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Enterprise Architecture Method for Continuous Improvement of PLM based on Process Mining

Eugen Rigger^{1*}, Thomas Vosgien², Samuel Bitrus¹, Piroska Szabo², Benoit Eynard³

¹ V-Research GmbH, Digital Engineering, Austria

² Hilti Befestigungstechnik AG, 69121 Heidelberg, Swiss

³ Université de Technologie de Compiègne, Department of Mechanical Systems Engineering, France

eugen.rigger@v-research.at

Abstract. The complexity and dynamics of IT landscapes and related PLM strategies of engineering enterprises are continuously growing due to trends such as Industry 4.0 and ever shorting product development cycles. To ensure interoperability, robustness, flexibility and efficiency of the IT systems and PLM, methods are needed that can handle these dynamics and complexities. In this paper, a method is presented that combines principles from enterprise architecture as well as business process mining to enable continuous improvement of PLM processes and the related IT systems. In particular, process mining is applied to validate the alignment of IT systems with related PLM processes. The method is demonstrated using an industrial case study that highlights the requirements from industrial practice and the applicability of the approach for PLM related processes. The method is shown to be particularly beneficial for the enterprise architects to support them with quantitative data as a basis for the design of continuous improvement cycles to make the PLM evolve. Future work will address the application of process mining for PLM related processes with distributed IT systems and the handling of the related complexity.

Keywords: PLM, Enterprise Architecture, Process Mining, Continuous Improvement.

1 Introduction

Digitalization of engineering companies [1] which builds upon trends such as Industry 4.0 [2] lead to increasing complexities in the IT landscape of engineering enterprises. In this context, Enterprise Architecture (EA) aims to ensure interoperability among IT applications as well as the related business processes and infrastructure satisfying the needs of an enterprise regarding robustness, flexibility and efficiency [3]. EA methods for modeling and management of architectures [3] have been proven to be beneficial in industrial practice with respect to monitoring and making enterprises evolve [4], [5] but are still subject to improvement with respect to new challenges stemming from the new opportunities in digital engineering and production [6].

With respect to handling of data and applied tools among the lifecycle of a product, Product Lifecycle Management (PLM) is applied as a strategic management approach

for product information, engineering workflows and related applications [7]. Hence, it can be governed and supported by enterprise architecture methods.

However, ever shortening product development cycles, the application of new technologies in industry such as Industrial Internet of Things or web-based technologies in general as well as the use of domain specific applications in engineering render the monitoring of enterprise architecture in a PLM context a challenge [1] calling for agile approaches to manage the continuous changes [8]. Hence, strategic approaches such as PLM and enterprise architecture require means to monitor and validate theoretically derived models of the enterprise architecture based on the actual operational use of applications. In this respect, process mining has been established as a means to validate and analyze business processes with respect to conformance based on analysis of event logs [9]. This enables to consolidate and optimize processes. Hence, the processes that are being applied in an enterprise, can be reengineered based on log data from the used systems. However, currently, process mining is applied to business processes with vast amount of data and single IT solutions which makes it difficult to be applied in a PLM context.

In response to these needs, this paper proposes a method enabling continuous PLM improvement combining principles from enterprise architecture as well as business process mining. The needs for this method are validated based on a use case reflecting the requirements from industrial practice and the actual method is illustrated using a reference process from PLM. Thus, this paper contributes by introducing a means that support business and operation excellence in the PLM area.

In the following, Section 2 reviews the state of the art and state of practice regarding business process mining. Following this, enterprise architecture methods are introduced and critically reviewed with respect to the applicability in agile and dynamic contexts. Section 2 is then summarized highlighting the research gaps that build the motivation and basis for derivation of the method that is presented in Section 3. Section 4 introduces case studies reflecting the current situation and application scenarios of the method in an industrial context. Section 5 comprehensively discusses these findings and Section 6 closes this paper by some concluding remarks.

2 Background

In this section the state of the art as well as state of practice of business process mining are discussed. Focus is put on currently applied industrial use cases of business process mining and its application in a context of product lifecycle management. Similarly, existing methodologies and supporting methods regarding enterprise architecture are reviewed. The background section is concluded by a summary highlighting the research gaps.

2.1 Business Process Mining vs. PLM

Process mining is a set of analysis techniques in the field of business process management [10] that applies machine learning and data mining to re-engineer and discover business process models using logs of information systems [9]. Correspondingly,

the three main fields of application of business process mining refer to discovery, where a model is generated from event logs; conformance checking, where the data obtained from the model are compared to identify deviations from actual execution of a business process; and enhancement, where an existing process model is improved and optimized [11]. Recent reviews of the technology show that business process mining is an established technology [12] and multiple commercial platforms exist that address open research issues related to usability and understandability of the techniques with respect to non-experts.

In the context of PLM, reported applications of business process mining mainly focus on the improvement of manufacturing processes based on data from manufacturing execution systems [13]–[16] or decision making during operation of systems [17]. Considering the central data management systems that build the core of PLM such as the product data management system (PDM), only few works can be identified. The work presented in [18] claims PDM related process improvement. However, the work is available in Korean, only. Zhaoxia et al. [19] extends the attributes of the data format within the standardized Mining XML format [20] that enables mining of events related to data management in PDM systems such as the approval process of documents. Monitoring of process in PDM are particularly important due to the rapid evolution of new tools and technologies from fields such as CAx or design automation each interfacing with PDM.

2.2 Enterprise Architecture

Enterprise Architecture (EA) provides means to describe, analyze, represent and design different dimensions of an enterprise [3], [21]. EA aims to manage the organizational structure and related processes of an enterprise as well as the supporting information systems and infrastructure so to understand complexity and manage change [22], [23, p. 201]. Multiple EA methods and standards have emerged since the origins of enterprise architecture in the late 1980s [21], e.g. [24], [25], [26], [27].

An essential part of PLM is concerned with the design process that is hard to formally model due to its situated [28] and iterative [29] character. Further, the engineering domain is characterized by domain specific tools featuring support for highly specific tasks, e.g. CAx [30] or design automation [31], [32]. Still, the works presented in [33], [34] have shown that the principles of enterprise architecture are also applicable in a PLM context. Hence, in this work methods of enterprise architecture are also used for the design and monitoring of PLM strategies.

Regarding the formal modeling of the enterprise architecture so to communicate and validate the knowledge about enterprise architecture, the ArchiMate graphical modeling language has been established as a standard [35]. Archimate features task precedence modeling in the three relevant layers for formalization of an enterprise architecture, namely business, application, and technology. The graphical modeling supports communication [36], participation and reengineering of enterprise architectures [37]. Archimate differentiates itself from other standardized notations for task precedence modeling, e.g. BPMN [38] or IDEF3 [39], by enabling modelling of the additional layers for applications and technologies.

2.3 Summary

Business process mining is an established technology that has gained recent interest in a PLM context due to the availability of structured data within the related information systems. However, there is a lack of methods with respect to systematic integration of business process mining in the context of the core applications of PLM such as the PDM to enable continuous improvement of the related business processes for data management. Existing EA methods need to be elaborated on to incorporate analysis and improvement cycles based on the monitoring capabilities provided by business process mining.

3 EA Method for continuous improvement of PLM

As highlighted in the review of the state of the art, existing methods from the field of enterprise architecture do not feature the continuous evolution process required to manage the dynamics of enterprise architecture within the field of PLM. Hence, in this work we propose a method featuring both the agility and flexibility required to account for the opportunities stemming from emerging technologies in the context of PLM as well as the monitoring capabilities required to guarantee streamlined application of these technologies based on process mining. The method is illustrated in Figure 1.

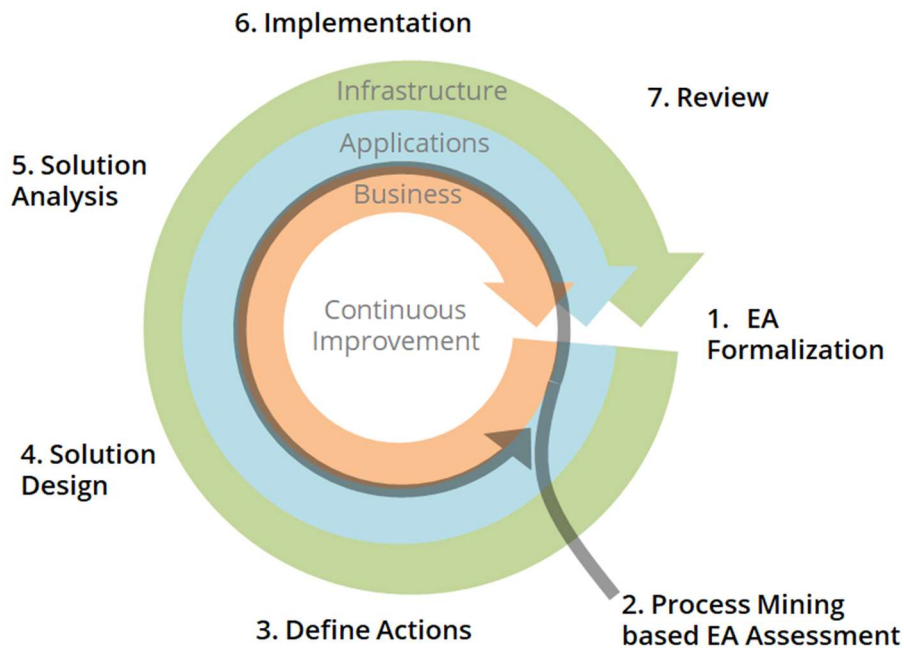


Fig. 1. Overview of the EA Method for continuous improvement of PLM

As can be seen in Figure 1, the method presented in this work is based on the main principles of continuous improvement [40], [41] so that the dynamics of PLM can be taken into account. The method is constituted by the following steps:

1. The enterprise architecture is formalized using the ArchiMate modelling language. The business processes, related applications as well as the supporting infrastructure are captured holistically in one model repository. Each architecture artifact is then documented with additional metadata that will be used for the EA assessment.
2. The enterprise architecture is evaluated based on a comparison of the formalized EA with the practically applied PLM processes. The monitoring of processes as well as the evaluation of multiple dimensions of PLM maturity [42], [43] such as the level of IT alignment allow to draw a balanced scorecard indicating the maturity of a selected process.
3. Based on the yielded score card, informed decisions regarding the adaptation of the EA can be taken. Potential actions include the adaption of business processes, the inclusion/exclusion of specific application functions etc.
4. A potential solution reflecting the changes within the EA to realize the previously defined action is designed by the solution architects. Defining a potential solution follows basic software development principles as defined in ISO 25010 [44]
5. The potential solution is evaluated with respect to non-functional requirements reflecting the EA conformance.
6. When conformance is guaranteed, the solution is implemented and integrated to the enterprise IT systems.
7. The newly integrated IT solution is reviewed with respect to functional requirements and if necessary adapted.
8. The EA model is adapted to incorporate the newly integrated IT solutions.

Step 1 and step 8 encompass the same activity of EA modeling. Hence, these actions indicated the continuous character of the method that should be permanently applied to ensure robustness, flexibility and efficiency of modern engineering companies.

4 Case Study

In the following, the current state of application of the method in an engineering enterprise producing a large variety of high value-added manufacturing systems for the construction industry. In a first step, the challenges of this business with respect to EA are briefly introduced. Following this, the current state of application of the EA Method for continuous improvement of IT system is presented. Thereby, focus is put on assessment of the EA based on process mining as well as heat maps that enable multi-dimensional assessment of business processes and the related EA. Finally, an outlook including a representative PLM process is presented to highlight how the company wants to move towards comprehensive application of the method to fully grasp the potential of simultaneous application of enterprise architecture and business process mining.

4.1 Industrial Challenges for Applying EA in the PLM Area

The industrial case deals with products of large system complexity and like any other manufacturing industry product data is cross-functionally used among the various departments of the company, e.g. product data is shared and exchanged among the various disciplines involved in the design process. The IT systems that enable product data and configuration management processes require a stable and robust IT landscape where IT architecture guidelines and principles are fully applied. Contrarily, the cross-functionality and multidisciplinary character of the product development call for a variety of IT systems and authoring applications, which makes the PLM IT landscape particularly difficult to govern from an EA perspective. For example, the engineering business units ask for flexibility and efficiency in implementation of desired authoring applications without necessarily taking care of applying the company standards, whereas these standards are necessary for ensuring the full traceability and consistency of the processed product data. Eventually, this leads to data quality issues downstream the product life cycle.

From another perspective, the emergence of cloud solution for PLM enabling IT systems poses additional challenges to the enterprise architecture, since a mix of on-premise, desktop and cloud solutions needs to be integrated. This makes EA governance and EA principles difficult to apply and requires the definition of new integration patterns.

Finally, to align PLM enabling IT systems with the IT strategy of the company, costly and risky PLM transformation projects are necessary. However, complex PLM IT systems need to be validated regarding the operational usage in order to assess the alignment of the IT systems with the business process and eventually the IT strategy. This is particularly true for the PLM systems for product data management that need to cover many business use cases and are complex. This leads to gaps between the defined and applied processes. Therefore, potential future solutions need to be assessed with respect to the possibilities for setting up process mining cases for the application.

4.2 State of Practice of Application of Enterprise Architecture

This section shows how the EA Method for continuous improvement of PLM introduced in section 3 is currently applied in practice to general business processes. Focus is put on the second step of the method, i.e. the EA assessment necessary to align the PLM IT systems with the EA strategy and principles of the company. The assessment itself consists of a compliance assessment with respect to EA architecture principles and also relies on a process mining solution to identify the state of application of a specific IT solution with respect to applied processes.

Assessment of Systems' Compliance and Maturity to EA Principles

Regarding the assessment of a systems maturity, the company introduced "assessment" metadata attributes for IT systems directly within modeling environment ADOit. Metadata comprises information such as the operating model (e.g. On Premise, XaaS), the mission criticality of a system, the level of customization of a system, the used

integration patterns and technologies, lifecycle information, etc. This enables the solution architects and enterprise architects to classify and assess the various software applications based on different IT strategy and principles criteria. Given the complete assessment of the corporate IT systems, a heatmap of IT systems maturity can be drawn as shown in **Fig. 2** so that a comprehensive overview of the current state of IT system maturity is given. Alternatively, this data can also be visualized using balanced scorecards. One of the first principles which is checked is “A system is supporting and is aligned with business processes and avoids functional redundancy”. Until now, this assessment was based on the qualitative and subjective evaluation of the architect and/or owner of the solution. In this paper, we propose now to complete this assessment by applying process mining to the respective supported business processes.

Software Systems	EA Score	A system is aligned with business processes and avoids functional redundancy	A system follows "best practice" architectures to foster reliability	A system has a managed lifecycle	A system has managed interfaces and follows interoperability standards
Principle Score		53.6	78.6	85.0	67.9
System A	65.9	P	M	M	M
System B	75.0	L	M	M	F
System C	68.2	M	L	F	L
System D	75.0	L	F	F	F
System E	54.5	P	M	M	P
System F	84.1	M	F	F	F
System G	72.7	M	M	M	P

Fig. 2. Excerpt of EA heat map report with columns indicating the different levels of IT system maturity. The systems are hidden for confidentiality reasons.

PLM Process Mining for Operational Alignment between PLM IT Systems and Processes

In the following, the application of process mining to assess the alignment of the used ERP/PDM system SAP S/4 HANA with applied engineering change management process. The case has been implemented using the Celonis process mining toolbox.

Whereas the company already applies the proposed method in the context of sales and marketing business processes (e.g. purchase-to-pay and order-to-cash), the PLM related processes are currently not yet operationally mined. One of the reasons is that the PLM environment is subject to current major changes and the engineering change management processes is currently involving several software applications which are currently not yet in the scope and roadmap of the process mining initiative. Moreover, each new process mining case requires additional costs, efforts and time, not only for integrating Celonis with other software systems but also for formalizing, setting up, implementing, executing the case and analyzing the results.

In the following, the data model of SAP S/4 HANA is investigated with respect to its capabilities to support and monitor the engineering change management process (ECM). ECM is taken as a representative PLM process since it is critical with respect to its impact on data quality and information traceability required in downstream engineering processes. Hence, misalignments between the software implementation and its usage by the end-users are critical and need to be avoided.

Fig. 3 depicts the engineering change management reference process and the related data structure in SAP S/4 HANA as implemented in the company. This allows the identification of business processes based on the analysis of interrelations of the identified

process activities. Given this information, the definition of process activities as required for setting up a process mining case can be performed.

Fig. 4 shows some of the proof of concept results for the analysis of the ECM process. Even though the details cannot be provided due to confidentiality, it can be seen that multiple variants of processes are identified when tracking the data event logs for engineering change request/orders. This information can then be used to elaborate on the defined processes as well as to support the assessment of the IT system with regards to its capabilities alignment with their operational usage. In this specific case, the results of the process mining enabled the enterprise architect to adjust the EA assessment “A system is supporting and is aligned with business processes and avoids functional redundancy” so that a qualitative estimation is replaced by quantitative evaluations. Further, the setup of process mining cases right from the start of implementation of a new IT system in the PLM context, will be used to monitor the adoption of new systems so to enable continuous improvement of the IT systems also in a PLM context.

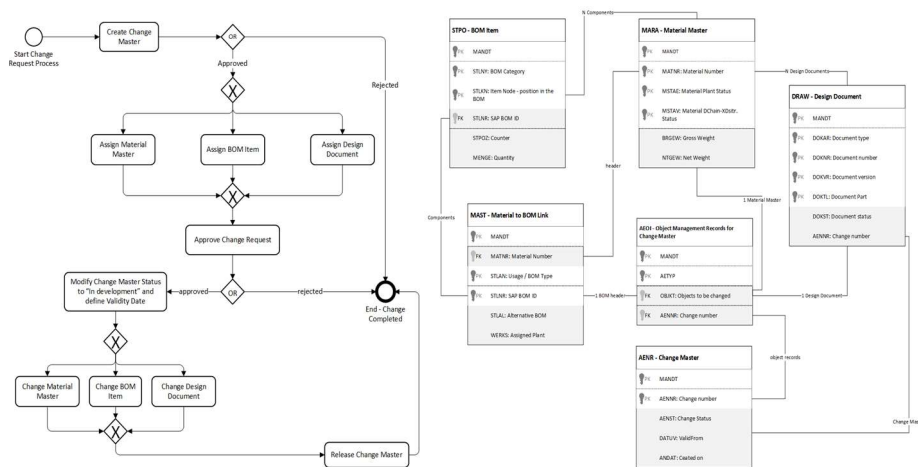


Fig. 3. Engineering Change Management Process and related data structure in SAP S/4 HANA.



Fig. 4. Process deviations report in Celonis for the usage of SAP S/4 HANA.

5 Discussion

In the following, the work and results presented in this work are discussed with its impact with respect to industry as well as academia.

Regarding the contributions with respect to industry, the business case introduced in Section 4 summarizes the challenges of a manufacturing engineering enterprise with respect to PLM and EA adoption. Building upon these challenges, different dimensions of PLM / IT systems maturity are introduced to assess these challenges and enable continuous improvement of the PLM / IT systems. In this work, the application of process mining is proposed to support the assessment of PLM / IT systems also based on quantitative data stemming from the evaluation of data logs. In this respect, the results stemming from the process mining case can be used to rework the processes as well as the supporting IT systems and application functions. The enterprise architectures benefit from this data since it enables them to lead informed discussions with related stakeholders based on quantitative data rather than qualitative estimations. Further, the enhanced understanding of the As-Is state of the enterprise architecture also increases applicability and quality of the potential To-Be states since reality is reflected in more detail.

The introduced process mining case in Section 4 indicates how the ability to setup a process mining for a potential IT system can be an evaluation criterion for the evaluation of IT systems. Having the ability to conduct process mining for PLM related processes is key to improve the collaboration of the different engineering disciplines. Different disciplines have different requirements for product data management leading to

potential misalignments in applied processes. Having the overview of different processes, established processes can be adapted eventually leading to a better data quality when PLM processes are well adopted by the different users. Considering the overview of the various instances of PLM processes from an applied process mining case, the origins of misalignments in data can be identified, e.g. when a discipline keeps ignoring specific process activities. Using this information, the related users can be identified and informed with respect to the effects of this misalignments. Thus, motivation of the related stakeholders can be increased to actively contribute to PLM and EA design and compliance. With regards to the number of observed process deviations, the real complexity of the case is much higher than expected. This leads to consider some limitations regarding the application of process mining in industrial practice. These great number of process deviations have been observed by analyzing the data logs of only one IT systems, whereas, in practice, the ECM process' actors generally uses several data management and authoring systems. Reflecting the operational reality would require more investigations and more process mining investments. On the other hand, by mining other data sources, the amount of data to analyze as well as the amount of process deviations would increase, leading to the risk of not being able to efficiently analyze these deviations. Therefore, industrialists must be careful when willing to apply process mining excessively. One of the challenges is to coordinate and align the process mining activities with the PLM transformation roadmap to avoid a negative perception or non-adoption of the approach by both management and process 'actors point of views.

With respect to academia, the proposed work contributes by the introduction of an EA framework that considers state-of-the-art technologies and puts a focus on the challenges stemming from the PLM domain. This work particularly takes into account the point highlighted in [23] that the future directions of EA need to push the boundaries of EA by integrating different field and pursue a multidisciplinary approach and therefore increase visibility and dynamics in the field.

The future work needs to focus on the actual implementation of PLM process mining cases and the development of a method to detect isolated (non-integrated) IT systems within PLM based on process mining.

6 Conclusion

This work contributes by introducing an enterprise architecture-based method for continuous improvement of PLM processes and the related IT systems. To quantitatively evaluate the As-Is state of PLM, the method applies process mining monitor the alignment of IT systems with the related PLM processes. The validation of the method based on an industrial case shows the applicability to support enterprise architects in the review of the As-Is state to enable continuous improvement of PLM. Further, the method contributes by merging different previously unconnected fields of research.

However, the industrial case also shows the complexity of process evaluation in a PLM context. Hence, future work needs to address the development of methods that enable the application of process mining for PLM related processes with distributed IT systems.

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