Towards Coordinating Production Reconfiguration

Stefan Biffl[†§] Kristof Meixner[*†] David Hoffmann[‡] Jürgen Musil[*†] Hossein Rahmani[†] Arndt Lüder[‡§]
[*]Christian Doppler Laboratory SQI, [†]Inst. of Information Systems Engineering, TU Wien and [§]CDP, Austria
E-Mail: [first].[last]@tuwien.ac.at
[‡]Institute of Ergonomics, Manufacturing Systems and Automation, Otto-von-Guericke U., Germany
E-Mail: [first].[last]@ovgu.de

***Abstract*—The engineering of production systems requires capabilities for the coordinated reconfiguration between production variants, i.e., product, process, and resource (PPR) variants with multi-disciplinary dependencies. However, traditional approaches to coordinate reconfiguration, e.g., scripted workflows, consider production dependencies only implicitly and require validation regarding multi-disciplinary PPR dependencies. In this paper, we explore knowledge representation to coordinate production reconfiguration with Industry 4.0 components. For validating pre- and post-conditions of a flexible, coordinated reconfiguration process, we introduce the *PPR Asset Network with Reconfiguration (PAN+R)* approach, which builds on the PPR Asset Network to represent PPR model variants with their dependencies and states in transition between variants. We initially evaluate the PAN+R approach with a use case on a work cell for joining car parts. We conclude with a research agenda towards coordinating production reconfiguration with human and machine agents.**

***Index Terms*—Production Systems Engineering, Industry 4.0 component, VDI 3695-3, dependency management.**

I. Introduction

Changing customer requirements on product designs force production system owners to adapt production capabilities, i.e., product design, production process behavior, and production system design [1]. In the Industry 4.0 (I4.0) vision, the challenge of production adaptation is tackled by reconfiguration capabilities for a production system under uncertainty, e.g., adapting a robot work cell to changing products, as envisioned in the ARENA 2036 project [2]. In this paper, we consider a minimal use case of changing dependent elements of a screwing process for car parts: a screw, a screwdriver bit, and the force curve that describes the screwing behavior.

Production reconfiguration concerns coordinated, multi-step, and often iterative change activities [3] in the configuration management [4] of Product-Process-Resource (PPR) variants [5], which have multi-disciplinary dependencies that require support for multi-disciplinary configuration management [6]. Adapting a production system to products, which were not envisioned during design, is likely to lead to inconsistencies during reconfiguration, in particular across disciplines.

Therefore, engineers, who design production changes, and operators, who conduct system changes, require (i) support for validating changes between production system variants [7] and (ii) coordination regarding dependencies between reconfiguration tasks, e.g., conditions when a reconfiguration task can start. These validation and coordination capabilities require the representation and validation of dependencies between PPR elements for a configuration, i.e., products, processes, and production system components [1], where each PPR element can be considered an I4.0 component [8]. Combining a production system variant model with knowledge about the required change actions can (i) support engineers to design the configuration change and (ii) assist operators to achieve valid reconfiguration. As traditional reconfiguration management focuses on discipline-specific configuration management tools [4], it does not support efficient result validation regarding multi-disciplinary PPR dependencies.

To tackle this challenge, this paper aims to represent the knowledge required for validating a reconfiguration process that concerns PPR elements. In this paper, we address the following Research Question: *What knowledge graph can represent the knowledge on PPR elements, their variants, and dependencies that are required for the validation and coordination of production reconfiguration in manufacturing?*

Therefore, we build on the PPR Asset Network (PAN) coordination artifact [9] to introduce the *PPR Asset Network with Reconfiguration (PAN+R)* approach that represents (i) in a *production model* the required knowledge on PPR model variants, transition states between these variants, and their dependencies; (ii) a *reconfiguration process* from a PPR model start variant to a goal variant; and (iii) the links of domain concepts, used in pre-/post-conditions of reconfiguration tasks, to PPR model elements, as a foundation for designing the PAN+R knowledge graph that facilitates reasoning on task dependencies, and coordinating production reconfiguration.

The remainder of this paper is structured as follows. Section II summarizes related work. Section III introduces the use case *reconfiguration of a screwing work cell* for validating a reconfiguration process with dependencies. Section IV proposes the *PPR Asset Network with Reconfiguration (PAN+R)* approach for validating a reconfiguration process with PPR engineering knowledge, illustrated with data from the use case. Section V concludes and delineates future work.

II. Related Work

Configuration management in Production System Engineering (PSE) [4] intends to ensure the migration between consistent versions of a production system, i.e., configurations. A configuration combines all elements in a consistent and correctly applicable way.

Traditional reconfiguration management focuses on production system reconfiguration with discipline-specific configuration management tools [4] and implicit domain knowledge.

Domain-crossing dependencies like PPR concerns are only implicitly considered based on expert knowledge. This makes reconfiguration processes hard to validate regarding the completeness and correctness of pre- and post-conditions of as well as dependencies between reconfiguration tasks.

System-assisted, cross-discipline configuration management [4] requires an integrated, discipline-crossing view on the production system. The PPR Asset Network (PAN) [9] can represent PPR dependencies for a specific configuration of a production system, but does not consider variants.

In this paper, we explore moving (i) from discipline-specific to discipline-crossing configuration management [4] by building on the PAN, and (ii) from a static engineering activity model towards a workflow driven by engineering artifacts, by extending PAN models with an adaptation process.

Change planning in PSE is traditionally based on discipline-specific artifacts [10], even in case of component-based engineering. More recent approaches consider iterative change management of production systems [3] with explicit evaluation of pre- and post-conditions. However, they do not consider dependencies between artifacts/disciplines. Göring [11] explicitly models the impact of configuration changes, but does not integrate comprehensive PPR knowledge.

This paper goes beyond the state of the art in production system reconfiguration planning by introducing an approach to represent multi-disciplinary production knowledge linked to a reconfiguration process, as a foundation for data-driven, coordinated, and validated reconfiguration intended by [4].

III. Use Case Work Cell Reconfiguration

Based on a domain analysis of screwing work cells [12], [13], we abstracted the use case *reconfiguration of a screwing work cell*. Furthermore, we derived requirements for knowledge representation on reconfiguration. We focus on production reconfiguration regarding a screwing process to join car parts. In particular, we describe parts of a robot cell with an electric screwdriver, consisting of a bit and a screwer controller that uses a force curve to define the screwing process behavior.

In the use case, a quality expert works with process experts and detail planners to define and validate reconfiguration guidelines for the operator who conducts the reconfiguration. An activity that involves changes in several disciplines is modifying the screw type, an input product. This change requires checking and possibly modifying the screwing bit, and the force curve of the screwing process behavior. Therefore, this use case involves dependencies between all PPR aspects and between mechanic and automation engineering disciplines.

This paper focuses on modeling capabilities for validating a reconfiguration process towardS coordinating production reconfiguration. For validating a reconfiguration process with PPR change dependencies, we identified the following required capabilities: (R1) representation of production change knowledge, (R2) representation of the reconfiguration process, and (R3) linking the reconfiguration process and the PPR model.

IV. PPR Asset Network with Reconfiguration

This section introduces the *PPR Asset Network with Reconfiguration (PAN+R)* approach and an initial evaluation.

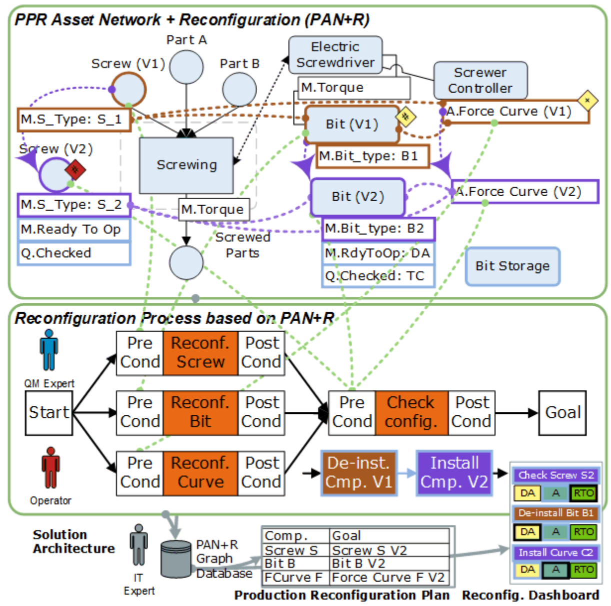

Fig. 1. *PPR Asset Network with Reconfiguration*: Solution Overview.

Fig. 1 illustrates the PAN+R solution approach. First, the quality expert designs a *production model* with variants and the required production change knowledge (cf. Fig. 1, top). Second, they design a *reconfiguration process model* with the required reconfiguration knowledge (cf. Fig. 1, bottom). Then they link the reconfiguration process elements to the production model (cf. Fig. 1, green dashed lines) for validating the pre- and postconditions in a coordinated reconfiguration process. These linked models form a knowledge graph that can be stored and queried in a graph database to (i) derive a production reconfiguration plan and (ii) inform operators on a dashboard regarding the reconfiguration state and next tasks.

Production model with variants. The PAN+R production model builds on the PAN [9] to represent PPR assets and properties (circles and boxes in light blue color), such as the screwing process, and functional dependencies between PPR assets (black arrows). To represent production variants, the production model contains variants of PPR assets and properties (PPR elements with frames in brown or violet colors), such as screw variants V1 and V2. Transition dependencies connect the variants of a PPR element (violet arrows with dashed lines). To represent change dependencies between (variants of) PPR elements, the production model contains brown/violet dashed lines, e.g., between the screw and the bit.

PAN+R production model properties can represent reconfiguration states of components, such as their assembly or validation states. State machines for these reconfiguration states (cf. Fig. 2) define valid states and transitions, considering multi-disciplinary dependencies, as a foundation for validating a sequence of reconfiguration tasks. To represent reconfiguration

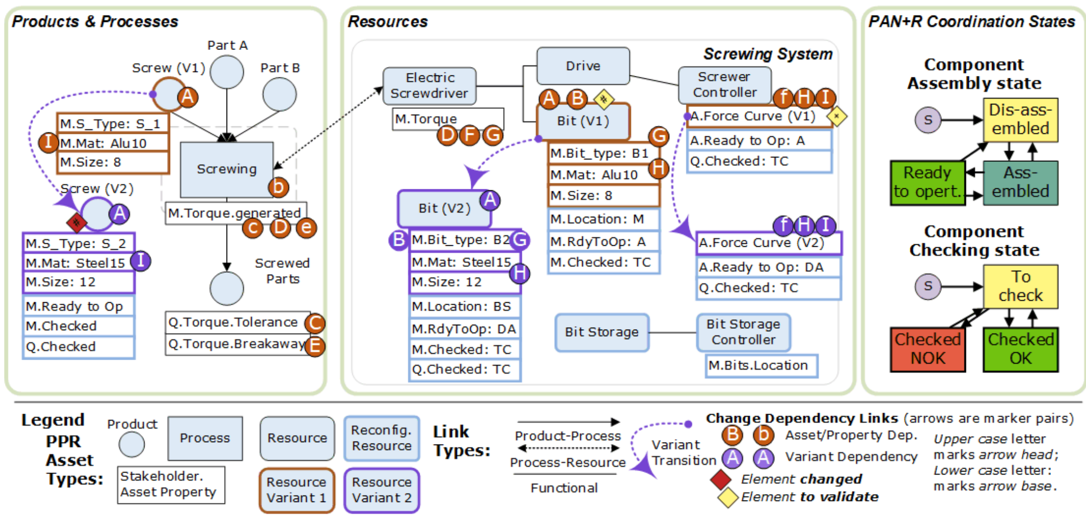

Fig. 2. PPR Asset Network with Reconfiguration (PAN+R) production model for the use case *reconfiguration of a screwing work cell*, in VDI 3682 notation with extensions [9], [14] and state machines based on [15].

assets or properties that are required for coordinating the transition, but not for production, the production model contains PPR elements with light blue frames, such as *Bit Storage*. For marking a changed PPR asset and PPR elements to validate, the production model contains red and yellow diamonds.

Reconfiguration process model. A reconfiguration process consists of tasks with pre- and postconditions, leading from a start to a goal state (cf. Fig. 1, bottom). For instance, the reconfiguration of the screwing system requires reconfiguration tasks for the screw, bit, and screwing curve, and for checking the configuration. The process expert can define task conditions considering dependencies and states in the PAN+R production model. When conducting the reconfiguration, a task management system can coordinate the reconfiguration tasks.

Knowledge graph of reconfiguration process model linked to the production model. The domain concepts in task pre- and postconditions can be linked to PPR elements (cf. Fig. 1, green dashed lines) as a foundation for validating these concepts and their dependencies in the PAN+R knowledge graph.

Evaluation. For an initial evaluation, we conducted the PAN+R approach for the use case *reconfiguration of a screwing work cell*. Fig. 2 shows the resulting production model with the screw, bit, and force curve variants V1 and V2 as start and goal states. A PPR asset property indicates the stakeholder, mechanical (M), automation (A), or quality (Q) expert, e.g., *M.Size*, to represent the disciplines required for reconfiguration and validation. Fig. 2 shows PPR dependencies as pairs of circles with the same letter, e.g., *I* links the screw and the force curve. The PAN+R coordination states represent the assembly and checking states of a PPR component variant, e.g., a component can be *disassembled*, *assembled*, or *ready to operate*. Fig. 2 shows coordination markers (colored diamonds) that indicate a screw change, which requires validating the dependent elements: asset *Bit* and property *A.Force Curve*.

In the use case, the reconfiguration process consisted of (i) a top-level iterative change process of planning, conducting, and checking the reconfiguration tasks; (ii) a reconfiguration precedence graph that describes valid reconfiguration task sequences; and (iii) reconfiguration tasks for adding and removing a PPR asset with consideration of change dependencies.

The bottom part of Fig. 1 illustrates the reconfiguration process for the use case *reconfiguration of a screwing work cell*. Reconfiguring the screw or bit requires reconfiguring the dependent components, including the force curve. Reconfiguring a component requires first deinstalling component variant V1, then installing component variant V2 (cf. Fig. 1, top). These tasks allow for process variations concerning coordinated changes regarding the bit (resource), screw (input product), and force curve (process data, in a resource); and associated engineering (and operation) artifacts, e.g., bit in M-CAD, change guideline, screw loading technology and operation guideline, and screwer controller data provision.

This precedence graph can support different bottom-up or top-down coordination approaches for reconfiguration. For instance, an orchestration of reconfiguration tasks or a group of distributed agents that can act independently based on information on which reconfiguration tasks are ready to start.

Tab. I illustrates pre- and postconditions of tasks in the reconfiguration process, using domain concepts that refer to the production model, typically production asset properties that represent component reconfiguration states, e.g., assembly or checking states, or the location of a component variant. For example, the *Screw.Reconfig* precondition requires the mechanical property *Ready To Op* of *Screw S1* to be *assembled* or *ready*, while property *Ready To Op* for *Screw S2* needs to be *disassembled*. Therefore, a knowledge graph [9] can explicitly represent these links (cf. Fig. 1, green dashed lines), as a foundation for queries that combine knowledge in the *reconfiguration process model* and the *production model*.

The PAN+R model was able to represent the reconfiguration

Condition Id	Condition Description
Screw.Reconfig. Precondition	'Screw S1'.M.'Ready To Op' == assembled ∨ ready ∧ 'Screw S2'.M.'Ready To Op' == disassembled.
Screw.Reconfig. Postcondition	'Screw S2'.M.'Ready To Op' = assembled ∨ ready ∧ 'Screw S1'.M.'Ready To Op' == disassembled.
Bit.De-install Precondition	'Bit B1'.M.'Ready To Op' == assembled ∨ ready ∧ 'Bit B2'.M.'Ready To Op' = disassembled.
Bit.De-install Postcondition	'Bit B1'.M.'Ready To Op' == disassembled ∧ 'Bit B1'.M.Checked == 'Checked OK' ∧ 'Bit B1'.M.Location == 'Bit Storage'.
Start: System Reconfig. Precondition	System.Ready To Op = ('Screw S1'.'Ready To Op' = ready ∧ 'Bit B1'.M.'Ready To Op' = ready ∧ 'Curve C1'.A.'Ready To Op' = ready).
Goal: System Reconfig. Postcondition	System.Ready To Op = ('Screw S2'.'Ready To Op' = ready ∧ 'Bit B2'.M.'Ready To Op' = ready ∧ 'Curve C2'.A.'Ready To Op' = ready).

TABLE I
PRE- AND POSTCONDITIONS OF RECONFIGURATION TASKS (CF. FIG. 1 BOTTOM).

knowledge for the use case joining car parts, encouraging evaluation in a broader range of reconfiguration cases.

V. Conclusion

The Industry 4.0 vision of adaptable robot work cells [2] requires capabilities (i) for multi-disciplinary reconfiguration based on a model that considers PPR dependencies; (ii) for the flexible design of reconfiguration processes according to a production model to accommodate for new products, processes, and production system components; and (iii) for coordinating human and machine agents. However, traditional reconfiguration processes are often workflows for a specific production system and not aware of production dependencies.

In this paper, we introduced the PAN+R approach that goes beyond the state of the art by representing PPR dependencies in a production model to facilitate validating a flexible reconfiguration process as a foundation for coordinating production reconfiguration. Together, the PAN+R production model and the reconfiguration process model can represent the data required for change planning and monitoring. Further, the PAN+R knowledge graph facilitates queries to PPR elements, their variants, and dependencies [9]. Therefore, the PAN+R approach provides the foundation for effective change coordination of human and machine agents, which are compatible to the I4.0 asset administration shell [8]. An initial evaluation of the PAN+R knowledge graph with a use case on reconfiguring a joining work cell showed promising results that warrant its application to a wider range of production settings.

Research agenda. *Towards self-adaptive production.* We plan to apply the PAN+R approach to coordinating production system reconfiguration (i) by coordinating the PPR reconfiguration process design and validation regarding dependencies in and across engineering disciplines; and (ii) by coordinating one or more operators with computer support towards valid reconfiguration according to the process, with run-time input data. We consider investigating (i) operator assistance with a reconfiguration dashboard (cf. Section IV); and (ii) automating selected reconfiguration tasks towards a self-adaptive production system for a suitable scope of reconfiguration.

Scalability. We will explore how to derive a reconfiguration process from a PAN+R production model for larger use cases. In particular a robot for flexible use in various work cells and lines, which may require dozens of production dependencies and a dozen change variants to the robot configuration.

Reconfiguration process FMEA. We will explore process FMEA to analyze risky effects of reconfiguration task sequences and their causes that should be considered in the pre- and post-conditions of reconfiguration tasks [16].

Information security. The PAN+R approach requires research on security concerns as the configuration information in a PAN+R model is valuable for planning or mitigating attacks on production systems.

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