A generic product and resource description to enable capability matchmaking for Production as a Service

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Abstract: The shift from mass production to mass customization and product personalization has a strong impact on the manufacturing industry. The production of small lot sizes or completely individualized products on large scale remains a challenge for the manufacturing companies. Concepts such as "Production as a Service" promise a more efficient manufacturing of small lot-sizes while making better use of existing production resources. In a world where different products will compete for the same resources alternative process chains gain in importance to achieve a global optimum in manufacturing. This paper reviews existing approaches for a generic description of products and the matching of product and manufacturing resources allowing for the generation of alternative process chains. Based on the findings product and resource are described and a matching approach is outlined.

Keywords: - Industry 4.0 technologies and concepts, Cyber Physical Systems modelling and applications, generic product and resource description, Production as a Service, Matchmaking approach

1. INTRODUCTION

Digitization and globalization lead to new requirements for manufacturing and result in challenges such as shorter product lifecycles and the demand for individualized production. Combined with the technological progress these challenges will change the way of manufacturing whereas changeability will be the key for manufacturers to adjust to the new challenges. (Abele and Reinhart 2011). Modern communication technology enables the use of service orientation to encapsulate the Cyber physical production modules capabilities to a manufacturing network (Jammes and Smit 2005).

With the possibilities of virtualization, the paradigm of cloud manufacturing emerges. Xu 2012 defines cloud manufacturing as: "[…] a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction". A subset of the paradigm is "Production as a Service" (PaaS). Within the concept PaaS the manufacturer acts as provider of production capacities and capabilities. Especially for individualized products the manufacturing can be optimized to meet customer and market requirements as well as improve the utilization of manufacturing equipment (BMWi 2016). This approach can tackle the problem that product developers with small lot-sizes and customized products lack opportunities to find manufacturing companies with sufficient manufacturing capacity and flexibility and on the other hand, there are manufacturing companies with underutilized and therefore inefficient manufacturing equipment (Balta et al. 2018).

The objective of PaaS is the dynamic combination of "manufacturing services" as a virtual supply chain. The customer can select the required manufacturing services without any knowledge about the physical location of the resource or the infrastructure which provides the service (Hermann et al. 2019). The requirements from this scenario deviate fundamentally from the capabilities of classical systems of production planning and control (PPC). In the classical approach production resources and capacities are optimized for a specific product and a fixed production plan is created, an adaptation is often associated with high expenditure (Keddis, Kainz and Zoitl 2014). In the case of individualized products, the optimization of single processes is questionable to reach a global optimum in production (Denkena, Dittrich and Jacob 2019). In a manufacturing environment where many products compete for the same manufacturing equipment local optima must be avoided. That leads to the requirement that manufacturing relevant product properties must be described as general as possible and without a defined specific process chain. Matched with the capabilities of the available manufacturing equipment different alternative process chains are generated. However, for such an automated approach the interdependencies between the different production technologies must be considered.

This paper evaluates different approaches of a generic description of the product and its properties as well as the corresponding resources to enable capability matching. A new approach is developed describing the product and in a generic way as well as the manufacturing equipment allowing a matchmaking for the PaaS scenario of generating alternative process chains without predefined manufacturing processes. Outside of the scope of this paper are assembly processes as well as fixture requirements to perform a manufacturing process.

2. STATE OF THE ART

The state of the art is divided into publications concerning a generic product description in the engineering domain and publications concerning the matchmaking procedure between product and resource.

2.1 Generic product description

A generic and detailed product description is required for a matchmaking process between product and resource. The field already gained different approaches for that product description.

Brunetti and Golob (2000) introduce a semantic feature-based product description modelling the relationship between functional description, requirements and physical information. They give a definition for a feature as the representation of products regions of interest in information elements. Furthermore, a feature consists of properties from several classes and their relations (Brunetti and Golob 2000). Fallböhmer (2000) separates product properties into product-related and form-element related properties as a part of an approach for generating technology chains. Product-related properties, such as weight, number, material and material properties, relate to the product. Additionally, geometric properties like dimension and form tolerances as well as surface zone properties are required for a holistic product description. Those form-element-related properties can be combined with manufacturing parameters to features to enable a matching to resources Fallböhmer (2000). Knoche (2005) introduces an approach for a generic description of manufacturing technologies. Product-specific descriptions are required as an input for that approach. Comparing different description models he comes to the insight that only a description with features can contain all required information. Specifically, the product description must contain information about geometry, material and material properties and tolerances. On top of that an approach to divide geometries in features and their interdependencies is developed. Those features are organized in input and output states that can be transformed with manufacturing technologies (Knoche 2005). Especially in distributed environments usually seen in global production as a service networks the need for service-oriented product models rises. To tackle that challenge Lu, Wang and Xu (2016) develop an ontology that contains all required concepts for product description in those environments. Product specifications, production processes, organizational information, cost expectations, logistic requirements as well as quality constraint are among others included in the concepts. Containing that information, a module-based, reconfigurable and standardized approach for modelling production service request can be introduced (Lu, Wang and Xu 2016). Wakhare and Sormaz (2016) focus on a knowledge-based sequencing approach such that minimal conflicts between setups can occur. An expert system is introduced that breaks down setups in smaller setups such that an optimal planning can take place due to minimal tolerance violations (Wakhare and Sormaz 2016). Klocke et al. (2017) introduce features in a sense of carriers of functions. Functions can be divided into different levels of sub-functions. To fulfill a function or a subfunction all subfunctions on a lower level need to be fulfilled. Functional requirements are mapped to physical product elements to identify corresponding product features. A classification of product features into the categories material properties, macro geometric properties, micro geometric properties and near surface zone characteristics is introduced. Different manufacturing technologies can be used to fulfill the product features (Klocke et al. 2017)

2.2 Matchmaking approaches

Especially in recent years an increase of papers in the scientific field of automated matchmaking can be observed Therefor recent publications are focused.

In his doctoral thesis Ostgathe (2012) developed a capability description of resources in the context of highly variant production programs. A product related production control was implemented using a data model relating to VDI 2815 and DIN 8580. The resource description is classified into organizational information, equipment capabilities, economic information as well as environmental influences. The matchmaking of product and resource are not automated and must be modeled as Petri-nets including alternative process chains. (Ostgathe 2012). A methodology for product driven holonic manufacturing systems was developed by Quintanilla et al. (2016). In combination with a service-oriented architecture it aims to create more flexible and reconfigurable production systems. Developing ontologies, the process design is facilitated. However, the mapping of the physical product description on available resources is made manually by product designers. Malakuti et al. (2018) develops a skill-based engineering model. To classify skills a four-dimensional classification is developed distinguishing atomic and composed, process-independent and process specific, product-independent and product specific as well as resource-independent and resource specific skills. To enable a rapid mapping of manufacturing processes on specific products represented by CAD models (Malakuti et al. 2018). Katti, Plociennik and Schweitzer (2018) developed an approach for resource virtualization in the context of decentralized manufacturing. Functional and non-functional capabilities of resources are modeled semantically as well as a set of inputs and outputs of the main functionality. Sormaz, Gouveia and Sarkar (2019) developed the IMPlanner, which by using CAD design enable the selection of manufacturing processes as well as sequencing and scheduling plans. The parameters such as accuracies are directly assigned to manufacturing processes. For now, it is restricted to hole-making and milling operations. Based on the German BaSys 4.0 initiative Perzylo et al. (2019) develop a semantically description of manufacturing skills in a cognitive manufacturing framework. This enables the aggregation of basic skills, orchestrating them into higher-level skills. Using OWL, the semantic capabilities models can be mapped onto given processes and their requirements. The approach is implemented for a Pick&Place resource.

2.3 *Shortcomings of the state of the art*

There are a variety of generic product descriptions. However most work focuses on the interoperability in terms of the design process. The usage of these models is therefore not considering how an efficient mapping of products and manufacturing resources can be implemented. In respect to the matching processes most publications define the matching of product description with general manufacturing processes manually. Though for an industrial application such top down matching is not sufficient. A decentralized approach is necessary since the technical result of a machining process is highly dependend on the ability of a company to manufacture certain product features. Additionally the properties of a machined feature depends on tool, material and machine properties and therefore it is not sufficient to describe manufacturing capabilities as generic manufacturing processes.

Moreover the scenario of PaaS induces challenges such as a lack of prior knowledge of the product engineer about required manufacturing processes for a product. The advantage of a matching using a manufacturing process independent description to easily integrate new technologies is not exploited.

3. PRODUCT-RESOURE MATCHING

The following approach is designed to overcome the above-mentioned limitations of the state of the art. To stay technology neutral for the conceptualization UML is used to describe the entities. Inspired by the skill-based engineering process of Malakuti et al. (2018) the link between product and production equipment is defined in Fig 1. Because of the context of PaaS the approach requires the focus on the product. A Product (P) is defined by its properties (PP) and intermediate product states (IPS), which is also described by its properties (IPSP). While the PP describe abstract requirements of the customer such as delivery time or willingness to pay, the IPS describe technical requirements which must be fulfilled during the processing of the intermediate product. The transformation of the product from one intermediate state to the next one is described as a process step (PS). The process step is performed by a resource (R). The resource is, analogous to the description of the product, defined by its properties (RP) and its capabilities (RC). The capabilities of the resource are described by one or more properties (RCP). To enable the matching on a first level the intermediate product state (IPS) and the available resource capabilities (RC) are defined by a set of logical descriptions (LD). For the next level of matching first the RC and the required IPS as well as their corresponding property values must match from the technical point of view.

This process is enabled by the definition of a set of technical-mathematical descriptions (TD). After the technical matching the product property such as maximal willingness to pay of the customer must align with the cost of production, which can be evaluated by a set of economical & organizational—logical (EOLD) and mathematical (EOTD) descriptions. In the following this paper develops a common description of the product with its requirements and the existing distributed manufacturing equipment with the focus on the LD and TD.

3.1 *Product description*

For the modelling of the generic product description which allows for the matchmaking without predefined manufacturing technologies several requirements must be considered. The product model:

- … must be described by a unified structure and semantics, so it can be reasoned by humans and machines (Lu, Wang and Xu 2016).
- … must contain all technically relevant properties (e.g. material, macro geometric, micro geometric as well as near surface zone properties)

Fig. 2 describes the hierarchic structure of a product. An aggregation of features is called a compound feature consisting of multiple semantic features according to VDI 2218 (2003). This aggregation approach allows for each

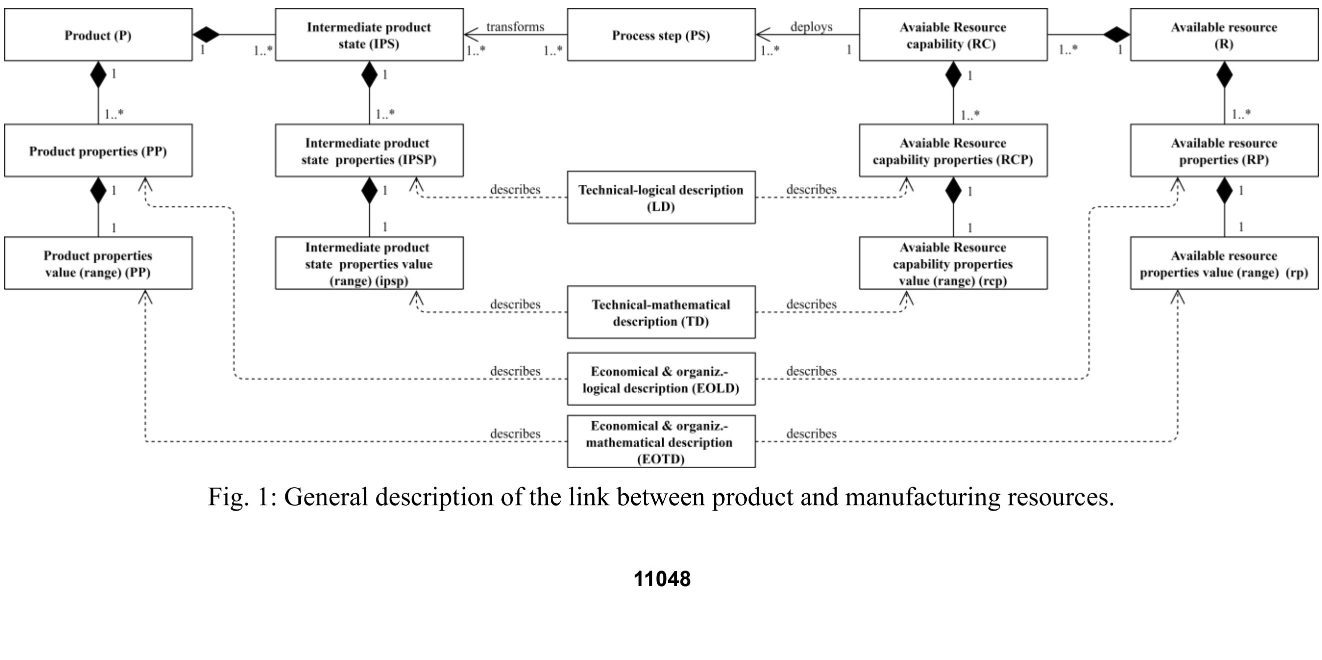

Fig. 1: General description of the link between product and manufacturing resources.

individual resource to browse through the product model to identify providable features. A resource then deploys a process step to manufacture a product feature. Each semantic feature is divided into form-feature and other properties. Form features and their dimensional description are standardized by the DIN EN ISO 17450-1 (2012). Additional properties of the semantic features are the positioning, tolerance and the surface finish such as adhesion and roughness as well as near surface zone properties for instance residual and critical stress a manufacturing resource must meet and material properties such as e.g. elasticity or plasticity. It is possible that multiple process steps and multiple resources are necessary to create one feature.

3.2 Resource description

The resource must be modeled such that it can be matched with the product requirements. Therefore, it is described by its capability to manufacture certain features including their properties. Concerning the process explained in Fig.1, the resource provides the transformation of one intermediate product state to the next. For the modelling of the resource some requirements must be considered. The resource model:

- … must be described by its capabilities, consistent to the product description.
- … should include all processable input and achievable output states of its capabilities (Knoche 2005).

Especially in the case of PaaS the "bottom-up" description of capabilities is very important. The ability of performing an operation in a certain quality, time and for certain costs heavily depends on the skills of a company utilizing its resources as well as the usage of certain machines, tools and materials. The "top-down" approach of creating a process chain just considering generic manufacturing technologies does not provide a reliable result.

Therefore, the feature requirements of the product model can now be mapped onto the resource's logical and technical-mathematical descriptions, whereas each resource is able to provide one or more capabilities. Additionally, the distinguished processable input states and achievable output states can be described by the semantic feature already used for the product description. For an efficient matching, a hierarchical subdivision of resources can reduce the computing efforts. Regarding Fig. 1 the resource description can be divided into logical, technical-mathematical and economical-mathematical description. In the following the logical description is further divided into three level. The VDI 4499-1 (2008) classifies resources in the context of discrete manufacturing into different resource types (ResType) such as manufacturing and storage entities. Concerning the description of the capability of production resources the resource classification allows for a first level of differentiation.

Because this paper focuses on alternative process plans manufacturing processes equivalent to DIN 8580 (2003) processes can be described by process characteristics (ProcCharacteristic), e.g. creating the form, changing the form and altering material properties. Each process characteristics is expanded by processes (shaping, reshaping, cutting, (joining), coating and altering material properties). According to the norm they can be provide the capability to provide the general material property requirements. Relating to Fig. 1 to perform one process step on the intermediate product state the resource capability is described by the initial states and final states it can provide. Keeping the matching process in mind, certain dependencies exist. There are for example the maximum permitted total weight of the product (PermTotalWeight) or the permitted dimensions (PermDimensions). Before the machining, the basic part and its material must be determined. Only then the ability of performing a machining action such as "making a hole" by drilling can be evaluated.

Each of the resource abilities can be described within the framework of the resource description developed in Fig. 3.

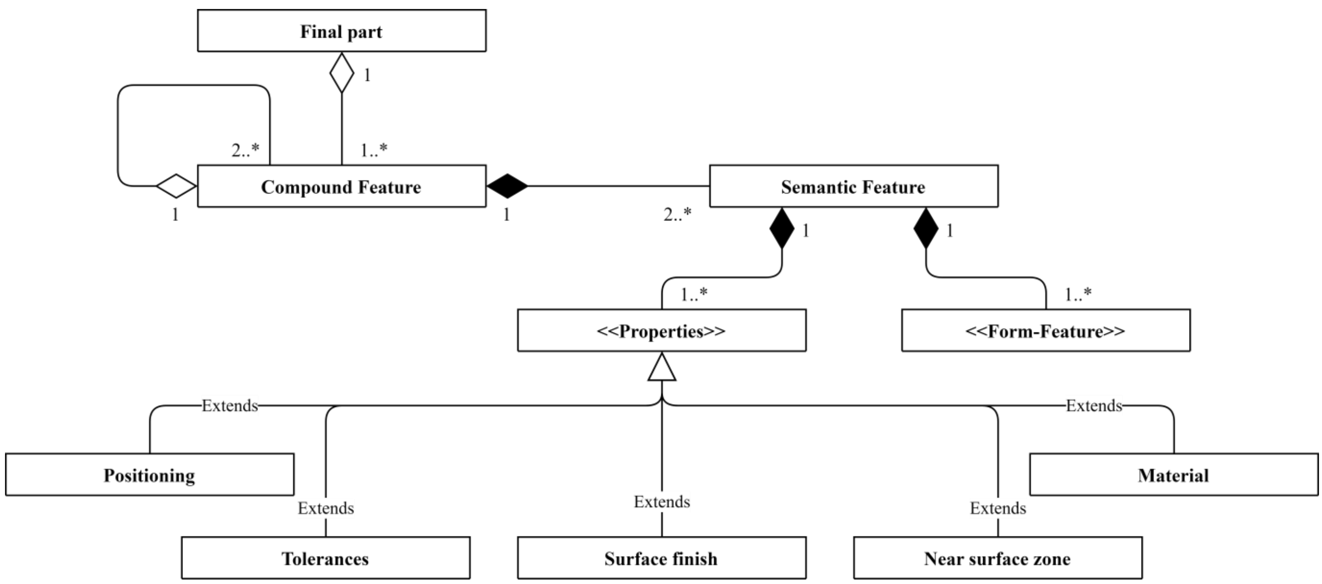

Fig. 2: A generic technical description of product parts

For example, the capability for a machine to transform a product without a hole into one with the hole respecting certain characteristics. The semantic feature (hole) is then then described analogous to product.

3.3 *Matching approach*

To do so the approach of Hermann et al. (2019) is extended. For the PaaS approach the matching system needs access to all decentralized resources. The matchmaking process can be divided into three steps. First, there is the capability check which matches the logical descriptions of product and resource. If a hole must be provided first the resource type (manufacturing), its process characteristics (changing the form) and finally the form feature (cylinder) are reviewed. If all three levels of the capability check are fulfilled by the machine it is principally capable to provide the needed logical product requirements.

The feasibility check takes place after the capability check and is about the technical-mathematical description of the product and resource. Each semantic feature (example cylindric hole) is unambiguously described by its dimensions (height, diameter), positioning (axis moved +30mm in x-direction), tolerance (shape tolerance +3mm), surface finish (roughness under 3µm), near surface zone properties (53 HRC hardness) and the general material properties (180 GPa Young's modulus), allowing to map the product requirements directly to the capabilities of the resource. It is possible that multiple process steps and multiple resources are necessary to create one semantic feature. To achieve the feasibility to perform one process step on the intermediate product state the resources capability is queried and verified whether it can provide the necessary final state. When there are resources able to meet the requirements of each product feature as well as the general material property of the product an individual feasibility is achieved. However, there are restrictions for the matching approach. If for example the dimensional requirement of a "hole" with the diameter of 10mm is matched without considering that the resource cannot provide the micro geometric feature requirements, the finishing process may not be provided in the required tolerances of the diameter. Therefore, the sequence of the matchmaking must be considered for finding the appropriate resources to perform all the process steps necessary to manufacture the final part.

In consequence, the individual feasibility check must be extended by a feasibility check including the interactions between the implemented processes of individual resources and the implemented manufacturing technologies. This requires the matchmaking to a variety of restrictions. There are restricting interactions between the product features affecting the sequence of manufacturing (Agnosti 2000). Each resource uses a specific technology to deploy a process step. These technologies influence each other over several process steps (Knoche 2005). Also, some technologies can negatively influence features changing the overall workpiece properties (Klocke et al. 2017). If these restrictions are considered, all technically feasible process chains are created. In a last step the choice of the optimal process chains considering other products and non-value adding activities is performed using the economical-mathematical description during for each connected resource. For the dynamic matchmaking:

- … a standardized sequence for mapping feature requirements on resources is required.
- … the product must contain a description on feature to feature restrictions.
- … a model must contain a description on technology to technology restrictions.
- … manufacturing resources must be able to negotiate with each other in order to create valid process chains.

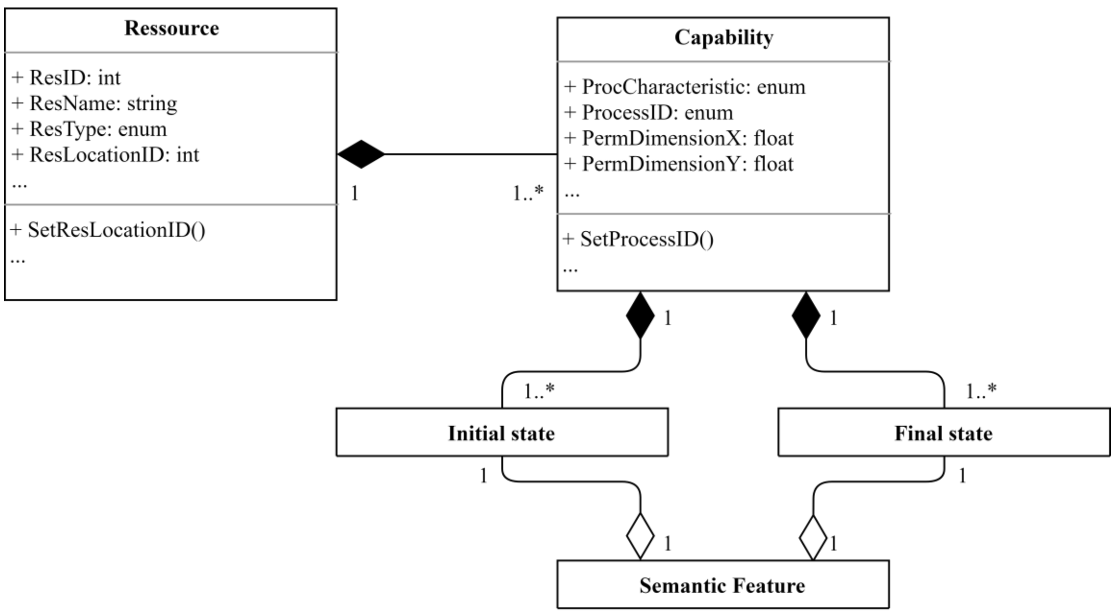

Fig. 3: General technical description of resources

4. CONCLUSIONS AND OUTLOOK

Concerning the suitability of the resource and machine description a more detailed description is necessary. Both descriptions must be extended beyond the capability and feasibility descriptions. There is a further need to define the optimization criteria for the product and resources to incorporate economic properties for optimization. In this regard the recent developments concerning the Asset Administration Shell should be taken into account (Belyaev and Diedrich 2019). While this paper is just a theoretical approach especially the matchmaking process must be detailed beyond the given description. The dependencies between the manufacturing processes during matching as well as dependencies of the sequence of manufacturing resources must be modeled and combined in a system architecture for generating alternative process chains in the context of PaaS.

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