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Variability Modeling of Products, Processes, and Resources in Cyber-Physical Production Systems Engineering

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Abstract

Cyber-Physical Production Systems (CPPSs), such as *automated car manufacturing plants*, execute a *configurable* sequence of production steps to manufacture products from a product portfolio. In CPPS engineering, domain experts start with *manually* determining feasible production step sequences and resources based on *implicit knowledge*. This process is hard to reproduce and highly inefficient. In this paper, we present the Extended Iterative Process Sequence Exploration (eIPSE) approach to derive variability models for products, processes, and resources from a domain-specific description. To automate the integrated exploration and configuration process for a CPPS, we provide a toolchain which automatically reduces the configuration space and allows to generate CPPS artifacts, such as control code for resources. We evaluate the approach with four real-world use cases, including the generation of control code artifacts, and an observational user study to collect feedback from engineers with different backgrounds. The results confirm the usefulness of the eIPSE approach and accompanying prototype to straightforwardly configure a desired CPPS.

1. Introduction


Software Product Lines (SPLs) are “a set of software-intensive systems that share a common, managed set of features satisfying the specific needs of a particular market segment or mission developed from a common set of core assets in a prescribed way [7].” *Variability modeling* is a crucial activity of SPL engineering. It captures the commonalities and differences of these software-intensive systems explicitly and manifests them in a variability model, such as a Feature Model (FM) [37] or Decision Model (DM) [61]. FMs focus on configuring products by respecting tree and cross-tree constraints, whereas DMs also allow configuring sequences of options, which, in particular, is useful to model process variability.

Cyber-Physical Production Systems (CPPSs), such as *automated car manufacturing plants*, use the latest information and communication technology to manufacture customized products with modern production techniques [50]. Each CPPS is built by assembling various hardware components (e.g., sensors and actuators) that are controlled by

software to deliver one or more production system functionalities. Such systems execute a *configurable and flexible* sequence of production steps to manufacture products from a product portfolio, provoking variation in how to realize the CPPS [36, 50]. Hence, variability modeling for CPPSs faces the challenge of capturing multiple aspects [18, 27] that reach from the variability of products to the sequence of production steps and employed production resources. Furthermore, engineers of different disciplines, such as mechanics, electricians, and software engineering, with different views on the planned CPPS collaborate to build it iteratively [3]. Due to this multidisciplinary nature, *separating the concerns is essential*, which is also true for variability modeling [1].

To build a CPPS, typically, CPPS engineers start with determining a feasible sequence of production process steps *manually* for the products in the portfolio [42]. Then, they define which production resources can execute these production process steps, examine the performance characteristics, and estimate the CPPS variant’s construction cost. The production process steps and production resources are later used for designing and implementing CPPS artifacts, e.g., the control software. As the result originates from a completely manual process founded in *implicit domain knowledge*, resulting primarily from *experience and undocumented dependencies*, it is *hard and, most of the time, impossible to reproduce*. However, repetition of the planning may be necessary when a new product variant is introduced, “a frequent scenario in CPPS engineering” [65]. The manual configuration is also highly inefficient and tedious due to

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the large number of possible production sequences, challenging engineers to find practically feasible ones. Thus, this laborious, time-consuming, and error-prone activity calls for a methodology to automate and document the derivation of production sequence and resource configurations from a product configuration.

To address some of these challenges, we developed different automation facilities in previous work. We developed (i) the Product-Process-Resource Domain-Specific Language (PPR-DSL) [49] to model products with the required production processes and resources systematically; (ii) the TRAVART framework [25] to transform engineering artifacts containing variability information into state-of-the-art variability models automatically; (iii) the Iterative Process Sequence Exploration (IPSE) [46] approach that utilized these approaches to handle CPPS variability through SPL techniques and transformations of the PPR-DSL into a FM and a DM. However, the IPSE approach had *no automation and tool support to explore and configure process sequences, and did not include production resource modeling and configuration and artifact generation.*

In this paper, we extend the semi-automated IPSE process and aim to answer the following research questions:

RQ1 *How can CPPS engineers be supported in modeling, exploring, and configuring the combined variability of products, production processes, and production resources, to generate corresponding CPPS artifacts?* The Extended Iterative Process Sequence Exploration (eIPSE) approach establishes a process that includes these artifacts and incorporates feedback loops that reflect the iterative development.

RQ2 *How and to what extent can CPPS design be automated using variability modeling and CPPS concepts?* We provide the eIPSE tool architecture, which starts with the manually defined PPR-DSL and derives the remaining artifacts automatically.

In its first state [46], the IPSE converted a given PPR-DSL into a FM to capture the variety of products and their parts, and a DM, to represent the production process sequences, using TRAVART [25]. We extend IPSE to derive a second kind of FM to capture the variability in production resources. Additionally, we utilize Cross-Discipline Constraints (CDCs) [13, 14] to express dependencies between variation points from those three variability models. Furthermore, we reduce the effort of manually configuring the resulting DM by offering an editor, which decreases the number of configuration options with each decision taken, and we empirically examine the gained automation. Thus, on top of our previous work, this paper contributes:

- The eIPSE approach with additional steps for production resource definition and configuration, artifact generation, and feedback loops.
- An extended prototype to assess the feasibility of the eIPSE approach, complemented with

- support for transforming the PPR-DSL into a Resource FM and CDCs to elicit resource variability and dependencies among the different variability models
- a novel DM editor for modeling and configuring DOPLER DMs, used in this context to represent and configure production process sequences
- an automated reduction of the possible Process DM configuration based on the product configuration to lower the complexity of production process sequence configuration
- support for resource configuration and control code artifact generation through integration with Variability for 4diac (V4rdiac) [13, 14] to automate the creation of control software.

- An empirical evaluation of
 - the feasibility of selecting an adequate CPPS variant in four *real-world case studies* [45]
 - applying the eIPSE approach in a new case study performed by engineers with heterogeneous backgrounds inexperienced in the approach, and thereby
 - the first exploration of the joint usage of feature and decision models for configuring CPPSs and creating CPPS artifacts.
- A report on the gathered insights from exploring production sequences in this highly automated way.

We postulate that the eIPSE approach, compared to the baseline of the traditional manual and hard-to-reproduce approach, (i) helps to externalize the implicit knowledge of engineers, (ii) reduces the effort of CPPS configuration, including the exploration of feasible production process sequences and (iii) separates the concerns of different engineering disciplines and, further, (iv) benefits the reproducibility of the configuration process. With these aspects, the approach directly addresses criteria of the VDI 3695 guideline for optimizing industrial plant engineering [67, 35]. In particular, configuration and knowledge management, description languages, re-use, and the integration of disciplines. Additional material to this paper, such as the model artifacts and variability models, can be found online.¹

The results of our empirical evaluation demonstrate that we can automate the subsequent configuration process of a CPPS by using variability models; a clear benefit compared to the manual assembly and exploration process. Our subjects spend the most time defining the PPR-DSL, while configuring the CPPS boils down to generating and configuring the variability models. However, this shows how much effort it is to externalize their implicit knowledge, which, on the other hand, supports engineers downstream the engineering process. Particularly, configuring the production process sequences through the DM benefits from our prototype, which displays only the decisions that can be made in the respective configuration step. Furthermore, the

¹Additional material to eIPSE: <https://github.com/tuw-qse/eipse>

separation of concerns of splitting and linking the variability models for products, production processes, and production resources allows their configuration by respective experts. Consequently, the eIPSE process with tool support meets the expectations of automating and eliciting the configuration process of CPPSs, improving its reproducibility.

The remainder of this work is structured as follows: Sec. 2 summarizes the background on CPPSs engineering and variability modeling. Sec. 3 presents an illustrative use case. Sec. 4 describes our research methodology. Sec. 5 presents the eIPSE approach and corresponding tooling. Sec. 6 describes the evaluation of the eIPSE approach. Sec. 7 discusses the results and implications of the approach. Sec. 8 summarizes related work that aims at achieving similar goals and Sec. 9 concludes this work by providing an outlook on future work.

2. Background

This section provides background information on CPPS engineering and variability modeling.

2.1. CPPS Engineering

CPPSs are next-generation production systems that interact autonomously with their environment, aiming for flexible production of customized products that build a product family [48, 50]. CPPSs are Cyber-Physical Systems (CPSs) [29] with the purpose of manufacturing goods. CPPS engineering resides in a multidisciplinary environment that involves engineers from diverse disciplines, such as mechanical, electrical, and computer sciences [3].

The engineers collaborate to create various artifacts representing aspects of the CPPS. For instance, they create technical documents such as text documents or spreadsheets for defining requirements or *bills of materials*. The engineers also create engineering artifacts, e.g., CAD drawings or AutomationML artifacts [33] to represent the CPPS's physical and functional design. Additionally, the engineers use domain-specific language defined by industrial standards, such as IEC 61499 [34], to implement the control software. Furthermore, several of these artifacts, e.g., type comparison matrices (TCMs), contain information on variability in the CPPS, such as product types or production processes [20].

One prominent concept in CPPS engineering is the Product-Process-Resource (PPR) approach [59], which describes (i) products and their parts, (ii) production processes required to manufacture the products, and (iii) production resources that execute the processes. The Formalized Process Description (FPD) [66] allows for modeling these PPR aspects in a visual (and partly formalized) model (cf. Fig. 2). Complementary, we contributed the PPR-DSL [45], which we use in this work, as a machine-readable PPR format that represents the variability and constraints among the PPR aspects.

2.2. Variability Modeling

Modeling variability explicitly is crucial for (software) product line engineering. In this work, two dimensions of

variability play a role: CPPSs manufacture a product line of goods, such as families of cars, whereas CPPSs can also be configured in various ways. Furthermore, the sequence of the production steps involves dependencies between product parts and production resources and may vary in the estimated cost. The multidisciplinary nature of CPPS engineering calls for different views on the CPPS involving different variability models [44, 47]: feature models to capture structural variability of product parts and production resources, and decision models to capture the behavioral variability of production process sequences.

Feature models [37] elicit commonalities and differences in a feature tree and allow for defining cross-tree constraints, e.g., that one feature requires or excludes another. Given this model, we can perform a configuration by selecting and deselecting features while conforming to the expressed constraints. For instance, the FM on the top of Fig. 1 captures commonalities and differences of a shift fork (c.f., Sec. 3). The model consists of *mandatory* features representing product parts required in all variants, such as a *Screw* and the three types of forks. The model also contains *optional* features, such as *Barrel1_2*, and feature groups, such as the alternative *Pipe* group that allows selecting only one type of pipe. The FM on the bottom of Fig. 1 captures commonalities and differences of potential production resources, such as two *Linefeeds* that can be used to feed material into the CPPS.

Decision models [61] are rooted in the Synthesis method [4], which supports the reuse of processes and the necessary assets for configuring an application engineering process. DMs include only varying features and their constraints. For instance, the DOPLER approach [9] comprises DMs and asset models for defining variability in the problem space and reusable elements and their dependencies in the solution space, respectively. It maps assets onto the decisions, but decisions are unaware of the assets.

Tab. 1 represents an exemplary DM in tabular representation. A decision in a DM consists of a unique ID and a text describing the decision (usually a *Question*). These decisions are configured based on the specified *Range*. For instance, only one of the three locks can be selected in the enumeration decision *Lock*. *Constraint/Rule* and *Visible/Relevant if* relationships between decisions specify (*post-conditions* and hierarchical or logical (*pre-conditions*). The *Visible/Relevant if* relationship defines preconditions that need to be satisfied for the decision to be selectable. For instance, *InsertLock1* can only be selected if *Lock1* is selected. A visibility condition *false* (e.g., *InsertLock*) entails that the decision can not be selected by developers but rather by selecting another decision that relies on this decision. Similarly, abstract features in FMs are automatically selected if one of their child features is selected. For instance, the selection of *InsertLock1* triggers the selection of *InsertLock*. These explicit dependencies among selected decisions reflect a configuration order, which models behavioral variability.

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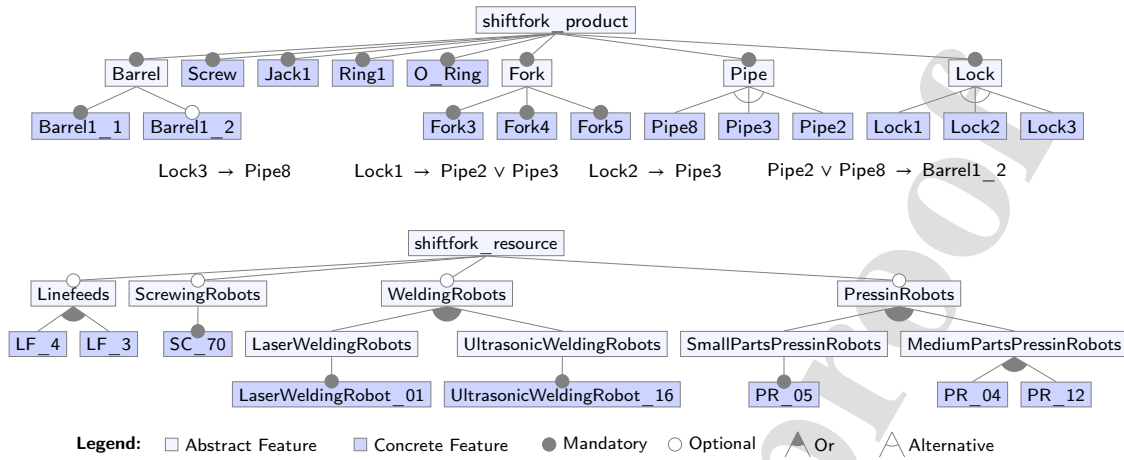


Figure 1: FeatureIDE FMs [43] of product (top) and production resource (bottom) variability of the *shift fork* case study.

Table 1

Excerpt of the generated DOPLER DM [9] representing the process variability of the *shift fork* case study in tabular notation [60].

ID	Question	Range	Visible/Relevant if	Constraint/Rule
Pipe	Which Pipe types?	Pipe2 Pipe3 Pipe8	false	
Barrel1_2	Install Barrel1_2?	true false	false	
Lock	Which Lock types?	Lock1 Lock2 Lock3	false	Lock1 \implies Pipe = Pipe2 \vee Pipe = Pipe3 Lock2 \implies Pipe = Pipe3 Lock3 \implies Pipe = Pipe8
InsertPipe	Install InsertPipe?	true false	false	
InsertPipe2	Install InsertPipe2?	true false	Pipe == Pipe2	InsertPipe2 \implies InsertPipe
InsertLock	Install InsertLock?	true false	false	
InsertLock1	Install InsertLock1?	true false	Lock == Lock1	InsertLock1 \implies InsertLock
InsertLock2	Install InsertLock2?	true false	Lock == Lock2	InsertLock2 \implies InsertLock
InsertBarrel1_2	Install InsertBarrel1_2?	true false	Barrel1_2	
PressBarrel1_2	Install PressBarrel1_2?	true false	Barrel1_2 & InsertBarrel1_2 & InsertPipe	
...

```

1 CDC1) shiftfork_product#Pipe2 => shiftfork_process#Pipe2
2 CDC2) shiftfork_product#Pipe2 => shiftfork_process#InsertPipe2
3 CDC3) shiftfork_process#WeldLock =>
4   shiftfork_resource#WeldingRobots
5 CDC4) shiftfork_product#Lock1 => shiftfork_product#Pipe2 ||
6   shiftfork_product#Pipe3;

```

Listing 1: Excerpt of CDCs [14] of the *shift fork* case study.

CDCs [14, 13] model the relationships among different types of variability models, likely employed by different (engineering) disciplines, as shown in Lst. 1. A CDC identifies the involved variability model using the variability type and the unique id. For instance, *CDC1* in Lst. 1 refers to the relation of a Product FM feature (*shiftfork_product#Pipe2*), which concerns product engineers, to the Process DM decision (*shiftfork_process#Pipe2*), which concerns production process engineers, to model dependent processes in the decision model. Similarly, *CDC3* models the relation of the *WeldLock* process to the *WeldingRobot* production resource that concerns production resource engineers.

3. Motivating Case Study

This section presents the *shift fork* case study [45], one example of a CPPS, based on which we illustrate our contribution in the following sections. Shift forks are part of a manual transmission in a car.² They shift the cuffs with two forks along the pipes to their correct position to connect the transmission's gears. Typically, a single shift fork moves a particular cuff for two gears, e.g., the first and the third gear. This design results in a product portfolio of four shift fork variants required for a particular type of car transmission.

In the first CPPS engineering phase, so-called *basic engineers* analyze the product portfolio that the CPPS should produce [45], which represents a classical (mechanical) product line with common and varying features. The engineers examine various artifacts, such as CAD drawings or product prototypes, to identify the commonalities and differences of the product line [45]. Furthermore, the engineers examine the required partial production steps, such as

²Exemplary figure of *shift forks*: <https://w.wiki/3DCF>

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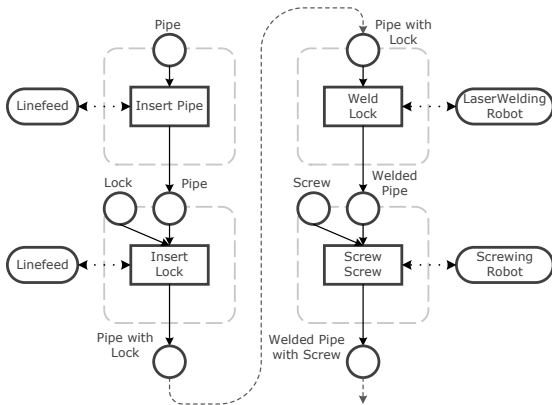


Figure 2: Excerpt of a PPR model for the production steps of a shift fork in VDI 3682 notation [66].

joining the fork and the pipe of the shift fork by welding them together [45]. Fig. 2 shows a section of such a production step sequence for a single product in VDI 3682 notation [66] (cf. Sec. 2), where, in the first step, a *Pipe* (product) is inserted (process) into the CPPS using a *Linefeed* (resource).³ In this step, they often disassemble the prototypes and put them “back together” [42]. The engineers aim to design feasible production processes for the requested product line. They complement these designs with potential basic CPPS designs and corresponding rough cost estimates [45].⁴

Some product parts require a specific production sequence. For instance, the pipe must be available to mount forks onto the pipe. Still, several degrees of freedom to assemble a particular product remain, which must be resolved either in engineering or operation. Traditionally, the engineers design feasible process sequences, e.g., in tools like DelMia,⁵ based on implicit knowledge, by using heterogeneous and partial data representations. The engineers use the sequences to reason about process characteristics, such as the production duration. However, as the decisions are typically undocumented, a change to the CPPS, which occurs frequently, may cause redesigning the entire CPPS from scratch [53, 45]. Therefore, making this knowledge more explicit is a decade-old challenge in CPPS engineering [12, 10].

To elicit their domain knowledge, CPPS engineers can use the PPR-DSL [49] to represent PPR aspects and their constraints. Lst. 2 shows an excerpt of a PPR-DSL file that defines *shift fork* product parts (lines 1-12), the atomic production process steps and variants (lines 14-29), the production resources (lines 31-35), and the constraints between these PPR aspects (lines 37-39). The entire PPR-DSL file is available online.¹

³In contrast to the figure, the engineers first plan the single process steps, e.g., *insert pipe* in an isolated way.

⁴If customers accept a CPPS design and cost estimate, the artifacts of *basic engineering* are handed over to the different disciplines of *detail engineering*. As the time of a cost estimate and its acceptance can be wide apart, the engineers in *detail engineering* need to reiterate over those designs, ideally, reuse, and detail them.

⁵DelMia: <https://www.3ds.com/products-services/delmia/>

```

1 Product "Pipe": { name: "Abstract Pipe", isAbstract: true }
2 Product "Pipe2": { name: "Pipe 2",
3   implements: ["Pipe"],
4   excludes: ["Pipe3", "Pipe8"]
5 }
6
7 Product "Lock": { name: "Abstract Lock", isAbstract: true ,
8   requires: ["Pipe"]
9 }
10 Product "Lock1": { name: "Lock 3",
11   implements: ["Lock"], excludes: ["Lock2", "Lock3"]
12 }
13
14 Process "InsertPipe": { name: "InsertPipe", isAbstract: true }
15 Process "InsertPipe2": { name: "InsertPipe2",
16   implements: ["InsertPipe"],
17   inputs: [ {productId: "Pipe2"} ],
18   outputs: [ {OP1: {productId: "Pipe2"}} ],
19   resources: [ { resourceId: "Linefeeds" } ]
20 }
21 Process "WeldLock": { name: "WeldLock", isAbstract: true ,
22   requires: [ "InsertLock", "InsertPipe", ... ],
23   inputs: [ {productId: "Lock"}, {productId: "Pipe"} ],
24   outputs: [ {OP2: {productId: "ForkProduct"}} ],
25   resources: [ {resourceId: "WeldingRobot"} ]
26 }
27 Process "WeldLock1": { name: "WeldLock1",
28   implements: [ "WeldLock" ], inputs: [ "Lock1" ]
29 }
30
31 Resource "WeldingRobot": { name: "WeldingRobot",
32   isAbstract: true }
33 Resource "LaserWeldingRobot_01": { name: "LaserWeldingRobot_01",
34   implements: [ "LaserWeldingRobots" ]
35 }
36
37 Constraint "C1": {
38   definition: "Lock1,Pipe2,Pipe3 -> Lock1 implies Pipe2 OR Pipe3"
39 }

```

Listing 2: Excerpt of a PPR model for the *shift fork* case study in PPR-DSL [49].

For instance, Line 1 defines the abstract Product *Pipe* that builds the central part of a *shift fork*. The Product *Pipe2*, defined in the following line, represents a concrete pipe and excludes another variant of a pipe (i.e., *Pipe3* and *Pipe8*). Similarly, *InsertPipe* in Line 14 represents an abstract Process which is implemented, for instance, by the Process *InsertPipe2*. The PPR-DSL further enumerates its input and output products, i.e., *Pipe2*, and required production resources. Examples of production resources, which can be abstract or concrete, are stated in Lines 31-33. The last lines of the excerpt, Lines 37 to 39, add the Constraint *C1* which defines that the *Lock1* implies the presence of either *Pipe2* or *Pipe3*.

Thus, the PPR-DSL describes the products and their parts, the required production process steps, and the production resources of the shift fork case study precisely. Particularly, it elicits the variability and dependencies among the three aspects.

4. Methodology

To develop the eIPSE approach, we applied the Design Science methodology [30, 31]. This methodology aims to solve problems by covering the design and investigation of

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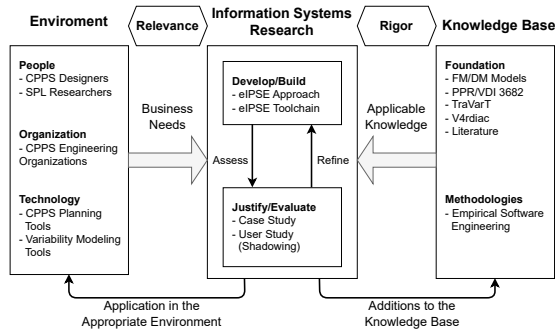


Figure 3: Design Science methodology [30, 31] for this work.

artifacts that define, above others, methods and technical solutions in a problem context to improve something in that context [31, 68]. In this work, the method is the iterative design and investigation of the eIPSE approach in the context of CPPS engineering. Fig. 3 shows the Design Science methodology adapted to this work, with the *relevance* cycle on the left, the *design* cycle in the middle, and the *rigor* cycle on the right.

Our previous work [20, 25, 46, 49] builds the *grounding* in the *rigor* cycle. Furthermore, we aim to address literature gaps, in particular, the integration of different variability models of CPPSs [41] including their behavior [18, 27] and the separation of concerns between engineers of different disciplines [1]. Based on discussions with stakeholders of our industry partners and our previous work, we obtain additional requirements for an integrated CPPS variability modeling approach (cf. Sec. 5.1) for the *relevance* cycle.

We iteratively perform the following tasks for the *design* cycle and the *develop/build* activity (cf. Sec. 5): First, to address the identified requirements, we extend our former approach with respective steps, resulting in the eIPSE approach, and investigate which steps can be further automated (cf., Sec. 5.2). We lay out the architecture of the eIPSE toolchain to illustrate a prototype implementation (cf., Sec. 5.3). We integrate a DOPLER DM into the state-of-the-art technology and develop the remaining transformation operations for converting the PPR-DSL into three variability models. We develop a *DM Editor* as a prototype for modeling and configuring the Process DM and design the automated reduction of the Process DM configuration based on the configuration of the Product FM. Then, we adapt V4rdiac to use the distinct configurations of the Product FM and Process DM for generating artifacts. In this way, we establish the eIPSE toolchain to support the steps of the eIPSE approach (cf. Sec. 5). Furthermore, we aim to separate the concerns of *basic engineers* and the disciplines involved in *detail engineering*, particularly product design, production process engineering, and production resource engineering.

For the *evaluate* activity of the *design* cycle, i.e., the evaluation of the approach and prototype, we rely on a three-fold approach. First, we applied the eIPSE approach to a set of previously published case studies [45] from the CPPS domain to investigate the feasibility of the approach (cf. EQ1

and Sec. 6.3). Second, we conducted an observational user study [69, 55, 63] with six engineers to provide evidence on the perceived usability of the eIPSE approach and learn about its usage. Therefore, we requested study subjects to perform the eIPSE process on a newly introduced case study (cf. EQ1 and Sec. 6.4). A detailed description of the user study can be found in the appendix, cf. Section A. Third, we investigate the configuration space's reduction for the production sequences of one particular case study using the eIPSE approach (cf. EQ2 and Sec. 6.5). Finally, we examined the generation of parameterized CPPS artifacts for a particular CPPS configuration for each of the four previously mentioned case studies (cf. EQ3 and Sec. 6.6). These measures complete the *design* cycle.

We discuss our findings and lessons learned and accompany them with additional material¹ and a demonstration video⁶ as additions to the knowledge base. Furthermore, we briefly describe measures to assess the practical impact of the application in CPPS engineering. These measures aim to reach a broad audience in academia and industry and complete the *rigor* and *relevance* cycle (cf. Sec. 7).

5. Adopting Variability Modeling for CPPS Process Exploration and Configuration

This section details employing variability modeling for exploring configuration options in deriving a functional CPPS design. Firstly, Sec. 5.1 states the requirements for a CPPS production process exploration and production resource configuration approach as elicited from industrial needs in previous work. Inferred from these requirements, Sec. 5.2 describes increasing automation in CPPS planning and configuring through the Extended Iterative Process Sequence Exploration (eIPSE) approach. To assess the feasibility of the eIPSE approach and to follow the Design Science methodology, Sec. 5.3 presents our prototype implementation, respectively.

5.1. Requirements for eIPSE

To gather requirements for automating the configuration of CPPSs, we conducted interviews with industrial partners in previous work [46] on which we build in this article. The resulting requirements **R1-R3** mainly motivate knowledge representation and tool support as follows:

R1. Production Variability Exploration. The approach shall collect variability knowledge from CPPS engineering (artifacts) that is required to explore production process sequence options efficiently. The approach must incorporate new knowledge from product line evolution, such as changes of the products that the CPPS manufactures or process simulation and optimization iteratively.

R2. Product & Process Variability Representation. The knowledge representation shall describe

- (i) the products, which form a product line,
- (ii) the atomic production process steps, which form a process line, both with their dependencies and CDCs

⁶eIPSE demonstration video: <https://youtu.be/eoNND0usXKA>

in an industrial variability artifact, e.g., using the PPR-DSL [49], and

- (iii) variability models of the product and process line in state-of-the-art variability models (e.g., FMs or DMs).

R3. Variability Transformation & Configuration. The IPSE method and tool support shall (i) automate transformations of the variability represented in the industrial artifacts into state-of-the-art variability models and (ii) provide guidance through product and process variability model exploration and configuration supported by tools, such as the FeatureIDE [43] or DOPLER tool [9] to better support multidisciplinary engineering.

However, requirements R1-R3 only focus on exploring and configuring products and processes without considering production resources. Thus, based on previous work and discussions with stakeholders, we defined two additional requirements (**R4** and **R5**) that address the necessity to include the production resources in the IPSE.

R4. Resource Variability Representation. After exploring feasible production sequences, the engineers goal is to “search” for suitable production resources, e.g., welding robots, that are able to execute the production steps (cf. Sec. 3). Therefore, the eIPSE knowledge representation shall model a product line of potential production resources that can execute respective production process steps. The product line should be represented in an industrial variability artifact, e.g., a variability model. Additionally, the eIPSE method shall respect the production resource variability model when being transformed and configured (**R3**). The production resource variability model shall be transformed into state-of-the-art variability models and adequate tool support shall model configuration.

R5. Cross-Discipline Constraint Representation. The CPPS engineering process expects engineers to link the developed concepts to a system design, e.g., that a production process requires a particular type of welding robot. To complement the overall eIPSE knowledge representation, we must be able to describe dependencies (include/exclude relations) between variability knowledge across different PPR concepts.

These requirements reflect the need of engineers to continuously incorporate additional product requirements and subsequently assign production processes and resources to the CPPS design. Furthermore, they represent the engineers’ demand to obtain a holistic overview of a CPPS’s variability in their preferred engineering artifacts and models that can be better computed, e.g., for satisfiability, such as state-of-the-art variability models. Beyond that, the requirements build the foundation for the automation of an integrated CPPS variability modeling approach.

5.2. The Extended IPSE Approach

In prior work [46], we introduced the linear IPSE approach, which utilizes state-of-the-art variability models to enable the systematic and reproducible exploration of potential production process sequence and resource configurations based on a product configuration. These variability

models need to support *structural* variability to represent the hierarchical structure of products and *behavioral* variability to represent the potential sequences of process steps. The tool support for the original IPSE approach allows for *exploring process sequences* manually, but *does not* include the modeling and configuration of *production resources* and the *artifact generation*. To address these issues and satisfy the additional requirements **R4** and **R5**, we utilize a FM to represent resource variability and CDCs [14] to represent one or more dependencies across PPR concepts of different disciplines. Here, each CDC is a propositional logic constraint based on the variation points defined in Product FM, Process DM, and Resource FM (cf. Lst. 1). To this end, we extend our previous work with the eIPSE approach and toolchain.

Overview In this article, we contribute the eIPSE approach, which extends the *linear* IPSE approach with

- (i) automated transformations from the PPR-DSL to the Resource FM and the CDCs for linking the variability models,
- (ii) an automated reduction of the Process DM configuration based on the Product FM configuration and the *tool-supported* process exploration that guides engineers,
- (iii) the automated reduction of the Resource FM configuration and its *tool-supported* configuration,
- (iv) the generation of CPPS artifacts, such as control code artifacts,
- (v) and feedback loops to respect its iterative character.

This way, eIPSE aims to support the disciplines of functional product design, production process engineering, and production resource engineering. Fig. 4 illustrates the resulting eIPSE process. Steps with dashed contours in Fig. 4 were carried over *as-is* from the IPSE approach, steps with solid contours were adapted, and steps with solid contours and in dark green were newly introduced in the eIPSE approach. The process consists of “human” tasks conducted by engineers with tool support (persona with cog icon) and automated tasks (cog icon). eIPSE provides automation support by utilizing the eIPSE tool. While the eIPSE tool performs the automated tasks entirely, it supports CPPS engineers during the “human” tasks that require access to models.

The eIPSE process starts with the definition of the PPR element variants of the desired CPPS by engineers in the PPR-DSL and ends in creating the artifacts for a configured CPPS automatically. The PPR-DSL is automatically transformed into three variability models (Step 2a-c) and their respective CDCs (Step 2d). The variability models are configured by engineers and automatically and subsequently configured for the next configuration step (Steps 3-7).

In contrast to the IPSE process, the eIPSE process splits the second step into sub-steps to demonstrate the various variability models that the eIPSE tool creates based on the PPR-DSL. It creates an additional Resource FM to represent the production resources (Step 2c) and derives and elicits the CDCs among the three variability models (Step 2d). The

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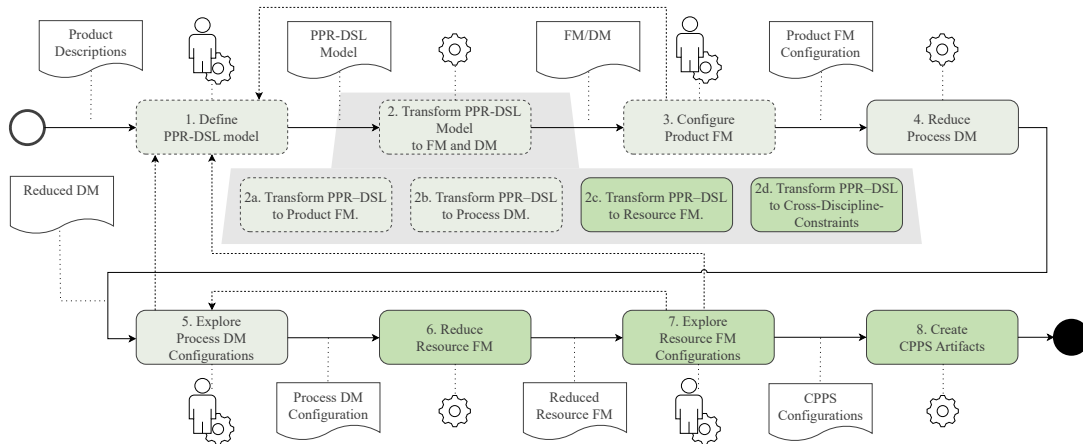


Figure 4: (Human & automated) eIPSE process steps for exploring production process steps based on a product configuration (updated steps have solid contours, novel steps, additionally a darker color).

reduction of the Process DM configuration (Step 4) is automated. The exploration and configuration of the Process DM (Step 5) is integrated with *state-of-the-art* technology and supported by the eIPSE tool. Subsequently, in Step 6, the additionally created Resource FM configuration is automatically reduced based on the decisions taken (i.e., the configuration of the Process DM), and next, configured by the CPPS engineer with the eIPSE tool. Finally, Step 8 creates the control code for the configured production resources to operate the CPPS. The following descriptions highlight the added and adapted steps compared to the original IPSE and explain the eIPSE tool.

Details First, CPPS engineers model product parts and product variants and identify atomic production steps and production resources to manufacture these products based on analyzing the product descriptions and production requirements in Step 1. In this way, they iteratively define a PPR-DSL model (cf. Lst. 2). In practice, engineers typically select and adapt such atomic process steps and, particularly, production resources from an artifact catalog.

After defining the PPR-DSL, in Step 2, the eIPSE uses transformation technology, such as TRAVART [25], to create the variability models automatically. In contrast to the IPSE process, which derived a Product FM and a Process DM only, this second step transforms the PPR-DSL into three variability models with shared CDCs (cf. requirement R3 & R5). It creates

- (i) a Product FM to represent the product variants, their parts, and structure (cf. upper FM in Fig. 1),
- (ii) a Process DM to represent the atomic process steps and their dependencies, representing partial behavior of the CPPS, and product decisions not shown to engineers during the configuration but required for the satisfiability calculation of the model (cf. Tab. 1),
- (iii) a Resource FM to represent the hierarchical structure of production resources (cf. lower FM in Fig. 1), and

- (iv) CDCs capturing the dependencies between the Product FM, the Process DM, and the Resource FM in propositional logic (cf. Lst. 1).

The following steps configure and reduce the possible configuration spaces of the variability models. The CPPS engineer starts with configuring the Product FM in Step 3, resulting in a valid configuration according to the FM. For instance, an engineer selects the *Pipe2* and *Lock1* in the in the Product FM configuration (cf. Fig. 1). Based on the configuration, the eIPSE tool in Step 4 automatically reduces the subsequent Process DM configuration to exclude decisions that are unnecessary to produce the configured product. For each selected feature in the Product FM configuration, the configuration value for the corresponding decision in the Process DM is set to true. For instance, for the selected *Pipe2* feature, the eIPSE tool will set the configuration value of the *Pipe2* product decision to true. For all product features that are not selected, the configuration value of the respective decision remains false. The configuration values in the Process DM set in this way affect which process decisions are visible during the configuration, e.g., decision *InsertPipe2* in Tab. 1, due to its visibility conditions.

In this reduced Process DM configuration, in Step 5, a CPPS engineer can explore the remaining process decisions iteratively and interactively with the eIPSE tool. Based on a constant evaluation, the tool only displays the process steps feasible during the configuration stage according to the visibility conditions. Based on the internal constraints of the Process DM, the eIPSE tool sets the subsequent configuration values. Furthermore, the eIPSE tool stores and visualizes a queue representing the sequence of the currently taken decisions. The final sequence of the configured decisions represents the desired production sequence. This production sequence can be used to define and optimize a valid production process model that is executed on the CPPS.

In Step 6, the eIPSE tool automatically reduces the Resource FM configuration (cf. requirement R3) by considering the Process DM configuration of Step 5. This results in a partial Resource FM configuration, where the configuration possibilities are a valid subset of production resource configurations for a particular product and process sequence configuration. For each selected decision in the Process DM configuration from Step 5, the eIPSE tool considers the CDCs for the production processes and resources. If a process requires a type of production resource, the configuration value for the corresponding features in the Resource FM is preselected. For instance, if the *WeldLock1* decision is part of the configured process sequence, the *WeldingRobot* group is selected.

Based on the Resource FM, in Step 7, a CPPS engineer can configure the desired production resources with the eIPSE tool. As the Resource FM is pre-configured by the Process DM configuration (Step 5), the configuration of the Resource FM only contains the production resources to be used in the production process.

In the final step, Step 8, engineering and operation artifacts should be generated from the combined configuration of the Product FM, the Process DM, and the Resource FM. For instance, IEC 61499 [34] or AutomationML [11] code can be parameterized and generated from reusable artifacts. This step aims to increase the reusability of artifacts and decrease artifact creation time to increase engineering productivity. To support this automation, an eIPSE tool requires additional mechanisms for generating CPPS artifacts. Therefore, CPPS engineers need to decide on a *variability mechanism* [2], such as *Delta Modeling* [58, 70], to implement the shared and the varying CPPS artifacts. In Delta modeling, engineers create elements, such as stubs, templates, and lines of code, that represent the base implementation, in our case, particular CPPS artifacts such as control code. Then, they define Delta models comprising modifications to enrich the base implementation. These operations can modify the base implementation or add or remove code (cf. Lst. 3). During artifact generation, a generator parameterizes and combines this base implementation and the variable code parts, i.e., the Deltas, depending on the variability models' configuration.

Summary The result of the eIPSE process is a set of configurations as well as engineering and operation artifacts, such as control code for a possible design of a CPPS or plan for the assembly of a concrete product. This set of configurations can be used, for instance, to generate a layout of the CPPS, optimize it, and initiate its operation.

5.3. eIPSE Toolchain Architecture

This section describes our implementation of an eIPSE tool. In particular, it presents the architecture of our prototype as well as further implementation details. Fig. 5 depicts this architecture with its main components, which consist of (i) the PPR-DSL to define, read, and evaluate PPR models (eIPSE, Step 1), (ii) TRAVART to transform PPR-DSL models into FMs and DM (Step 2), (iii) the FeatureIDE to configure the Product FM (Step 3), (iv) the eIPSE DM editor

to read or define, manipulate, and configure DMs (Steps 4 & 5), and (v) V4rdiac to read, manipulate, and configure models with CDCs (Steps 6 & 7) and generate IEC 61499 code based on Delta models [6] (Step 8). Compared to our previous work, we provide additional automation support with extended TRAVART transformations for production processes and resources in the PPR-DSL, introduce the novel eIPSE DM editor, and integrate V4rdiac. To this end, in Figure 5, unchanged components are depicted with dashed contours, and novel or adapted components are depicted with solid contours.

PPR-DSL environment. The PPR-DSL environment is realized as a standalone Java application (cf. Fig. 5, top left in yellow). Its main components are the PPR Model (based on an extended VDI 3682 model [66]), the PPR Command Line Interface (CLI), the PPR Parser, and the PPR Evaluator for constraints. The parser reads the PPR File, which includes the products, production process steps, production resources, and constraints via the CLI and builds the PPR Model. The constraints are mapped onto (recursive) SQL queries and evaluated using a PostgreSQL database. This strategy also allows the use of aggregation functions, such as the sum or average of attribute values, over a PPR hierarchy and an easy integration with industrial standards.

Currently, the tool support for the PPR-DSL comprises a set of snippets and code completion functions implemented in SublimeText.⁷ The snippets provide stubs of PPR aspects with their attributes (cf. Lst. 2 lines 1, 14, 31, and 37) that engineers can easily fill in. The code completion allows the recommendation and autocompletion of keywords and the aspects' IDs and names, such as the resource *Linefeeds* in Lst. 2 line 19, so engineers can quickly find existing aspects. However, the text editor does not highlight incorrectly written keywords or whether engineers deleted aspects that are used in other aspect definitions. To this end, the development of an improved editor that supports features, such as code highlighting and missing aspects, using Eclipse XText⁸ for better integration into the ecosystem, is ongoing.

TRAVART environment. TRAVART [25] is a plugin-based variability model transformation environment (cf. top right of Fig. 5).⁹ The TRAVART core plugin is implemented in Java and uses the Universal Variability Language (UVL) [64] as the pivot model, building on the current parser implementation.¹⁰ For each supported variability model, a plugin needs to be implemented.

Such a plugin must provide functions for reading and writing the supported variability model. Furthermore, one has to specify Transformation Operations, which transform the supported variability model into the pivot model and vice versa. These operations are usually built upon a mapping table between the supported variability model and

⁷SublimeText: <https://www.sublimetext.com/>

⁸Eclipse XText: <https://www.eclipse.org/Xtext/>

⁹TraVarT: <https://github.com/SECPS/TraVarT>

¹⁰UVL Parser: <https://github.com/Universal-Variability-Language/uvl-parser>

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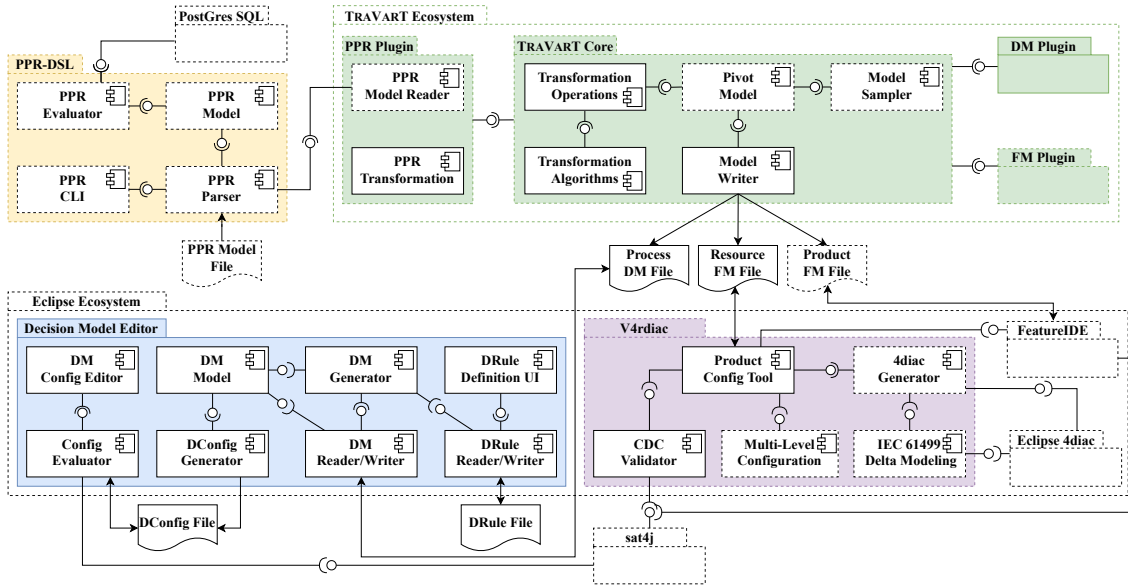


Figure 5: Architecture of the eIPSE toolchain in UML component diagram notation (novel and updated components are depicted with solid contours).

Table 2
Mapping table of PPR–DSL onto Variability Model Elements

	PPR–DSL	FM and DM elements
Unit	Product	Feature with attribute, Decision
	Process	Decision
	Resource	Feature with attribute
Properties	Name	-
	Abstract	Abstract feature
	implements	Feature tree if only one other unit and feature attribute otherwise feature attribute
	children	Feature tree
	requires	Implies constraint
	excludes	Excludes constraints
Constraints	Not	Not constraint
	And	And constraint
	Or	Or constraint
	Implies	Implies constraint

the pivot model and then implemented in Transformation Algorithms [19, 22, 23]. Tab. 2 shows a mapping between the PPR–DSL and FM and DM aspects. Optionally, a plugin can implement a configuration Model Sampler to enable further testing of the resulting models.

Available plugins for TRAVART, including FeatureIDE FMs [43] and DOPLER DMs [9], implement transformation operations [25] that map their concepts to the UVL [64] and vice versa [23]. For instance, a decision in the DOPLER DM is mapped to a feature in the UVL [64]. Also, a rule in the DOPLER DM is mapped to either a feature property (mandatory), the FM tree, or a constraint [23]. In the opposite direction, the hierarchy of the FM tree is captured via the visibility conditions of the DOPLER DM. To support the needs of the eIPSE tool, we extended the DM Plugin by a

new writer. This writer creates a file conforming to the DM editor’s syntax, a propositional logic syntax for constraints and visibility conditions (cf. Sec. 5.3).

Moreover, we iteratively extended the existing PPR–DSL Plugin [19] and transformation operations (cf. Tab. 2) to transform PPR–DSL processes into a Process DM and PPR–DSL resources into a Resource FM. Specifically for the Process DM, the plugin creates a single Boolean decision for each process in the PPR–DSL with its input products and required preceding processes as visibility conditions. For instance, the plugin creates a decision *InsertPipe2* in the Process DM in Tab. 1 from the *InsertPipe2* process in Lst. 2. Furthermore, it creates a visibility condition that fires, if for decision *Pipe*, the value *Pipe2* is selected. Subsequently, it creates a constraint that selects the abstract decision *InsertPipe*. Abstract processes are transformed to Boolean decisions with a visibility condition false, to be implicitly selected by those constraint rules. Further, the transformations create a feature for each PPR–DSL resource and derive its properties (e.g., whether the feature is abstract or mandatory) from the respective PPR–DSL properties. For example, for the *WeldingRobot* (cf. Lst. 2), an abstract feature is created in the Resource FM, defining a group of welding robots. For the *KUKA_KR_Agilus*, a concrete feature is generated in the *WeldingRobot* group. Each group of PPR–DSL resources is converted into an *OR*-group because at least one of the grouped resources will have to be selected if these resources are necessary to produce the configured product. Finally, the plugin derives a list of CDCs by connecting the features and decisions from the resulting variability artifacts, i.e., Product FM, Process DM, and Resource FM. For instance, the necessary PPR–DSL resources for a given process result

in a CDC between the respective process decision in the Process DM and the respective resource features in the Resource FM (cf. CDC2 in Lst. 1).

Eclipse Ecosystem The Eclipse Ecosystem¹¹ is a cross-platform, open-source integrated development environment (IDE) for (software) engineering in different languages and domains. The IDE provides a plugin system that allows the dynamic exchange of components. Thus, it allows combining different independent software components into a suitable toolchain, in our case, for variability modeling.

FeatureIDE environment. The FeatureIDE [43]¹² is the current de-facto-standard open-source plugin for feature-oriented software development. It supports several FM types, among others, graphical FMs modeling and textual variability modeling using UVL [64]. Furthermore, the FeatureIDE allows for configuring FMs and validating them through sat4j.

Eclipse 4diacTM Eclipse 4diacTM¹³ [71] is an open-source Eclipse-based tool for developing IEC 61499-based [34] control software for CPPSs.

DM Editor environment. The eIPSE DM Editor (bottom left of Fig. 5) is inspired by the DOPLER DM editor [9]. The latter was developed for an industry partner and is a closed-source tool. Instead, our eIPSE DM Editor (cf. Fig. 5) is an open-source Eclipse plugin, compatible with the latest version of FeatureIDE. Our DM Editor offers the following key features: (i) the import of DOPLER DMs, used here to import the Process DM, (ii) the creation of DRule files, where each file represents a single decision, (iii) the generation of DOPLER DMs from those DRule files, (iv) the generation of DConfig configuration files for DOPLER DMs, and (v) the configuration of DOPLER DMs via those DConfig configuration files, used here to explore and configure the Process DM.

DRule files exhibit a similar structure as the DOPLER DM in Sec. 2.2, supporting a propositional logic syntax for constraints and visibility conditions. Currently, we limited the syntax to types that can be translated into common SAT solvers, in this context sat4j, to enable the DOPLER DM's configuration validation and integration into the toolchain. On user-triggered generation, the DM Generator component maps the DRule files onto an internal DM Model. From this DM Model, the DM Writer writes a DM File with the specific syntax. In our case, this model and the corresponding files contain the decisions for the production process steps that need to be selected to create a suitable process step sequence. However, this model could also be used for other types of decisions.

The DConfig Generator component generates a configuration for a DM in a DConfig File. It uses the DM Reader that reads the DM model file created either by the DM

Generator or by TRAVART. The DM Config Editor reads the generated DConfig File and presents configuration options in a configuration view. In this view, users can configure the DM model, which is validated in the background by the Config Evaluator. The selected sequence of decisions is stored in the DConfig File for further processing, for instance, to export or visualize the production process sequence.

V4rdiac. V4rdiac [14] is a, currently closed source, multidisciplinary variability management approach for CPPS variability realized as an Eclipse plugin (cf. bottom right of Fig. 5). The eIPSE tool uses several V4rdiac components for generating customer-specific control software based on the selected products, production processes, and production resources. Specifically, the eIPSE tool uses the components IEC 61499 Delta Modeling, Multi-Level Configuration, CDC Validator, Product Config Tool, and the 4diac Generator.

Eclipse 4diacTM is used to develop the base implementation of the IEC 61499 control software. Beyond that, the IEC 61499 Delta Modeling component is used to implement the Deltas for the control code artifacts (cf. Lst. 3). Afterward, a mapping between the base implementation artifacts and the Deltas needs to be established. In our case, CPPS engineers define an additional attribute in the PPR-DSL, which specifies the location of corresponding Deltas, e.g., as URI (cf. Lst. 4 Line 8). The Multi-Level Configuration is used to define a step-wise configuration in which different variability models can be configured separately. In our case, the Product FM and Process DM with their configurations and the Resource FM are loaded into the component and ordered into this sequence. During the configuration of the Resource FM, which allows the configuration of multiple production resources for a production process, the CDC Validator ensures that the selected configurations are valid according to the CDCs. The Product Config Tool component displays the configuration user interface for the Resource FM. After the Resource FM configuration in the Product Config Tool, the eIPSE process is finished with a valid configuration. The eIPSE tool requires an artifact generator that evaluates the mapping between PPR-DSL attributes and CPPS artifacts to remove, combine, and build CPPS artifacts given a set of selected products, production processes, and production resources. The IEC 61499 Delta Modeling component is linked to Eclipse 4diacTM and the 4diac Generator to generate the IEC 61499 control code. The 4diac Generator then generates the control software for the production resources in IEC 61499. For a detailed description of Delta modeling for control software, we refer to [15, 16].

The eIPSE tool aims to support a straightforward integration of different CPPS artifact generators and formats, such as IEC 61499 [34] or AutomationML [11] code.

¹¹Eclipse Foundation: <https://www.eclipse.org>

¹²FeatureIDE: <https://github.com/FeatureIDE/FeatureIDE>

¹³Eclipse 4diacTM: <https://www.eclipse.org/4diac>

6. Evaluation

This section describes the evaluation of the eIPSE approach and prototype. Sec. 6.1 presents the evaluation questions to be answered. The subsequent sections (cf. Sec. 6.2-6.6) first present the general setup of the evaluation activities, followed by describing the concrete setup and the results.

6.1. Evaluation Questions

To evaluate the eIPSE approach and prototype, we address the research questions (cf. Sec. 1) and stated requirements (cf. Sec. 5.1) with the following evaluation questions.

EQ1 *Is it feasible to apply the eIPSE approach*

- (a) in different real-world case studies?
- (b) by engineers from heterogeneous backgrounds?

We postulate that the eIPSE approach facilitates the externalization of knowledge, reduces the effort of CPPS modeling and configuration through automation, including the exploration of feasible production process sequences, and benefits the reproducibility of the configuration process. To examine EQ1, we applied our approach to different real-world case studies from industry [45]. Beyond that, we shadowed [62] subjects with different backgrounds to investigate the utility of our approach, i.e., whether it is feasible enough to be used in CPPS engineering. Therefore, we measured their efforts as “time spent” when applying the eIPSE approach step-wise and configuring a CPPS as a notable factor of CPPS engineering optimization [67] and for future investigation. Furthermore, we collected feedback from the subjects in post-task discussions. For both investigations, we take the engineers’ hard-to-reproduce and manual approach as a baseline for optimization, where engineers employ mostly implicit domain knowledge to design and configure CPPSs.

EQ2 *By how much can using eIPSE reduce the number of decisions needed to configure a production process sequence for a CPPS?*

The eIPSE approach is grounded on the hypothesis that the configuration of a single product and the formulation of pre- and postconditions for process steps can significantly reduce the configuration space for production process sequences. By reducing the configuration space, the users are guided to only configuring necessary process steps, which is essential when configuring commercial and/or industrial software [32]. Therefore, the eIPSE approach uses DOPLER DMs due to the concept of visibility conditions that allows for a subsequent unfolding of configuration options in contrast to FMs. We address EQ2 by comparing the entire configuration space of a Process DM with the configuration space for the reduced Process DM resulting from using eIPSE by utilizing combinatorics. In particular, we focus on a subsequently created production process sequence for a particular product configuration of the *shift fork* case study [45].

EQ3 *Can the eIPSE tool chain generate consistent CPPS control software code?*

The logical consequence of exploring the process sequences and configuring the production resources for a particular product configuration is generating artifacts that represent various CPPS aspects. In our work, we are currently focused on one type of CPPS artifact, i.e., IEC 61499 [34] control software. We address this question by preparing multiple valid combinations of selected products, production processes, and production resources. We use each valid combination to generate IEC 61499 control software variants using our toolchain. Then, we evaluate the consistency of the control software code by verifying whether the elements related to the selected product, production process, and production resources exist in the generated control software.

6.2. General Evaluation Setup

For the evaluation, we installed the eIPSE toolchain on one of the author’s notebooks. This is due to the company policies of some of our evaluation subjects from industry, they are not allowed to install any additional software, including our eIPSE toolchain. Our setup included (i) SublimeText as a text editor to manipulate the PPR–DSL including a “cheat sheet” for its syntax (eIPSE, Step 1), (ii) TRAVART with the PPR–DSL as the library to transform the PPR–DSL models to the required variability models (Step 2), (iii) Eclipse with FeatureIDE (Step 3), the DM Editor (Steps 4 & 5), and V4rdiac to manipulate and configure the variability models (cf. Step 6 & 7), and to generate the CPPS artifacts (Step 8) showing them with 4diac as plugins. We used this setup in the sessions to investigate the evaluation question **EQ1+EQ3**.

Additionally, our evaluation subjects are distributed in diverse locations. To solve this limitation, we utilize Zoom’s *Screen Sharing* and *Remote Control* features to use the eIPSE toolchain remotely. In this way, we can use the same machine specification for every subject using the eIPSE toolchain in the evaluation. Furthermore, we can record those Zoom sessions for later analysis.

6.3. Application of eIPSE to Case Studies

This evaluation activity addresses **EQ1 a** by investigating the applicability of the eIPSE approach to real-world case studies from industry and by measuring the resulting design and configuration space.

Setup In prior work [45], we introduced four real-world CPPS case studies: *truck*, *shift fork*, *rocker switch*, and *water filter*, modeled their products in the PPR–DSL and implemented TRAVART transformation operations. In [46], we extended the *shift fork* model with processes and added the corresponding TRAVART transformation.

For the evaluation activity, the author most familiar with the PPR–DSL and the particular CPPSs modeled the remaining atomic process steps and resources (eIPSE, Step 1) for each case study. The author utilized engineering artifacts of

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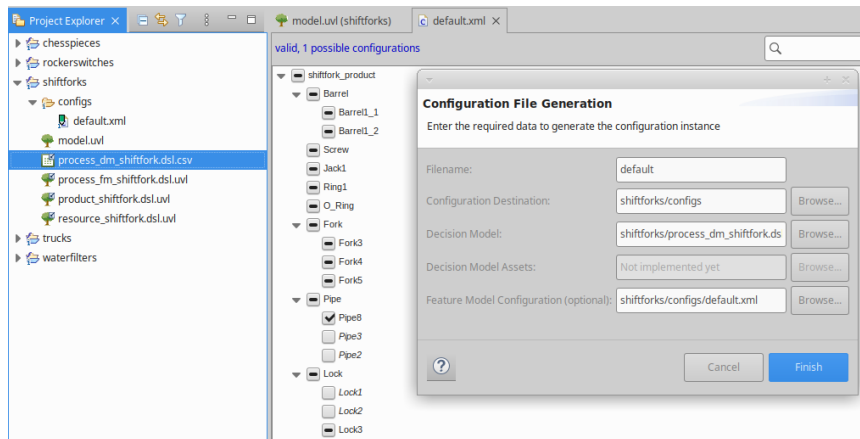


Figure 6: After configuring the Product FM in Step 3 of the eIPSE process (background) for the *shift fork* case study [45], the reduced Process DM configuration is created in Step 4 of the eIPSE process using the eIPSE prototype's wizard (front).

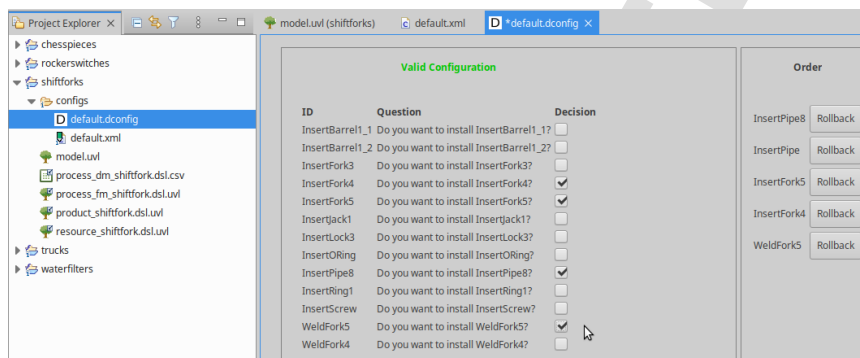


Figure 7: During the configuration of the production steps in the Process DM in Step 5 of the eIPSE process, a suitable production process sequence for the *shift fork* case study [45] is defined. The eIPSE prototype provides a *rollback* option (right-hand side) for systematic process sequence exploration [46].

the respective CPPSs. In the *shift fork* case study, the author most familiar with TRAVART iteratively improved the existing and newly implemented transformation operations, sustaining the research methodology. These adaptations primarily concerned the hierarchy and grouping of PPR aspects but did not change the nature of the CPPS designs.

The two authors alternately applied the remaining steps of the eIPSE approach (Steps 2 to 7) to each of the four case studies. Fig. 6 to Fig. 8 show (i) the configuration view of the Product FM in Step 3 (background) and the wizard to create the Process DM configuration in Step 4 (front), (ii) the DM Editor and a step in configuring the Process DM in Step 5, and (iii) the Resource FM configuration in Step 7 for the *shift fork* case study using our eIPSE prototype.

According to the feedback loops shown in Fig. 4, the two authors incorporated changes during the evaluation activity iteratively to correct errors in the PPR-DSL model, such as missing exclusion or grouping constraints and to omit errors in the generated variability models. To this end, we also used the eIPSE approach to *validate* the PPR models

of the case studies. A third author took notes and acted as a referee to minimize bias during the evaluation activity, which could have been introduced by the familiarity of the other two authors with the case studies. Additionally, during the transformations, we ran automated statistics for each case study to obtain various metrics for the PPR-DSL file and resulting variability models. We built on previously defined metrics [19], such as the size of the models, their constraints, and configuration space. We summarize the resulting statistics in Tab. 3 and explain them below. We used the notes by the third author and the collected statistics to further improve the implementation of our prototype (cf. Section 4).

Results Our evaluation showed that we were able, with the feedback loops, to apply the eIPSE approach in the four selected case studies. While we had to adapt the PPR-DSL models iteratively throughout the process, we were able to configure reasonable production process sequences and production resources for a particular product configuration. This

Table 3

Statistical data on the PPR-DSL artifact and the generated Product FM, Process DM, Resource FM, and CDCs.

Case study	PPR-DSL artifact					Product FM				Process DM			Resource FM				CDCs			
	#Products	#Product _{comp}	#Processes	#Resources	#Constraints	#Features	#Constraints _{xor}	#Constraints _{gr}	#Constraints _{tree}	Tree height	#Configs	#Decisions	#Constraints	#Constraints _{vis}	#Features	#Constraints _{xor}	#Constraints _{gr}	#Constraints _{tree}	Tree Height	#Rules
Truck	12	7	13	3	30	8	1	0	0	2	4	20	32	20	5	0	1	0	2	15
Shift fork	24	19	36	16	52	20	2	0	10	2	4	55	27	53	17	0	8	0	3	35
Rocker switch	46	33	59	13	63	34	0	0	20	2	44	92	26	92	14	0	5	0	3	63
Water filter	46	37	36	13	108	38	8	0	54	3	10	73	127	73	14	0	5	0	3	43

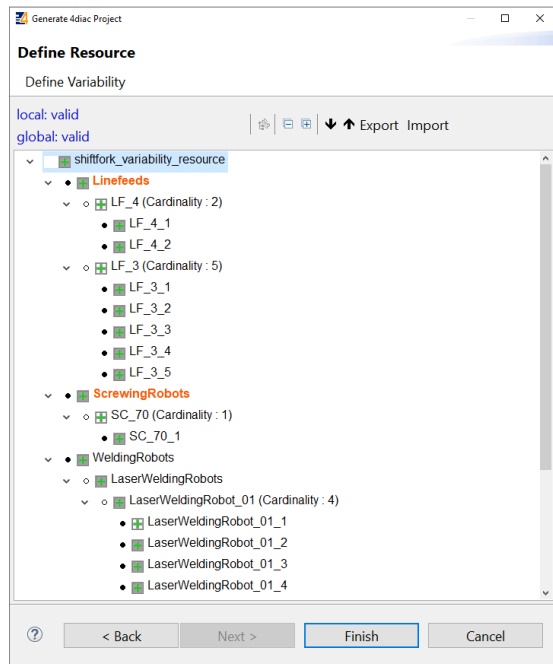


Figure 8: The configuration of the Resource FM in Step 7 of the eIPSE process for the production resources necessary to execute the configured production process steps of the Process DM in Step 5 of the *shift fork* case study [45].

indicates that applying eIPSE to industrial CPPS product lines is feasible.

As a supplementary result, we gathered metrics of the variability models resulting from the transformation, listed in Tab. 3. As a representative of the case studies, we explain the *shift fork* case study in detail. The first category summarizes the metrics of the *PPR-DSL artifact*. For the *shift fork* case study, there are 24 product definitions with 19 product component definitions included, 36 atomic process step definitions, 16 resource definitions, and 52 constraints. The next set of metrics concerns the generated *Product FM*. We measured 20 features resulting from the set of 19 product components plus the root feature. The constraints in the *PPR-DSL artifact* were transformed into 2 *xor* groups and 10 cross-tree constraints. The reduced complexity compared

to the *PPR-DSL artifact* results from the number of constraints necessary to describe an alternative group in the *PPR-DSL*. The 4 possible configurations for the products in the *Product FM* represent exactly the 4 shift fork types produced in the real-world CPPS. The same holds for the 4 trucks in the *truck* case study. However, the *Product FM* is underconstrained, resulting in more possible configurations than the modeled final product types in the *PPR-DSL* of the *rocker switch* (44 configurations vs. 12 product types) and the *water filter* (10 configurations vs. 8 product types) case studies. In the generated *Process DM*, we measured 55 decisions, consisting of 19 product component decisions, of which 4 were abstract, 15 were concrete, and 36 processes from the *PPR-DSL artifact*. Those 19 decisions are used to pre-configure the *Process DM* for the process exploration (cf. Step 4 in Sec. 5). The table shows the large number of decisions (55), rules/constraints (27), and visibility constraints (53) compared to the constraints in the *PPR model* (52). The generated *Resource FM* contains 17 features derived from the 16 defined resources in the *PPR-DSL model* plus the root feature. The features are grouped in or groups based on the constraints defined in the *PPR-DSL*. The last category shows the generated *CDCs*, which are 35 derived *CDC rules* for the *shift fork* case study. The table shows that the *PPR-DSL model* requires fewer constraints (52) than the variability models combined; 2+10 for the *Product FM*, 27+53 for the *Process DM*, 8 for the *Resource FM*, and 35 *CDCs*.

6.4. Application of eIPSE by Different Engineers

This evaluation activity addresses **EQ1 b**. In a user study, we investigate how much effort engineers from heterogeneous backgrounds inexperienced in the eIPSE approach spend for each step of applying eIPSE by shadowing them [62]. We report on their effort, experience, and perceived usefulness. For a detailed description of the user study, we refer to Appendix A.

Setup For this evaluation activity, we introduce the new *chess piece* case study originating from the TU Wien pilot factory.¹⁴ The product line consists of six chess piece types with a body and an aluminum base with either one or two

¹⁴Pilotfabrik TU Wien: <https://www.pilotfabrik.at>

carved reamings. The body and the base are joined via threaded rods of two lengths.

Five subjects applied the eIPSE approach to this case study. An overview of the subjects and their domain can be found in Tab. 4. The first and the second columns of the table state the subject and whether the subjects are engineers (*E*) or researchers (*R*) and their domain. Subject S1 is an engineer at an industry partner in the field of high-speed CPPS automation with a background in mechanical engineering (*ME*). Two subjects (S2 & S3) are engineers from an industry partner in the automotive domain with a background in mechanical engineering. Subject S4 is a senior systems engineer (*SE*) in the CPPS domain from a research collaboration. Subject S5 is a computer science researcher with a mechanical engineering background. All subjects know the principles of the PPR concept.

All subjects conducted the evaluation activities in individual Zoom sessions after the evaluation activity for **EQ1 a** (cf. Sec. 6.3) under the supervision of at least two authors.¹⁵ If the subjects had questions concerning the PPR-DSL, the eIPSE approach, or the toolchain, these authors provided tips and support. These authors gave hints on how to model aspects of the product line once a subject got stuck and asked for help. We also measured the time the subjects took to execute each step of the evaluation activity and eIPSE process. We aimed to understand better where subjects need more automation support and where we can further improve the eIPSE approach. Furthermore, we wanted to compare the use of the eIPSE process with a control group that performs the same tasks without the eIPSE process.

The subjects had to model the chess piece types and their parts, reasonable atomic production steps, and production resources in a PPR-DSL model (eIPSE, Step 1). In this evaluation, it is not necessary for each subject to model the full version of the chess piece product line. We mainly focused on ensuring that the subjects grasp the overall idea of using our PPR-DSL and gain feedback from them. Furthermore, we wanted to get an indication of the relation between the tasks for engineering and configuration. The subjects then use their resulting PPR-DSL model to generate the Product FM, the Process DM, and the Resource FM using the TRAVART CLI (Step 2). Then, the subjects configured the Product FM (Step 3) and loaded the configuration into the DM Editor to create a reduced DM configuration file (Step 4) (cf. Fig. 6). Afterward, the subjects explored the process sequence and configured the Process DM (Step 5). Lastly, they configured the Resource FM in V4rdiac, which reduced the model based on the configured Process DM (Step 6 & 7). If the subjects thought it was necessary to improve their variability models, they used the feedback loops (cf. Fig. 5) to improve their product line.

After the subjects had completed this evaluation task, we asked them for their experience with and feedback on the eIPSE approach as well as its perceived usefulness. We analyzed the notes taken by comparing them and finding

¹⁵The time frame was limited to roughly two hours for industrial subjects.

Table 4

"Time spent" by engineers with different backgrounds for eIPSE to the *chess piece* case study. E... Engineer, R... Researcher; ME... Mechanical engineering, SE... Systems engineering, CS... Computer science

Subject		Activity					
Participant	Profession	Intro	Engineering		Configuration		
		Definition	Updates	Product FM	Process DM	Resource FM	
S1	E,ME	10m	60m	30m	3m	5m	1m
S2	E,ME	13m	70m	15m	2m	7m	3m
S3	E,ME	9m	72m	3m	2m	5m	4m
S4	E,SE	6m	62m	4m	1m	4m	1m
S5	R,ME	9m	63m	9m	6m	9m	3m
Summary (avg)		9m	65m	12m	3m	6m	2m

evidence for the usefulness and benefits of the approach, its steps, and potential limitations and improvements.

Results Tab. 4 presents the times spent on this evaluation activity. The third column states the time to introduce the eIPSE approach and the *chess piece* product line. The fourth and fifth column concern the domain engineering phase, showing the time spent to define the chess piece product line as a PPR-DSL model. The fifth column shows the time the subjects used to update the product line after an initial configuration. This update corresponds to the feedback loops of the eIPSE approach (cf. Fig. 4 dotted arrows). The last three columns present the times spent during the configuration phase (i.e., application engineering) indicating the efforts for configuring the Product FM in the FeatureIDE [43], the Process DM in the eIPSE DM Editor, and the Resource FM in V4rdiac [14]. The last row summarizes the rounded average time of each step in minutes.

The introduction to eIPSE and the *chess piece* case study took, on average, 9 minutes, [min. 6 mins, max. 13 mins]. Spending on average 65 minutes, [60 mins, 72 mins], the subjects spent most of the time on *defining the product line*. While most of the subjects did not model the entire product line of the six chess pieces with all the required production processes and resources, they could all grasp the concepts of the approach and continue with the configuration. *Updating the product line* according to the feedback loops took the subjects on average 12 minutes [3 mins, 30 mins] depending on how much they updated their models. For the initial PPR-DSL model transformation to the variability models and their configuration, we used the subjects' PPR-DSL models. However, as the subjects often did not model all products, production process steps, and production resources for timely reasons, after the first investigation of their generated variability models, we switched to a prepared *chess piece* PPR-DSL model to ensure a likewise feedback regarding the configuration with the eIPSE approach.

The *CPPS configuration* in this approach was fast for the Product FM and the Resource FM (both have avg. 3 minutes). The Process DM configuration took the evaluation subjects on average 6 minutes, [4 mins, 9 mins], slightly

longer than the configuration of the other variability models. One reason might be that users novel to the approach do not have enough experience in ordering process steps in a meaningful way. Additionally, it seems that more domain knowledge is required to decide which process steps seem reasonable to be ordered in a particular way. Thus, subjects used more time to experiment with different sequences before finalizing and deciding on a specific one.

In post-task discussions, we gathered feedback on the approach from each subject. Overall, the eIPSE approach was well received. Impressions were that the approach

- “is very helpful and the toolchain works great.” (S2)
- “makes sense from an engineer’s perspective.” (S1/S4)
- “makes the knowledge about the production sequence explicit” (S2/S3/S4)
- “is straightforward.” (S1/S4)
- “allows for a more economic and optimized design of the CPPS.” (S3)

Subject S3 stated that “the process digitalization is a great idea that can improve reuse of existing configurations” and it is “easy to understand and use.” Several subjects stated that it “supports the reproducibility of process selection.” S4 confirmed that the separation of concerns through “modeling relations from different discipline perspectives” is important. S2 meant that “the often rigid integration structures of large companies might render the approach better suited for small and medium companies.”

On the constructive side, the subjects also pointed out some issues and suggested several improvements. Most subjects noted that the approach “definitely requires better tool support to use it efficiently,” such as “better tool feedback” and “a better overview of PPR concepts” using, for example, “low code approaches.”

Concerning the PPR-DSL for modeling the chess piece product line, the subjects stated that

- it “provides the means for better reuse” of engineering artifacts (S4) and
- was “straightforward and easy to use once the syntax is clear.” (S2)
- “the PPR-DSL is great because it is not as complex as, e.g., SysML.” (S2)

Nevertheless, three subjects noted that the PPR-DSL “has a steep learning curve.” Several subjects commented that the PPR-DSL “is sometimes redundant and partially confusing,” for instance, because a “product” is the same as a material,¹⁶ and that the “difference between the requires and children relation is unclear.” Such limitations and the “several times missing overview” can make the PPR-DSL “as-is error-prone for larger models.” This concerns, for instance, “the definition of constraints in the model with a large number of products/processes.” While the “cheat sheet was of great use,” the PPR-DSL “should be simplified to be usable for engineers” and “redundancies should be omitted.”

¹⁶We note that the VDI 3682 standard uses the term *product* for materials as well as complex composite products.

A suggestion was also to “provide more examples and best practices” and “improve the documentation” for the PPR-DSL. Furthermore, the subjects desired the “introduction of parallel processes,” “definition of transport in the CPPS,” and “use of libraries.” We aim to enhance the PPR-DSL and its tool support to address these comments in the future.

Feedback on the transformation to the variability models was positive: “extremely fast and happens in the background once syntax errors are fixed.” However, the transformation “may cause iterative loops of updating the PPR-DSL.” We argue that these feedback loops are intended and should be used by engineers to improve their PPR models. We also argue that more experienced users and product designers presumably define better PPR models.

Feedback on the configuration was mainly positive:

- it “provides an easy configuration.” (S1/S4)
- “having the dependencies explicitly transferred into the configurable models helps to build feasible production sequences” (S5)
- “the experimentation with different process sequences through simulation is a good idea.” (S3)
- the exploration makes sense particularly with “digital twins and asset administration shells for simulation and provides additional value with the modeling of the process relations.” (S4)

All subjects also provided several remarks to improve our eIPSE approach and toolchain. In particular, Subject S5 stated that “cost/risk assessment would be nice to further enhance and evaluate the process sequences.” Several subjects also stated that “the toolchain requires better integration.” For instance, one subject mentioned that “executing the process using the eIPSE toolchain requires a lot of preparatory steps, which could be reduced.” Asking for clarification, the subject explained that copy-pasting the necessary files in between the process steps should be enhanced. We argue that the current state of our toolchain, not the eIPSE process itself, caused this statement. In future work, we aim to integrate all involved toolchain tools into a single tool environment, such as Eclipse.

6.5. Reduction of the Process Configuration Space

This evaluation activity addresses EQ2 by investigating the reduction of the configuration space of a Process DM.

Method To measure the reduction of the configuration space, we utilize combinatorics. Considering the sequence of process steps, the Process DM configuration follows a permutation, an arrangement of elements in a specific sequence. Additionally, only visible process steps (visibility condition is true) can be configured in the Process DM configuration. The formula to calculate permutations, where n denotes the total number of visible atomic process steps and r denotes the number of steps occurring only in combination, is defined as:

$$P(n, r) = \frac{n!}{(n - r)!} \quad (1)$$

To this end, we compare the entire configuration space of a Process DM, where process steps can be combined arbitrarily, with the configuration space for the reduced Process DM resulting from a configured product using eIPSE (cf. Step 3 and Step 4). As a representative, we examine a subsequently created production process sequence in the *shift fork* case study.

Results In this evaluation, we perform a simulation to configure the *shift fork*'s Product FM (cf. Fig. 1 and in Fig. 6) by selecting the features *Pipe2* and *Lock1* (Step 3). This selection results in a valid configuration representing a single shift fork product. Step 4 reduces the configuration options of the Process DM to this product where only the investigation of this product's process sequence is progressed.

Consequently, the visibility conditions and configuration values of *Pipe2* and *Lock1* are set true in the Process DM (cf. Tab. 1). The Process DM configuration is further reduced by setting the visibility conditions of the mandatory process steps to true. Additionally, any alternative group within the Process DM is reduced by setting the visibility conditions of only one of the available options to true, leaving the engineer to select only truly variable process steps. For instance, the *InsertLock1* visibility condition is set to true and, thus, the *InsertLock2* and *InsertLock3* visibility conditions are set to false.

The overall Process DM configurations in the *shift fork* case study comprise 21 process step decisions and the 3 alternative process step group decisions when considering the *Pipe2* and *Lock1* product configuration AND the constraints between the decisions. In the case of the production process sequence exploration [46], $r = n$ since we can combine all visible production process steps in the particular configuration step. Furthermore, arbitrarily combining the atomic process steps visible to developers at any time results in $n!$ permutation possibilities for n decisions. Thus, the entire permutation space comprises $24! = 6 \cdot 10^{23}$ possible process step sequences.

Transforming the pre- and postconditions of the production processes in the PPR-DSL to visibility conditions in the Process DM enables the subsequent unfolding of the production process steps for creating a production process sequence. The *shift fork*'s product configuration allows 11 process steps, e.g., *InsertPipe2* and *InsertLock1*, with no visibility conditions that build the starting point of the Process DM configuration. Furthermore, the *shift fork*'s product configuration allows 4 process steps with visibility conditions related to the 11 previous steps, e.g., *InstallLock1*. Following the visibility conditions, the eIPSE approach reduces the configuration of the Process DM to five consecutive steps with 11, 4, 6, 2, and 1 remaining production process steps. In each step, engineers had to decide in which sequence the currently possible production process steps have to be executed. Consequently, the eIPSE approach reduced the set of possible process sequences to a minimum of $11! + 4! + 6! + 2! + 1! \approx 39.9 \cdot 10^6$ possible sequences – a reduction of about 10^{17} sequence options.

Even though many sequence configuration options remain, the reduction is significant and helps to reduce the cognitive level of deciding on a valid and feasible sequence. However, the exploration of optimized production process sequences still demands additional knowledge and training from the engineers, which is a complementary activity to introducing the eIPSE workflow.

6.6. Generation of Control Software

This evaluation activity addresses EQ3 by investigating how to create parts of the control software for a particular CPPS configuration as an example for a CPPS artifact.

Setup The author, most familiar with V4rdiac, defined the necessary Delta files to generate IEC 61499 control code in 4diac as a CPPS artifact of the four case studies during Step 8. In close cooperation with the authors of the first evaluation activity, the link between the processes and resources in the PPR-DSL to the Delta files was realized using a newly introduced PPR-DSL attribute.

```

1  delta DLock1;
2  uses ShiftForkCaseStudyApp;
3  {
4    <Remove> NetworkElement name=InsertLock1;
5    <Remove> NetworkElement name=WeldLock1;
6    <Remove> NetworkElement name=E_REND_WeldLock1;
7    <Add> FB name=UltrasonicWeldingRobot16
8        type=UltrasonicWeldingRobot_16;
9    <Add> EventConnection UltrasonicWeldingRobot16.CNF
10       PopulatedPipe.REQ;
11 }

```

Listing 3: Snippet of an IEC 61499 Delta model for the *shift fork* case study.

An example of a Delta model can be seen in Lst. 3. Each Delta model may define a unique identifier by using the delta keyword. The uses keyword sets the context for the modification. A <Remove> and an <Add> operation define which element will be removed from or added to the CPPS artifacts, respectively.

Next, the author introduced a new attribute deltaFile to the PPR models of the four case studies and used it to refer to the particular Delta files (cf. Lst. 4) from the processes and resources (eIPSE, Step 1). Afterward, the author reran the TRAVART transformations (Step 2) to generate the attributes in the variability models. Then, the author went through the configuration and reduction steps of the eIPSE approach according to the setting of the first evaluation activity (cf. Sec. 6.3) covering Steps 3 to 7 as input for Step 8. In Step 8, the author triggered the generation of parts of control software in IEC 61499 in V4rdiac.

Results Our toolchain successfully generated an IEC 61499 control software based on a set of selected products, production processes, and production resources. Additionally, all elements in the generated control software also reflect the selected products, production processes, and production resources. For instance, Fig. 9 shows a generated control software based on selecting production processes, e.g., the

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```

1  Attribute "deltaFile": {
2    description: "delta file for V4rdiac configuration",
3    defaultValue: "", type: "String"
4  }
5
6  Process "WeldLock1": { name: "WeldLock1",
7    implements: [ "WeldLock" ], inputs: [ "Lock1" ],
8    deltaFile: "!DLock1"
9  }
10
11 Resource "WeldingRobot": { name: "WeldingRobot",
12   isAbstract: true }
13 Resource "LaserWeldingRobot_01":{ name: "LaserWeldingRobot_01",
14   implements: [ "LaserWeldingRobots" ],
15   deltaFile: "DLaserWeldingRobot01"
16 }

```

Listing 4: Excerpt of the PPR-DSL model of the *shift fork* case study with the `deltaFile` attribute.

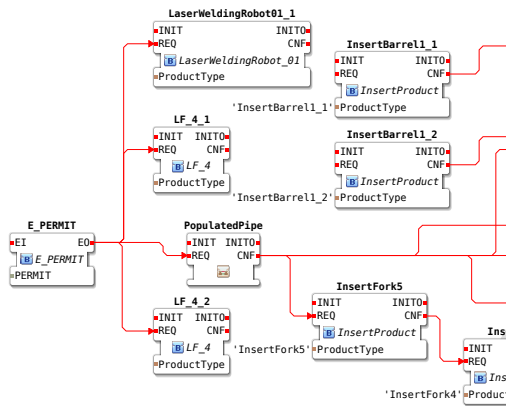


Figure 9: Excerpt of a generated IEC 61499 control software with production process and resource function blocks for a shift fork configuration.

PopulatedPipe, *InsertFork5*, and *InsertFork4*, and production resources, e.g., *LF_4_1* and *LF_4_2*, of the shift fork case study.

7. Discussion

This section concludes on the evaluation questions from the previous section and answers the research question raised in the introduction (cf. Sec. 1). Furthermore, it discusses the limitations of the prototype and threats to validity.

7.1. Observations and Lessons Learned

This section discusses the observations and lessons learned from the evaluation of the eIPSE approach.

General Comments To examine the applicability of eIPSE, we conducted a feasibility study with users experienced in the eIPSE approach on four published case studies [45] and an observational user study with users inexperienced in the eIPSE approach on a novel case study. We also investigated the reduction of the Process DM's configuration space by eIPSE and experimented with generating control code from such eIPSE configurations. These studies gave us valuable

insight into potential benefits and perceived limitations of the eIPSE approach.

To this end, we go beyond our previous work [46], i.e., by providing feedback on the eIPSE approach of users from different domains. This feedback indicates that the users perceived the eIPSE approach and toolchain as useful. In particular, users perceived the *externalization of knowledge* [44] as valuable (requirements R1, R2, R4), the *separation of concerns for the configuration steps* [1, 14] as helpful (R3, R5), the *production process sequence exploration* as significant [18] (R1), and the *integration of variability models* as beneficial [41] (R1, R2, R5). Furthermore, the users provided valuable feedback for approach improvements and future work.

The following paragraphs summarize the observations and lessons learned for each evaluation question.

EQ1a Application of eIPSE to Case Studies The primary lesson learned from applying eIPSE to the case studies was that modeling the PPR model combined with Steps 2 to 7 led to critical feedback. Additionally, we experienced that this feedback gained importance with the growing complexity of the product line of products and processes. For instance, while the *truck* case study contained no defects in the PPR model, it required significant improvement for the *rocker switch* and *water filter* case studies. This improvement mainly concerned missing requires or excludes constraints or additional CDC rules to limit the configuration options of the manufactured products suitably. Therefore, it is also possible to configure "semantically" incorrect products in the Product FM, which can be prevented by more carefully defining the variability in the PPR-DSL. This confirms research and industry voices [21] and further stakeholders from industry regarding the importance of these constraints [51]. To this end, the eIPSE approach helped to reveal flaws, even in the already published PPR models [45]. For instance, in Product FMs resulting from such PPR models, relevant products could not be configured anymore, the feature groups were incorrect, or the Product FM allowed many more configurations than products in the product line. This also implies that software and CPPS product lines significantly differ regarding the configured output products, where, in the latter, each manufactured product must contribute to the cost and "return on investment" of the planned CPPS. Therefore, it requires support for variability model analysis to constrain the models and ensure that unintended products can not be configured.

Second, the PPR-DSL [49], TRAVART [25], FeatureIDE [43] FMs, DOPLER [9] DMs, and V4rdiac [14] were originally designed as independent tools. Thus, we had to align the constraint formats and, respectively, the transformations.

EQ1b Application by Engineers The first insight from observing engineers applying the eIPSE approach is that the engineering phase for the CPPS takes significantly longer (avg. 77m) than the configuration phase (avg. 11m). This is

partly expected because application engineering is supposed to be faster than domain engineering. However, the editor support for defining the PPR-DSL may contribute to the time spent on the definition and update tasks and may need improvement. Still, the numbers confirm that much (mental) effort is invested in the product line definition. In more detail, we observed that most of the time was spent defining the products and the atomic production process steps rather than the production resources. The numbers also show that the configuration of the production process sequence in the Process DM took longer than the feature models' configuration. This indicates that creating a meaningful production process sequence is more complex but also requires means to evaluate and simulate the sequences economically. Furthermore, it implies that the time spent on different tasks requires a *separation of concerns in multidisciplinary engineering* (requirement R3, R5) and the *externalization of knowledge* (R1, R2, R4), which the engineers confirmed.

Secondly, the results show that the automatic creation and reduction of the variability model configuration space is fast and leads to a low time expenditure for the configuration of the models. This beats the definition of an additional product and potential production process steps as an increment in the PPR-DSL, which is still done manually with our approach. We argue that the eIPSE approach thus supports the challenge of an evolutionary creation of the product and its production process line.

Thirdly, the feedback of the subjects confirmed the usefulness of the eIPSE approach, in general. While the tool support for defining the PPR-DSL and the integration and feedback of the entire toolchain should be improved, the syntax seems to be straightforward for members of the intended user group despite a steep learning curve. Furthermore, the variability models could be configured quickly and intuitively because they only required little guidance from the supervising authors. However, the feedback explicitly points out *low code approaches* as a potential aim for industry.

EQ2- Configuration Space Reduction Our results confirm our previous hypothesis [46] and indicate that reducing the configuration space for decision models improves the guidance for engineers during production process exploration for valid and feasible production process sequences (requirement R1). We also argue that the eIPSE approach provides better reproducibility of the CPPS configuration through logging the selection sequence in the Process DM configuration. Nevertheless, it requires additional effort to explicitly model more domain-specific knowledge, such as throughput, cost, or risk, *to evaluate and simulate particular process sequences.*

EQ3 - Generation of Control Artifacts The primary lesson learned was that the generated function block networks already present a working version of the control software for the configured CPPS. This shows that the integration of the variability models and their configuration works to a large extent (requirements R2, R4). Nevertheless,

the control software engineers still need to connect some process blocks manually. For instance, the control software engineers must adjust the connections represented in the generated IEC 61499 function block networks to follow the process configuration.

Secondly, the control software engineers need to manually connect the generated production resource instances to the particular processes that use them. We could improve that by further incorporating the Process DM configuration as a basis for automatically generating the Delta models.

Final Remarks The evaluation with the (i) application by engineers to existing and a novel case study, (ii) an investigation of the Process DM configuration space, and (iii) the successful creation of control code artifacts shows that eIPSE is applicable to realistic cases and demands. However, the approach also implies an additional overhead. In particular, this concerns the explicit definition of the PPR model in the PPR-DSL, which also took the evaluation subjects the most time in the evaluation. The additional overhead also concerns the development of the toolchain and its future refinement. Nevertheless, we argue that the latter is a one-time effort while the former addresses the challenges of *implicit domain knowledge* and *configuration reproducibility* more than counterbalancing the additional effort. Still, an in-depth investigation of the additional effort implied by the eIPSE approach compared to completely manually finding feasible production process sequences needs to be conducted.

7.2. Answering the Research Questions

This section answers our research questions (cf. Sec. 1).

RQ1 *How can CPPS engineers be supported in modeling, exploring, and configuring the combined variability of products, production processes, and production resources, to generate corresponding CPPS artifacts?*

To address this research question, this paper introduced the eIPSE approach. The approach aims at externalizing CPPS domain knowledge and the underlying variability by utilizing a domain-specific engineering artifact, i.e., the PPR-DSL, combined with two well-established variability models, i.e., FMs and DMs (cf. requirements **R1**, **R2**, and **R4** in Sec. 5.1). Furthermore, it aims to integrate the structural and behavioral variability of CPPS design aspects. It also provides defined feedback loops to proactively incorporate changes in requirements or design during CPPS engineering.

To this end, we go beyond the state-of-the-art [1, 18, 40, 44, 47] by providing a framework for externalizing domain expert knowledge, integrating the structural and behavioral variability of CPPSs and their configuration, including the separation of concerns of different engineering domains.

RQ2 *How and to what extent can CPPS design be automated using variability modeling and CPPS concepts?*

To address this research question, this work introduced the semi-automated eIPSE toolchain architecture supporting the modeling and configuration process of a CPPS' design based on a product configuration with a corresponding prototype. Therefore, we

- adapted the TRAVART transformation operations for production processes according to the new Process DM notation (cf. Fig. 4, Step 2b and **R2**),
- implemented TRAVART transformation operations for production resources (Step 2c and **R4**),
- implemented transformation operations for CDCs (Step 2d and **R5**),
- implemented the eIPSE DM Editor including the configuration space reduction of the Process DM (Steps 4 and 5), and
- adapted V4rdiac to integrate the transformed CDCs and included a pre-configuration step to read the configurations of the three variability models and generate CPPS implementation artifacts (Steps 6 to 8)

Thus, we go beyond the state-of-the-art by providing an integrated semi-automated toolchain for modeling and configuring the multidisciplinary structural and behavioral variability of CPPSs [14, 44, 47]. Additionally, we adapted the DOPLER DM [9] constraints so that they are solvable via standard SAT solvers, such as sat4j, and provided a DM editor not limited to the CPPS domain. To this end, we enable the transformation between the PPR model and state-of-the-art variability model types [22, 24] integrating them into the *de facto* standard tool FeatureIDE [43] for further dissemination. Furthermore, we go beyond the state of the practice of the manual approach of engineering CPPS design also opening the way for better reuse of CPPS concepts.

Finally, we will discuss our work with industry partners to assess its practical impact. Therefore, we will investigate which concepts can already be implemented and what needs to be altered or adapted. Additionally, we will examine which parts of the prototype need to gain a higher technology readiness level for practical use. We argue that our approach can start a discussion on variability modeling and configuration in CPPS engineering and that the tools provide a solid foundation for future use.

7.3. Prototype Limitations

The Process DM and eIPSE DM editor currently only support Boolean decisions rather than a broader range of decision types defined by the DOPLER approach [9]. However, unlike the closed source DOPLER approach, our constraint definition syntax is SAT-solvable and thus usable with state-of-the-art software such as FeatureIDE. Integrating the multiple tools into the eIPSE toolchain still has room for improvement. For instance, aligning the syntax of the constraint definitions may be investigated.

7.4. Threats To Validity

One threat to validity is that *several authors of the paper were involved in steps of the evaluation*. We tried to mitigate this threat by closely sticking to the provided engineering artifacts for the case studies and, where possible, gathering feedback from the engineers that provided the case studies. For the user study of the eIPSE toolchain, we involved five external subjects.

Due to its unstructured nature, another threat concerns the hard-to-measure *effort of the traditional manual approach*. The eIPSE approach mainly targets the automation of manual undocumented steps for CPPS engineering in alignment with the VDI 3695 [67].

Additionally, measuring the “time spent” for certain tasks might not be the best metric. However, in alignment with the VDI 3695 [67], we argue that the engineering time is a significant factor that should be elicited and optimized. Furthermore, it at least shows how fast relatively complex tasks can be completed with the eIPSE toolchain and certainly demonstrates that with the approach one would be faster than doing it manually. We try to demonstrate users’ experiences by presenting their feedback.

Finally, the evaluation of *the approach’s feasibility was conducted only for a limited set of case studies* of comparable size. Furthermore, the evaluation of *the approach’s usefulness was conducted only for a single case study* and with a *small number of engineers*. Therefore, it is unclear how our approach would perform for systems of larger size and complexity. This may threaten the generalizability of the eIPSE approach. However, especially DMs in literature are smaller than the DMs created by our approach [61]. Consequently, our case studies, at least concerning the DMs, go beyond the state of the art.

8. Related Work

This section presents approaches related to the eIPSE and work on variability modeling for CPPS.

Safdar et al. [56] created a framework for supporting product configuration in the CPSs domain based on their evaluation of existing variability modeling approaches [57]. The framework mainly uses UML and OCL constraints for expressing CPS commonality and variability. The framework is also designed to support automated multi-stage and multi-level product configuration.

Fang [17] developed a multi-view modeling approach for expressing variability in manufacturing. Variability is expressed in three different views: (1) software, (2) production process, and (3) plants’ topology. The approach combines a feature meta-model with a topology and process meta-model to define a relation between variability from different views. Using this meta-model, one can create a topology and process models that are related to a FM when expressing variability in the manufacturing domain. At a later step, one can derive a customer-specific topology and process model that complies with the features selected from the FM.

Fadhilillah et al. [14] developed V4rdiac as a multi-disciplinary variability management approach for CPPSs. V4rdiac is designed as a generic approach where CPPS engineers can use any types of variability model to express CPPS control software. CPPS engineers still need to decide which variability model best suits their domain. We use V4rdiac to showcase how our approach can be used to generate CPPS control software artifacts.

Existing works also use multiple FMs to model CPS system variability from different views or perspectives [26, 39, 54, 5, 28] in the machine manufacturing, industrial automation domain, and deployment of IoT application. They use cross-tree constraints or cross-model constraints to define the relation of features in the same or from different FMs. Expressing variability for industrial and complex software using multiple variability models is more beneficial in terms of maintainability and scalability compared to using a single variability model [8, 38, 52]. However, managing multi-view variability modeling, especially using heterogeneous types of variability models, is still a challenge [41].

In contrast to existing works, our work expresses CPPS product, production process, and production resource variability. We use the PPR-DSL for expressing CPPS variability based on a modeling concept that CPPS engineers are already familiar with. The PPR-DSL offers a unified syntax for expressing product, production process, and production resource variability as well as dependencies among them. Additionally, we can transform our PPR-DSL into a Product FM, a Process DM, and a Resource FM to enable reasoning and configuration of a CPPS using existing product line tools (e.g., FeatureIDE). Additionally, production resources in our PPR-DSL can be related to CPPS artifacts (e.g., IEC 61499 control software). Thus, we provide a product configuration mechanism where we can generate customer-specific variants that conform to the selected product, production process, and production resource variants.

9. Conclusion and Outlook

This paper introduced the Extended Iterative Process Sequence Exploration (eIPSE) approach to decrease the manual and unstructured efforts while facilitating reproducibility in Cyber-Physical Production System (CPPS) engineering. On top of our previous work [20, 25, 46, 49], we contributed (i) the eIPSE approach with additional steps to transform and configure production resource definitions and control software artifact generation, (ii) an extended prototype which realized the eIPSE approach (including a novel Decision Model (DM) editor and configuration of SAT solvable DMs). We provide the corresponding artifacts in additional online material¹ and a demonstration video⁶. Furthermore, to investigate how the approach performs in practical settings, we: (i) conducted an evaluation of the feasibility in four published CPPS case studies [45], (ii) conducted an observational user study with users inexperienced in the eIPSE approach and a novel case study, (iii) investigated the reduction of the CPPS configuration space, and (iv) examined the generation of IEC 61499 [34] control software artifacts.

In this way, we go beyond the state-of-the-art [14, 40, 44, 47] by providing a framework and semi-automated toolchain for CPPS variability modeling. This framework allows CPPS engineers to externalize better their domain expert knowledge, which comes primarily from experience and

undocumented dependencies. Furthermore, the approach enables engineers to model and configure the multidisciplinary structural and behavioral variability of CPPSs while separating the concerns of the different engineering disciplines. Beyond that, the production process sequence exploration fosters reproducibility by recording the exploration steps in the toolchain. To evaluate the eIPSE approach, we collected the first feedback on the eIPSE approach from users from different domains who perceived the approach and toolchain as useful and recommended improvements for future work.

In future work, we aim to broaden the approach's applicability and perform further evaluation, initiating the next iteration cycle of Design Science. On the one hand, currently, the prototypes only support Boolean decisions, which may limit their usability in large industrial settings. When integrating advanced solvers, like SMTs, we plan also to support Non-Boolean decisions. On the other hand, the Product-Process-Resource Domain-Specific Language (PPR-DSL) may be improved in terms of editor support and by decoupling the processes from the production resources. Describing the overall CPPS variability may involve heterogeneous multi-view variability models for expressing the variability of different organizational units (e.g., business department, electrical engineering, or signal engineering). Thus, we also plan to extend further our eIPSE tool for creating a product configuration tool capable of enacting configuration options from heterogeneous multi-view variability models. Given this setup, we plan to conduct a large-scale evaluation with external practitioners from the CPPS domain to examine the feasibility of the eIPSE approach.

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A. Chess Piece User Study

This section describes the user study for evaluating the eIPSE approach.

A.1. Introduction

We report the user study of the evaluation of the eIPSE toolchain. We investigate the modeling of an industrial product line and the subsequent production process exploration and production resource artifact derivation for a real-world *chess piece* product line designed at TU Wien Pilotfabrik¹⁷. Users assessed should go through the eIPSE process and evaluate the feasibility and usability of the approach and the tools.

We undertook the evaluation reported here as part of a collaboration between different academic and industrial initiatives. The subjects conducting the user study are, on the one hand, computer scientists and, on the other hand, engineers from companies that design or operate CPPSs.

A.2. Rationale

The user study of the eIPSE evaluation was carried out in the focus of this paper and as part of three of the authors' dissertation projects. The research scope is to investigate variability modeling for CPPSs engineering and the required transformation of industrial artifacts to well-established variability models. The research in this context focuses on the reproducible exploration of production process sequences based on an integrated variability modeling approach. This variability modeling approach uses different types of variability models, i.e., feature models and decision models, to separate the concerns of the different stakeholders. There is limited published research on adopting state-of-the-art variability modeling and configuration approaches in the CPPS engineering industry, and the user study sought to contribute to the body of research in this area.

A.3. Objective

The user study took place in an academic setting, which is also the primary audience for the user study. The overall objectives were as follows.

- To perform a eIPSE toolchain evaluation in a setting with subjects from different domains with the focus on CPPS engineering using a formal evaluation methodology.
- To learn from the evaluation about the following:
 - Can engineers model the functional view of CPPS for a small industrial product line with its products, process steps, and resources (domain engineering).
 - Can engineers efficiently explore and configure the design space for products, process sequences, and resources.

- Does the integration of feature models and decision models allow for the configuration of a reasonable process sequence and corresponding resources based on a product configuration.
- The time spent to model the functional view of CPPS for a small industrial product line (domain engineering).
- The time spent to configure a CPPS design variant (application engineering).
- The perceived usefulness of the eIPSE approach and toolchain for the engineers.
- The lessons learned from using the eIPSE approach and toolchain for industrial product line modeling and configuration.

- To learn from the usage of eIPSE approach and toolchain.

These objectives are decidedly broad and ambitious. For conciseness, this chapter focuses on the objectives of learning from the evaluation about the time spent, the perceived usefulness, and the lessons learned.

A.4. Chess Piece Use Case

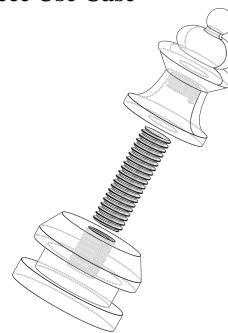


Figure 10: CAD drawing of a pawn chess piece

For the evaluation, we consider the *chess piece* use case from TU Pilotfabrik. The use case concerns a CPPS that manufactures the six chess piece types, i.e., king, queen, bishops, knights, rooks, and pawns. Figure 10 shows a CAD drawing of the pawn chess piece.

Each chess piece consists of a *base*, a *body*, and a threaded *rod* that connects them.

The *base* is produced from *aluminum bars* of 1m length on a *turning machine*. The *aluminum bar* is loaded into the *turning machine* with a *bar loader*. The *turning machine* cuts the *aluminum bar* into the raw *bases* of suitable length for further processing. These *bases*, which come in two variants, are *turned* on the *turning machine* to get their specific shape. The king and the queen have a base with *two circumferential reamings* that are *carved into the aluminum*. The other chess pieces have a base that has *one circumferential reaming*. After creation, a *laser profiler* measures the bases for turning accuracy.

¹⁷TU Wien Pilotfabrik. <https://www.pilotfabrik.at/>

The *body* of the particular chess pieces is *3D-printed* from Polyactic Acid (PLA) on an industrial *3D printer*.

The *base* and the *body* each have a hole with a thread carved respectively printed in the middle. The threads each have a diameter for a standardized M6 *rod*.¹⁸ Similarly to the base, the threaded *rod* comes in two variants, one with *20 millimeters* and one with *30 millimeters* in length.

The *base*, the *body*, and the threaded *rod* are assembled in an *assembly station*, where each individual part needs to be loaded into the station. The parts need to be *screwed* together, which can be done in an arbitrary sequence.

A.5. Subject Guideline

Conduct the eIPSE process, as described in Section 5, for the chess piece use case for an imaginative CPPS.

Chess piece product line modeling This task represents *Step 1* of the eIPSE approach in Figure 4. As a user, create a functional PPR–DSL model of the chess piece product line in the Sublime text editor. Use the provided cheat sheet for the syntax of the PPR–DSL. The model shall represent three parts, which are (i) the partial and final products that should be manufactured by the CPPS, (ii) the atomic process steps that create the products with their required input products, predecessors, and resources, as well as (iii) the production resources that can execute a particular process required to manufacture a product.

Products For the chess piece use case, create partial products and final products in the PPR–DSL. Find out which partial products you could group using abstract parent products. Furthermore, define which of the partial products *exclude* each other because a similar partial product more or less supplements them.

Processes As a user, think about how to assemble partial products via specific atomic “manufacturing” processes. Realize these atomic process steps in the PPR–DSL and, similar to the products, group them on their abstract products and *exclude* process steps that you deem unnecessary. Furthermore, consider which process steps in a particular assembly process need to be direct predecessors and refer to them as needed in the required section.

Resources As a user, model the resources similar to products. For modeling them, you should apply similar rules as for the product variability model.

Model Transformation This task represents *Step 2* of the eIPSE approach in Figure 4. Use TRAVART from the Iterative Process Sequence Exploration (IPSE) toolchain from the command line to transform the chess piece PPR–DSL model to the product and resource feature model (*uv1* file extension) and the process decision model (*dmodel* file extension).

Iterative Process Exploration This task represents *Steps 3 to 5* of the eIPSE approach in Figure 4. Configure a desired product of the chess piece product line, i.e., one of the six

chess piece types, using the configurator for feature models in Eclipse (*Step 3* in Figure 4) by ticking the checkboxes for the features. Then, generate a reduced *decision model configuration* (*dconfig* file extension) by right-clicking on the decision model and selecting the configuration file of the previously configured product (*xml* file ending) (*Step 4* in Figure 4). Open the decision model configuration file in the *decision model configurator* and explore feasible production process sequences for the configured chess piece by ticking the decision checkboxes (*Step 5* in Figure 4). Therefore, you can investigate the process sequence in the right pane of the decision model configurator.

Resource configuration and artifact generation This task represents *Steps 6 to 8* of the eIPSE approach in Figure 4. Use the delta models (*delta* file extension) that are prepared according to the features or decisions in product *feature model*, process *decision model*, and resource *feature model* that might affect the control source code of the CPPS. Additionally, use the prepared delta configuration file (*deltaconf* file extension) in Variability for 4diac (V4rdiac) to map the delta models into its corresponding feature or decision. Then, use V4rdiac to load the previously configured product and production processes sequence and configure the desired resources. You can generate the control source code for the CPPS according to the selected features or decisions after the configuration is finished.

A.6. Study Protocol

No formal study protocol was developed or maintained for the user study.

A.7. Evaluation Questions

We formulated the following questions for the evaluation.

- Is it feasible to apply the eIPSE approach?
 - in different scenarios
 - by novices from heterogeneous backgrounds

A.8. Methods of Data Collection

We used *shadowing* [63] to investigate the subjects during performing the eIPSE approach on the *chess piece* use case. Due to the distributed locations of the subjects performing the evaluation, we used Zoom to connect them to the eIPSE toolchain and provided them with remote control. At least two of the authors shadowed the subjects during the evaluation sessions. One author helped the evaluation subject if questions arose, additional explanations were required, or the subjects were stuck in the process. The other authors present took notes for later investigation. Furthermore, one author stopped the time for each of the activities and steps of the evaluation process. Additionally, we recorded the evaluation sessions to replay them later during the internal result analysis. Afterward, we asked the subjects about the perceived usefulness of the toolchain and the lessons learned during the process.

¹⁸ISO metric screw threads: https://w.wiki/_wm23

A.9. Methods of Data Analysis

No particular strategy for coding the notes taken was used. We extracted quotes from the notes that concerns the perceived usefulness and could lead to improvements of the approach and the toolchain.

A.10. Case Selection Strategy

The case itself was selected on the basis that its main feature, i.e., the chess pieces, are well known by most people. Furthermore, the production of the chess pieces seems lucid enough for engineers of different domains to be manageable. To this end, it should be straightforward to understand how the possible production process could be modeled. Yet, the case appears to be complex enough to properly investigate the problem of the large configuration space.

A.11. Data Selection Strategy

The strategy for selecting data was driven primarily by the activities defined in the subject guideline.

A.12. Replication Strategy

There was no strategy for replication on the basis that there was no comparable evaluation previously conducted or even comparable evaluations of other technologies. We aim that future case studies of the evaluation of the eIPSE approach adopt the here described description for partial replication.

A.13. Quality Assurance

To help ensure that data collected were representative of a broad range of stakeholders in the domain of CPPS engineering, we selected engineers and stakeholders from different companies and domains.

A.14. Data Collection

We used *shadowing* [63] with X participants to investigate the subjects during performing the eIPSE approach on the *chess piece* use case. Due to the distributed locations of the subjects performing the evaluation, we used Zoom to connect them to the eIPSE toolchain and provided them with remote control. At least two of the authors shadowed the subjects during the evaluation sessions. One author helped the evaluation subject if questions arose, additional explanations were required, or the subjects were stuck in the process. The other authors present took notes for later investigation. Furthermore, one author stopped the time for each of the activities and steps of the evaluation process. Additionally, we recorded the evaluation sessions to replay them later during the internal result analysis. Afterward, we asked the subjects about the perceived usefulness of the toolchain and the lessons learned during the process.

CRedit authorship contribution statement

Kristof Meixner: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - Original draft preparation, Writing - review & editing.

Kevin Feichtinger: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - Original draft preparation, Writing - review & editing. **Hafiyyan Sayyid Fadhilillah:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - Original draft preparation, Writing - review & editing. **Sandra Greiner:** Conceptualization, Formal analysis, Investigation, Methodology, Writing - Original draft preparation, Validation, Writing - Original draft preparation, Writing - review & editing. **Hannes Marcher:** Software, Writing - Original draft preparation. **Rick Rabiser:** Conceptualization, Funding acquisition, Resources, Writing - Original draft preparation, Writing - review & editing. **Stefan Biffl:** Conceptualization, Funding acquisition, Resources.

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Highlights:

- The eIPSE approach for configuring products, processes, and resources of a new CPPS.
- An automated reduction of production process options using a product configuration.
- An implementation prototype for the eIPSE approach.
- Automatic generation of control code using using a CPPS configuration via V4rdiac.
- An empirical evaluation of the feasibility and application of the eIPSE approach.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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