tools that combine some of the aforementioned methods. Many of the approaches shown are not initially designed for automated use, but nevertheless provide a basis for building data-based procedures on them.

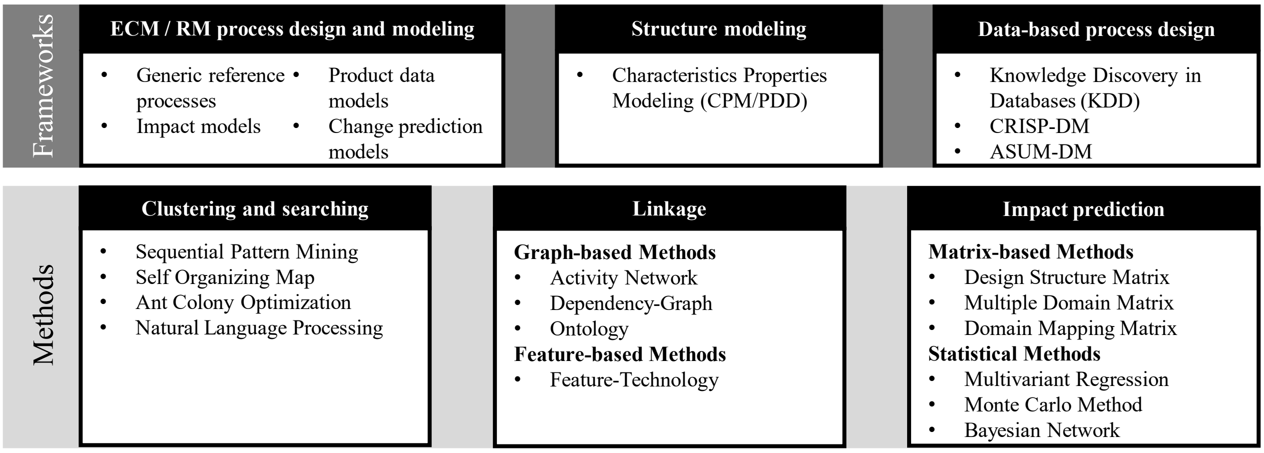

Figure 3: Categorization of identified frameworks and methods

6. Conclusion and Outlook

Parts of RM and ECM processes, that are gaining importance in agile PDP, can be designed more efficiently using data-based methods. Considering quality management standards, the data required for this should be available but is not used sufficiently due to a lack of formalization and modeling. An initial impact model towards sustainable handling of requirements and engineering changes was developed by showing a path to gain predictive capacity from data. Preliminary success criteria for an adaptive engineering change system were determined. An evaluation of approaches with respect to their usability in the present environment of an interdisciplinary, dynamic PDP was performed. Referring to the research question, approaches could be categorized based on the literature review. This analysis revealed the interdisciplinary nature of the use case as different domains have influence on modeling of the PPS. The results obtained offer solutions within their specific disciplines. However, for the applicability in agile PDP, an overlaying framework concept is still missing, which connects the identified methods and embeds the individual frameworks by forming an additional level above them. The methods serve as enablers for the stages visibility, transparency, and predictive capacity presented in the developed model towards an adaptive engineering change system. Predictive introduction of requirements based on data would make it possible to increasingly align the handling of engineering changes with the introduction of initial requirements and, at the same time, to reduce consequential changes. In the derivation of leading criteria, a large number of influencing factors must be taken into account. A variety of existing approaches provides the opportunity to form a holistic solution that represents a sufficient representation of applicable methods in an adequate framework. Therefore, it needs to be further developed by the authors in future research.

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