Recipe-Based Engineering and Operator Support for Flexible Configuration of High-Mix Assembly

Jack Verhoosel, Michael Bekkum

Recipe-based Engineering and Operator Support for Flexible Configuration of High-Mix Assembly

Jack P.C. Verhoosel[1] and Michael A. van Bekkum[1]

[1]TNO Data Science, Soesterberg, The Netherlands
jack.verhoosel@tno.nl, michael.vanbekkum@tno.nl

Abstract. Nowadays, manufacturers must be increasingly flexible to quickly produce a high mix of on-demand, customer-specific, low volume product types. This requires flexible assembly lines with operators that are well-supported in their constantly changing assembly task, while producing high-quality, first-time-right, zero-defect products. Information coming from various supporting systems, such as ERP, MES and operator support systems, needs to be combined by the operator that configures the assembly line with materials, instructions and machine initialization settings. In this paper, we present a knowledge model that captures the main concepts and their relations in flexible manufacturing to deal with these challenges. This model is constructed by integrating existing manufacturing ontologies and can be used as the basis for information collection, exchange and analysis in information systems used in flexible manufacturing. The model supports (1) easy definition of recipe-based manufacturing instructions for engineers and operators, and (2) flexible, modular and adaptive support for human/cobot instructions. We also describe a demonstration set-up with an existing operator support system (OPS) in which the recipe concept is used in the engineering process to easily reuse existing modular components for assembling different product types.

Keywords: Recipe-based manufacturing, operator support, modular and adaptive instructions

1 Introduction

In the manufacturing industry, there is currently a trend towards personalized manufacturing to meet specific customer needs. Instead of mass-production of a single product type, manufacturers must be able to quickly produce on-demand, customer-specific, slightly different types of the same product. To avoid maintaining a large stock of each of these product types, these manufacturers must be able to handle a high mix of low volume product types. This requires flexible assembly lines with operators that are well-supported in their constantly changing assembly task. Flexibility in executing these assembly activities should increasingly lead to high-quality, first-time-right, zero-defect products.

In the context of this trend towards flexible manufacturing, currently available assembly manufacturing systems cannot cope well with the resulting requirements. These systems are usually manually configured for a new product order, which is increasingly inefficient in a flexible manufacturing environment that combines manual assembly cells, collaborative robots (cobots) and automated test stations. Information coming from various supporting systems, such as ERP, MES and operator

adfa, p. 1, 2011.

support systems, needs to be combined by the operator that configures the assembly line with materials, instructions and machine initialization settings.

The IT support in current MES solutions is very solution-specific and does not make use of standardized, modular components to build recipes for production processes. Furthermore, state-of-the art operator support systems do not consider adaptability based on the actual skill level and instantaneous operator capacity. Feedback from real-time measurements of performance, workload and motivational aspects and assembly instructions can provide customized instructions to the human operator and thereby improve motivation, workload and productivity/product quality.

In this paper, we present a data-driven approach to deal with these challenges that results from the cooperation within the Dutch FlexMan project between three industry partners in the manufacturing area, Bronkhorst, Omron and TE Electronics, and TNO as knowledge institute. The FlexMan project is one of the fieldlabs in the Smart Industry Initiative, that aims to accelerate development, test and implementation of smart industry technologies in collaborating networks of companies[1]. We define a knowledge model that captures the main concepts and their relations in flexible manufacturing. This model can be used as the basis for information collection, exchange and analysis in information systems used in flexible manufacturing. The model supports (1) easy definition of recipe-based manufacturing instructions for engineers and operators, and (2) flexible, modular and adaptive support for human/cobot instructions.

In the next section, we discuss the concept of flexible, recipe-based assembly and describe in more detail the environment in which the engineer and the operator need to deal with a high mix of low-volume product types. Then, we introduce our knowledge model and describe the various views on products, processes, resources and recipes. Successively, we describe a set-up in which the recipe concept of this knowledge model is used in the engineering process to easily reuse existing modular components for assembling different product types. In addition, we describe how the operator is supported with generic instructions defined in the knowledge model. Finally, we present our conclusions and future work in this field.

2 Flexible, recipe-based assembly

Manufacturers offer flexibility in products by giving customers the option to select for instance different colors, sizes, materials and other variables of the product in low volumes. This creates a few process engineering and operator support challenges.

Before introducing these flexibility options to the customer, the process engineer needs to design manufacturing processes for multiple types of the same product with only small differences. These manufacturing processes consist of a combination of assembly, configuration and testing steps including operator instructions that are mostly generic and thus reusable for each product type. They only differ in the specific materials and resources to be used which can vary in number, size, colour etcetera as well as in the order in which the process steps need to be executed.

---

[1] Smart Industry initiative, https://www.smartindustry.nl/en/

Consequently, the process engineer needs a design environment that gives support to the task of easily developing a manufacturing process for a new product type. The (re)use of recipes with basic configurations of process steps and their operator instructions is a good approach to this engineer task. From these recipes, flexible instruction sets can be automatically generated to guide the division of the tasks of the operator possibly in combination with a collaborative robot (cobot) during the manufacturing process.

In a flexible manufacturing environment, the assembly line operator is confronted with a high mix of assembly tasks resulting from customer-specific low-volume product orders. In principle, any next assembly task differs from the previous one as a different product or product type needs to be assembled.

In such a rapidly changing environment, the operator support should be maximally suited towards the operator by giving him/her simple and clear instructions on what to do. An example of such a support system can be found in Fig. 1 in which instructions and assembly locations are projected onto the working space of the operator. Apart from the exact technology of the front-end operator support system (projection, presentation, hololens), the main challenge is to switch rapidly between the instructions of different product types. A recipe-based IT system that supports the operator is well-suited for this challenge.

Fig. 1. Flexible operator support system with instruction projection.

Consequently, a recipe-based knowledge model is needed that is used to make the various IT systems involved in manufacturing interoperable, such as the ERP system with product orders, the engineer system that produces the recipes, the MES system that guides the operational manufacturing and the operator support system that instructs the operator. In the next section, we describe this knowledge model in more detail.

3 Related work

Ontologies are explicit, formal specifications of terms in the domain and of the relations among them [1]; the fact that formal logic underlies the model makes the ontology machine-readable and – interpretable. Our knowledge model is an ontology of concepts and relations relevant to the processes of flexible manufacturing and recipe-based assembly.

Existing assembly design and manufacturing models have been studied to define our knowledge model. These ontology models for assembly processes focus among others on unified approaches towards reconfigurable assembly system design [2], geometry information or variability in an extensive assembly design ontology (AsD) [3] and assembly process planning, defining process operations and required resources [4]. MASON [5], is a well-known model that presents generic core ontologies for knowledge sharing and interoperability in the manufacturing domain, specifying concepts for products, operations and manufacturing resources. . An MDA approach to define concepts in the product lifecycle is presented in [6]. The ontology we present here builds on these existing domain models by reusing concepts relevant to the context and needs of our model.

A recipe-based semantic approach to assembly has been presented in [7] as a methodology for product-resource requirement integration, without taking the concept of a recipe explicitly into account. International standardization for process control ANS/ISA-88-2010 [8] defines a procedural control models for batch process control. The ontology discussed in this paper, adapts some of the ideas behind this standard and defines the concept of recipe as well as recipe procedures explicitly in order to support recipe-based manufacturing in an assembly cell.

4 Knowledge model for flexible manufacturing

We discern four distinct models to formally define the domain: (1) a product model that defines building blocks for products and how they are related, (2) a process model that describes both logical and temporal structures for activities, (3) a resource model that expresses a functional and logical structure for manufacturing facilities and resources and finally (4) a recipe model that defines recipes as a set of instructions for manufacturing products. The model has been designed with input from all stakeholders in the FlexMan project to assure its compliance with current practices in manufacturing.

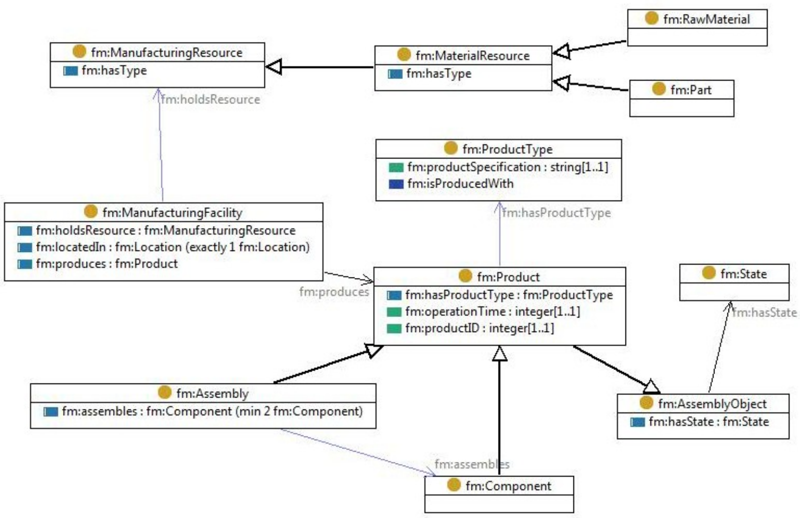

Fig. 2. Product modelling in the knowledge model.

Product model

The product model (Fig. 2) consists of products (*Product*) as things that have been manufactured to be sold to a customer (third party). Products are manufactured in a facility (*ManufacturingFacility*) and are either components (*Component*) provided by third parties or complex subassemblies (*Assembly*) of their own that come from a source outside the assembling system in question. Every product is an assembly object (*AssemblyObject*) that has a certain state (*State*). That state (ready, nearly-ready, in-progress, etc.) changes due to activities in the manufacturing process (cf. process model). Manufacturing resources such as parts (*Part*) and raw material (*RawMaterial*) are input to the assembly process.

Process model

The process model (Fig. 3) describes both logical and temporal structures for activities (*ActivityType*) on four different levels:

- Processes (*ProcessType*), are collections of lower level activities with the purpose of facilitating assembling of an assembly or subassembly. They are described by means of recipes (e.g. assemble PC) and are composed of tasks.
- Tasks (*TaskType*) are processes which facilitate a clearly definable portion of work towards the completion of a product (e.g. assemble parts A and B). A task is composed of a set of operations.
- Operations (*OperationType*) are activities which facilitate a state change of entities that are part of a product within the scope of a specific Task. An Operation is composed of a set of Actions. Operations are normally carried out by Equipment Units.
- Actions (*ActionType*) are the most fundamental activities (hold part A with tool 1), defined by use of equipment (*EquipmentResourceType*) and requiring a certain capability (Capability) from a physical agent (human, robot/cobot).

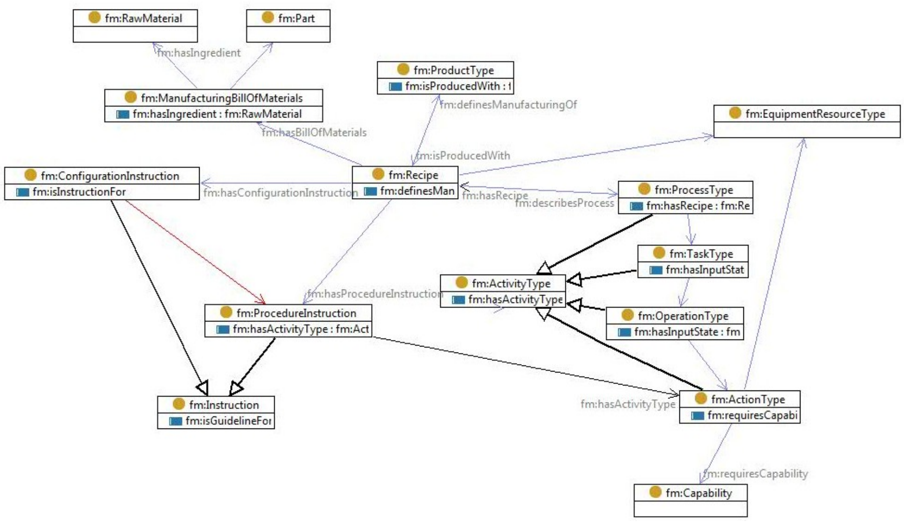

Fig. 3. Recipe and process modelling in the knowledge model.

Every activity has a description (*ActivityDescription*) and several time parameters (*TimePoint*), such as start-/stopping time.

Recipe model

In the context of assembly, we consider a recipe to be a set of instructions on manufacturing a product. Rather than viewing it as an object with properties we consider it to be a process, which has a series of steps or activities required for its execution and the materials and utensils needed. In our model (Fig. 3), a recipe (*Recipe*) holds the necessary set of information that uniquely defines the production requirements for a specific product, in accordance with [8]. It consists of a set of instructions (*Instruction*) that detail a manufacturing process by describing:

- What equipment is required (*EquipmentResourceType*).
- How equipment must be configured (*ConfigurationInstruction*).
- What ingredients are required (*ManufacturingBillofMaterials*).
- The procedure to execute the recipe in several steps (*ProcedureInstruction*)

Resource model

Our resource model expresses both a functional and logical structure for manufacturing facilities and resources (Fig. 4). A manufacturing resource (*ManufacturingResourceType*) is (1) a piece of equipment (*EquipmentResource*) such as a tool or a machine, (2) an agent (*PhysicalAgent*), being either a human (*Human*) or a robot (*Robot*) that has the capability (C*apability*) to perform an activity or (3) a certain material (*MaterialResource*). Manufacturing resources are present in a production facility (*ManufacturingFacility*), in a toplogy that may contain cells (*Cell*) with optionally one or more work stations (*WorkStation*).

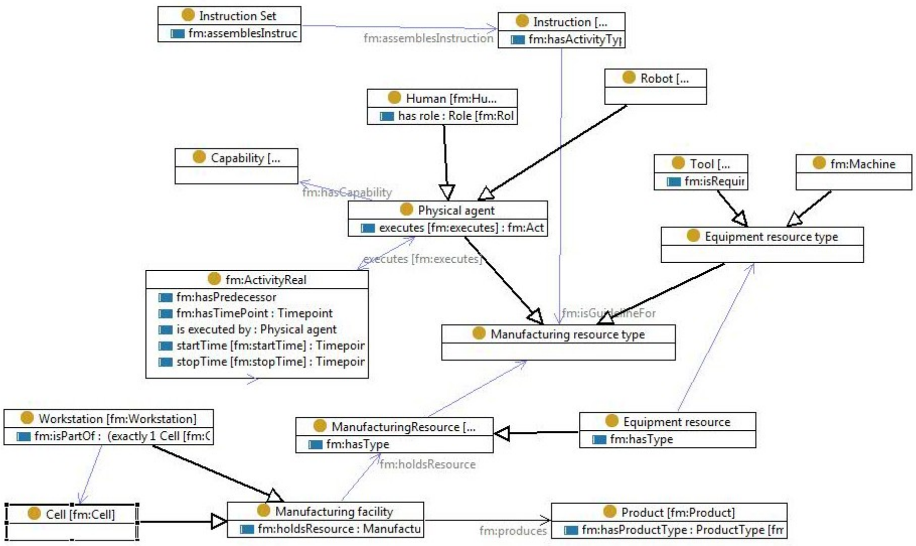

Fig. 4. Resource modelling in the knowledge model.

The current knowledge model provides a vocabulary and model for reasoning about recipe-based operator support in flexible manufacturing. By adhering to Gruber's principle of minimal ontological commitment and extendibility [9], we allow freedom to specialize and instantiate the model in a variety of manufacturing environments and provide support for a variety of assembly activities. The minimal manufacturing facility topology or equipment resource type specification e.g. both provide a basis for future extensions.

5 Demonstration set-up

To validate the usefulness of our knowledge model, we have created a demonstration environment (Fig. 5). The environment contains a process engineering system with a knowledge modelling tool, Topbraid Composer, that is used by the process engineer to instantiate basic, reusable process steps and their operator instructions based on our knowledge model. The process engineer can then use these reusable process steps and their operator instructions to define a master recipe for the assembly of a certain product type. These reusable process steps in the master recipe are independent of the actual OPS system that is used to support the operator in the assembly task.

The master recipe is being exported as an XML-file from the knowledge modelling tool and imported into the OPS MES system. This system has a specific editing tool that is used to extend the master recipe with OPS-specific configuration actions, such as the exact position on the assembly canvas. This results in an OPS-specific control recipe to be used by the operator. In our demonstration set-up, we use the OPS Light Guide system as the operator support system that instructs the operator.

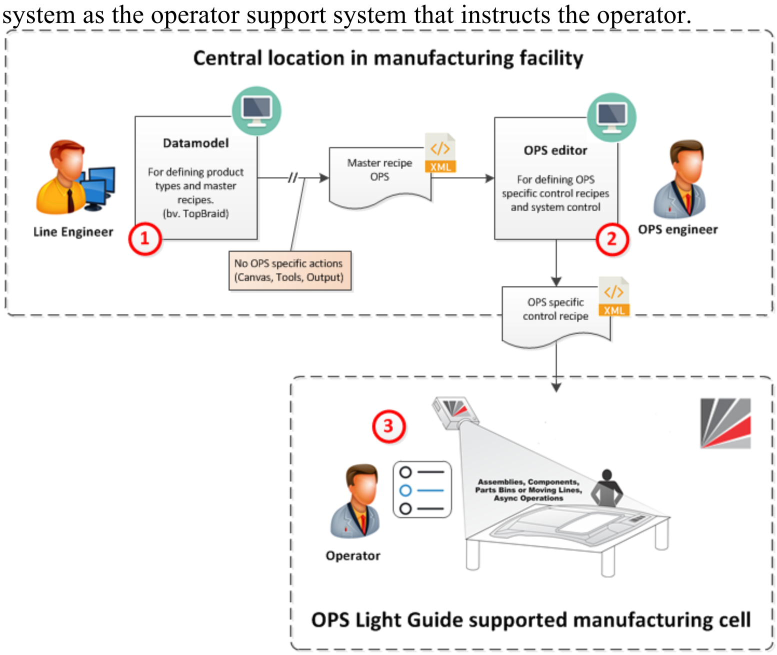

Fig. 5. Demonstration set-up of flexible manufacturing based on the knowledge model.

For demonstration purposes, we have used our knowledge modelling tool to define modular reusable process steps for three different types of the same flowsensor product manufactured by one of our project partners in the FlexMan project. A master recipe was generated for each of the three flowsensor types using these reusable process steps. The master recipes were only slightly different for each type in terms of size and color of material to be used. The master recipes could then be easily used to define three control recipes for the three types of flowsensors. When generating the master recipes, we encountered the following limitations and challenges:

- Generating a master recipe was done by instantiation of the knowledge model for a flowsensor type. Although the master recipe can be reused, adapting it to get a new master recipe for another flowsensor needs to be done carefully. Some of the instances can be copy-pasted and adapted, while others need to be reused as they are. For instance, *ProcessType* and *TaskType* instances need to be copy-pasted and slightly changed, while *OperationType*, *ActionType* and *OperatorInstructions* can be reused as they are or extended with new ones. This needs to be well-thought of by the process engineer.
- Although the master recipe is meant to be independent of OPS-specific configurations, most of the instructions in these configurations are the same. Therefore, the wish emerged to add these reusable configuration instructions to the knowledge model. The challenge is then to not mix up the master recipe and the control recipe in the knowledge model and its instantiations.

Finally, we emulated an ERP system with product orders for the three types of flowsensors. These sequence of product orders was such that the operator was presented with a mix of the three types and thus with a flexible and changing assembly task. When using the knowledge model in the process engineering environment and the operator support system, we learned some lessons:

- Usage of modular reusable process steps simplifies the task of the process engineering for quickly designing a manufacturing process for a new product type.
- Designing an OPS-independent master recipe for a product type is an advantage for the process engineer as he/she does not have to deal with all the configuration details of a specific OPS-system.
- The assembly line can easily switch between different product types as the control recipes are available for the operator with a specific set of assembly instructions to be executed.

6 Conclusions and future work

This paper discusses the development of a knowledge model for (1) recipe-based product design and configuration of assembly cells and (2) automated generation of operator instructions. The first version of the knowledge model specifies a model that focuses on composite assembly activities and provides recipe-based support for instruction sets that can be generated specifically for the product type that is to be assembled. This ontology is then used in a scenario to provide the master recipe with accompanying instruction set to an operator support system. Currently, the application scenario focuses on flexibility in providing operator support in a high-mix product variety. In more advanced scenarios, we can further improve flexibility by considering specific human/cobot capabilities, manufacturing facility dynamics and operator context, operator behavior and/or experience. As a future enhancement to the knowledge model, we are also considering product feature variability scenarios, that introduce more complex configurations of the same product type in manufacturing.

7 References

1. Gruber, T.R. 1993. A translation approach to portable ontology specifications. *Knowledge Acquisition*. 5, 2 (1993), 199–220.
2. Lohse, N. et al. 2005. Towards a unified assembly system design ontology using Prot{é}g{é}. *Proceedings of the 8th Intl. Prot{é}g{é} Conference, Madrid, Spain*. July (2005).
3. Kim, K.-Y. et al. 2006. Ontology-based assembly design and information sharing for collaborative product development. *Computer-Aided Design*. 38, 12 (2006), 1233–1250.
4. Huang, Z. et al. 2015. Ontology Model for Assembly Process Planning Knowledge. *Proceedings of the 21st International Conference on Industrial Engineering and Engineering Management 2014*. (2015), 419–423.
5. Lemaignan, S. et al. 2006. MASON: A proposal for an ontology of manufacturing domain. *Proceedings - DIS 2006: IEEE Workshop on Distributed Intelligent Systems - Collective Intelligence and Its Applications*. 2006, July (2006), 195–200.
6. Chungoora, N. et al. 2013. A model-driven ontology approach for manufacturing system interoperability and knowledge sharing. *Computers in Industry*. 64, 4 (2013), 392–401.
7. Agyapong-Kodua, K. et al. 2014. Recipe-based integrated semantic product, process, resource (ppr) digital modelling methodology. *Procedia CIRP*. 17, (2014), 112–117.
8. ANSI/ISA-88.00.01-2010 Batch Control Part 1: Models and Terminology (2010)
9. Gruber, T. 1995. Toward principles for the design of ontologies used for knowledge sharing. *International Journal of Human-Computer Studies*. 43, 5–6 (1995), 907–928.