Methods

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Organizing reuse for production systems engineering with capabilities and skills

Organisation der Wiederverwendung im Engineering von Produktionsystemen mit Capabilities und Skills

Adapting the VDI 3695 procedure model to reuse with capabilities and skills
Eine Anpassung des VDI 3695 Vorgehensmodells für Wiederverwendung mit Capabilities und Skills

Abstract: The flexibility of production systems is a key factor for Industry 4.0. *Capabilities and skills (C&Ss)* aim at improving engineering flexibility along the production system life-cycle by decoupling production processes and resources. However, traditional reuse approaches in production systems engineering, such as the VDI 3695, do not yet consider C&Ss. This paper proposes the *Capability and Skill Reuse (CSR)* framework to define how VDI 3695 activities require adaptation for C&S models. The paper analyzes how the framework can facilitate reuse along the production system life-cycle and identifies open issues for research.

Zusammenfassung: Die Flexibilität von Produktionssystemen ist ein wesentlicher Faktor für Industrie 4.0. *Capabilities und skills (C&Ss)* bezwecken die Flexibilität entlang des Lebenszyklus von Produktionssystemen zu verbessern, indem sie helfen Produktionsprozesse und -ressourcen zu entkoppeln. Traditionelle Wiederverwendungsansätze im Engineering, wie die VDI 3695, berücksichtigen C&Ss jedoch noch nicht. Dieser Beitrag schlägt das *Capability und Skill Reuse (CSR)* Rahmenwerk vor, um zu definieren, wie VDI 3695-Aktivitäten für C&S-Modelle Angepassungen erfordern. Der Beitrag analysiert, wie das Rahmenwerk die Wiederverwendung entlang des Lebenszyklus' von Produktionssystemen erleichtern kann und identifiziert offene Fragen für die Forschung.

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1 Introduction

Key factors for the Industry 4.0 transformation are the flexibility and adaptability of production systems to manufacture a range of products from a product portfolio [1, 2]. Further, the Industry 4.0 vision concerns connecting single production systems to production networks for enabling production as a service (PaaS).

An established approach to model the functionality of a system in Production Systems Engineering (PSE) is the *Product-Process-Resource (PPR)* approach [3] representing products, production processes, and the necessary production resources. However, in PSE practice, production

processes and resources, and their models, are often tightly coupled, impeding production flexibility. Complementing the PPR approach, *capabilities and skills (C&Ss)* aim to support flexibility along the production system life-cycle by decoupling and abstracting production processes and their requirements from the production resources that execute these processes [4]. For instance, recent research proposed formal and machine-readable C&S descriptions, e.g., using ontologies, to overcome tacit expert knowledge [5, 6]. Such semantic descriptions also aim at an automated matching of production process requirements to resources, easing PSE and lowering manual work that is prone to error [7]. Further works investigated the automated derivation of capability descriptions along with executable skills [8]. Machine-readable capability and skill (C&S) descriptions combined with automated matching and decoupled executable production services should facilitate the required flexibility and creation of production networks.

A crucial prerequisite for efficient and high-quality PSE and operation is the systematic reuse of engineering artifacts, such as resources with their models and reference sheets. Systematic reuse promises to reduce engineering cost and time to market, lower maintenance effort and improve the quality of products [9]. Jazdi et al. [10] investigated the *project-independent activities (PIAs)* of VDI 3695 [11] to improve the efficiency of PSE by increasing artifact reusability. The same applies to C&Ss, where *reusability* and *reuse* were identified in a recent literature survey as both a requirement for and a benefit of using C&Ss [4]. This especially holds in distributed environments, such as PaaS.

However, to the best of our knowledge, the elicitation of C&Ss from existing engineering artifacts, such as PPR models, for their systematic reuse has not been reported. Therefore, we aim in this paper to address the research question: *How do VDI 3695 activities for domain and application engineering require adaptation to facilitate reuse with capabilities and skills in PSE?*

To address this research question in this work, we provide the following contributions. We categorize requirements towards C&Ss from a recent literature survey [4] and investigate how these requirements need to be considered to facilitate C&S-based reuse. We propose the *Capability and Skill Reuse (CSR) framework* for the elicitation of C&Ss from engineering models and artifacts and their reuse. Therefore, we describe how the VDI 3695 reuse activities for domain and application engineering in PSE require adaptation to enable C&S-based reuse. Further, we discuss the benefits and limitations of C&S models as a foundation to facilitate reuse along the production system life-cycle.

The remainder of the paper is structured as follows. Section 2 describes the background and related work on knowledge representation and reuse in PSE. Section 3 categorizes requirements towards C&S and introduces the Capability and Skill Reuse (CSR) framework for the reuse of production system models and artifacts. Sections 4 and 5 discuss the research results and conclude.

2 Background

This section summarizes the background and related work and sketches an illustrative use case.

2.1 Knowledge representation in PSE

PSE consists of several life-cycle phases, from basic and detailed planning to commissioning and operation. Additionally, PSE takes place in a multidisciplinary environment, where engineers from various domains, such as mechanical or electrical engineering, maintain different views on the production system [12]. The PPR approach [3] unifies three main aspects of PSE. The model represents input and output **p**roducts, production **p**rocesses required to transform input into output products, and production **r**esources that automate the production processes. The Formal Process Description (FPD), defined in the VDI 3682 [13], provides a visual and formal model to describe these aspects.

Pfrommer et al. [14] introduced *skills* as a complementary element to PPR. They defined *skills* as semantic, vendor-independent representations of process functionality *required by a product* and *provided by a resource*. Keddis et al. [15] distinguished *required capabilities*, defined in production step plans, from *provided capabilities*, implemented by resources. While a recent literature survey found early literature on C&S to use the concepts interchangeably [4], later works distinguished more clearly between C&S. Nevertheless, both concepts aim to abstract and decouple processes and resources for more flexible production.

Several works proposed models for C&S, including their relations to PPR, and formal machine-readable specification, e.g., via ontologies [5, 16, 17]. Järvenpää et al. [7] investigated how formally described resource capabilities can be automatically matched to product requirements. Furthermore, recent research studied the automated derivation and execution of skills, e.g., via OPC UA [8, 18].

This paper builds on the PPR and C&S concepts, in particular, on the definitions and the model of C&S described in [19]. In their model, capabilities are implementation-independent specifications of functions in industrial

production. While production resources can provide such capabilities, production processes can require them, encapsulating the product requirements. On the other hand, skills are executable implementations of capabilities on a resource (cf. Figure 1), where several skills might realize a capability.

2.2 Knowledge reuse in PSE

Jazdi et al. [10] investigated how PSE efficiency can be increased by identifying reusable engineering artifacts and systematically using them extensively in upcoming engineering projects. Their work is based on the VDI 3695 procedure model for project activities [11] and the *two-life-cycle model* from Software Product Line Engineering (SPLE) [9].

The VDI 3695 [11] for optimizing engineering organizations describes a *two-phase procedure model*. The model consists of *project-independent activities (PIAs)* to identify and provide reusable artifacts and *project-dependent activities (PDAs)* that use these artifacts (cf. Figure 2). The PIAs for domain engineering consist of (i) an *analysis* of the domain and artifacts suited for reuse, (ii) the *planning* of a reference architecture and reusable artifacts, and (iii) the *realization* and *testing* of reusable artifacts. Jazdi et al. [10] translate these activities into detailed tasks for PSE. The VDI 3695 specifies five target states of reuse maturity in PSE that range from isolated reuse by single engineers to reuse with reference models and standards. The *PDAs* for application engineering consist of (i) the *acquisition* and requirements engineering of new PSE projects, (ii) the *planning* and *realization* of a production system or production services using the reference architecture and reusable artifacts, and (iii) *commissioning* of the realized system and services. Ideally, requirements, acquired knowledge, and

artifacts from the individual projects are inputs to the PIAs (cf. Figure 2, dashed arrow).

Similarly, *SPLE* investigates the reuse, flexibility, and configuration of software portfolios and their engineering [20]. Therefore, van der Linden et al. [9] identified the four fundamental principles of *variability management*, *business-centric* and *architecture-centric* engineering, and the *two-life-cycle* approach. The *two-life-cycle* approach describes *domain engineering* and *application engineering*, similar to PIAs and PDAs of the VDI 3695 [11]. The reusable artifacts are stored in a *common artifact repository* (cf. Figure 2) for use in the PDAs. SPLE also investigated models and methods to represent and manage variability in artifacts and their configuration. Two SPLE approaches to model and configure variability, also mentioned by Jazdi et al. [10], are *feature modeling* and *decision modeling* [20].

A recent survey [4] elicited expected *requirements* towards C&S and *benefits* of C&S in PSE. The survey reported *reusability* both as a requirement to enable C&S-based PSE and as a benefit as C&Ss foster *reuse* of knowledge. However, to the best of our knowledge, very little work on the systematic reuse of C&S in PSE has been reported. Therefore, this paper investigates the reuse in and for C&S-based PSE, in particular, the elicitation and abstraction of C&Ss from engineering artifacts, such as PPR models.

2.3 Illustrative use case

To illustrate the CSR framework, this section reports on a use case abstracted from real-world applications. These applications stem from engineering organizations of high-performance automation for car part manufacturing in Germany and Austria [21]. In particular, we consider *joining processes* of large car parts, such as doors, to car bodies.

In the use case, we consider a system integrator which, for particular customers, plans and engineers work line production systems that manufacture a portfolio of car parts automated in typical car production plants. The plant operators should be able to offer their production services in a marketplace in the future, aiming at PaaS. Therefore, the system integrator wants to reuse existing well-described engineering artifacts, such as robot cell models, for various company-wide projects. To this end, the solution candidates should be decoupled from specific product and production process requirements of previous projects.

Figure 1 shows a section of a PPR model in VDI 3682 notation [13] with the products (represented as circles in a blue frame), e.g., the door, one process step (depicted
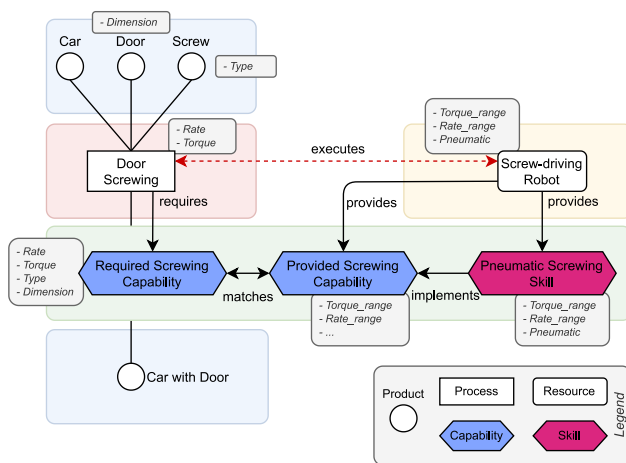
Figure 1: PPR model for a *screwing process* in VDI 3682 [13] notation *without* (dashed connection *executes*) and *with* C&Ss.
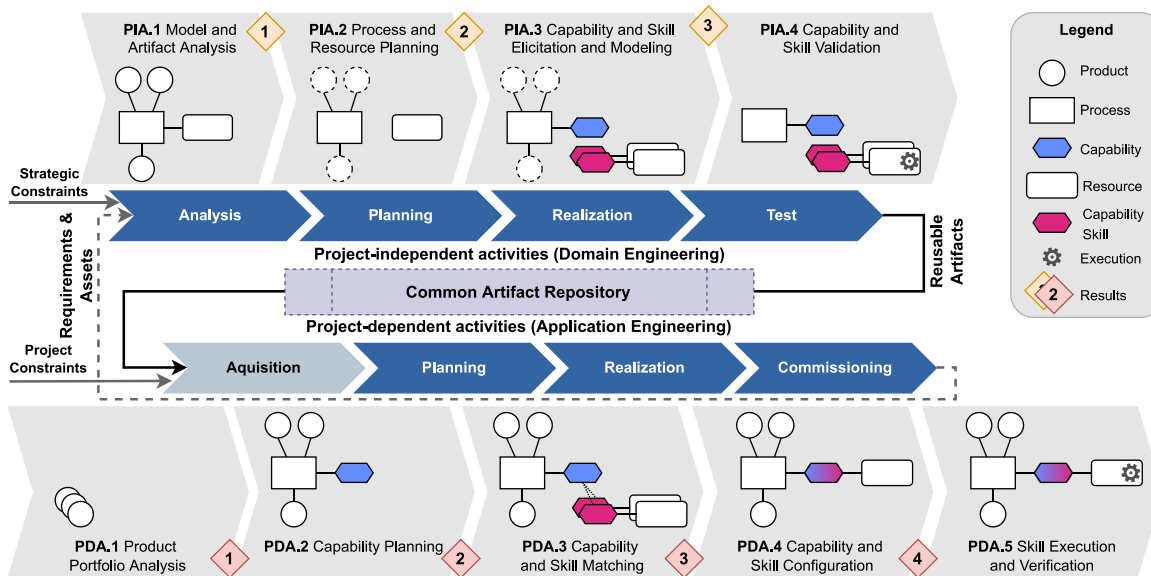
Figure 2: The *Capability and Skill Reuse (CSR) framework* for PPR models and artifacts, based on the *VDI 3695* guideline [11].

as a rectangle in a red frame), i.e., the door screwing process, and a resource (shown as a rounded rectangle in a yellow frame), i.e., the screw-driving robot. A corresponding engineering artifact can be, e.g., the model in the Product-Process-Resource Domain-Specific Language (PPR–DSL) [22].

In the use case, the door is mounted to a car body with screws. The screws have different types depending on the doors, which have different dimensions. The processes have technical and economic requirements, such as the required torque or the production rate. Furthermore, the processes need to consider the characteristics of the products, i.e., the torque and dimension. The screw-driving robot has several characteristics, such as torque or rate range, required for correct process execution. While some of these characteristics are similar in the assembly line, others are variants of originating processes and resources.

Traditional PSE and reuse [10, 23] often maintain a quite resource-centered perspective, where processes are modeled only as part of the resource and its behavior (cf. dashed red arrow in Figure 1).

In C&S-based PSE, the process requirements are modeled as *required capabilities*, e.g., a *screwing capability* (cf. Figure 1) or even more abstract a *joining capability*. However, some characteristics, such as electric or pneumatic screwing, might be irrelevant to the production processes. Resources, such as screw-driving robots, on the other hand, provide the means to execute a functionality, in this case, to join two parts, respectively, screw them together. In C&S-based PSE, the functionalities of resources are

modeled as *provided capabilities* and implemented as, e.g., *skills* [19]. This way, the required and provided capabilities can be matched, e.g., in the engineering phase or on a marketplace.

3 The CSR framework for reuse with capabilities and skills

This section categorizes requirements for C&Ss regarding their relevance for reuse and presents the *Capability and Skill Reuse (CSR)* framework.

3.1 Requirements towards capability- and skill-based engineering and reuse

Froschauer et al. [4] elicited requirements towards C&Ss in a literature survey. We categorize these requirements to identify which of them are particularly relevant in what reuse activity of the CSR framework. In Table 1, we introduce four categories and assign each requirement to one of them.[1] In the next section, we use this categorization to highlight the relevance of the particular requirements in the activities of the CSR framework.

The first category concerns the *description of capabilities* to support their interpretation by machines and humans, exchange, and ideally openness [24]. Therefore, capability descriptions shall be *formal* and *vendor-neutral*.

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1 Note that the requirement *reusability* in [4] is not part of this categorization due to the overall focus of this paper on reuse.

Table 1: Categorized *requirements* for *capabilities and skills*.

Category	Requirements
Capability description	Vendor-neutral
	Formal
Capability and skill selection	Identifiable
	Classifiable
	(Auto-)discoverable
	Matchable
Skill implementation time	(Re-)configurable/Adaptable
	Modular
	Extensible
Skill run time	Executable
	Stateful/deterministic
	Scalable
	Communication interface

To facilitate the *selection of C&Ss*, i.e., the appropriate selection of C&Ss for a purpose, during the PSE life-cycle, they shall be (i) *identifiable*[2] for reliable distinction (ii) *classifiable* to categorize C&Ss according to well-known PSE semantics, e.g., the DIN 8580 [25], (iii) *matchable* to automatically find suitable production resources for production requirements, and (iv) *discoverable* to find production services in a distributed environment, e.g., on a marketplace.

Skills encapsulate the functionality of a production resource implementing a particular capability. Therefore, they need to fulfill requirements at implementation and at run time. During the *implementation time of a skill*, engineers need to consider the following requirements with the aim of flexibility and usage variability. A skill should be (i) *configurable* respectively *adaptable*, to choose from their internal variations [9], (ii) *modular* to combine them to higher-level functionality, and (iii) *extensible* to adapt them for future purposes.

At production system *run time*, skills shall be (i) *executable* to run directly on a resource, (ii) *stateful* respectively *deterministic* for reproducibility and to know their current state, (iii) *scalable* to deploy them to many similar resources and handle growing production requests, and (iv) provide a *communication interface* to control their behavior.

[2] For instance, the RFC 2396 URI syntax provides a scheme for identifiable assets – https://www.rfc-editor.org/rfc/rfc2396.

3.2 Activities for capability- and skill-based reuse of PPR artifacts

This section introduces the *Capability and Skill Reuse (CSR)* framework for reuse in PSE with C&Ss. Figure 2 shows the *PIAs* and *PDAs* of the VDI 3695 procedure model [11]. This paper focuses on the activities depicted in blue, i.e., the core activities of domain and application engineering [9] without considering *acquisition*. Between the PIAs and PDAs, Figure 2 further shows the *common artifact repository* to store reusable artifacts. Furthermore, the figure shows the iterative character of the framework as backflow from the PDAs to the PIAs. As a novelty, Figure 2 highlights the activities for engineering with C&Ss based on reusable PPR artifacts (areas in grey).

The first four activities of the CSR framework concern the **PIAs** of the VDI 3695 procedure model for domain engineering.

PIA.1 – Model and artifact analysis. This activity maps to the *analysis* PIA of the VDI 3695.

In this activity, engineers responsible for company-wide reuse analyze the domain and its requirements. The result is a reference model for the domain, such as the system architecture for a work line in car manufacturing. This reference model can specify common requirements but also technical solution elements for the PDAs. Furthermore, the engineers analyze existing artifacts, like PPR models in PPR–DSL [22], from previous projects to assess their reuse potential. The analysis aims to find and document artifacts that have been used in several projects and that engineers can adapt for more generic use. In the context of the use case (cf. Section 2.3), such artifacts could be PPR models of screwing processes with parameters in a similar range, like the *torque* or *workpiece dimensions*.

In the **traditional approach**, the engineers often do not differentiate between the products, processes, and resources in the analysis. For instance, engineers analyzed and collected resources for reuse in future projects at one company from the use case but mixed them with concrete products rather than, e.g., more generic dimensions. While such an analysis is efficient for local engineering, it makes reuse beyond local environments riskier and less efficient.

In the **CSR framework**, the reuse engineers pursue two goals to find and document reuse candidates. First, they identify processes in the artifacts independent of the products and resources they use, e.g., the screwing process. Based on that, more generic process characteristics can be derived in the next activity. The overall goal is to identify process candidates that seem relevant for *required capability* descriptions (cf. Figure 1). Second, the engineers identify resources in the artifacts that seem promising

for reuse, e.g., the screw-driving robot. For instance, one company in our use case maintains a database of regularly used resources with particular characteristics, such as power consumption. In another company, a domain analysis showed that the types of screw-driving robots could be reduced by grouping them by their functionality [21]. The overall goal is to identify functionality candidates that seem relevant as input to describe the functionalities of these resources as *provided capabilities* and implement them as *skills*.

The **result of the analysis** (cf. Figure 2 yellow diamond 1) is a *reference model* for the domain, e.g., for joining work lines, and a *documentation* of (partial) PPR artifacts identified as processes or resources. This reference model and the documentation are the inputs for activity PIA.2.

PIA.2 – Process and resource planning. This activity maps to the *planning* PIA of the VDI 3695.

In this activity, the engineers define the utilization of the assets from the analyzed PPR artifacts, e.g., usage as reference assets or parameterized assets in future projects. Therefore, the engineers need to generalize and categorize the assets and plan their parameterization, i.e., assess their variability and configuration options.

In the use case, we consider the PPR model of the door screwing process. First, the PPR artifacts might need to be split to single out the section with the screwing process. Then, the engineers need to generalize the products as the products are most likely different in other projects. For instance, the type of screw used, e.g., with a specific inventory number, needs to be generalized to its relevant properties, e.g., slotted or Phillips head. Similarly, the door might be generalized to a workpiece with particular dimensions. Figure 1 illustrates this generalization of products as dashed outlines in activity PIA.2.

In the **traditional approach**, process and resource assets are often mixed or merged in the artifacts. For instance, the screw-driving robot might be modeled to directly manipulate the products, only implicitly representing a screwing process. Thus, artifacts resulting from this planning activity are less modular and decoupled and, hence, represent the requiring and provisioning side of production insufficiently.

In the **CSR approach**, the engineers decide which (parts of the) artifacts concern process capabilities, i.e., required, or resource capabilities, i.e., provided. If an artifact mixes process requirements and resource functionality, the engineers plan how to separate the process from the resource descriptions. In the use case, the PPR artifact requires splitting or remodeling to separate the

process and the resource, e.g., into different artifacts that can then be imported as libraries. The engineers must then categorize and group the processes and resources by similar requirements and functionality. This task can follow domain-specific guidelines, such as the DIN 8580[3] for manufacturing methods. For instance, screwing and welding processes can be part of a higher-level group of joining processes. Similarly, catalogs, such as company-specific taxonomies or databases or the *EClass* standard,[4] can help to categorize resources.

The **result of the planning activity** (cf. Figure 2 yellow diamond 2) are *separated and categorized processes (with generalized products) and resources*. These resulting artifacts are the input for activity PIA.3.

PIA.3 – Capability and skill elicitation and modelling. This activity maps to the PIAs *planning* and *realization* of the VDI 3695.

In this activity, domain engineers realize the reusable assets as PPR artifacts. For instance, they create templates from particular assets that can be parameterized and reused in different PSE projects.

In the **traditional approach**, such PPR template designs often consist of resources only that realize the functionality for the production of a product. Therefore, the resulting artifacts concern product and process requirements as well as the functionality of particular resources like robots. While this might make the configuration of such templates easier, it makes, e.g., the exchange of resources solely based on the required functionality harder [7].

In the **CSR framework**, the domain engineers elicit and model processes and their requirements as process capabilities. In several cases, the engineers might want to aggregate the found process requirements for an abstraction to higher-level groups, e.g., serving a range of parameter values [26]. Similarly, the engineers model the resource functionality as capabilities and potentially implement them as skills. Modeling the C&Ss requires using appropriate models or languages, such as ontologies [5, 17] or domain-specific languages [22]. For the skill implementations, engineers can utilize technologies, such as OPC UA [8, 18] or PackML.[5]

In the use case, we would model the screwing process as required capability, e.g., in a process ontology [5], with the required rate, torque, and screw type as configurable parameters. The screw-driving robot would be modeled

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3 DIN 8580 – https://standards.globalspec.com/std/1742169/DIN%208580.

4 EClass – https://eclass.eu/en/eclass-standard.

5 PackML – https://www.omac.org/packml.

as provided capability with its rate and torque range, i.e., the minimal and maximal values, e.g., 100 Nm to 200 Nm. Furthermore, the concrete functionality of the screw-driving robot would be implemented as a skill, e.g., with specific control software, that implements the provided capability.

The capabilities shall fulfill the *capability description* and *C&S selection* requirements (cf. Table 1) that are then relevant in the PDAs. Similarly, the skill implementations shall fulfill the *implementation time* requirements. While this is an extra effort in this step, fulfilling these requirements pays off in the project-dependent realization.

The **result of the realization** is modeled as C&Ss that are deployed into the common artifact repository using an agreed-on structure. Figure 2 illustrates these artifacts as processes with generalized products with their corresponding capabilities in blue and as resources with their corresponding capabilities (and skills) in magenta.

PIA.4 – Capability and skill validation. This activity maps to the *testing* PIA of the VDI 3695.

After modeling the capabilities and implementing the skills, the provided C&Ss must be tested and validated to qualify them for the production systems. This task should already be executed on physical resources, such as a testbed, indicated by the cog wheel in the resources.

Therefore, skills must fulfill the *run time* requirements. This means, they need to be *executable*, *stateful* and *deterministic*, and *scalable* [4]. Furthermore, they need to have a *communication interface* to control their behavior.

The artifacts resulting from the PIAs are stored in the common artifact repository for use in the PDAs.

The activities in the lower part of Figure 2 concern the project-dependent activity (PDA) of the VDI 3695 procedure model.

PDA.1 – Product portfolio analysis. This activity maps to the *planning* PDA of the VDI 3695 and is similar in the **traditional approach** and the **CSR framework**.

In this activity, application engineers analyze the product portfolio that the production system should manufacture. Therefore, they investigate its production requirements, such as quality concerns or the planned order quantity, based on input from the *acquisition* activity. Figure 2 shows a product portfolio as small product icons. For instance, in the use case, a range of different doors types shall be mounted to similar types of car bodies.

In the use case, the engineers analyze the doors and car bodies with their commonalities and variability. From this analysis, they can derive which products are similar enough to manufacture them on one production system, e.g., door type *A* and *B* with similar dimensions in a robot cell.

The **result of this analysis** shall be a *bill of materials* for the products with *corresponding variability and configuration models* [9]. In Figure 2 the red label 1 at the lower part represents the results that are input to PDA.2.

PDA.2 – Capability planning. This activity maps to the *planning* and *realization* PDAs of the VDI 3695.

In this activity, application engineers receive the production system requirements and the product portfolio analysis from PDA.1. From this data and the reference architecture from PIA.1, they derive a suitable production system architecture. Second, the application engineers define the requirements and the functionality for the products' single production steps. Therefore, they take up the analyzed product portfolio, investigate ways to assemble these products, and derive properties for the production steps. In the use case, the engineers decide, e.g., to mount the doors to the car body with screws of a certain type using a screwing process with a specific torque and rate.

In the **traditional approach**, the engineers often define a bill of processes and tie them to reusable resource templates from the common artifact repository. However, without adequate abstraction, this limits the exchange and reconfiguration of resources and impedes the search for adequate production services, e.g., in a production network.

In the **CSR framework**, the engineers take up the product portfolio description to plan the capabilities required to produce the products. In the use case, the engineers define that a door is screwed to the car body, e.g., with a Phillips and 150 Nm torque. Based on these requirements, the engineers search in the common artifact repository for process capabilities that fit their requirements, i.e., a screwing capability with configuration parameters for the screw head and the torque. Therefore, the capabilities have to fulfill the requirement categories *capability description* and *C&S selection* (cf. Table 1) to find suitable reusable capabilities in the common artifact repository.

In the second step, the engineers configure the retrieved capabilities with the known values of the products from the product portfolio. In the use case, this means configuring a screwing capability with, e.g., the required torque of 150 Nm ±5 Nm, and the required Phillips screw head. Modeling classes of parameter ranges can be helpful to support better matching to provided C&Ss in the next step.

Figure 2 illustrates the **resulting configured capability** as a PPR model with concrete products and a configured

process capability in blue. These configured capabilities (cf. red diamond 2 in Figure 2) are then inputs to PDA.3.

PDA.3 – Capability and skill matching. This activity maps to the *planning* and *realization* PDAs of the VDI 3695.

In this activity, the product requirements, expressed through process descriptions, must be matched and bound to concrete production resources. The resources must then be configured to execute the processes correctly.

In the **traditional approach**, the engineers manually match the process requirements to resources from the common artifact repository. This step is mainly based on implicit knowledge by a single key engineer. A major limitation of this approach is the need for experts with high domain knowledge suitable to conduct this task. Thus, this task is challenging, error-prone, hard to teach, and limited by the availability of these key experts.

In the **CSR framework** application engineers use computational support to match the partially configured process capabilities with resource capabilities. Therefore, the tooling environment shall enable to match C&S descriptions. The selection requires C&Ss to be (cf. Table 1) *identifiable* to find unique ones, *classifiable* to search for them systematically, *discoverable* to retrieve them from the common artifact repository, and *matchable* to assign them to the required process capabilities. Ontology reasoning is a promising approach to match C&Ss [7]. In the use case, we would set up, e.g., an ontology query that searches for provided capabilities with a torque range that includes the configured torque of 150 Nm. The result would be the previously described provided capability with a torque range from 100 Nm to 200 Nm. Similarly, other provide capabilities with torque ranges around 150 Nm could be returned. Furthermore, the engineers can now select from different skills that implement these capabilities, e.g., based on robots that they regularly use in their projects.

The **results of this step** are matched required and provided capabilities (cf. red label 3 Figure 2) that are input to *PDA.4*. Figure 2 depicts the icon of the processes with concrete products and their required capabilities that are matched to one or more capabilities.

PDA.4 – Capability and skill configuration. This activity maps to the *planning* and *realization* PDAs of the VDI 3695.

In the **traditional approach**, one of two cases applies. If the artifacts are tightly coupled, they require adaption to the particular project. If the artifacts are loosely coupled, they require adaption to each other and the project. This specific adaptation makes it hard to exchange production resources in case they do not fit as expected.

In the **CSR framework**, the engineers receive C&Ss from activity PDA.3 that match each other but are only partially configured. For instance, the torque in the screwing capability has been set to a particular value, in the use case 150 Nm. However, the engineer might need to set further C&S parameters to concrete values for the production. Furthermore, the engineers need to bind the particular capability to the finally selected and configured skill.

In Figure 2 the **bound and configured capability and skill** for a process are shown in a PPR model with connected C&Ss. The results of this step (cf. red label 4 Figure 2) are input to *PDA.5*.

PDA.5 – Skill execution. This activity maps to the *commissioning* PDA of the VDI 3695.

During commissioning, the designed production system runs for the first time with different resource configurations for various products from the product portfolio.

In the **traditional approach**, the engineers configured the resources based on product and process knowledge which is often diluted over the engineering process. While they might have used reusable artifacts for the configuration, we argue that it is harder to reconfigure resources in case they do not prove as efficient or suitable as expected.

In the **CSR approach**, the finally configured skills are executed for the first time on the production system with the particular configuration. This activity shall ensure, beyond other things, that the C&Ss are configured correctly. To run on the production system, skills must fulfill the same requirements as in *PIA.3*, where the skills are tested and validated. Concretely, they have to fulfill the *run time* requirements of Table 1. Issues during the execution of the skills shall be fed back directly to the PIAs, e.g., validation and testing.

Experiences and assets from the PDAs are fed back to the PIAs to improve the reuse lifecycle.

As a summary, the CSR framework defines activities that motivate which tasks should be taken to (i) elicit C&Ss from previous projects, (ii) model and validate them as reusable artifacts in a common artifact repository, and (iii) use and configure them in particular engineering projects. In the next section, we discuss the CSR framework in context to the related work and research question.

4 Discussion

In PSE, engineering organizations aim at establishing reuse to improve the quality and efficiency of engineering [11].

This paper investigated the research question: How do VDI 3695 activities for domain and application engineering

require adaptation to facilitate reuse with capabilities and skills in PSE?

To address this research question, this paper introduced the *Capability and Skill Reuse (CSR)* framework that defines how the VDI 3695 procedure model for reuse for domain and application engineering requires adaptation to support but also benefit from C&S models.

The CSR framework organizes the design and application of C&S models that fulfill essential C&S requirements (cf. Table 1) to facilitate C&S-based reuse in PSE. In particular, the CSR framework guides engineering activities to move from traditional reuse of tightly coupled engineering artifacts for a specific reference architecture towards an approach aimed at higher reuse. C&S-based reuse of loosely coupled C&S artifacts facilitates both internal reuse and the exchange of C&S on a marketplace with a wider audience, possibly for similar but different reference architectures.

In these contexts, Table 2 lists expected benefits of C&S-based (reuse in) PSE towards flexible production [4]. However, these benefits require investment into C&S-based assets, which should be organized in increments that each provide a benefit to justify the cost and mitigate migration risks.

The activities of CSR framework themselves require the means and methods of the C&S community. This includes C&S description methods, such as ontologies [5, 17] and domain-specific languages [22], and technologies to implement skills, such as OPC UA [8, 18] or PackML/ISA 88. To this end, the CSR framework requires a future discussion and validation by the community.

The explicit modeling of C&S knowledge represents currently implicit domain expert knowledge to improve the automation of designing C&S-based solutions that match defined process capability requirements. To this end, the CSR framework facilitates integrating scattered domain knowledge on reuse from several engineering disciplines,

Table 2: Expected *benefits* of *capabilities and skills* [4].

Category	Benefits
Usage advancement	Flexibility
	Automatic matching
	Optimization
	Interoperability
Development streamlining	Planning efficiency
	Development efficiency
Reuse support	Abstraction
	C&S reuse

in particular, product and process design, as well as a variety of detail engineering disciplines [27].

The research in this paper goes beyond the state of the art in PSE reuse [10, 11] and C&S-based engineering (i) by defining how engineers responsible for reuse can create and exchange reusable C&S-based engineering artifacts and models from PPR artifacts and (ii) by illustrating its applicability in a reuse use case.

The following **limitation** requires further investigation. While there are promising contributions towards C&S-based reuse, experiments and case studies in typical application contexts are required to provide sound *empirical evidence* on the expected benefits and associated costs and risks.

5 Conclusion and outlook

The Industry 4.0 initiative indicated the flexibility and adaptability of systems as a crucial success factor for future production. The Product-Process-Resource (PPR) concept aims to provide a model to represent the key aspects of Production Systems Engineering (PSE). Complemented by capabilities and skills (C&Ss), which aim to abstract process requirements and resource functionality and decouple them using semantic descriptions, this approach supports the required flexibility for building production networks [4].

There is maturing work on C&S foundations for engineering and exchange in a marketplace [28]. However, less emphasis has been put on the question of how to combine reuse concerns with C&S-based engineering to provide a framework for starting and growing C&S-based engineering in a company. An example are system integrators that consider providing or procuring solution elements on a marketplace for C&Ss. However, traditional reuse approaches in PSE, such as the VDI 3695 guideline [11] and domain engineering [9, 10], do not consider C&S. Therefore, this paper introduced the Capability and Skill Reuse (CSR) framework to extend the reuse activities of the VDI 3695 procedure model towards the use of C&Ss. Therefore, we build on and integrate basic C&S representation and processing capabilities [5, 8, 17, 18].

Traditional reuse works well for a system integrator in a limited domain with well-known solution partners and a stable set of reference architecture and solution technologies. However, considering incremental investment into C&Ss seems advisable if more flexibility regarding these concerns is required. In this context, C&S-based reuse can facilitate the work of domain experts with computer functions for reuse processes to use scarce expert resources

efficiently. Researchers and practitioners in PSE can take up the results of this research to investigate and improve reuse in PSE. For instance, they can apply and validate the framework in various application contexts.

Future Work. *Capability and Skill Reuse (CSR) architecture*. We plan to design and explore options for a software solution architecture for the CSR framework for a particular domain, such as automotive manufacturing. To this end, we want to consider aspects of typical reference architectures and ways for knowledge representation.

Empirical studies of CSR framework applications. Further, we plan to conduct case studies with system integrators to detail and validate selected parts of the CSR framework. For instance, this comprises lifting skill knowledge from reuse assets or the co-evolution of solution elements in domain and application engineering.

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