# A Coordination Artifact for Multi-disciplinary Reuse in Production Systems Engineering

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***Abstract*—In Production System Engineering (PSE), domain experts from different disciplines reuse assets such as products, production processes, and resources. Therefore, PSE organizations aim at establishing reuse across engineering disciplines. However, the coordination of multi-disciplinary reuse tasks, e.g., the re-validation of related assets after changes, is hampered by the coarse-grained representation of tasks and by scattered, heterogeneous domain knowledge. This paper introduces the Multi-disciplinary Reuse Coordination (MRC) artifact to improve task management for multi-disciplinary reuse. For assets and their properties, the MRC artifact describes sub-tasks with progress and result states to provide references for detailed reuse task management across engineering disciplines. In a feasibility study on a typical robot cell in automotive manufacturing, we investigate the effectiveness of task management with the MRC artifact compared to traditional approaches. Results indicate the MRC artifact to be feasible and to provide effective capabilities for coordinating multi-disciplinary re-validation after changes.**

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

## I. INTRODUCTION

In Production System Engineering (PSE), domain experts design Product-Process-Resource (PPR) assets [1] based on reusable assets from prior projects [2]. Production systems consist of physical assets, e.g., manufacturing cells or sensors, and non-physical assets, e.g., recipes, configurations, and control programs. Together, these resource assets execute production processes to manufacture products with required properties, e.g., quality and throughput [1]. Modern production systems are complex and software-intensive, and interact closely with their environments for flexible and efficient production towards the vision of sustainable manufacturing [3]. In this paper, an *asset* denotes a PPR asset with stakeholder property views [4]. The *properties* of an asset are a multi-disciplinary collection of attributes that stakeholders from several engineering disciplines, such as mechanical, electrical, and software engineering, use to characterize assets.

This paper focuses on multi-disciplinary reuse processes in PSE to adapt a reusable robot cell, e.g., for joining car parts, with the following stakeholders [5]. Basic planners use the PPR concept to analyze required adaptations on reusable assets and engineering artifacts from historical projects for designing high-level production processes and resources [6]. Detail planners detail the designs of these high-level production assets in their disciplines [5], such as adapting the screwdriver power in a robot cell. Detail planners work iteratively and in parallel to adapt their designs to changes, e.g., from related disciplines. The project manager tracks task progress and asset validation states to ensure sustainable asset re-validation after changes. These stakeholders coordinate their individual activities on assets in a so-called team workspace by sharing engineering artifacts, e.g., plans, datasheets, or programs. They act on document rather than artifact level [6]. Further, they conduct follow-up validation and rework tasks after changes, e.g., for revised asset property values within the engineering artifacts.

Engineering organizations aim at establishing reuse across engineering disciplines according to the guideline VDI 3695-3 [2]. In this context, a quality assurance *coordination policy* [7] is to validate the required multi-disciplinary scope after a change to a PPR asset, focusing on the necessary scope of assets to reduce quality assurance cost and risk. This effort requires the validation of consistency among disciplines after design changes, using quality assurance approaches, such as reviewing or simulation. Typically, engineering teams use task management systems, such as Jira[1], to represent analysis, design, and validation tasks, their states, and dependencies.

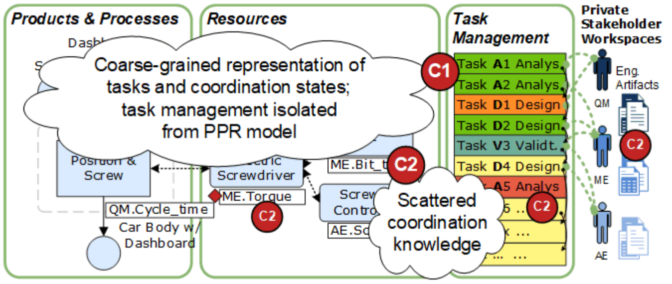

Fig. 1. Multi-disciplinary Reuse Coordination Research Challenges.

Fig. 1 illustrates two key challenges that impede effective coordination of multi-disciplinary reuse tasks in iterative and parallel PSE.

*Challenge C1. Coarse-grained representation of tasks and coordination states.* Tasks and coordination states, like engineering, design, validation, or change states, have been traditionally documented for engineering artifacts that include several assets, e.g., work cells or robots, which are typically in

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[1] Jira: www.atlassian.com/software/jira

various states due to parallel and iterative engineering [8]. Further, due to the isolation of task management from engineering models, typical workflow-based coordination has only scarce information on engineering content, provides weak support for iterative engineering, and may miss risky dependencies [4].

*Challenge C2. Scattered coordination knowledge required for reuse tasks.* The distribution of coordination knowledge, e.g., PPR asset states and dependencies, on partial views of stakeholders in several engineering artifacts and information systems makes coordination of reuse tasks harder and less efficient. Heterogeneous multi-disciplinary engineering artifacts make it hard to maintain change dependencies between design elements. For instance, the change of a property may require validation and re-design in several disciplines.

To tackle these challenges, this paper introduces the *Multi-disciplinary Reuse Coordination (MRC)* approach to coordinate re-validation tasks for multi-disciplinary reuse.

The remainder of this paper is structured as follows: Section II summarizes related work. Section III motivates the research question and approach. Section IV describes an illustrative use case for evaluation. Section V introduces the MRC approach. Section VI reports and discusses results from a feasibility study with the MRC approach on a real-world robot cell. Section VII concludes and outlines future work.

## II. RELATED WORK

**Multi-disciplinary reuse in PSE.** Modern PSE aims to reuse engineering results of prior projects to work more effectively and efficiently [9], [10]. The VDI 3695-2 guideline [2] proposes a procedure model for project-dependent and -independent engineering activities. The latter focus on reuse activities further detailed in the VDI 3695-3 [2] with particular target states. This paper considers an organization moving from single-disciplinary reuse (state B) to multi-disciplinary reuse (state D). Target state D requires the validation of consistency among disciplines after design changes. Possible quality assurance approaches, therefore, are, e.g., engineering artifact review, simulation, and testing.

Risks in PSE stem, i.a., from improper coordination of change and validation tasks related to the engineered assets. Late identification of such risks can significantly increase the cost of production [11], making efficient quality task management essential. However, keeping track of the task scope may be difficult, as it evolves due to new findings during task execution in multiple disciplines. Therefore, engineering organizations often struggle with eliciting the required scope of reusable assets across disciplines in prior projects [10].

*Artifacts as embodied coordination mechanisms* concern the effective and efficient coordination in a heterogeneous PSE engineering team [12]. Weyns and Omicini [7] introduced the concept of a coordination artifact based on principles of mediated agent-based coordination. Coordination artifacts (i) provide an effective, shared, and collaborative working space, (ii) mitigate coordination hurdles for domain experts, and (iii) establish a coordination policy. The knowledge representation in multi-disciplinary artifacts required for coordination in modern systems engineering paradigms like Industry 4.0 led to the development and increased industry adoption of the *asset administration shell* specification [13]. Addressing the multi-disciplinary nature of PSE, we consider artifact-based coordination [7] with PPR assets and sub-tasks on the assets.

The *PPR Asset Network (PAN)* coordination artifact [4] provides a knowledge graph representing multi-disciplinary views on Industry 4.0 assets [13]. The PAN facilitates coordinating change re-validation on PPR assets and their properties [4]. However, it remains open how to leverage this capability to coordinate re-validation tasks during reuse in PSE.

**Traditional approaches to task management in PSE** use task management systems, such as *Jira*[1], to represent and track reuse process tasks with task content and relevant engineering artifacts. The progress of engineering tasks may be represented in engineering artifacts, in engineering objects as discipline-specific representations of engineered assets, or in private work spaces. Stakeholders, who represent the views for a scope of work, conduct multi-disciplinary reviews on task progress.

*Engineering-artifact-based task management* [14] collects discipline-specific engineering artifacts, such as mechanical or electrical plans or robot programs, in a team workspace as a reference in task management. However, the artifacts use heterogeneous semantics and lack explicit engineering object identification. These issues make it hard to determine required information for the task, task progress and dependencies between asset descriptions in several artifacts.

*Engineering-object-based task management* [9] represents assets, such as a robot, as engineering objects in a tool suite's database, which ensures a common model for several engineering disciplines. However, tool suites represent a limited set of assets only, making it hard to represent dependencies outside the scope of the tool suite.

Task management in PSE is usually combined with the ideas of work flow management [15] that can be combined with technologies such as Jira[1] to provide engineers with static task structures. However, sub-tasks may be medium or small, e.g., validating an engineering model or a set of engineering model elements. Therefore, a core requirement is the light-weight, technology-agnostic representation of sub-task progress and result states on elements of multi-disciplinary models, and their engineering dependencies.

In this paper, we develop the MRC approach by applying the combination of asset based task management with coordination artifacts on the re-use of engineering assets. Main characteristics of this approach will be representation of sub-tasks on a network of assets, the PAN, to automate the aggregation of a task's state from the states of its sub-tasks and to facilitate task analysis.

## III. RESEARCH QUESTION AND APPROACH

To improve the coordination of re-validation after changes in a multi-disciplinary reuse process in PSE, we followed the *Design Science* approach [16]. After reviewing literature on knowledge representation for reuse in PSE and artifact-based coordination of agent systems, two authors conducted stakeholder focus workshops with 30+ domain experts from 10+ domains (i) on engineering artifact exchange between PSE stakeholders, (ii) on required knowledge, and (iii) on gaps in artifact exchange [8]. From a domain analysis on the reuse of 80 types of robot cells at large PSE companies in automotive manufacturing [11], we elicited the use case *Multi-disciplinary Engineering Reuse Coordination* (cf. Section IV) that illustrates typical multi-disciplinary reuse process phases and tasks, and requirements for coordinating reuse task management. Building on the domain analysis [11], on guidelines for coordinating agent systems [7], and on the Industry 4.0 initiative [13], we derived the following research question.

***RQ.*** *What approach can represent the knowledge required for coordinating multi-disciplinary reuse tasks on assets in parallel and iterative production systems engineering?* We focus on the reuse of robot cells to automate joining car parts. As a prerequisite to move the reuse target state in an engineering organization from single- to multi-disciplinary reuse [2], we focus on quality assurance for several disciplines after the re-design of a property value. We address the RQ by designing and evaluating the *Multi-disciplinary Reuse Coordination artifact* [7] for reuse in parallel and iterative PSE.

The MRC artifact shall fulfill particular requirements to address this aim. The MRC artifact shall provide a reference system (*R1.*) to manage critical reuse processes that shall facilitate the efficient re-validation of high-value/risky assets after changes to their properties. Therefore, the MRC artifact shall represent *assets*, in particular, products, processes, and resources, and the engineering views on these assets, with domain-specific dependencies among assets (*R2.*). A core capability of the MRC artifact shall be the light-weight, technology-agnostic *representation of sub-tasks* and their progress and result states on assets and their properties (*R3.*). These are, especially, the elements of multi-disciplinary models that stakeholders use to review engineering progress on major design concerns in PSE, e.g., correct reuse of a component. The MRC artifact shall facilitate efficiently answering stakeholder questions on the progress state of tasks based on their sub-tasks (*R4.*).

Furthermore, *MRC methods* (*R5.*) shall facilitate instantiating the MRC artifact, e.g., reading/changing coordination states and change dependencies, to enact a coordination policy and aggregate a task progress state from its sub-task states as a foundation for quality assured multi-disciplinary engineering.

## IV. ILLUSTRATIVE USE CASE

This section introduces the use case *Multi-disciplinary Engineering Reuse Coordination* to illustrate requirements for improving artifact-based coordination of quality management in PSE based on assets. We report on reuse processes abstracted from a domain analysis [11] from real-world application engineering regarding the reuse of robot cells at system integrators of automation for car part manufacturing. A typical car factory consists of 200 to 300 robot cells that use 20 to 30 robot types [11].

The engineering goal is to reuse robot cells for assembling cars, in particular, for positioning and screwing car parts. Application engineering with a reusable robot cell requires coordinating up to 30 stakeholders [11]. These are mainly detail engineers, who adapt and validate robot cell engineering artifacts according to technical and business goals, such as technical feasibility and throughput of the cell. The use case focuses on a minimal set of stakeholders to design and validate the adaptation of a robot cell: project/quality manager, basic planner, and detail planners in mechanics and automation.

**Multi-disciplinary application engineering with reuse.** The domain analysis [11] revealed three application engineering phases [2] for reusing a robot cell.

*Phase 1. Reuse scoping and analysis.* Following the design of the overall production system, i.e., a car body assembly line, the basic planner selects reusable assets, such as a robot cell. The planner analyzes which parts of an asset are likely to require re-design due to specific production process requirements, reusable asset variants, such as robot cell types, and the asset environment in a work line. This phase results in a set of tasks for detail planners to re-design and validate robot cell assets (cf. Fig. 3).

*Phase 2. Re-design and re-validation of a reused asset.* In this phase, detail planners from several disciplines, with partial views on a asset, conduct tasks coming from the basic planner. Results are re-designed engineering artifacts in various disciplines and re-validation reports for changed asset elements. A cascade of changes and validation tasks may occur as changes may require (i) changes of and in related asset elements, possibly by another discipline, and (ii) the re-validation of asset elements with dependencies. Therefore, it is important to correctly understand the scope of required re-design and re-validation tasks to cover all necessary asset elements efficiently, and track task progress and results.

*Phase 3. Analysis of reuse results for improvement.* After the detail engineers concluded re-design and re-validation, the project manager analyzes the results to (i) ensure that all required tasks concluded consistently to continue with the engineering process; (ii) consider how to address failed tasks that prevent using results in the following process steps; and (iii) derive lessons learned to improve reuse on the type of asset reused. Therefore, the manager requires tracking the tasks and their results to provide high-quality data for analysis.

**Reuse task sequences.** Re-design and re-validation of a reused asset in Phase 2 of the multi-disciplinary application engineering process is a sequence of engineering tasks on scopes of PPR assets (cf. Fig. 2). An engineering *task* has a type, e.g., analysis, design, or validation, a multi-disciplinary scope of a set of assets and their properties, and a progress state, such as *in progress* or *closed*. Fig. 2 (right-hand side) shows typical task sequences on asset scopes and the process outcome. A *simple case* consists of analyzing an asset, re-designing a property, validating the change, and finishing successfully. A *defect fixing cycle* occurs if validation detects a defect that requires re-design and validation, until the validation succeeds. A process *failure* occurs if a task is found infeasible to

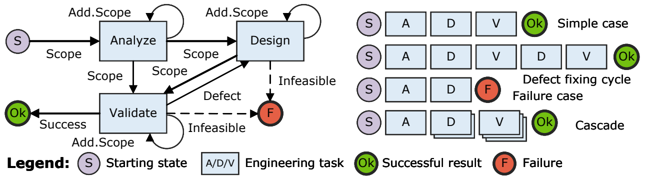

Fig. 2. Task sequences in multi-disciplinary application engineering w/reuse.

conduct, requiring re-planning on a higher level. A *cascade* occurs if a task on an asset has to address dependencies that require extending the scope of work. This scope extension may lead to new sub-tasks, e.g., a designer may require support from engineers of other disciplines, or validation dependencies require inspecting further assets. The tasks may look similar to the simple case, but concern a larger scope that may be hard to observe for the task management (cf. Fig. 6).

**Reuse coordination policy.** In this use case, we focus on the policy that successful re-design requires re-validation of all assets and properties that depend on a changed asset property.

**Traditional task management.** The use case includes up to 10 stakeholders in weekly multi-disciplinary reviews of task progress. Determining the actual progress state of design and validation tasks required domain experts to search for dependencies on assets in engineering artifacts, tools, and private notes, with imprecise results or requiring high effort. The project manager and planners estimated spending 10% to 20% of their effort on task management and coordination.

## V. MULTI-DISCIPLINARY REUSE COORDINATION

To address the research question and the coordination artifact requirements, this section introduces the *Multi-disciplinary Reuse Coordination (MRC)* approach, consisting of the MRC artifact and its application to a multi-disciplinary reuse process in PSE.

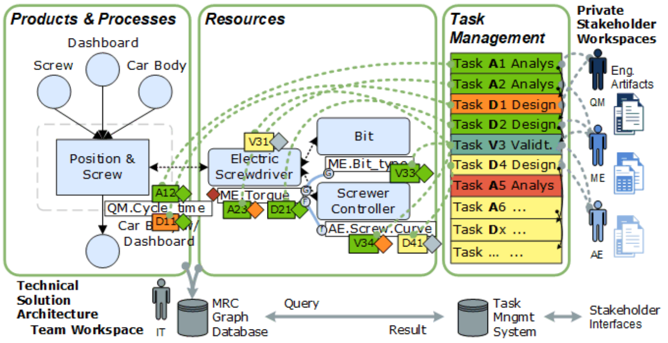

Fig. 3. Multi-disciplinary Reuse Coordination (MRC) Solution Overview.

Figure 3 shows an overview on the MRC solution approach: sub-task markers on PPR assets and properties are linked to tasks in task management (green dashed lines) to provide stakeholders with sufficiently detailed information on the progress and results of sub-tasks their work depends on. Technical dependencies between PPR assets and properties (blue solid lines) explicitly represent domain knowledge that is typically implicit expert knowledge [4], e.g., the relationship of screwing torque to the controller's screwing force curve. The MRC graph database stores the MRC artifact for efficient querying to inform the task management system on sub-task states and dependencies. For tasks they are involved in, stakeholders can see dependencies in their task management interfaces, augmented with information on relevant PPR assets and related stakeholders to facilitate informal coordination.

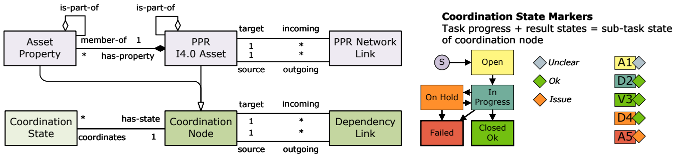

Fig. 4. MRC meta-model (in UML notation, based on [4]), with coordination state markers for sub-tasks on PPR assets and properties.

The goal of MRC is to design a minimal coordination artifact to represent sub-task states in relation to task states for iterative application engineering on a reusable robot cell.

**MRC artifact.** To design the MRC artifact for multi-disciplinary reuse, we extend the PPR Asset Network (PAN) meta-model [4] with a light-weight, technology-agnostic representation of sub-task progress and result states. These sub-tasks inform task management on sub-task progress on assets and on sub-task cascades that may extend the scope of a task.

Figure 4 (left) shows the PAN meta-model [4], based on the *I4.0 Asset Network* design [17]. The meta-model consists of (i) a network of PPR assets with properties (cf. Fig. 3, blue boxes) to address requirement To address requirement *R1.* (cf. Section III); and (ii) a dependency network (cf. Fig. 3, blue circles with letters) of coordination nodes to address *R2.*, i.e., assets or properties, with coordination states (cf. Fig. 3, colored markers).

The *Coordination State* of an asset or property represents the information required to define a specified coordination policy in the application context, e.g., engineering phase, design/validation lifecycle state, and update information, in a distributed project. To address requirement *R3*, Fig. 4 (right-hand side) introduces the coordination states of an asset or property referring to sub-task progress and result states, and their combination into sub-task markers.

*Sub-task progress states.* Similar to the best-practice Defect Life Cycle[2], a sub-task starts in the state *open* and typically moves to state *in progress* and finally to *closed ok*. A sub-task may be put *on hold*, e.g., if it has to wait for input, or finally move to state *failed*, if the task cannot be completed and requires escalation in task management. If a finished sub-task has to be re-opened, it will become a follow-up sub-task, linked to the original sub-task.

*Sub-task result states.* The result of a sub-task starts in state *unclear* and typically will move to result state *ok* or *issue*, depending on the nature and outcome of the sub-task.

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[2] Defect Life Cycle: www.guru99.com/defect-life-cycle.html

The progress and result states of the sub-task inform task management for aggregating the task state, e.g., a task may become *closed ok*, if all sub-tasks have this progress state.

A task management system can refer to assets and their sub-task progress states to aggregate sub-task states for a task. In their periodic review meetings, domain experts can review task states and dependencies of assets in the MRC PAN (cf. Fig. 5). The MRC PAN (i) provides references to sub-tasks and their progress and result states on engineering assets, (ii) represents domain-specific dependencies between the engineering assets and their properties that represent stakeholder disciplines, and (iii) provides knowledge required for enacting coordination agreements, e.g., for change management on sub-tasks.

**MRC artifact application to task management.** To address requirement *R5*, coordination artifact methods facilitate configuring and instantiating the coordination artifact, e.g., reading/setting coordination states concerning sub-tasks and change dependencies, as input (i) to enact a coordination policy, e.g., to identify re-validation candidates, such as assets that depend on a changed asset, and (ii) to aggregate a task's progress state from its sub-task progress states, foundations for quality assured multi-disciplinary engineering. Hence, the MRC PAN inherits the PAN interface [4] to instantiate, update, and query assets, their properties and relationships. In addition, the MRC PAN interface provides methods for sub-tasks (i) to instantiate a sub-task with an id, name, progress state, and result state, e.g., *set*(id, V31, open, unclear) (cf. Fig. 5); (ii) to update a sub-task with parameters similar to the method *set* (cf. Listing 1); (iii) to query assets for sub-tasks with query (MRC scope, sub-task name, progress state, result state), resulting in a list of sub-tasks that fit to the query criteria (cf. Listing 2); and (iv) delete a list of sub-tasks.

For a multi-disciplinary reuse process in PSE (cf. Section IV), the project manager wants to enact quality management coordination policies. Such policies are, e.g., (i) to identify re-validation candidates, such as assets that depend on a changed asset, or (ii) to aggregate the progress state of a task from its sub-task progress states. Task management represents the engineering tasks: analysis, design, and validation of reusing a robot cell (cf. Fig. 3) and their related tasks and engineering artifacts. Sub-tasks represent the task for one asset or property assigned to a specific stakeholder view as a basis for detailed tracking of task scope and progress. To address *R4.*, task management can query the MRC PAN to update the state of a task depending on its sub-tasks. Together, the assets, their properties, and coordination states concerning sub-tasks facilitate describing coordination policies that precisely refer to the engineering concepts in the reuse process. Fig. 3 illustrates a MRC PAN instance with selected sub-task markers and the associated task management list of engineering tasks.

## VI. EVALUATION AND DISCUSSION

This section reports and discusses results from a feasibility study (i) instantiating a *MRC PAN* from typical PSE artifacts; (ii) estimating the number of sub-tasks in MRC PANs for typical robot work cell sizes; (iii) designing graph database queries to the MRC PAN; and (iv) investigating the effectiveness of the MRC PAN in comparison to traditional engineering coordination artifacts. The feasibility study focuses on phase 2 of application engineering with reuse for a typical robot work cell in automotive manufacturing in the use case *Multi-Disciplinary Engineering Reuse Coordination* (cf. Section IV).

**MRC PAN.** Two authors of this paper instantiated a MRC PAN in a *Neo4J*[3] graph database. The MRC PAN elements were selected from a sample of robot cells [17] from the use case *Position and Screw* [4] (cf. Fig. 5). The graph database facilitated browsing and querying the MRC PAN according to the coordination policy in the use case *Multi-disciplinary Engineering Reuse Coordination* (cf. Section IV).

Fig. 5 shows a MRC PAN for the production process *Position and Screw a dashboard to a car body*, automated by a typical robot work cell with a robot and an electric screwdriver. Fig. 5 focuses on the most important assets and properties to illustrate the coordination policy for re-validation after changes. Fig. 5 (left-hand side) shows products, such as *Car Body* and *Dashboard*, transformed in processes, such as *Fasten Screw and Measure*. Products and processes are assets with properties, such as the property *Q.Cycle_time*. The property name contains the stakeholder view, such as *Q* for the quality manager, and a property path, in this case *Cycle_time*. Product and process assets are linked by *product-to-process* relationships according to the VDI 3682 guideline [18].

Fig. 5 (right-hand side) shows resources, such as *Robot* and *Electric Screwdriver*, automating the production processes, such as *Fasten Screw*, linked by *Process-Resource* links. Resources may consist of sub-resources, such as a *Screwer Controller*, related by *functional* links. Robot cells may contain several robots, and industrial PCs for their orchestration. These assets and links define the PAN [4], representing technical dependencies for change coordination. Assets, their properties, and links provide the basis to specify graph queries that answer questions from the coordination policy, e.g., *which assets are linked to a changed PPR Network Node?* Fig. 5 contains a task list in task management section, with tasks associated to sub-tasks that sub-task markers represent on assets, according to the sub-task coordination state model (cf. Fig. 4).

Fig. 6 (left-hand side) shows traces of typical task sequences in a multi-disciplinary reuse process, starting with the analysis of adaptation points of the robot cell to identify adaptation points that require design tasks. For example, the task sequence starting with task *A2* leads to a design-validation sequence. On the right-hand side, the associated sub-task tree, starting with sub-tasks *A2x*, reveals the task scope of assets, e.g., four validation sub-tasks *V3x* triggered by a design change in sub-task *D21* of the property *M.Torque* (cf. Fig. 5). While task *V3* appears to be *in progress*, the sub-tasks *V31* to *V34* exhibit diverse progress and result states, which inform the project manager on issues to address. In particular, which assets are involved in sub-tasks with issues (A23, V34) or failure (A51), i.e., the *Electric Screwdriver* and its controller.

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[3] Neo4J graph database: http://neo4j.com/

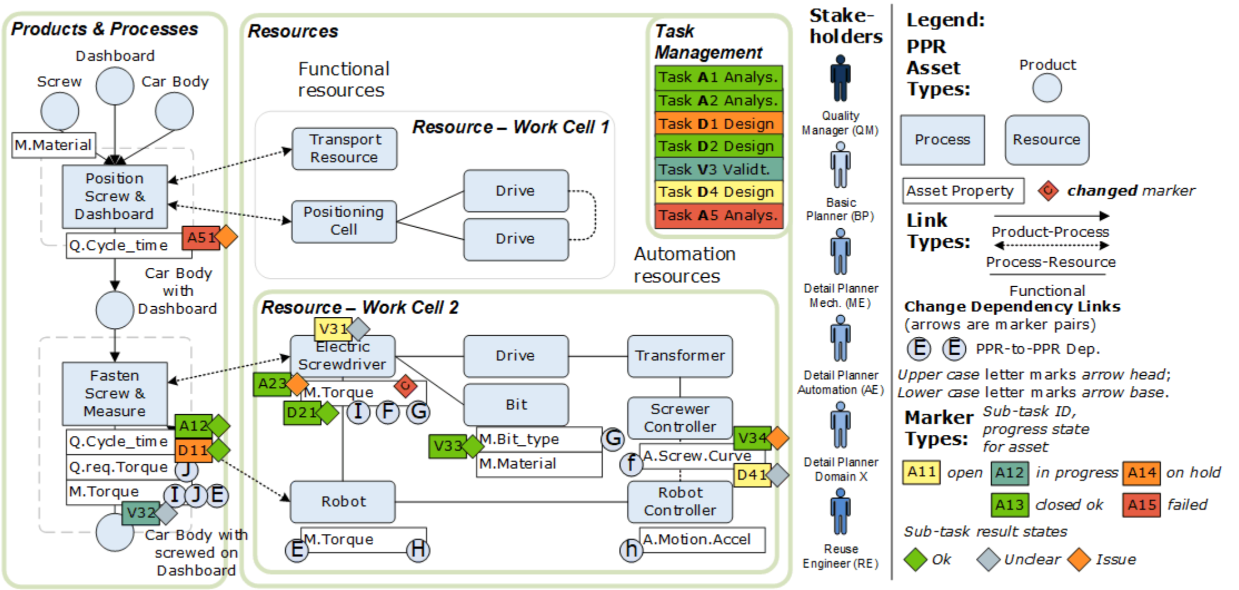

Fig. 5. *Snapshot of sub-task progress and result state markers in an MRC PAN* for the process *Position and Screw* with a robot work cell (based on [4], [17], notation: extended formalized process description based on VDI 3682 [18]).

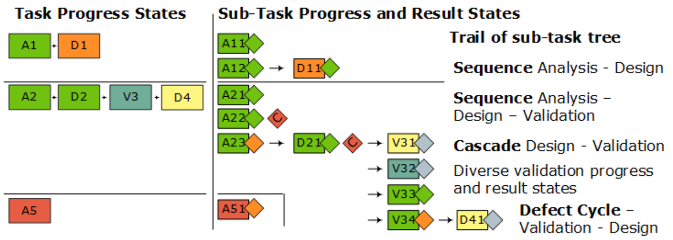

Fig. 6. Tasks and sub-tasks with progress and result state markers for a robot cell in use case *Multi-disciplinary Engineering Reuse Coordination*.

Further, issues (A51, D11) concern the cycle time, a core business requirement, of the production processes *Position* and *Fasten Screw*, and require project management attention.

The engineering of a complex production system requires fine-grained management of reuse tasks (i) for awareness of scope of activities and (ii) as a foundation for the analysis of traces of tasks and their outcomes (cf. Fig. 6). Advanced analysis includes considering the impact of a potential production change, e.g., a process that requires stronger screwing force, on the production system to assess the likely cost and risk of conducting a late design change before its implementation.

**MRC PAN size.** To investigate the viability of collecting and maintaining sub-tasks in a MRC PAN for the multi-disciplinary reuse of typical robot cells in automotive manufacturing (cf. Fig. 5), three authors built on a data sample from a domain analysis [11]. The analysis was conducted for a selection from 80 types of robot cells in a car plant [17]. Main drivers for the number of sub-tasks for application engineering were (i) the number of adaptation points on assets in a work cell, (ii) the number of stakeholder views, and (iii) factors for design and validation tasks, e.g., the ratio of design tasks to design detailing, to design and validation dependencies, and to defect fixing cycles. A *small robot cell* consisting of one robot and 10 resources, had 3 adaptation points and 3 main stakeholder views, leading to 7 design sub-tasks and 10 validation sub-tasks. A *large robot cell* consisting of 8 robots and 116 resources, had 25 adaptation points and 20 main stakeholder views, leading to up to 450 design sub-tasks and up to 800 validation sub-tasks.

```
MATCH pan=(a:Attribute)-[:has_PPRDependency *]-(b)
  WHERE a.name="M.Torque" AND
↪   a.ChangeState="Changed"
  WITH pan, COLLECT(b) AS candidates
  FOREACH(m IN candidates | SET m +=
↪   {Issue:$issue_id, Type:"Subtask",
    ProgressState:"Open", ResultState:"Unclear" } )
```

Listing 1: Cypher query marking validation sub-tasks on assets and properties.

**Graph database queries.** To facilitate analyzing the MRC PAN, *Cypher*[4] queries in Listings 1 and 2 illustrate the interface to access and change sub-task markers. The query in Listing 1 marks validation sub-tasks *V3x* for assets and properties that depend on the changed asset attribute *M.Torque* (cf. Fig. 5). Task management agents review and adapt these sub-tasks, e.g., to sub-tasks V31 to V34, to guide re-validation after a change. The query in Listing 2 retrieves a MRC PAN sub-graph of nodes with sub-tasks in progress state *failed* (cf. Fig. 5). Task management can aggregate task progress states from the retrieved sub-tasks.

**MRC artifact effectiveness.** *Coordination artifact design.* By design, the MRC PAN represents the required assets, coordination states, and change dependencies very well (*R2.*,

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[4] Open Cypher: http://www.opencypher.org/

```
MATCH pan=(a:Attribute)-[:has_PPRDependency *]-(b)
  WHERE a.Type="Subtask" AND
↪  a.ProgressState="Failed"
  RETURN pan
```

Listing 2: Cypher query for retrieving assets dependent on sub-tasks that failed.

cf. Section III) providing a reference system for reuse coordination (*R1.*). *Sub-tasks* represent required progress states and result states of a task for one asset or property very well (*R3.*). In comparison to traditional approaches, typical engineering artifacts represent engineering views for one stakeholder role, not collected by assets, and hence fall short in all aspects regarding assets, and their dependencies or associated sub-tasks [8]. Tool suites represent assets as engineering objects with progress states, but do not represent dependencies between assets beyond their scope, often resources [8]. Engineering objects could be extended, likePAN assets, to represent asset-specific progress states, providing overall average to good representation capabilities.

*Coordination artifact application to task management.* To instantiate and update a MRC PAN (*R5.*), a graph database, or a comparable data storage technology, provides efficient knowledge graph capabilities to interact (i) with a task management system, for keeping task and sub-task states consistent, and (ii) with other external information systems. In comparison, engineering artifacts provide coordination knowledge only for engineering progress or change of an artifact, not assets or sub-tasks. Tool suites provide good support for data aggregation and analysis for assets as engineering objects, but do not consider dependencies or sub-task progress for task management beyond their limited scope of engineering [8]. The coordination artifact allows (i) browsing, analyzing, and editing a PAN representation, e.g., in a periodic review meetings and (ii) access to sub-task information and trails via a graph database interface for further querying and processing, such as design or risk management (*R4.*).

These results indicate the MRC PAN to provide a more effective coordination artifact for multi-disciplinary reuse than traditional approaches in PSE (*R5.*).

**Discussion.** In PSE, engineering organizations aim at establishing reuse across engineering disciplines, such as mechanics and automation [2]. This paper investigated the research question: *What approach can represent the knowledge required for coordinating multi-disciplinary reuse tasks on assets in parallel and iterative production systems engineering?* To address this RQ, this paper introduced the coordination artifact *Multi-disciplinary Reuse Coordination (MRC) PAN* with a focus on the quality assurance coordination policy to re-validate assets after changes to related assets. The *MRC PAN* is based on coordination artifact design [4], [7] of the PAN and on recent advances in I4.0 asset data integration [13].

The MRC PAN provides essential coordination artifact capabilities [7], (i) an effective shared work space by extending the PAN and by representing sub-tasks with progress and result states for assets and their properties, as a reference system for reuse and re-validation task management across disciplines in multi-disciplinary engineering; (ii) mitigating coordination hurdles by providing a suitable level of detail for analyzing and guiding multi-disciplinary reuse tasks, e.g., to inform on sub-task cascades for task scope analysis; and (iii) establishing a coordination policy, such as re-validation after changes.

The modeling of sub-tasks as first-class model elements enables representing currently implicit domain expert knowledge and the automation of coordination rules. To this end, the MRC PAN facilitates integrating scattered domain knowledge on multi-disciplinary reuse. The asset-based design is compatible to the *I4.0 asset administration shell* design [13], facilitating light-weight integration with existing information systems (and artifacts) compatible to this standard.

The research in this paper goes beyond the state of the art in PSE reuse [2], [19]–[21], (i) by defining a fine-grained coordination artifact based on engineering assets and (ii) by initially demonstrating its applicability to task management for quality-assured reuse processes in PSE.

**Limitations.** The following limitations require further investigation. *Feasibility study.* The study focused on a use case derived from projects at large PSE companies in automotive industry, which may introduce bias due to the selection of coordination challenges, alternative approaches considered, and domain expert roles. To overcome these limitation, we plan case studies in a wider variety of application contexts. *Expressiveness.* The expressiveness of coordination dependencies and sub-tasks used in the evaluation may be limited. Industrial scenarios may require more complex sub-tasks and coordination conditions. Coordination problems with many asset types and properties require further investigation. *Data collection effort.* The information on assets, their properties, and asset network links can be efficiently derived from a PAN of a reused robot cell and associated engineering artifacts in a team work space. However, the considerable number of sub-tasks will require an approach for the prioritization and/or automation of sub-task definition and maintenance. Fortunately, similar structures of robot cells facilitate describing sub-tasks on robot cell and asset types, as a foundation for the efficient definition of graph queries that will be applicable to a range of similar robot cell types.

## VII. CONCLUSION

In PSE, engineering organizations aim at establishing reuse across engineering disciplines, such as mechanics and automation. However, (i) the coarse-grained representation of tasks and their coordination states and (ii) the scattered and heterogeneous domain knowledge make it hard to coordinate multi-disciplinary reuse tasks, in particular, the efficient re-validation of assets after changes to related assets, and increase the risk of unplanned rework and project delay.

In PSE, an adaptation in one discipline is likely to require focused design or validation activities in related disciplines, leading to design/validation cascades. Managing and automating design and validation activities requires capabilities for defining and tracking task progress and results states both for human experts and computers. Traditional approaches in PSE share artifacts and rely on domain experts to organize adaptation and validation tasks, with the risk of overlooking important tasks and insufficient results that lead to late unplanned rework or risky systems in operation.

Building on coordination artifact design [4], [7] of the PAN and recent advances in I4.0 asset data integration [13], this paper introduced the *Multi-disciplinary Reuse Coordination (MRC) PPR Asset Network.* For assets and their properties, the MRC PAN represents sub-tasks with progress and result states to provide a reference system for reuse and re-validation task management across engineering disciplines in in multi-disciplinary engineering. Assets reflect key design decisions, such as the configuration of a force curve for screwing that depends on the design of the selected screwdriver and the materials of the screw and products to join. Therefore, tracking sub-tasks on assets seems to provide a suitable level of detail for analyzing and guiding application engineering tasks for multi-disciplinary reuse.

In a feasibility study on reuse and re-validation for a typical robot work cell in automotive manufacturing, this paper investigated the capabilities of the MRC approach in comparison to traditional reference approaches for task guidance and tracking during reuse in PSE. Results show the MRC approach to be feasible and to provide effective capabilities for identifying risky assets for re-validation after changes during reuse.

Introducing a MRC PAN as a coordination artifact seems advisable in medium-to-large PSE reuse projects, where it can be expected to be less risky and more efficient than task management with heterogeneous artifacts. In this context, the MRC approach can facilitate automation for human and computer collaboration to address reuse processes, in order to efficiently use scarce expert resources.

**Future Work.** *Empirical studies of MRC PAN applications.* We will investigate MRC PAN-based methods in various PSE organizations to validate our findings. For instance, this comprises the automation of reuse processes and the investigation of advanced analysis methods, such as a change impact analysis in the co-evolution of robot cells in domain and application engineering.

*Scalability.* Due to the comprehensive scope of engineering tasks, the complexity of a MRC PAN, e.g., for a typical automotive plant with 200 to 300 work cells, may grow considerably. We plan to investigate means for reusing and exploring dependencies of sub-tasks for the efficient specification and tracking of sub-tasks.

*Security.* Aggregating domain knowledge in a MRC PAN creates high-value assets that require research on security concerns, e.g., using the knowledge to impede security attacks on many reused instances in several production systems.

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