Technical Report

Product-Process-Resource Asset Networks as Foundation for Improving CPPS Engineering

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Product-Process-Resource Asset Networks as Foundation for Improving CPPS Engineering

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***Abstract*—In the engineering of Cyber-Physical Production Systems (CPPSs), the coordination and data exchange of Product (P), Process (P´) and Resource (R) assets is success-critical for creating high-quality engineering products. In industry, product, process, and resources are often addressed individually without explicitly expressing their dependencies. Therefore, isolated assets can hinder efficient collaboration within CPPS engineering projects that can lead to risks in case of overseen dependencies. Thus, we see the need for explicitly expressing PPR assets within an PPR Asset Network (PAN) that is (a) capable of handling assets from different viewpoints and (b) can enable efficient added value application such as risk, requirements, and configuration management. The goal of this paper include a process description for the elicitation of the PAN and to illustrate added-value applications based on a selected use case, i.e., the Industry 4.0 Testbed at CTU in Prague. We build on the PPR concept as foundation for the PAN and for added-value applications. PAN added-value applications aim at supporting risk management, requirements engineering, or configuration management by focusing on PPR assets and dependencies in context of CPPS engineering. Although PAN provides a valuable foundation for added-value applications there is the need for initial effort for the creation/generating the PAN.**

***Index Terms*—Cyber-Physical Production Systems, Product, Process, and Resource Assets (PPR), PPR Asset Network, PAN.**

I. INTRODUCTION

In context of Industry 4.0 [10], the engineering of *Cyber-Physical Production Systems (CPPSs)* require efficient coordination and data exchange to support collaboration within an engineering team [2]. Engineering teams often consist of a variety of disciplines, such as electrical, mechanical, and software, forming a multi-disciplinary engineering team to address individual aspects of the planned CPPS [16] from various viewpoints. Beyond the involvement of various disciplines, different aspects of a production system need to be considered: (a) *Product information* focuses on individual products and sub-products as main output of the CPPS; (b) *Process information* is related to individual steps for producing the product; and (c) *Resource information* focuses on facilities to enable the construction of products in context of the manufacturing process. The PPR concept [1] combines product, process, and resource information sets as *Engineering Assets* [7]. Dependencies between engineering assets are implicitly available but are often not explicitly expressed [3]. Therefore, overseen dependencies between engineering assets can lead to additional risks and defects in the CPPS that can require high effort for risk mitigation, defect detection, and repair. In this paper, we aim for a *PPR Asset Network (PAN)*, that adds dependencies to engineering assets forming an engineering network. The PAN provides an overview of the structure of the engineering system with dependencies that can represent the foundation for added value components (on top of the PAN), such as risk mitigation and defect detection [3], requirements tracing [4], or systems maintenance and configuration support [15].

In this paper we (a) define a process how to derive a PAN based on domain expertise and (b) discuss selected added value components for PAN extensions that can bring additional value to CPPS engineering projects. We illustrate the outcome of the PAN elicitation process in a real world use case based on the Industry 4.0 Testbed at CTU in Prague[1].

The remainder of this paper is structured as follows: Section II summarizes related work on CPPS and PPR. We describe the research questions in Section III. Section IV presents the use case in context of the Industry 4.0 Testbed and Section V shows the resulting PAN. Finally, Section VI provides a discussion, concludes, and proposes future work.

II. RELATED WORK

In a typical class of software-intensive systems, such as in the automotive business area, a *Cyber-Physical Production System (CPPS)*, consists of more than 50k system elements [6] including 200 to 300 work cells for positioning and joining. A broad range of different engineering disciplines, e.g., mechanics, electrics, and software engineering, coming from various domains, departments, and organizations need to collaborate within the joint project [2]. Each engineering discipline and domain focuses on individual (and partly isolated) views on the CPPS, applying a variety of different engineering tools. This setup often leads to many, often partial, local views and make the engineering process risky and error-prone [12], [17]. Especially product design changes might require changes in the design of the CPPS [8]. Thus, isolated views and the heterogeneity within the CPPS engineering process adds additional complexity and might lead to increased risks in case of missing or overseen dependencies between different system elements. The concept of PPR (Product-Process-Resources) [11]

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[1] Industry 4.0 Testbed: www.ciirc.cvut.cz/teams-labs/testbed/

bring together different viewpoints on individual aspects of the CPPS. These viewpoints are often related to different stakeholders, such as product management, process management, and engineering disciplines (like mechanics, electrics, and software). Processes transform input products into output products using dedicated resources [7]. Therefore, the PPR concept is able to describe core engineering knowledge, e.g., dependencies between production processes that consume and produce products using specific production resources. The products and their characteristics are typically defined in the *Bill of Material*. Related production processes are defined in the *Bill of Operation*. These processes are executed by production resources. These individual aspects – product, process and resource – are treated as first-class objects in PPR. PPR knowledge can be considered as engineering assets that form - together with dependencies between these assets - a PPR Asset Network (PAN) [3]. Engineering assets and related dependencies, represented as a PAN, can support risk assessment and mitigation [3] and requirements tracing [4] during engineering phases and configuration management during operation [15]. However, it remains open how to elicit a PAN in context of CPPS engineering.

III. RESEARCH QUESTIONS

Based on the need for setting up a PPR Asset Network (PAN) and for identifying promising candidate added-value components, we define two main research questions:

RQ1. What are the basic steps for creating a PPR Asset Network (PAN)? The large number of involved system elements (e.g., 50k+ systems elements in Automotive CPPS) within a CPPS require a systematic approach to identify engineering assets and their dependencies. Therefore, a process is required that supports the definition of a PAN, representing the structure of the CPPS as foundation for added value components.

RQ2. What are benefits and limitations of added-value components that can improve CPPS engineering processes? The second question focuses on a selected set of added value applications that are often requested by industry in context of CPPS to improve engineering and maintenance processes.

IV. ILLUSTRATIVE USE CASE

As an illustrative application case, we use the *Industry 4.0 Testbed* (I4.0 Testbed)[2], located at CTU in Prague. The *I4.0 testbed* is an educatory and testing facility bridging the gap between scientific state-of-the-art and industrial practice in various domains, including advanced process control and planning [14], automated precise robot calibration [9], and the design of (collaborative) robotic work cells.

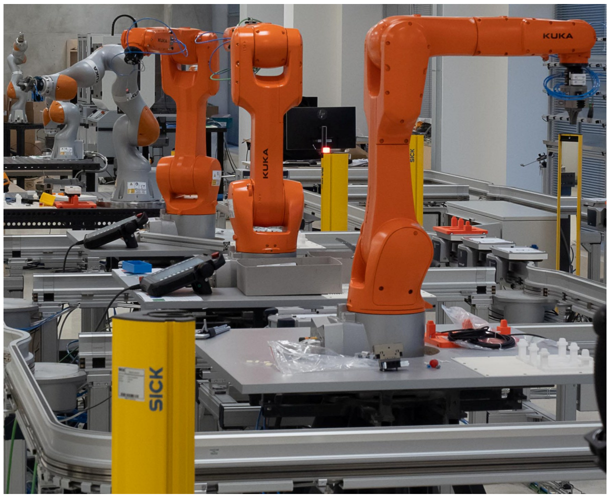

Fig. 1. Industry 4.0 Testbed at CTU in Prague.

Figure 1 depicts the core part of the *I4.0 Testbed*, an Industry 4.0 Production line. The production line consists of three industrial robots *KUKA*[3] *Agilus* and one cooperative robot *KUKA iiwa*. The robots are connected with a transportation system *montrac*[4]. *Montrac* is a mono-rail transportation system consisting of tracks, transportation shuttles, and positioning units, which assure exact stopping and positioning of the shuttles in specific locations, such as work cells close by robots. The production line is generic with focus on the final assembly of products. Similar to typical manufacturing processes in industry, the production line consists of a set of basic production operations:

1) *Pick* a component from given coordinates by a *robot*;
2) *Place* a component to given coordinates by the *robot*;
3) *Move* a semi-product on a *shuttle*.

The operations *Pick and Place* can be merged into one operation *Pick&Place*, which duration is faster than in case of two separate dependent operations pick and place [13].

V. PPR ASSET NETWORK (PAN)

In this section we described the PAN Meta-model the PAN elicitation and definition process, and a subset of the *I40 Testbed* related to the use case (see Section IV).

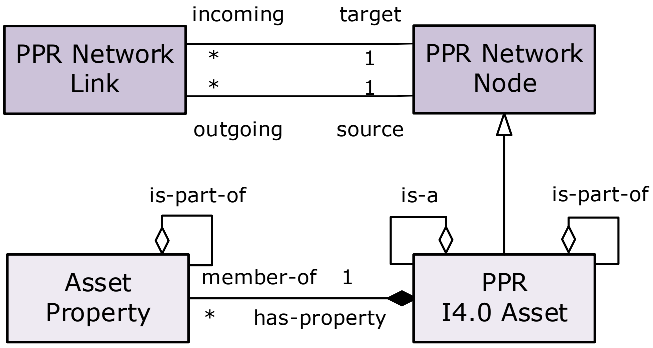

Fig. 2. Meta-Model of a PPR Asset Network (PAN).

A. PAN Meta-Model

Figure 2 shows the meta model of the PAN, derived from [5], including four building blocks: (a) PPR I4.0 Assets; (b) related Asset Properties;, (c) PPR Network Nodes; and (d) PPR

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[2] Industry 4.0 Testbed: www.ciirc.cvut.cz/teams-labs/testbed/
[3] KUKA: www.kuka.com
[4] montratec: www.montratec.de/en/

Network Links. The *PPR I4.0 Assets* contains PPR knowledge that are associated with other assets or that are part of assets, enabling a hierarchical structure of the CPPS. Each PPR asset can consist of related properties. Nodes are PPR Assets that are include PPR network links establishing dependencies.

B. Process Steps

A set of involved stakeholders provide knowledge and expertise of individual aspects of engineering assets from different viewpoints. Figure 3 summarize the individual steps of the PAN elicitation and definition process.

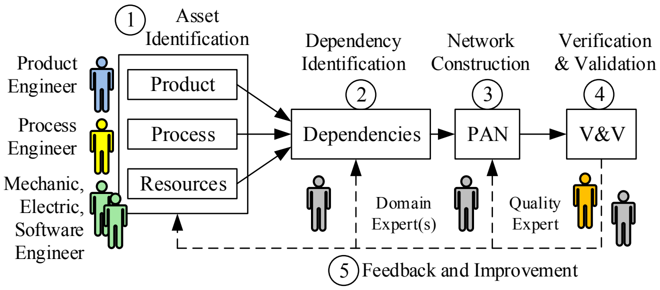

Fig. 3. PPR Asset and Dependency Elicitation and PAN Definition Process.

(1) Asset Identification. Product Engineers typically provide information in terms of a *Bill of Material* from a product perspective. They focus on the product, sub-products, and related attributes. *Process engineers* provide knowledge on the *Bill of Operation* with focus on process steps and related process attributes. Finally, *Discipline Specific Engineers* contribute with discipline specific knowledge and expertise from involved disciplines (such as mechanics, electrics and software). Product, process, and resource knowledge form a *PPR Asset* including related attributes. *(2) Dependency Identification and (3) Network Construction.* Typically, *Domain Experts*, who have experience in modeling the dependencies between individual assets (product, process, resources and related attributes) provide relationships as foundation for establishing a PPR Asset network. *(4) Verification and Validation.* Finally, *Quality* and *Domain Experts* provide verification and validation tasks, such as consistency checking, to ensure completeness and correctness of the resulting PAN. *(5). Feedback and Improvement*. In case of deviations, missing and incomplete information, or inconsistencies, feedback loops are included to improve the PAN.

C. PAN of selected Assets in the I4.0 Testbed

Based on the use case (see Section IV) and the process description (see Section V-B), we describe the PAN for the *Pick, Move, and Place* operation in context of the I4.0 Testbed. The resulting PAN (see Figure 4) includes relevant assets of all of the three types, i.e., products and processes depicted on the left-hand side, as well as resources depicted on the right-hand side. The network includes links between them, expressing how a particular production process is instrumented. This way of expression is very useful even for Industry-4.0-oriented production systems, because it enables easily assign and re-assign production operations to specific production resources.

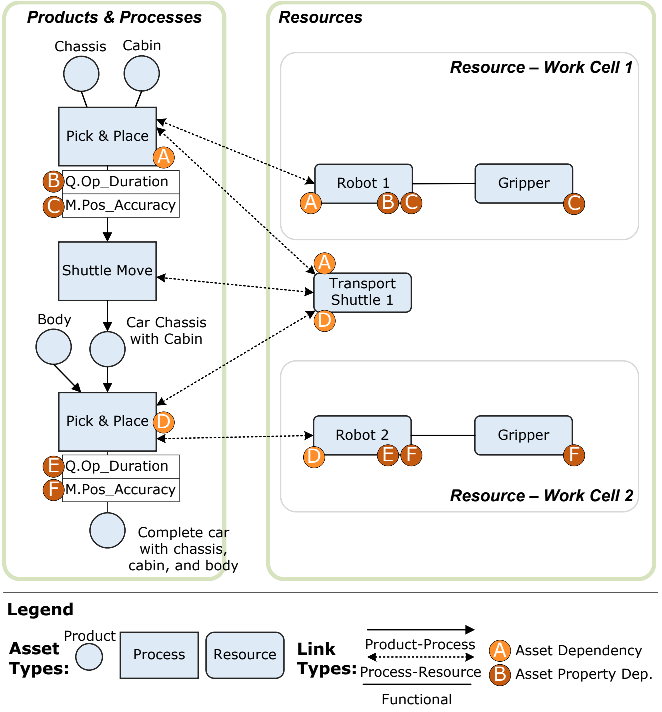

Fig. 4. PAN of selected Assets for the I4.0 Testbed.

In more details, the depicted truck assembling process starts with a pick-and-place operation when a cabin is put onto a chassis. This is done by a resource Robot 1 (by its gripper). The chassis is located on the transportation Shuttle 1, which is in the subsequent step moved close to Robot 2, where a next pick-and-place operation is done. This operation puts car body on the chassis (already equipped with the cabin). By performing this production operation the required truck is completed and the production process finishes.

D. Selected Added Value Components

The PAN of the I4.0 Testbed (illustrated in Figure 4) depicts the structure of the CPPS including PPR Assets and dependencies and, therefore, represents the foundation of added value components. Added value components build on the PAN and provide additional capabilities for industry applications. Based on discussions with industry partners, we identified three application areas that have been requested by industry:

(a) Risk Assessment and Mitigation during Engineering and Operation. Based on the *Root Cause Analysis* approach, PAN extensions with observed effects, related causes, and counter measures can help to mitigate risks and remove defects during engineering and operation [3]. Furthermore, *Decision Trees* that can help maintenance engineers to efficiently root causes in the operation phase of the CPPS and provide feedback for PAN knowledge extensions [15].

(b) Requirements Tracing. In order to improve engineering processes, a PAN can be extended with links to engineering

artifacts, such as requirements. Linking requirements with the PAN can help to trace changes from engineering documents to individual PPR Assets and properties in case of required system element changes to ensure consistency in a multi-disciplinary CPPS [4].

(c) CPPS Configuration. A typical industry request focuses on the configuration of an existing CPPS. The overall information model for the real system should provide an inventory of available resources and coherent setup of all components. This knowledge can be represented in an asset management system (such as a PAN), which is frequently required for managing machinery including versions of software and firmware.

VI. CONCLUSION AND FUTURE WORK

In CPPS engineering, isolated views of involved stakeholders, coming from various disciplines, and overseen dependencies between systems elements can lead to risks and defects that need to be addressed. The PPR concept [11] brings together different views from project, process, and resource perspective, forming a PPR asset. Dependencies between PPR assets form a PPR Asset Network (PAN) that represent a structural view on the CPPS (including relationships between assets and asset attributes).

In this paper, we introduced a process to elicit and define a PAN as foundation for improving CPPS engineering processes (RQ1). In context of the *I4.0 Testbed*, we presented three added-value application cases (RQ2) where a PAN can help to (a) assess and mitigate risks and support defect detection during engineering and operation, (b) enable requirement tracing to support change management, and (c) provide an overview of configuration items of a CPPS.

Future Work. We see the PAN as a valuable foundation for added-value applications in CPPS engineering. However, there is the need for an initial effort for creating/generating the PAN. PAN applications have been found promising and helpful for industry partners, the small-scale application cases are used to demonstrate the feasibility of PPR Asset Network and its applications. However, a more detailed analysis and evaluation in large-scale environments and real-world industry cases remain for future work.

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