# Production-Aware Analysis of Multi-disciplinary Systems Engineering Processes

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Abstract: The Industry 4.0 vision of flexible manufacturing systems depends on the collaboration of domain experts coming from a variety of engineering disciplines and on the explicit representation of knowledge on relationships between products and production systems (PPR knowledge). However, in multi-disciplinary systems engineering organizations, process analysis and improvement has traditionally focused on one specific discipline rather than on the collaboration of several workgroups and their exchange of knowledge on *product/ion*, i.e., product and production processes. In this paper, we investigate requirements for the *product/ion-aware analysis of engineering processes* to improve the engineering process across workgroups. We introduce a *product/ion-aware engineering processes analysis* (PPR EPA) method, to identify gaps in PPR knowledge needed and provided. For representing PPR knowledge, we introduce a *product/ion-aware data processing map* (PPR DPM) by extending the BPMN 2.0 standard, adding PPR knowledge classification. We evaluate the contribution in a case study at a large production systems engineering company. The domain experts found the PPR EPA method using the PPR DPM usable and useful to trace design decisions in the engineering process as foundation for advanced quality assurance analyses.

## 1 INTRODUCTION

The goal of *production systems engineering* (PSE) organizations is to create automated manufacturing systems (Biffl et al., 2017). These companies support achieving this goal by creating their own special information systems and tools (usually integrating best purpose tools) and by using them throughout the engineering process, similar to software developers using a tool chain for code development (Lüder, 2017). However, in the PSE process insufficient representation of important relationships between the product, the production process, and production resources (PPR) may lead to considerable risk of low quality and unanticipated costs during production system operation. Although PSE organizations build on profound PPR experience, surprisingly, PPR relationships are not routinely modeled explicitly in the PSE process. The equivalent in *information systems engineering* (ISE) would be not to communicate non-functional operational requirements, e.g., on performance or security, to the software developers, making it costly and risky to fulfill these requirements during systems operation. To address these challenges, the ISE and software engineering communities have introduced operation-aware processes and methods such as SCRUM (Schwaber, 2002), DevOps (Zhu, 2016), or rapid prototyping.

However, the involvement of several disciplines in PSE and the complexity of productions systems, which involve risky hardware, make it much harder to engineer and explore the target system in short feedback cycles. On the contrary, PSE domain experts tend to focus on the specific contribution of their discipline to the overall PSE process without specifically considering product or production process aspects (Biffl, 2018).

In this paper, we focus on the capability for the analysis and improvement of multi-disciplinary engineering processes that exchange knowledge between workgroups. We investigate the *product/ion* (i.e.,



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product and production process) *aware analysis of engineering processes* as there is significant potential for improvement in the collaboration and coordination of PSE workgroups by considering and explicitly representing *PPR knowledge*, like process parameters or product resilience. *Product/ion-awareness* in the context of software engineering, is knowledge on how to develop and configure a system, the product, to run ideally in a target environment like a web server (the process executing the product). In this paper, we use the term *PPR knowledge* for success-critical attributes, such as configurations and parameters, and dependency relationships between products, production processes, and production resources.

We illustrate the PSE process with the use case *fragile product*. A *customer* requires a production system for producing fragile products. In the PSE company, a *basic planner* specifies the production process and system according to the product requirements. A team of *detail planners* derives discipline-specific detailed plans for constructing and operating the production system from the specifications, including a high-throughput transport system. Unfortunately, during operation of the system, the high acceleration of the transport process potentially damages fragile product parts due to the *missing explicit PPR knowledge* of detail planners *on product fragility*, a critical *product-to-production-process* relationship, in the specifications of the *basic planner*. From this use case we derive the following key challenges.

*C1. The engineering process between discipline-specific workgroups is hard to trace and analyze.* Traditionally, the focus of organization in PSE is on one workgroup. Workgroups collaborate according to project needs in changing configurations by exchanging engineering artifacts, often inefficiently. However, there is no formal process or knowledge representation to guide or analyze the cooperation of workgroups in the engineering process.

*C2. Unclear benefit of representing PPR knowledge.* For domain engineers, e.g., basic planners, who have knowledge on the product and design the production process, it is not clear which roles would benefit to what extent from sharing their PPR knowledge. Therefore, they do not take the extra effort to explicitly represent PPR knowledge that could be beneficial for detail planners and other roles.

*C3. Unclear impact of PPR knowledge.* For product engineers, it is often not clear which effects their design decisions have on later phases in production systems engineering. The domain experts have only limited overview on the positive or negative impact their design decisions may have on the achievable product quality and similar systems planned in the future.

To address these challenges, we derive the following research questions for improving the *product/ion* (i.e., product and production process) *aware analysis of engineering processes* of workgroups following the design science cycle (Wieringa, 2014).

***RQ1. PPR EPA Method.*** *What adaptions or combinations of business/engineering process analysis methods allow overcoming their limitations regarding product/ion-aware engineering process analysis?* Based on existing approaches from *business process analysis* (BPA) and PSE, we identify capabilities and limitations of process and data analysis approaches for a *product/ion-aware engineering process analysis* (PPR EPA) method. Both domains have similarities that can be used for adapting an EPA method (Biffl *et al.*, 2017). Based on requirements elicited in workshops with domain experts, we introduce a PPR EPA method. We evaluate the PPR EPA method in a holistic case study (Runeson and Höst, 2009) by conducting process analysis tasks with stakeholders from workgroups on their exchanged artifacts in order to classify PPR knowledge in engineering artifacts.

***RQ2. PPR DPM Notation.*** *What adaptions or combinations of business/engineering process notations allow overcoming their limitations for representing stakeholders, processes and documents that may represent PPR knowledge?* Based on requirements coming from the PPR EPA method and on the analysis of existing notations, we propose an extension of BPMN 2.0 to design and evaluate a *product/ion-aware data processing map* (PPR DPM) as foundation for the analysis of gaps in the PPR knowledge representation in the engineering process. Following the design science approach, we validate the treatments, PPR EPA method and PPR DPM artifact, in the context of the case study. The result of RQ2 allows the stakeholders to express the PPR knowledge needs in the engineering process as foundation for overcoming identified shortcomings.

The remainder of the paper is structured as follows: Section 2 summarizes related work on strengths and limitations of process analysis approaches. Section 3 introduces requirements for the PPR EPA method and PPR DPM artifact, and the treatment designs. Section 4 presents the case study conducted with domain experts in a large PSE company. Section 5 evaluates and discusses the case study results. Section 6 concludes and proposes future research work.

# 2 RELATED WORK

This section summarizes related work on *production awareness* (PPR), on approaches for engineering process analysis, and on notations for representing the analysis results.

## 2.1 Production Awareness (PPR) in Multi-disciplinary Engineering

Technical systems are often distinguished into products and production systems (Biffl *et al.*, 2017). The product is typically characterized as the reason a company exists for, i.e., products are created in a value adding process to make profit by selling them (Stark, 2015). In contrast, a production system provides the means to create products by the appropriate combination of production factors (El Maraghy, 2009).

There are strong dependencies between product and production system. Schleipen (2015) coined the *PPR concept* for the relationships between products and production systems based on the production process, illustrated in Figure 1, as foundation for designing and analysing engineering processes. Each product requires for its manufacturing processes, which are executed by production resources. Each production resource processes sets of products and is able to execute processes. Finally, each process is used for the production of products.

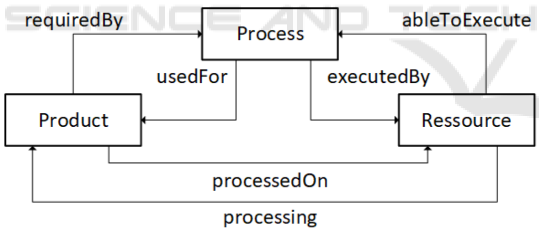


Figure 1: Product, production Process, and production Resource (PPR) relationships.

## 2.2 Engineering Process Analysis Method

*Business process analysis* (BPA) methods, like (Rosenberger, 2018), determine and define activities which need a business context and then execute a context elicitation. Santos and Alves (2017), follow the design science cycle from Wieringa (2014), and present a three phase in depth analysis of the business process, based on interviews. The BPA contributions, present detailed execution steps on how to represent the big picture of business processes for analyzing characteristics of multiple stakeholders and their activities, including exchanged documents. Vergidis *et al.* (2009), classified BPA methods and concluded that only few BPA methods allow for more detailed analyses going beyond the identification of stakeholders, tasks and input/output artifacts. As a limitation for engineering process analysis, BPA methods, do not consider individual disciplines, interfaces between workgroups for cooperation and collaboration or dependencies regarding knowledge transfers across an organization. However, the analysis of engineering processes across workgroups requires both the analysis of the overview on relationships of workgroups and a more detailed analysis of the exchanged engineering artifacts according to the dependencies between workgroups.

In the PSE community, Jäger *et al.* (2011) identified the need to “*systematically model the engineering workflow, which would allow a deeper knowledge of different engineering aspects and to improve the views of each discipline on the engineering objects.*” To fulfill this need, the authors analyzed engineering artifacts and their mappings to domain experts as foundation for creating cause and effect diagrams. Through these analyses, Jäger *et al.* (2011) gained insights into the needs of specific workgroups, and on dependencies between engineering artifacts.

Lüder *et al.* (2012) investigated a detailed engineering process analysis method focusing on single workgroups, but did not consider how the overall engineering process of multiple workgroups is constructed or could be improved. In a second publication Lüder *et al.* (2018) investigate challenges that arise in multi-disciplinary engineering processes regarding data exchanges and highlight the importance of an engineering process analysis method.

The VDI 3695 standard (VDI, 2009), presents a more general approach and coined the concepts of *engineering organizations*, which execute their work in a project-based manner. The standard, points out possible improvement areas, but does not consider concrete implementation guidelines, this stands out, because for example the need of a shared data model is identified, but how an engineering organization can achieve a unified view of their data is not presented.

*Engineering process analysis* (EPA) methods tend to focus more on discipline internal representations and improvements, whereas BPA methods allow representing an overall big picture of business processes.

Overall, the analyzed literature reveals a gap of analysis methods regarding workgroups. There are no considerations on how workgroups collaborate or coordinate common process tasks with each other. Furthermore, the analysis methods do not consider the PPR engineering knowledge exchanged as foundation for identifying risks from missing PPR knowledge in multi-disciplinary engineering tasks.

### 2.3 PPR Knowledge Representation in Process Analysis Outcomes

For modeling both process and data flows in business processes, there are several established methods with varying strengths and limitations. In the engineering domain, the IDEF0 system analysis standard (Presley, 1995) is widely used (Zhang, 2010) for providing an overview on processes, inputs and outputs, stakeholders and mechanisms. However, IDEF0 diagrams do not allow to easily represent the sequence of a process, represent the flow of PPR knowledge and involved stakeholders need to be annotated per process task, which makes the models cumbersome to work with.

Lüder et al. (2012) classify identified knowledge through tables, which allow a representation of the individual engineering tasks, but the approach does not scale well, due to the number of different tables and high level of detailed represented.

In business process modeling there are several options like: *Event-driven process chains* (EPCs) (Scheer, 1998), BPMN 2.0 (Allweyer, 2016), or the UML standard (Fowler, 2004). Merunka (2017) pointed out that the UML standard allows modeling system structure and behavior, but does not consider the combination of product and process knowledge in neither one diagram, nor in combinations of related diagrams.

Both EPCs and BPMN 2.0 are widely used for modeling business processes, and have similar strengths and limitations. When modelling multiple tasks for one stakeholder, the extended EPC is less efficient by requiring the annotation of each task with an organizational unit, whereas BPMN 2.0 provides a compact swim plane concept for parallel processes.

To overcome the limitations of popular BPA languages, Khabbazi (2013), Huang (2017), and Merunka (2017) proposed the combination of multiple concepts. Even though these combinations allow for working with “best-of-breed” approaches, they also increase the complexity for further analyses. As the mentioned authors did not coin a term for the combination of process and document flow, we use in this paper the term *data processing map*, whenever it is of importance that the data aspect of a business process is considered alongside the process aspect.

While the investigated notations do not consider expressing PPR knowledge and its flow through an engineering process, the notations provide a good foundation for closing this gap with an extension, e.g., in our case by extending BPMN 2.0 diagrams.

## 3 PRODUCTION AWARE ANALYSIS OF ENGINEERING PROCESSES

To address the limitations of general business process analysis and domain-focused EPA methods, we propose an approach for multi-disciplinary engineering environments, driven by uses cases that represent typical processes and requirements and are well known to the domain experts.

The goal of the *product/ion-aware engineering process analysis* (PPR EPA) method is to represent a repeatable process, which results in a PPR *data processing map* (PPR DPM) (see Figure 4). The PPR DPM is a visual representation of the engineering tasks in a selected scope that allows reasoning about workgroup interfaces and responsibility hand overs.

In Section 3.1, we present requirements for the proposed PPR EPA method, as well as for the PPR DPM notation. Section 3.2 presents the design of the treatment *PPR EPA* method. Section 3.3 introduces the design of the treatment *PPR DPM artifact* by extending BPMN2.0 with PPR knowledge elements.

### 3.1 Requirements

This section presents requirements for the PPR EPA method and for the PPR DPM notation. We elicited EPA requirements and illustrating use cases with artifact and data samples in workshops with stakeholders at a large PSE company.

***RQ1 PPR EPA.*** To address the goal of systematically collecting data on the use of PPR knowledge for engineering process analysis and improvement, we derived a set of requirements for capabilities of the *initial product/ion-aware engineering process analysis*. We focus on these requirements because they represent the PPR knowledge aspect missing in approaches from BPA and PSE literature.

**Identification of PPR Knowledge.** The PPR EPA method should be able not only to identify the sequence of engineering tasks but should also allow identifying PPR engineering knowledge, e.g., that product knowledge is represented in initial product drawings from the customer.

**Identification of PPR Knowledge Flows.** The PPR EPA method should follow the creation of PPR knowledge and tasks requiring PPR knowledge throughout the engineering process. An example process path is: 1. Create production process sequence with *process knowledge*; 2. create production system layout with *resource knowledge*, *process knowledge* is not carried on; and 3. submit production system offer to the customer with *resource knowledge*.

**Identification of PPR Knowledge in Interdisciplinary Interactions.** The PPR EPA method should allow identifying where engineering disciplines, typically workgroups, interact with each other, e.g., handover phases of project responsibility or artifacts, e.g., the change from basic to detailed planning where all artifacts are handed over to a new team.

***RQ2 PPR DPM.*** To support the reasoning of domain experts on improving the use of PPR knowledge in an engineering process, we derived the following set of requirements for concepts capabilities of the PPR DPM and its visualization. These requirements focus on representing PPR knowledge and the combination with process and data flow representations.

**PPR-specific Visual Elements.** The PPR DPM notation should provide specific elements for the concepts used in the PPR EPA, including different visual elements for: PPR knowledge, tasks with a priority indication for PPR knowledge, and representing which PPR knowledge an engineering process currently receives and what is additionally needed.

**Iterative Refinement.** The PPR DPM should allow for starting with a small initial model and for iteratively expanding the model to the desired level of detail. This allows representing only the most vital engineering process tasks per discipline in the beginning as context for collecting workflows that are more detailed.

**Process Overview.** The PPR DPM should provide an overview on the involved disciplines with their respective process executions, e.g., which role executes which sequence of tasks, as foundation for reasoning on improvements, e.g., where engineering disciplines would benefit from closer collaborations.

## 3.2 Design of a Production-Aware Engineering Process Analysis Method

To address RQ1, we build on a BPA method presented from Santos and Alves (2017) and extend it with perspective investigations from an EPA method (Lüder *et al.*, 2012). This allows for a combination of the best approaches of both BPA and EPA.

The proposed PPR EPA method is designed to work in multi-disciplinary environments where the process execution involves several domain experts making it crucial to investigate beyond the boundaries of a single discipline.

Figure 2 provides an overview on the steps and tasks of the PPR EPA method. The stakeholders are *engineering domain experts* (orange), *engineering management* (blue), *quality assurance* (green), and the new role *EPA facilitator* (red). The EPA facilitator conducts the interviews, draws an initial PPR

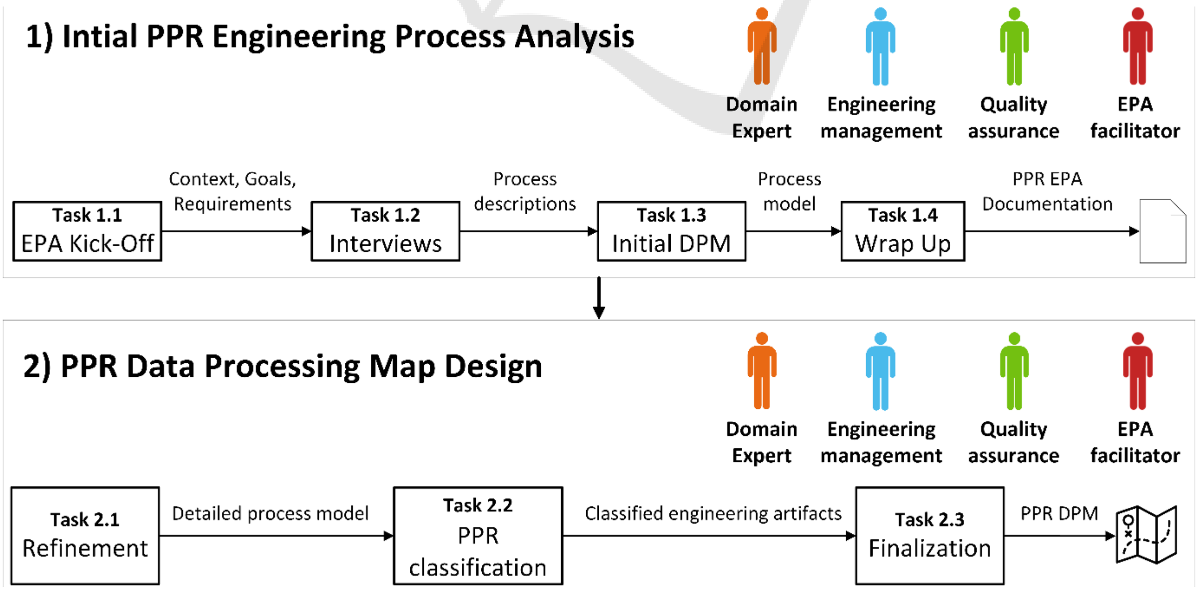


Figure 2: Steps of the product/ion-aware EPA method based on (Biffl, 2018).

DPM, and holds workshops. This role was also identified in (Fay, 2018) with its importance to the execution/integration of digital models in an engineering process. The remaining stakeholders provide information and are interested in improving the engineering process by avoiding rework, such as redrawing artifacts due to proprietary engineering tool data formats. In addition, the stakeholders are interested in capturing PPR knowledge in a reusable way for more efficient exchange of PPR knowledge in the engineering team.

*Phase 1 Initial PPR Engineering Process Analysis* elicits the context of the engineering process in the current state. The investigation already considers PPR knowledge, but the resulting documentation, including an initial DPM, focuses on outlining the context and not on representing PPR knowledge.

*Phase 2 PPR Data Processing Map Design* is concerned with the transformation of detailed PPR knowledge from qualitative interviews into a visual representation. This step classifies and visually represents the PPR knowledge in engineering artifacts.

**Phase 1. Initial PPR Engineering Process Analysis** starts with initial knowledge about the project under investigation. Outcome of this phase are interview documentation, representative engineering documents and an initial data processing map, which represents the engineering process and high-level artifact flows with no PPR knowledge consideration.

**Task 1.1. Engineering Process Analysis Kick-Off** outlines the context of the engineering process with a small team of stakeholders. Outcome of this task is a document collecting context, goals, and requirements as well as a first sketch of the data process map providing an overview on stakeholders and their major tasks building on standard modeling elements like events, tasks and data flow.

**Task 1.2. Interviews** with domain experts allow collecting detailed and diverse data for gaining deeper insights to the engineering process of the respective domain expert. The interviewer elicits PPR knowledge from domain experts, e.g., which PPR concepts are relevant for a selected process task, as foundation for an initial PPR classification of engineering artifacts. Outcome of this task is a set of detailed interview notes.

**Task 1.3. Initial Data Process Map** concerns the reassessment of the information gathered in the interviews with a basic process model of the data flow in the engineering project. Outcome of this task is a data processing map consisting of rough process sequences and input and output artifacts.

**Task 1.4. Wrap Up** finishes the first phase of the PPR EPA by revisiting domain experts to resolve open issues as it cannot be taken for granted that the same stakeholders will be available for follow-up interviews in the next phase. Outcome of this task is a report with an initial draft of the DPM.

**Phase 2. PPR Data Processing Map Design** starts off with an initial version of the *data processing map* and sets out to detail the current model with PPR knowledge. Outcome of this phase is the final and refined version of the PPR DPM (see Figure 4).

**Task 2.1. Refinement** integrates the detail information from the interview partners and stakeholders from Phase 1. Here too, detailed or coarse tasks can either be split up or be aggregated together. Outcome of this task is the final basic version of the DPM.

**Task 2.2. PPR Classification** classifies the input and output artifacts regarding product, production process and production resource (PPR) based on the insights from the interviews regarding the data flow and concepts represented in the artifacts. Outcome is a PPR DPM with PPR knowledge classifications for each artifact and tasks with high or critical need of PPR knowledge are identified.

**Task 2.3. Finalization.** The EPA facilitator creates the final version of the PPR DPM, with input from the remaining stakeholders. Outcome of this step is the PPR DPM, representing all disciplines and their process tasks, engineering artifacts and their flow as well as the classification of these artifacts.

### 3.3 Design of a Production-Aware Data Processing Map Notation

To address RQ2 and to be able to represent the outcomes of the PPR EPA, we explored business and engineering process notations and modeling techniques like UML, BPMN 2.0 or EPC. We extend these approaches by indicating PPR knowledge, where it is possible to label document content regarding product (P), process (P'), or resource (R) information.

In the first phase of the EPA, the kick-off, we explored several modeling notations, which revealed the following limitations: IDEF0 did not scale very well and was hard to analyze for multiple stakeholders and PPR knowledge. UML did not provide a single concept and would have required combining several. EPC and BPMN 2.0 provided similar features, but EPC was more cumbersome for the requirements needed for the PPR DPM. BPMN 2.0 fulfills many criteria presented in section 3.1 but has no means to classify PPR artifacts or knowledge in general. Therefore, we use from the BPMN 2.0 standard: events, tasks, documents and gateways and introduce our own extensions to express PPR knowledge.

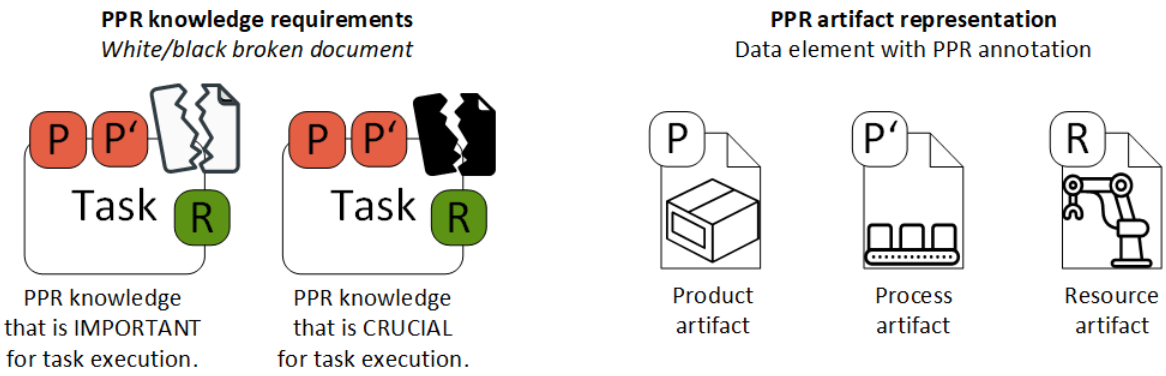


Figure 3: Custom BPMN 2.0 extensions for product/ion-aware (PPR) Data Processing Map based on (Biffl, 2018).

Figure 3 illustrates the extensions that we introduced to the BPMN 2.0 standard. On the left-hand side, we take the BPMN 2.0 task concept and add **PPR Knowledge Requirements**. These requirements are expressed by (a) annotations of P, P' and R and (b) white/black broken documents, if at least one PPR aspect is needed but missing. The annotations of P, P' and R indicate what information the task currently receives (coloured in green) and what information is missing (coloured in red). The white broken document expresses that it is important for a task to receive PPR knowledge, but that the process execution is not hindered if PPR knowledge is missing, but could be conducted more efficiently or with better quality. A black broken document indicates high risk: it is absolutely crucial for the task to receive the required PPR knowledge, otherwise the task cannot be executed properly, reducing the efficiency or quality of the overall engineering project outcome.

On the right-hand side of Figure 3, we present **PPR Knowledge Classification of Engineering Documents.** We extend the BPMN 2.0 representation of documents by adding on top an indication whether the artefact contains product (P), process (P'), or resource (R) information. The documents themselves are also distinguishable through the annotations in the middle: a package for a product, conveyor belt for a process, and a robot arm for a resource. In Figure 4, tag D1 highlights an engineering task receiving product- (P) and process-specific (P') knowledge.

The annotation of engineering documents with PPR knowledge is the foundation for describing the flow of PPR knowledge in the engineering process and for analyzing which tasks create, lose, or transform PPR knowledge in order to identify key gaps in the engineering process and propose improvements.

To evaluate the proposed PPR EPA method and PPR DPM notation, Section 4 reports on a case study, conducted at a large engineering company.

## 4 CASE STUDY

To evaluate the proposed approaches for RQ1, the PPR EPA and RQ2, the PPR DPM, we conducted a case study following (Runeson and Höst, 2009). We took the role of the PPR EPA facilitator described in section 3.2 to go through the tasks with the domain experts. In the case study, we collected data on the existing engineering process as well as the role and current representation of PPR knowledge. The interviewed domain experts communicated their needs regarding PPR EPA and PPR DPM.

**Study Subject.** The case study on the proposed *product/ion-aware engineering process analysis* (PPR EPA) method was conducted with seven domain experts, one quality assurance stakeholder and one engineering management stakeholder, and three researchers acting as EPA facilitators. The case study spanned over nearly two months from the initial kick-off to the final version of the *data processing map* and the final feedback from the involved stakeholders.

**Study Execution.** According to the PPR EPA Phase 1, *Initial PPR Engineering Process Analysis*, we held a *kickoff*, for a project on *ultrasonic welding*, at the company. The kickoff presented the context the company operates in and gave some insights into the current engineering workflow and tool landscape.

The nine *interview* sessions, for each stakeholder one, took place over the span of two days, where each interview lasted one hour. Each interview started with collecting data concerning the interviewee's field of work, usual project-specific tasks and responsibilities. More specific questions regarding engineering process tasks, the sequence of tasks, engineering artifacts and their content, as well as questions regarding the current representation of PPR knowledge followed. After each interview, there was a break, which

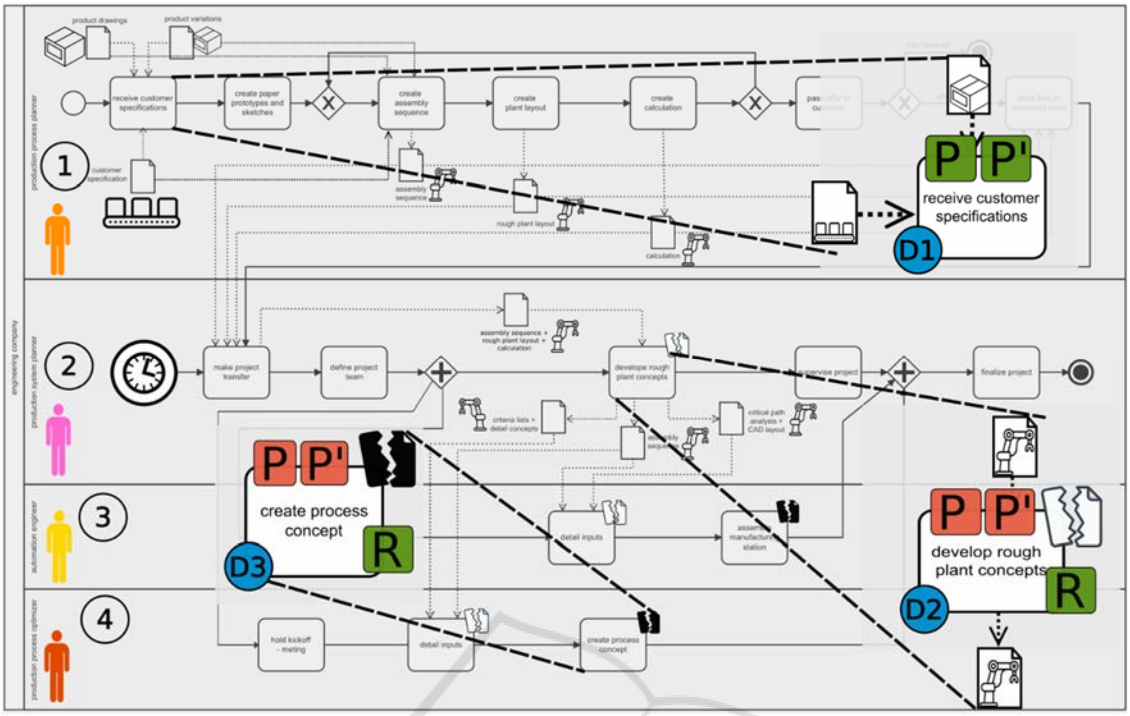


Figure 4: Production-aware (PPR) Data Processing Map based on (Biffl, 2018).

allowed a short modeling cycle to transform the qualitative knowledge into a first visual representation.

After the interviews were finished, the researchers reviewed the information gathered in the interviews, categorized artifacts and their content for sharing. Starting from an initial *data processing map* (DPM), we designed a *more detailed DPM* with information from the interviews. We discussed the *more detailed DPM* with the stakeholders involved, getting their approval and feedback for improvement as input to the *wrap up* step of PPR EPA method.

According to PPR EPA Phase 2, *PPR Data Processing Map Design*, we reexamined the gathered input carefully regarding PPR knowledge aspects and hidden implications that allowed for some *refinements* of the engineering tasks. The PPR DPM allows for a good overview analysis of an engineering process, but also linking represented artifacts to concrete associated files and examples in a separate document store. In cooperation with domain experts, we examined and *classified* the exchanged representations of engineering data artifacts for information regarding the product, production process or production resource. The classification builds on a mapping by Hundt (2012) between engineering phases and engineering artifacts, such as electrical or mechanical plans. In addition, we reexamined the identified engineering tasks and expressed their requirements for PPR knowledge as *no need*, *important need* or *crucial need*. Figure 4 illustrates a representative part of the final version of the PPR DPM.

In Figure 4, the *production process planner*, in the BPMN swim lane number one (light orange), starts each project and receives product and production process information, indicated by tag D1: *product drawings*, *product variations*, and the *customer specification*. With these input artifacts the production process planner creates new *resource knowledge* in the tasks *sketching*, *plant layout creation*, and *cost calculation*.

A *production system planner*, see BPMN swim lane number two (purple), starts working after the production process planner finishes with the handover of relevant documents, and when all team members from different disciplines find the time for a project kickoff, indicated by the timer event (clock symbol). The *production system planner* receives as input all the output artifacts from the previous role, the *production process planner*, and develops a *rough plant concept*, indicated by tag D2, where only *resource knowledge* is present, but it would also be important to receive product and process information.

The work of the *automation engineer*, see BPMN swim lane number three (yellow), runs in parallel to the *production system planner* and the *production process optimizer*, see BPMN swim lane number four (dark orange). The *automation engineer* is responsible for detailing the electrical point of view of the system under construction, whereas the *production process optimizer* aims at minimizing production system cycle times to maximize the overall production throughput. Both roles receive *resource knowledge* from the *production system planner*. However, as can be seen in Figure 4, tag D3, product and process information is crucial for their engineering tasks. In the current situation, the domain experts try to get a hold of the person responsible for a design decision to start personal, unplanned communication, which takes additional time, is very inefficient, and bears the risk of taking wrong decisions due to insufficient PPR knowledge.

We evaluate the findings of the case study for the PPR EPA method and PPR DPM in the next section.

# 5 EVALUATION AND DISCUSSION

This section reports on (a) a comparison between the outcomes of different data processing map notations in an initial feasibility case study (Runeson and Höst, 2009) with domain experts at a large multi-disciplinary systems engineering company and (b) a discussion of the overall process execution, observations, and lessons learned.

## 5.1 Evaluation

The conducted evaluation for the PPR DPM uses different requirements than in section 3.1. This is because the evaluation focuses on the non-functional parts of the designed artifact. We compare (a) the visualization of engineering processes with EPC currently used at the company, (b) a standard BPMN 2.0 model, and (c) an adapted BPMN 2.0 model, according to the notation adaptations introduced in Section 3.3.

The evaluation was conducted in an engineering company that creates custom, project-based, automation systems.

To evaluate the proposed PPR DPM artifact, we interviewed the engineering manager, the quality assurance stakeholder at the company and received feedback from domain experts regarding the parts that were most relevant for them. The stakeholders evaluated the PPR DPM regarding the following ISO 25010 (Bevan, 2009) metrics: functional appropriateness, learnability, performance efficiency, and analyzability.

*Functional appropriateness* measures to what extent the designed artifact allows expressing the engineering environment appropriately. *Learnability* measures how easy domain experts and stakeholders are likely to be able to understand and use the concepts represented in the *data processing map*. *Performance efficiency* measures the level of time and resources required to use the PPR DPM notation as part of the PPR EPA method. *Analyzability* measures to what extent future analyses can be conducted based on the PPR DPM.

Table 1 summarizes the results of the evaluation. The scores are based on a 5-point *Likert* scale (++, +, o, -, --), where "++" indicates high fulfilment of the criterion, "+" indicates good fulfilment of the criterion, "o" represents neutral fulfilment of the criterion, "-" indicates disagreement that the approach fulfills the criterion and "--" indicates strong disagreement that the approach fulfills the criterion .

The PPR DPM was effective for providing an overview on the engineering process, including stakeholder, their tasks and communication, as well as tasks that require PPR knowledge and engineering artifacts that may bear PPR knowledge aspects with

Table 1: Evaluation results for Data Processing Map visualizations based on (Biffl, 2018).

| Approaches->Criteria | Current DMP approach: Discipline-specific EPC workflows | Standard BPMN 2.0 model | Product/ion aware BPMN 2.0 model |
|---|---|---|---|
| Functional appropriateness | -- | - | ++ |
| Learnability | + | + | + |
| Efficiency | -- | o | o |
| Analyzability | + | o | ++ |
| **Overall DPM quality** | **-** | **o** | **++** |

new PPR-specific visual elements that extended the traditional BPMN 2.0 notation.

The case study results reveal that the current state of domain-specific isolated engineering "silos" bears significant risk for each new project and that the current representation form is not sufficient for any kind of analysis involving multiple disciplines and their interactions.

## 5.2 Discussion

This section discusses results regarding the research questions introduced in Section 1.

***RQ1. PPR EPA Method.*** *What adaptions or combinations of business/engineering process analysis methods allow overcoming their limitations regarding product/ion-aware engineering process analysis?* Section 3.2 introduced the PPR EPA method adapted from (Santos and Alves, 2017;) and from production systems engineering (Lüder, 2012). Our adaptations follow the design science cycle from Wieringa (2014), as presented in (Santos and Alves, 2017), and introduce production systems engineering aspects as presented in (Lüder, 2012) to overcome, the limitations of individual fields regarding product/ion-aware engineering process analysis. The resulting PPR EPA method, allows individual disciplines to focus on their work tasks of and on engineering artifacts that they receive, create, and exchange with related workgroups and was evaluated in a case study with real-world use cases. The new role of the *EPA facilitator* mediates the interests of the EPA in the EPA process. In the feasibility study, a member of the research team took this role.

The PPR EPA method facilitates identifying and collecting data on the engineering process to analyze where relevant PPR knowledge is required, created, or lost. The domain experts found the PPR EPA method usable and useful for better understanding issues in the engineering process that were hard to trace with the traditional focus on production systems, leaving out considerations of product and production process factors. The PPR EPA approach facilitates both, the independent investigation in workgroups for improving their local capabilities, and the analysis and improvement of cooperating workgroups by identifying interfaces and interactions between disciplines that may benefit from the explicit representation of PPR knowledge. Further, allows the PPR EPA method allows to introduce well-established concepts from software engineering in a new production systems engineering context.

**RQ2. PPR DPM Notation.** *What adaptions or combinations of business/engineering process analysis notations allow overcoming their limitations for representing processes and documents that may represent PPR knowledge?* Section 3.3 introduced the PPR DPM notation based on adaptations to the BPMN 2.0 standard as a foundation for representing PPR knowledge in a *data processing map*, resulting in a PPR DPM. The PPR DPM notation elements represent the necessary PPR knowledge on engineering tasks and documents for the use cases explored in the feasibility case study. The introduction of new elements, such as PPR knowledge requirements and PPR knowledge aspects in engineering documents, to a well-established standard allowed minimizing the number of newly introduced concepts , in comparison to alternative approaches (Khabbazi, 2013; Huang, 2017; Merunka, 2017). The interviewed domain experts required some instructions and training to move from their well-known EPC models to the BPMN 2.0 notation but found the PPR DPM notation easy to understand, usable, and useful. The PPR DPM concepts can be easily added to tools that support the BPMN 2.0 standard.

**Limitations.** The presented research in this paper entails some limitations that need further research.

*Feasibility Study.* We evaluated the PPR EPA process and the PPR DPM in cooperation with domain experts in a typical large company in PSE of discrete manufacturing systems. The company can be seen as representative for systems engineering enterprises, where business is conducted on a project basis focusing on the engineering of production systems, but without integrated consideration of PPR knowledge management. The evaluation results are based on observations from a limited sample of projects. To overcome these limitations, we plan a more detailed investigation in a broader selection of domains and application contexts. A lesson we learned was that it is very important to define a particular scope of the problem because it is easy to get lost in details of a complex engineering process, as the domain experts are very versatile in their field and can express deep insights into their work. In addition, it became evident that the quality of the researched process model strongly depends on the qualification of the EPA facilitator related to the aims of the EPA organization (production system to be engineered) and the engineering disciplines involved.

*Expressiveness of the PPR DPM Notation.* The DPM PPR notation enabled the beneficial representation of PPR knowledge aspects for engineering documents in the use cases of the feasibility study. However, the stakeholders foresee advanced applications based on a more detailed modeling of PPR aspects and relationships, e.g., for constraint modeling, which would require extending the expressiveness of the PPR DPM notation potentially exploiting basic concepts of ISA 95 (International Electrotechnical Commission, 2003) or formal process specification given in VDI Guideline 3682 (VDI, 2005). However, these aspects go beyond the scope of this paper. Working with PPR DPM revealed that it is common in engineering to exchange artifacts that are difficult to process for machines rather than data or knowledge.

# 6 CONCLUSION AND FUTURE WORK

In a multi-disciplinary system engineering environment with workgroups collaborating in varying project-specific teams, challenges and risks may go undetected, if the workgroups mainly focus on improving their internal processes, tools, and outcomes. This risk is amplified with the absence of a role that optimizes the collaboration and coordination between workgroups. Further, in systems engineering there is a tendency to focus on the properties of the system design, often with (too) little awareness of the product that the system should be able to produce in the production process.

In this paper, we introduced and investigated systems engineering use cases for *product/ion-aware engineering process analysis* (PPR EPA) and a notation for a *product/ion-aware data processing map* (PPR DPM). These contributions provide domain experts and the new role of an EPA facilitator with a systematic approach to represent PPR knowledge in EPA. It also facilitates pinpointing tasks that require PPR knowledge and engineering artifacts that contain PPR knowledge aspects as a foundation for analyzing and closing PPR knowledge gaps in the engineering process.

*C1. The engineering process between discipline-specific workgroups is hard to trace and analyze.* The PPR EPA method results in a graph of engineering tasks, which potentially require PPR knowledge, linked by the exchanged engineering artifacts, which possibly contain PPR knowledge aspects. The network allows effectively and efficiently tracing the engineering process tasks and documents across workgroups. Therefore, the PPR EPA method reduces the risk of low product and production process quality.

*C2. Unclear benefit of representing PPR knowledge.* The *product/ion-aware data processing map* (PPR DPM) can be analyzed for assessing the risk at engineering tasks from insufficient availability of PPR knowledge and for estimating the extra effort and cost to represent PPR knowledge in engineering artifacts explicitly. Consequently, the PPR DPM enables prioritizing and planning improvement candidates according to their expected cost and benefits.

*C3. Unclear impact of PPR knowledge.* The PPR DPM can provide the foundation for assessing the impact of specified PPR knowledge aspects in order to consider which PPR knowledge to model first. The PPR DPM further allows maximizing the benefits of an explicitly represented PPR knowledge element, by identifying all engineering tasks that potentially benefit from the awareness of this knowledge element. An example would be using PPR knowledge as a prerequisite for introducing Industry 4.0 applications, such as reasoning on the impact of production process changes on production systems engineering and operation.

The PPR DPM is the basis for research on advanced engineering process analysis and improvement methods. Future methods could, e.g., allow reducing the impact of risks in the engineering process from important PPR knowledge, such as low product and process quality. An advanced analysis would also provide machine-understandable PPR knowledge as a foundation for reasoning on capabilities, e.g., self-adaptive processes, during engineering and operation.

**Future Work.** *Advanced PPR knowledge representation.* Following the annotation of PPR knowledge aspects in engineering artifacts, there is a need to represent PPR knowledge explicitly in sufficient detail and to find ways on how to store this knowledge for efficient processing. This would allow the shift from engineering artifacts to data and knowledge that can be accessed for reasoning under the Industry 4.0 vision.

*Traceable design decisions.* The explicit representation of PPR knowledge is the foundation for reasoning about relationships between design decisions taken on product, production process, or production system levels. These relationships allow systems engineers to better understand the reason, e.g., for value ranges of system parameters that depend on characteristics of the product or of the production process.

*Generation of system design aspects.* In addition, explicitly modeled dependencies between design decisions may enable the efficient derivation of system design parameters from product/ion design decisions. While the efficient derivation of system design parameters is already beneficial for one system, the reuse in a production system family is a considerable business advantage for a PSE company.

*IT Security considerations.* The PPR EPA method enables the collection of PPR knowledge and the analysis of data flows across workgroups. This knowledge could be interesting to a potential IT security attacker and will require research on threats to the integrity of the collected PPR knowledge and industrial espionage.

Finally, future work will include the application and evaluation of the PPR EPA method and the PPR DPM notation in various engineering domains and application areas.

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