PPRS: Production skills and their relation to product, process, and resource

Julius Pfrommer, Miriam Schleipen, and Jürgen Beyerer
Fraunhofer Institute of Optronics, System Technologies and Image Exploitation (IOSB)
Fraunhoferstr. 1, 76131 Karlsruhe, Germany
{julius.pfrommer, miriam.schleipen, juergen.beyerer}@iosb.fraunhofer.de

Abstract

To model increasingly adaptive production systems, skills are used to describe generic capabilities of the system components. In this paper, the authors extend the well-known division of production entities into product, process, and resource (PPR) with a skill definition. There are two main advantages for this approach: First, using PPR for the skill definition allows easy integration into existing models and tools. Second, there is a natural tendency to define very generic skills to capture all possible use cases. But at some point, skills have to be translated into precise instructions for execution. The model makes this dichotomy explicit and provides a common taxonomy for stakeholders concerned with skills on different abstraction levels.

1. Introduction

Shortened product lifecycles and the increasing number of product variants make time-consuming re-engineering of automated production systems a costly bottleneck. The SkillPro[1] project (http://www.skillpro-project.eu, started in 2012) aims to improve this situation, using 'Plug&Produce'-devices and automated planning based on a model of the generic skills those resources provide. Available skills are configured and dynamically combined to achieve production goals. To integrate the skill descriptions in a model of the overall system topology, SkillPro plans on using and extending the open standard AutomationML [1].

This contribution is organized as follows: Section two recapitulates the PPR concepts. Section three gives some background on using skills to model adaptive production systems. In Section four, an integrated framework for skills and PPR is presented together with an example application. Section five draws conclusions and gives an outlook on future research.

2. PPR concept definition

The distinction between product, process, and resource has been widely adopted in manufacturing and production (see [2], [3]). AutomationML, a data format for exchange of plant engineering information, also uses PPR in its data model [4] (see Figure 1).
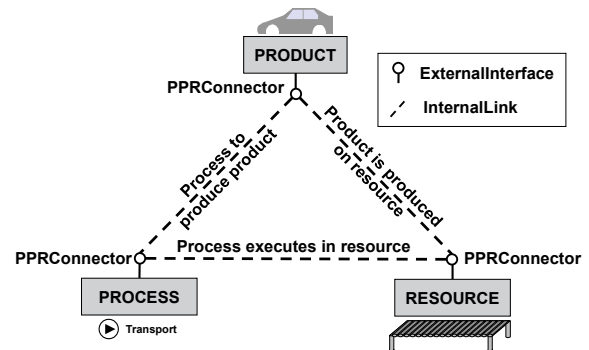

Figure 1. PPR concept in AutomationML [4].

In the following, a high level overview over the PPR concepts is given[2]:

Product: A product denotes a final or intermediate product type. Note the difference between a product type and the 'realized' work piece at runtime. In this work, it is assumed that all occurring (intermediate) product types are uniquely identified.

Process: A process represents changes to a product that occur during production. Processes may originate from several fields, such as manufacturing, transportation, assembly, etc. The network of all processes and their relations results in possible process plans or process chains.

Resource: A resource is a hardware or software entity involved in process execution. Examples for resources are robots, machines, or transport equipment. The set of resources and their relations result in the plant topology.

---

[2] See [3] for more detailed definitions

3. Related Works

Skills are a more recent concept for modeling production systems. They provide flexibility as they describe generic capabilities of production resources.

The authors from the SIARAS[3] project [5], [6], [7] differentiate between a top-down (AI, artificial intelligence,) approach and a bottom-up (engineering of components and programming of individual tasks) approach to skills. They use ontologies to store skills and their relations. This information is then used for automatic reconfiguration of production systems. The ROSETTA[4] project [8], [9], [10] aims to bring robotic skills in an environment where they interact with human workers. Huckaby and Christensen [11] provide a taxonomy for assembly tasks. They define skill primitives as necessary components to an assembly task. Constraints specify whether they are executable in a certain situation. Järvenpää et al. [12] define an ontology for capabilities in manufacturing and use it to map resources to production steps. Björkelund et al. [13] first make use of the PPR concepts in the context of skills. They relate skills to all three views of PPR and represent them as finite state machines. Smale and Ratchev [14] use capabilities for the multiple assembly system reconfiguration. Angerer et al. [15] and Barata et al. [16] model skills in an agent-based production system. They also combine skills in a dynamic fashion to accomplish more complex tasks. Weser and Zhang [17] discuss skill models with different levels of granularity and show how they can be combined in a planning framework. ISA95/IEC 62264 defines production- and process segment-capabilities not as generic skills, but rather as well-specified production steps (up to a start-time for execution) which can be committed to.

4. PPRS: A skill definition based on PPR

So far, there is no consensus on the definition of skills. Even worse, many authors use the same terms (skill, task, action, etc.), but assign different semantics. It is especially unclear which term denotes more abstract or generic skills, which term refers to compound skills, and at which point resource and product (required for the actual execution) come into play. Also, most existing skill definitions are closely linked to an implementation methodology.

In the following, the authors propose a skill definition that derives its semantics from the relation to the PPR concepts (see Figure 2). It is also independent of implementation technologies and can be realized for example using object-oriented concepts, agent-based systems, ontologies or relational databases. Figure 3 depicts a possible implementation by extending the AutomationML data format (drawing on the appropriate RoleClasses, InterfaceClasses, and SystemUnitClasses).
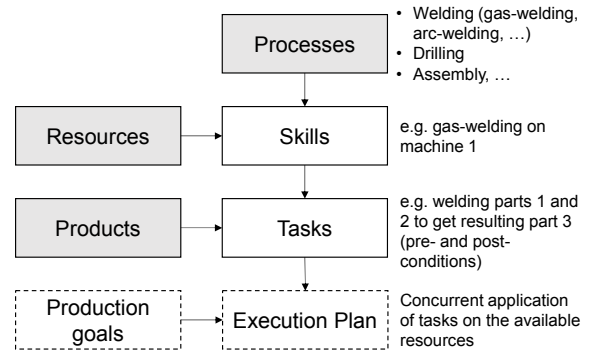

Figure 2. Skills integrated with PPR.

Product and **Resource** keep their original meaning.

Process: Processes ('abstract skills') are independent of products and resources: They denote generic capabilities that are useful in a production setting (e.g. 'welding'). Processes can form a hierarchy. Here, 'welding' would have 'gas-welding' and 'arc-welding' as child nodes. Many examples are listed in DIN 8580 (Manufacturing processes - Terms and definitions, division). But not all processes must relate to actual transformations of work pieces. They can also have origins in robotics (e.g. object detection, grasping), logistics, and other fields.

Skill: A skill is defined as the ability of a resource to perform a process. Skills are thus the relation of process and resource, enriched with additional information. For example, a CNC mill would be able to perform the process 'milling'. But this does not mean that every milling task is automatically executable on that resource. In case of the CNC mill, feasibility depends for example on the metal type and size of the work piece.

Task: A task is the application of a skill on a defined product type with a desired outcome. They form the relation between product and skill, defining the executing resource implicitly. From the outside, tasks are opaque (black boxes) with only the following information being publicly available:

- Pre-conditions (e.g. input type, tooling state)
- Post-conditions (e.g. output product type)
- Temporal constraints (duration, blocking of involved resources)

Internally, tasks of course contain all the information necessary for execution. They can also be constructed hierarchically, where a compound task is constructed from sub-tasks (basic or compound themselves) and ordering constraints:

- **Basic task**: Executable directly on a PLC or robot control. Basic tasks are either programmed using traditional instructions (such as IEC 61131-3 and others) or auto-generated, given a

---

sophisticated enough execution 'intelligence'. See [10], [7] on how to use work piece information and declarative descriptions of resources in order to define tasks. Basic tasks should have well-defined durations used for planning of concurrent task execution.

- **Compound task**: Combination of tasks, possibly stemming from different skills (e.g. detection, grasping, and movement). Every 'leaf' in a hierarchy of basic and compound tasks has to be a basic task for the hierarchy to be executable. Ordering constraints (e.g. task A must follow directly after task B) could be expressed by the temporal relations defined by Allen [18].

The tasks of a system represent all available production steps. They can substitute each other on a functional (e.g. gas-welding vs. arc-welding) or on a resource level (e.g. two identical machines). This knowledge can then be used by a planning entity.

Execution plan: Given the requirements and goals for production, a planning entity creates a feasible execution plan based on the available tasks. Efficient plans are likely to be highly concurrent, making parallel use of available resources.
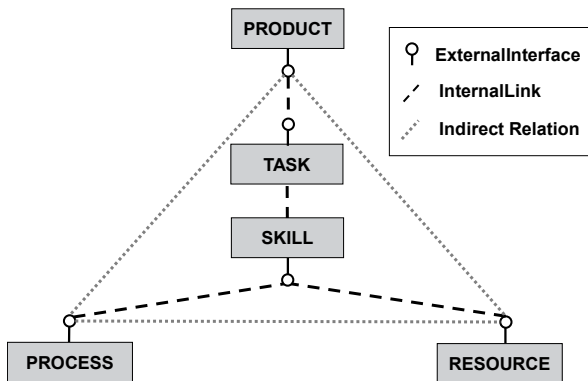

Figure 3. PPRS triangle with InternalLink-relations of AutomationML.

4.1. Example Application

The example application (see Figure 4) is part of a larger system to manufacture different kinds of wire baskets. Due to a large number of different products and small lot sizes, changing between product types needs to be done fast and with little human intervention.

Incoming raw wire is automatically fed into a cutting machine and cut into pieces of the desired length. All later movements of the wire pieces are performed by a robotic arm equipped with vision sensors and a grasping tool. The wire pieces are bent by one of two bending machines before being put in an output buffer for processing. But, only one of the resources is capable of 3D-bending. This has to be taken into account when planning the "route" products take within the system.
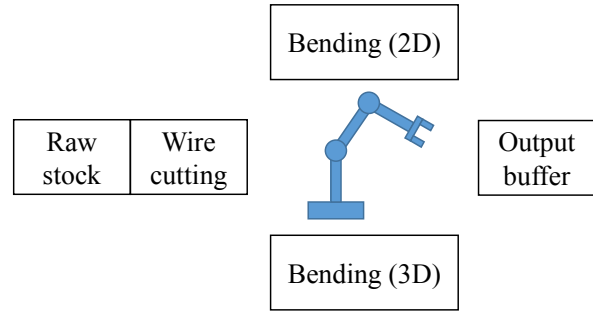

Figure 4. Example production system.

The following list contains the data objects that arise when modeling the example production system with four simple products in the PPRS framework.

Processes
- Cutting
- Bending (2D, 3D)
- Movement

Resources
- C – Wire cutting
- B', B'' – Wire bending (2D, 3D)
- R – Robotic arm

Products
- Four final products {p1, p2, p3, p4}. {p1, p2} need 2D-bending, {p3, p4} need 3D-bending; {p1, p3} are of the same length, {p3, p4} are of two different lengths
- Three intermediate products (after cutting, but before bending) {ip1, ip2, ip3}. Here, ip3 can be bent into either p1 or p3.

Skills (Process × Resource)
- C1 (cutting on machine C)
- B1 (bending on B'), B2 (3D bending on B'')
- M1 (grasp and move with robotic arm R)

Tasks (Skill × Product)
- C1.ip1 – C1.ip3 (cutting of the different pieces)
- B1.p1, B1.p2 (2D bending of products p1, p2)
- B2.p3, B2.p4 (3D bending of products p3, p4)
- M1.ip1 – M1.ip3, M1.p1 – M1.p4 (movement of intermediate and final products)

Note that there is an ambiguity for task M1.ip1 whether to move intermediate product ip1 to the 2D or to the 3D-bending machine. This can be modeled a) by defining additional tasks for the different locations or b) by having actions with an arity (requiring at least one additional parameter as input). Also, the movement tasks involve more than one resource (here, the robotic arm plus the involved machine) during execution.

A prototype planning entity has been implemented to find feasible execution plans based on the above tasks, the initial system state, and the production goals. The technical details are however outside the scope of this contribution.

5. Conclusion

The authors introduced a definition of skills in production systems as an extension of the PPR concept. Based on an example application, it was shown how skills can be applied in a production setting. As a next step, an extension of AutomationML with PPRS will be proposed to exchange information about skill-based adaptive production systems.

The remainder of this section enumerates some open research questions relevant for PPRS and production skills in general. First, several common features of production systems have not yet been incorporated into the skill model. For example machine tooling, mobile transportation units, or using containers to transport several work pieces at once. Second, automatically extracting executable tasks from product descriptions has been done only for a small number of production domains in the literature so far. Third, plan generation still raises runtime complexity issues. Fourth, plan execution is likely to be hindered by unforeseen events. These should be accounted for by either sufficient fallback strategies or the possibility to adapt the execution plan in an online fashion.

References

[1] R. Drath, A. Luder, J. Peschke, and L. Hundt, "AutomationML - the glue for seamless automation engineering," in *2008 IEEE Conference on Emerging Technologies & Factory Automation (ETFA'08)*, Hamburg, 2008.

[2] P. G. Maropoulos, K. R. McKay, and D. G. Bramall, "Resource-Aware Aggregate Planning for the Distributed Manufacturing Enterprise," *CIRP Annals - Manufacturing Technology*, vol. 51, no. 1, 2002.

[3] A. F. Cutting-Decelle, R. I. M. Young, J. J. Michel, R. Grangel, J. Le Cardinal, and J. P. Bourey, "ISO 15531 MANDATE: A Product-process-resource based Approach for Managing Modularity in Production Management," *Concurrent Engineering*, vol. 15, no. 2, 2007.

[4] M. Schleipen and R. Drath, "Three-View-Concept for modeling process or manufacturing plants with AutomationML," in *2009 IEEE Conference on Emerging Technologies & Factory Automation (ETFA'09)*, Mallorca, Spain, 2009.

[5] O. Angelsmark, J. Malec, K. Nilsson, S. Nowaczyk, and L. Prosperi, "Knowledge representation for reconfigurable automation systems," in *Proceedings of the 9th National Conference on Robotics*, Piechowice, Poland, 2006.

[6] J. Malec, A. Nilsson, K. Nilsson, and S. Nowaczyk, "Knowledge-based reconfiguration of automation systems," in *2007 IEEE International Conference on Automation Science and Engineering (CASE'07)*, Scottsdale, Arizona, 2007.

[7] M. Bengel, "Model-based configuration-A workpiece-centred approach," in *ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots (ReMAR)*, London, 2009.

[8] A. Björkelund, L. Edstrom, M. Haage, J. Malec, K. Nilsson, P. Nugues, S. G. Robertz, D. Storkle, A. Blomdell, and R. Johansson, "On the integration of skilled robot motions for productivity in manufacturing," in *2011 IEEE International Symposium on Assembly and Manufacturing (ISAM'11)*, Tampere, Finland, 2011.

[9] A. Björkelund, J. Malec, K. Nilsson, and P. Nugues, "Knowledge and skill representations for robotized production," in *Proceedings of the 18th IFAC Congress, Milano*, 2011.

[10] J. Malec, K. Nilsson, and H. Bruyninckx, "Describing assembly tasks in declarative way," presented at the Workshop on Semantics, Identification and Control of Robot-Human-Environment Interaction at ICRA 2013, Karlsruhe, Germany, 2013.

[11] J. Huckaby and H. I. Christensen, "A Taxonomic Framework for Task Modeling and Knowledge Transfer in Manufacturing Robotics," in *Workshops at the Twenty-Sixth AAAI Conference on Artificial Intelligence*, 2012.

[12] E. Järvenpää, P. Luostarinen, M. Lanz, and R. Tuokko, "Presenting capabilities of resources and resource combinations to support production system adaptation," in *2011 IEEE International Symposium on Assembly and Manufacturing*, Tampere, Finland, 2011.

[13] A. Björkelund, J. Malec, K. Nilsson, P. Nugues, and H. Bruyninckx, "Knowledge for Intelligent Industrial Robots," in *2012 AAAI Spring Symposium Series*, 2012.

[14] D. Smale and S. Ratchev, "A Capability Model and Taxonomy for Multiple Assembly System Reconfigurations," in *Information Control Problems in Manufacturing*, 2009, vol. 13.

[15] S. Angerer, R. Pooley, and R. Aylett, "Self-Reconfiguration of Industrial Mobile Robots," in *Proceedings of the 4th IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO'10)*, Budapest, Hungary, 2010.

[16] J. Barata, M. Onori, R. Frei, and P. Leitão, "Evolvable production systems in a RMS context: enabling concepts and technologies," in *Proceedings of the 2nd International Conference on Changeable, Agile, Reconfigurable and Virtual Production*, Toronto, 2007.

[17] M. Weser and J. Zhang, "Autonomous planning for mobile manipulation services based on multi-level robot skills," in *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'09)*, St. Louis, MO, USA, 2009.

[18] J. F. Allen, "Maintaining knowledge about temporal intervals," *Communications of the ACM*, vol. 26, no. 11, 1983.