Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 120 (2023) 1010–1015

www.elsevier.com/locate/procedia

56th CIRP Conference on Manufacturing Systems, CIRP CMS '23, South Africa

Asset administration shell-based engineering change management process: Challenges and ways forward

Mario Angos Mediavilla[a,b,*], Michele Lagnese[b], André Pomp[a], Tobias Meisen[a]

[a] *Chair for Technologies and Management of Digital Transformation, University of Wuppertal, Lise-Meitner-Strasse 27, Wuppertal 42119, Germany*
[b] *Digital Transformation Office, Coroplast Group, Wittener Strasse 271, Wuppertal 42279, Germany*

* Corresponding author. *E-mail address:* mario.angos_mediavilla@uni-wuppertal.de, mario.angos@coroplast-group.com

Abstract

Engineering change management (ECM) is a complex process that requires extensive documentation work and dedicated communication between the parties involved. In addition, the increasing complexity of products and the various fluctuations in market conditions lead to a significant increase in the quantity of engineering changes which are reflected throughout the stages of a product's life cycle. Recent studies show the lack of standards that enable the exchange of information resulting from the interaction of the actors involved in the change process. The advancing digitalization in industrial production has led to the establishment of the Asset Administration Shell (AAS) as a concrete implementation of the digital twin concept. In this regard, the recently published standards on AAS allow it to be considered as a candidate for improving the current ECM situation. Based on this consideration, in this paper we first present the challenges of the ECM process not only through an overview of the current literature and standards, but also based on observations from experts in industrial ECM processes. Afterwards, we present the potential of AAS for solution development with regard to the challenges identified for ECM. A concrete concept for streamlining the ECM process with the help of AAS concludes this contribution.

Keywords: Engineering Change Management; Digital Twin; Asset Administration Shell; Digital Transformation

1. Introduction and Motivation

High individualization of products and their services, shorter life cycle times, and dynamically changing international markets increase the complexity of value chain processes in manufacturing industries. Thereby, companies in the automotive industry, in particular, are confronted with these challenges and must react quickly and purposefully not only to strategic changes, but also to engineering changes (EC). An EC affects a large number of processes in the manufacturing industries that are part of the value chain [1]. Additionally, the realization of an EC involves a large collaborative effort between manufacturers, suppliers of raw materials and resources. On the other hand, a successfully performed EC provides increased resilience along the value chain, which is currently vital for manufacturing companies [2]. Jarratt et al. [3] define an EC as: "an alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time". According to this definition, ECM is the generalized process responsible for organizing, controlling and supporting the activities that take place during the implementation of an EC [3]. Moreover, ECM is a holistic process that addresses all phases of a product's life cycle as well as the interaction between the parties involved. However, as stated by Eickkhoff and Habib, the information needed to support a collaborative realization of an EC is currently usually provided in analog form in many industrial scenarios, originating from different established, heterogeneous and thus not interoperable IT systems [4, 5]. Regarding ECM processes, this paper is based on the approach proposed by Augustin et al. [6]. This complements the practical area considering the VDA 4965 [7] with the theoretical scope presented in several publications, such as Jarratt et al. [3] and Wildemann [8]. Augustin et al. introduced the three base processes of the ECM. First, the engineering change request (ECR) initiates the process with the identification of the

10.1016/j.procir.2023.09.116

problem potential as well as the presentation of possible solutions, followed by the technical evaluation and coordination by the development team. The ECR concludes with the decision to either approve or reject the proposed change. The second phase is the engineering change order (ECO) in which ECs are performed in the construction and development of the product, usually by changing the Bill of Material (BOM) and the respective computer-aided design. Lastly, the manufacturing change order (MCO) phase takes care of the production of the product with its new changes considering the parts involved and ends with the evaluation of the EC process in a controlling phase [6].

In recent years, the concept of a digital twin (DT) has gained acceptance in manufacturing companies. As defined by Qi et al. the DT describes the characteristics, states and behavior of a physical object by means of digital models and is fed by the data that is exchanged between the physical object, the virtual object and its services throughout the life cycle [9]. On this basis, the Industry 4.0 (I4.0) community proposes a concrete implementation of the DT concept called the Asset Administration Shell (AAS) [10]. AAS is defined as the standardized digital representation of information and services related to an asset[1]. Platform Industry 4.0 proposes in its specification the basic structure of the AAS, which is composed of a header and a body. The header presents the unique identifications of the asset itself and its AAS. The body indicates the submodels with their respective elements (properties). A submodel also has a unique identification and represents a hierarchical structure that describes the information and services directly related to an asset (its digital representation [10]) or to its relationship with other assets [2]. According to Cainelli et al. the AAS is a key component of Industry 4.0 [12] and according to Ye et al., is necessary for the realization of the digital transformation [13] in an industrial environment. This leads to the question of the degree to which the AAS can be used to support an ECM or to what extent the ECM is already part of it. To investigate this, we first looked at the extent to which the use of AAS in the context of ECM has already been discussed in the literature. However, after a thorough literature search we could not find any specific publications dealing with the use of AAS in the ECM process. For this reason, we review the literature regarding these two topics separately (cf. Section 2). Subsequently, we first introduce the ECM challenges present in the literature by means of a defined methodology and additionally the opinion of experts regarding the challenges encountered and their relevance in the industry (cf. Section 3). Finally, we address the potential of AAS by proposing a conceptual approach that aims to improve the current ECM situation (cf. Section 4). In doing so, we provide answers to the following two underlying research questions (RQ):

RQ1: What are the challenges present in both literature and industry in the ECM process?

RQ2: Based on the challenges identified in RQ1, how can AAS improve or even automate the ECM process?

[1] physical or logical object owned by or under the custodial duties of an organization, having either a perceived or actual value to the organization [11]

2. Methodology

In order to identify challenges in the ECM process, we first present the results of our structured literature review. Structured literature reviews are pertinent for the analysis of a particular subject, the identification of knowledge gaps and potential for improvement [14]. Several methods and frameworks have been introduced for conducting such a literature review. This publication adopts the concept presented by Snyder et al. [14] and follows the framework proposed by Patel et al. [15]. The databases that we use to gather the publications are Web of Science, IEEE Explore, and Springer Publishing. The query sequence in combination of strings with Boolean operators is defined as (“engineering change management” OR “change request management”). To provide an overview of the state of the art of ECM and its challenges, the search range is restricted to publications in the last few years (2015-2022). After selecting publications belonging to development and production domains and removing duplicates, we identify 23 publications. In the following section, we cluster the challenges identified and provide a concise overview of them. Simultaneously, we meet with five experts (two EC coordinators from tier 1 level, two from tier 2 and one from management level) to address the practical aspect of the ECM process. In order to establish comparability between the responses, the challenges mentioned are rated using a relevance scale. In the following section, we present the potential of AAS to overcome the challenges by reviewing the state of the art of AAS structure and specification. The search time period spans from 2017, year in which the first AAS publications were released, to 2022. For the review, we use the same databases, with the following query sequence (“asset administration shell”). Finally, after identifying the challenges in ECM and showing the potential of AAS, we present a concept to combine these two currently separate topics into one solution.

3. RQ1: Challenges present in both literature and industry in the ECM process

In this section, we present the challenges identified in the literature and their relevance to industry, based on the opinions of experts in the field of ECM. Table 1 shows the seven groups into which we classify the 25 challenges identified in this research. We then present a brief description of the challenges. In addition, we show the literature citations where the challenges are mentioned. Finally, we present their relevance to industry by means of an average of the experts’ opinions and by using the following scale: The fully-colored circle shows the challenges that severely hinder the ECM process and could be improved by means of information and automation systems. A half-colored circle means that the challenge is present in the industry, but has been partially solved or does not significantly hinder ECM. An uncolored circle means that the challenges have no industrial relevance or are already working properly.

The **general challenges** represent the drawbacks to achieving an ideal ECM, while the remaining challenges detail the roadmap to follow to overcome the general challenges. From

Table 1. Overview of the challenges in the ECM process found in literature (2015-2022) and their industrial perspective evaluation

Group	Challenge	Literature	Industry
General challenges	Long duration of the ECM process	[1, 5, 7, 16, 17, 18, 19, 20]	◑
	Excessive bureaucratic processes in the ECM	[1, 21, 22]	◑
	Increase in the number of changes	[1, 16, 17, 18, 21, 20]	◑
	High cost related to the implementation of changes	[1, 5, 16, 17, 18, 23]	◑
	Propagation of changes	[5, 16, 17, 18, 24]	●
	High manual effort	[5, 16, 17, 18, 19, 21, 22, 25, 26]	●
Single point of truth	Lack of access and search capability in established enterprise information systems	[17, 19, 22, 25, 27, 28, 29, 30]	●
	Increase in the amount of information during the ECM process	[18]	◑
	Lack of standardized storage of data	[5, 6, 21, 22, 24]	◑
	Excessive exchange of nonrelevant information in the ECM process	[17, 24]	○
	Lack of real-time availability of the necessary information	[6, 22, 25, 31]	●
Interoperability	Lack of an IT solution to facilitate communication and data transfer between the large number of internal and external stakeholders	[1, 4, 5, 6, 7, 16, 19, 21, 22, 24, 25, 26, 30, 31, 32]	●
	Lack of reusability of interfaces and software tools in the area of EC	[5, 7, 18, 21, 24, 31]	●
	Lack of global, collaborative and standardized information systems to process ECM	[5, 6, 7, 17, 18, 19, 21, 24, 25, 29, 31]	●
Security	Lack of security in transfer of cross-company information	[6, 4, 25, 33]	◑
	Lack of a governance and data management concept	[6, 25, 30]	◑
Quality	Lack of quality control throughout the ECM processs	[7, 16, 31]	◑
	Lack of traceability in the change process	[4, 16]	●
	Lack of a versioning and history system for each stage of the ECM	[1, 6, 17]	◑
	Lack of consistency and comprehensiveness in describing change	[1, 6, 7, 16, 17, 19, 24]	◑
Life cycle	Lack of consideration of the complete product life cycle information	[1, 5, 31]	◑
Autonomous systems	Lack of automation in the overall ECM process	[6, 18, 19, 20]	●
	Lack of an adaptive ECM	[18]	●
	Lack of use of historical data and knowledge to support decision-making	[1, 6, 18, 19, 24, 30, 33]	●
	Lack of an automated notification and reminder system of EC status	[6]	●

the specification for the implementation of the EC, the ECM process includes a large number of phases performed, which require excessive *manual effort*. According to experts, e.g., coordinating meetings, finding responsible persons for specific areas and exchanging information in analog form worsen this situation. In addition, the ECM is associated with *excessive bureaucratic* processes, such as the collection of signatures and approvals in analog form, which significantly *lengthens the duration and decreases the efficiency* of the realization of an EC. These problems are exacerbated when you consider the increasing complexity and individuality of products, which leads to an *increase in the number of changes* that need to be implemented. In addition, experts and literature both indicate that a very important aspect of risk analysis is the influence of the behavior of one change on other changes or business processes, which is referred to as *change propagation*. If we take these challenges into account as well as the fact that an EC involves the acquisition of new resources, the hiring of skilled personnel, and the development of prototypes, we can clearly see the *high cost* caused by the ECM process. Both experts and literature show the importance of ensuring availability and access to complete, current and consistent information at a **single point of truth**. The most critical point in this domain is the *absence of access "in one place"* to already internal established systems, e.g., Enterprise Resource Planning (ERP) or Manufacturing Execution System (MES), to search for information relevant to the realization of the EC. This information does exist, but it is distributed across many different systems and employees. Frequently, access to this information is often restricted and inaccessible. Moreover, the experts demand not just access but *real-time availability* of such information. They agree with the literature and maintain that this is the only way to improve the quality of analyses, such as risk analysis. In addition, the ECM process is linked to the transfer of a *large amount of information* that is temporarily *stored in nonstandardized locations*. Finally, while the literature indicates that *excessive exchange of unnecessary information* presents difficulties in ECM, experts do not consider this to be a challenge and mention that customers already offer innovative solutions such as web-based platforms to ameliorate this problem. The topic that is most present in the literature (about 75 %) and in the industry according to the experts (100 %) throughout this research, is the lack of **interoperability**. Since ECM is a process that needs the active collaboration of stakeholders such as customers, original equipment manufacturers (OEMs) and suppliers, experts confirm the *lack of a solution for interoperable communication and data transfer*. This point is also confirmed in the literature; about 65 % of publications are dedicated to this topic. This challenge has already been identified by most customers such as OEMs. According to the experts, the OEMs offer platforms on which EC information is stored and managed. Unfortunately these platforms differ for each customer. In addition, EC coordinators mention the *lack of standardized systems to support EC* and its phases in a holistic manner. This has led to the use of individualized interfaces and IT tools for each company and even for each department. This is also a subject that is very evident in the literature, with approximately 50 % of publications mentioning it. In summary, the multitude of different ECM support solutions is a challenge for experts, which is also reflected in the literature. The lack of reusability of solutions that have already been implemented and are in practical use is correspondingly high. Experts are aware of the importance of **security and control** during the *exchange of information cross-company* in ECM and trust that existing IT solutions provide the necessary security for their sensitive data. The literature confirms this major challenge in exchanging information with external parties in a secure way. EC experts are aware that *holistic control* at every stage of the ECM process goes hand in hand with the successful implementation of EC and they are confident that the quality processes already in place meet their objective. One issue that is more prevalent in the literature than in the industry is the lack of a *data management concept* to improve the management of sensitive information. In practice, this task is performed with web-based collaborative platforms that provide individual participants authorization to access sensitive data.Considering the aforementioned challenges, it is reasonable that all of them influence the **quality** of the ECM process. Both literature and practice show the importance of access to information at every stage of ECM to *control the quality* of the process. Due to the fact that at the moment only partial solutions for traceability are available, it is not possible to control the entire EC process. For EC experts the most critical point is the lack of *traceability* in the process. In practice, nonstandardized hybrid solutions are used to perform the traceability and versioning of each phase of the ECM process, either manually or with solutions, such as Microsoft Project and Jira from Atlassian. The literature introduces the challenge concerning *consistency in the description of changes*, focusing more on access to the information with which a change will be described. In practice, the focus is more on the idiomatic way of describing an ECR. The challenge of accessing and using information from specific phases of a product's **life cycle** is present both in the literature and in practice. In the case of the people consulted, they state that ECM is currently a process whereby information is handled in silos. Thus, the companies that build the EC (production) have no or limited access to information from the development process of the product in question. Despite the fact that the ECM process has been carried out for several decades, both literature and expert opinion show a lack of **automation** in ECM processes. Experts mention the existence of standardized procedures to be followed, but these are carried out company-by-company and not on an automated basis. Although the topic of an *adaptive* ECM is only proposed in one publication, experts point out its importance to tackle today's markets. In addition, experts and literature state the lack of a system that uses *historical data* as a support in the coordination of new ECs. Thus, reporting on best practices and lessons learned is neglected. Finally, the experts state the lack of a system that *notifies the current status* of the EC process.

4. RQ2: Asset administration shell-based engineering change management process

In this section we use the seven groups defined in the previous section (cf. Table 1), to address the potential of the AAS. In terms of **general challenges**, AAS does not address direct solutions to the identified challenges. But we are convinced that AAS is an enabler for innovative solutions and offers potential and the basis for improving the ECM process. Regarding the **single point of truth**, AAS aims to provide secure access to complete and available information and services in real time to all members of the value chain actively involved in a specific process [27], regardless of the source of the data, such as machines from different manufacturers, different information solutions, and different companies [34]. In the ECM process, the transfer of information from internal and external stakeholders is essential. In this regard, AAS enables not only the necessary **interoperability** to understand and use the information and services coming from an external source through the description of the submodels and their elements (semantic interoperability), but also the communication and transfer of data between involved parties (syntactic interoperability) [10]. In terms of semantics, ASS opts for the standardization of submodels, for the use of dictionaries [2] such as eCl@ss, where the properties of the submodels have also been standardized, and for the use of already standardized identifiers such as International Registration Data Identifier (IRDI) [10]. In terms of syntactic interoperability, Platform Industry 4.0 has already specified formats for serializations and mappings such as JSON, XML, OPC UA, RDF or AutomationML [2, 11, 35, 36]. To take the first steps towards the desired interoperability during the implementation of EC, an option is to use off-the-shelf solutions such as Eclipse BaSyx [37], PyI40AAS [38], or AASX Package Explorer [39], which offer application programming interfaces (API)s for HTTP, MQTT or OPC UA for direct interaction between AASs [36]. Regarding the **security** required for the transfer of information and services during the implementation of an EC, the AAS structure with its submodels customized to the requirements of the company offers protection of sensitive information from unauthorized users. Thus, the Platform Industry 4.0 proposes the use of well-known data management and control concepts such as attribute-based access control (ABAC) [11]. Additionally, in the case of the automotive sector, many efforts are being made to improve the security and sovereignty of information. One example is the Catena-X platform, which aims to develop a standard for the exchange of information in the automotive value chain and thus ensure information security through an infrastructure for decentralized end-to-end connectivity [40]. With regard to the traceability needed to improve **quality** in the ECM process, the AAS aims to cover the entirety of processes through the creation of continuous value chains [10]. To achieve this, AAS presents first in its specification [11], properties that will facilitate the traceability of processes. For example, the AAS proposes the use of standardized identification of each asset, their administration shells, submodels and submodel elements. Additionally, the referencing capability to other AASs throughout the life cycle (type or instance) by their *derivedFrom* attribute is enhanced. Finally, submodel and submodel elements can reference other elements in other submodels or even in other AASs by using the attribute *ReferenceElement*. The consideration of the different phases of a product's **life cycle** is essential for the realization of an EC. According to the literature, AAS aims to provide the necessary information and services from each of the phases of an asset´s life cycle in digital form [2, 9, 10, 41]. For example, the AAS registers data generated during the development process of a product and carries it through the preceding or subsequent life cycle, ensuring that the information is in a structural form so that it can be captured and interpreted automatically by stakeholders, without the need for the information to be transformed or reformatted [34]. Regarding the **automation of processes** in the ECM, the AAS serves as a basis for the realization of autonomous systems [2, 10]. An alternative to achieving this goal shows the literature with the concept of active autonomous AAS, which offers not only the possibility to react to changes in the environment (active), but also the ability to make decisions in interaction with other assets (autonomous) [42].

After addressing the challenges with the potential of AAS, we provide a concept for streamlining the ECM process in Figure 1. The concept consists of three parts that communicate through APIs according to the needs of the EC coordination team.

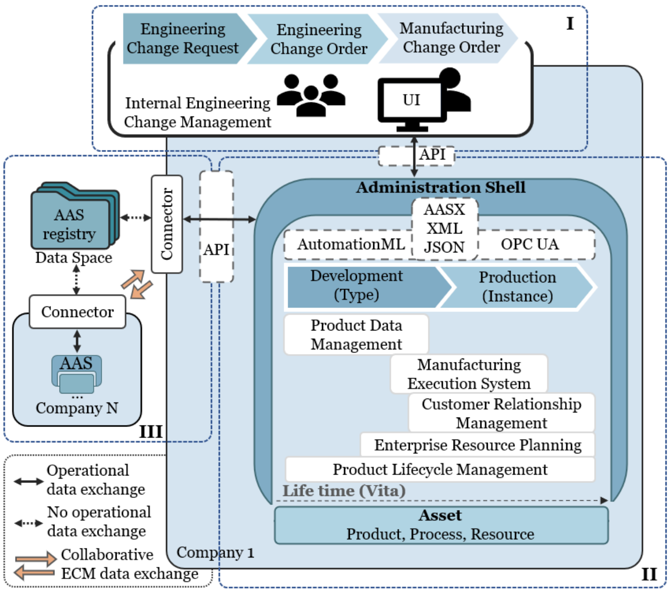

Fig. 1. Conceptual architecture of AAS-based ECM inspired by [6, 43, 40]

I: Our concept provides a *collaborative information system* for ECM processing, which supports the entire ECM process. The concept supports one or several people who lead the EC and are responsible for implementing it following the ECM phases (ECR, ECO and MCO), proposed by Augustin et al. [6]. Additionally, by means of a user interface (UI) we support the EC coordinator(s) from the first step of the ECM framework - identification of the change potential, belonging to the ECR phase - until the change has been successfully implemented. The idea is to enable an innovative and automated support, which until today does not exist, to enable the coordination of the ECM process, and to provide in parallel the necessary *real-time information* through the exchange of specific information, using the AAS as a mediator, from/to part II (for internal information) and from/to part III (for cross-company information) to facilitate *communication and information transfer between the stakeholders* involved in the process.

II: Part II shows the flow of information coming from the AAS (Asset + Administration Shell) necessary to support the ECM process. As a visual support, we show a horizontal axis (lifetime vita), which represents the life cycle of an asset. Additionally, we illustrate the differentiation between type and instance, proposed by the Reference Architectural Model Industrie 4.0 (RAMI 4.0) [43], to differentiate from which phase of the life cycle the necessary information required for the EC comes. This improves *traceability processes* and facilitates *quality control* processes. In addition, we present an illustrative classification of the most common enterprise information systems in a company along the life cycle. For example, MES is used in part of the production phase (Instance) and is employed to access the information of the resources on the shop floor. Thus, we illustrate that the AAS does not replace existing enterprise information systems, but based on its standardized structure, the ASS acts as a mediator and enables *interoperability*. This allows the *reuse of existing interfaces and solutions*. Finally, we indicate the formats already standardized in [11] for serialization and mappings such as AASX, XML, JSON, RDF and for the collection of information for the development phase (AutomationML) and the production phase (OPC UA). AAS (information + services) is sent and received by an API for the implementation of the EC.

III: In most cases, the implementation of an EC requires information and services from other companies. If external information is required, we propose the use of an international data space (IDS) concept for the collaborative transfer of information (see Part III). IDSs provide solutions for secure and reliable data exchange and data sovereignty [40]. In the automotive sector, the first IDS concepts have already been established, such as Catena-X, which proposes an AAS registry in which companies have access to a brief description of the information and services offered by external companies (yellow pages) [40]. In this case, we are talking about nonoperational data (see dotted arrow). Once a collaboration has been established by means of a contract between two companies, there is access to the information and services of the AAS, which is necessary to continue with the implementation of the change, see orange bidirectional arrow. At this point it should be noted that the exchange of information, both operational and nonoperational, will be done through connectors, which will serve as the only means for data transfer.

5. Conclusion

This paper highlighted the potential of AAS in the ECM process. For this purpose, we first showed the challenges in implementing EC by means of a review of the current literature. We identified 25 challenges from 23 relevant publications in the area of ECM. To better manage the identified challenges, we categorized them into seven groups. In addition, we included the opinion of experts by rating the challenges identified by means of a rating scale. From our research, we conclude that the most critical challenges in ECM are the lack of interoperability, followed by the lack of a single point of truth and lack of automation. To show the advantages of AAS with respect to the identified challenges, we reviewed the current literature on the concept, structure and specifications of AAS. We conclude that only by standardizing the identification, submodels and structure of the AAS can the lack of semantic and syntactic interoperability in the ECM be overcome, certainly, on condition of the participation of all parties involved during the whole process. Finally, we presented an innovative concept for streamlining the ECM process which aims to include the AAS structure and its advantages in the current ECM process. The concept shows the AAS as a mediator in the improvement of the ECM, without excluding the legacy enterprise information systems already established in the companies. For future work, we will realize the concept in a prototypical approach.

Acknowledgement

The authors gratefully acknowledge the support from The German Federal Ministry for Economic Affairs and Climate Action through the VWS4LS project (Grant No.13IK005A).

References

[1] G. Lashin, Engineering change management (2021).
[2] DIN EN IEC 63278-1, Asset administration shell for industrial applications - part 1: Asset administration shell structure (2022).
[3] T. A. W. Jarratt, C. M. Eckert, N. H. M. Caldwell, P. J. Clarkson, Engineering change: an overview and perspective on the literature (2011).
[4] T. Eickhoff, A. Eiden, J. C. Göbel, M. Eigner, A metadata repository for semantic product lifecycle management (2020).
[5] H. Habib, R. Menhas, O. McDermott, Managing engineering change within the paradigm of product lifecycle management (2022).
[6] M. Augustin, H. Zadek, Kooperatives änderungsmanagement (2015).
[7] ECM Recommendation Part 0, Vda 4965 (2009).
[8] H. Wildemann, Änderungsmanagement. leitfaden zur komplexitätsbeherrschung (2013).
[9] Q. Qi, F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, A. Nee, Enabling technologies and tools for digital twin (2021).
[10] B. Boss, S. Bader, A. Orzelski, M. Hoffmeister, Verwaltungsschale, 2019.
[11] Plattform Industrie 4.0, Details of the asset administration shell: Part1: The exchange of information between partners in the value chain of industrie 4.0 (2022).
[12] G. P. Cainelli, L. Underberg, L. Rauchhaupt, C. E. Pereira, Asset administration shell submodel for wireless communication system (2022).
[13] X. Ye, M. Yu, W. S. Song, S. H. Hong, An asset administration shell method for data exchange between manufacturing software applications (2021).
[14] H. Snyder, Literature review as a research methodology: An overview and guidelines (2019).
[15] A. B. Patel, T. N. Desai, A systematic review and meta-analysis of recent developments in sustainable supply chain management (2019).
[16] M. Altner, K. Duehr, H. Redinger, A. Albers, Requirements and challenges for engineering change management in the development of automotive wiring harnesses (2021).
[17] L. Jokinen, V. Vainio, A. Pulkkinen, Engineering change management data analysis from the perspective of information quality (2017).
[18] G. Schuh, G. Bergweiler, F. Fiedler, V. Slawik, C. Ahues, A review of data-based methods for the development of an adaptive engineering change system for automotive body shop (2021).
[19] D. Habhouba, S. Cherkaoui, A. Desrochers, Decision-making assistance in engineering-change management process (2011).
[20] R. Riascos, E. Ostrosi, J.-C. Sagot, J. Stjepandić, An approach for agile engineering change management within global product development, 2020.
[21] M. C. Wickel, U. Lindemann, How to integrate information about past engineering changes in new change processes (2015).
[22] G. Schuh, T. Gartzen, S. Soucy-Bouchard, F. Basse, Enabling agility in product development through an adaptive engineering change management (2017).
[23] I. Ullah, D. Tang, Q. Wang, L. Yin, I. Hussain, Managing engineering change requirements during the product development process (2018).
[24] N. Iakymenko, A. Romsdal, M. Semini, J. O. Strandhagen, Managing engineering changes in the engineer-to-order environment: challenges and research needs (2018).
[25] Arena2036, Innovation initiative wire harness (2021).
[26] M. Meißner, G. Jacobs, P. Jagla, J. Sprehe, Model based systems engineering as enabler for rapid engineering change management (2021).
[27] G. Schnauffer, D. Goerzig, C. Kosel, Diemer Johannes, Asset administration shell for the wiring harness system (2022).
[28] V. S. Avvaru, G. Bruno, P. Chiabert, E. Traini, Integration of plm, mes and erp systems to optimize the engineering, production and business, 2020.
[29] M. Eigner, T. Eickhoff, J. Ernst, A. Eiden, Systemübergreifendes änderungsmanagement zwischen plm und erp (2015).
[30] K. Wärmefjord, R. Söderberg, B. Schleich, H. Wang, Digital twin for variation management: A general framework and identification of industrial challenges related to the implementation (2020).
[31] S. D. Shivankar, G. M. Kakandikar, V. M. Nandedkar, Implementing engineering change management through product life cycle management in automotive field (2015).
[32] M. Bone, M. Blackburn, B. Kruse, J. Dzielski, T. Hagedorn, I. Grosse, Toward an interoperability and integration framework to enable digital thread (2018).
[33] J. Tavčar, I. Demšar, J. Duhovnik, Engineering change management maturity assessment model with lean criteria for automotive supply chain (2018).
[34] Arena2036 E.V., Innovationsinitiative leitungssatz: Scope-definition der iils zur weiteren definition der durchgängigen digitalisierung in der wertschöpfungskette (2021).
[35] E. Bratbak, Asset administration shell for life cycle management of safety systems (2022).
[36] M. Torben, T. Michael, H. Sebastian, G. Igor, M. Leon, K. Tobias, Realisierung und evaluation des verwaltungsschalen-metamodells: Python-sdk pyi40aas und lösungen für die praktische umsetzung (2022).
[37] Eclipse Foundation, Eclipse basyx (2022). URL `https://www.eclipse.org/`
[38] RWTH AAchen, Python industry 4.0 aas - pyi40aas (2022). URL `https://pypi.org/project/pyi40aas/`
[39] Plattform Industrie 4.0, Aasx package explorer (2022). URL `https://github.com/admin-shell-io`
[40] Catena-X, Catena-x automotive network (2022). URL `https://catena-x.net/de/`
[41] L. Stojanovic, T. Usländer, F. Volz, C. Weißenbacher, J. Müller, M. Jacoby, T. Bischoff, Methodology and tools for digital twin management—the fa3st approach (2021).
[42] A. Belyaev, C. Diedrich, Aktive verwaltungsschale von i4.0-komponenten (2019).
[43] R. Heidel, M. Hoffmeister, M. Hankel, U. Doebrich, Industrie 4.0 - the reference architecture model rami 4.0 and the industrie 4.0 component (2019).