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Cloud-Based Manufacturing-as-a-Service Environment for Customized Products

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Abstract: This paper describes the paradigm of cloud-based services which are used to envisage a new generation of configurable manufacturing systems. Unlike previous approaches to mass customization (that simply reprogram individual machines to produce specific shapes) the system reported here is intended to enable the customized production of technologically complex products by dynamically configuring a manufacturing supply chain. In order to realize such a system, the resources (i.e. production capabilities) have to be designed to support collaboration throughout the whole production network, including their adaption to customer-specific production. The flexible service composition as well as the appropriate IT services required for its realization show many analogies with common cloud computing approaches. For this reason, this paper describes the motivation and challenges that are related to cloud-based manufacturing and illustrates emerging technologies supporting this vision by establishing an appropriate Manufacturing-as-a-Service environment based on manufacturing service descriptions.

1. Introduction

The ability to customize products easily and at low cost is an emerging requirement for future manufacturing environments. Although CAD/CAM technologies have made the customization of individual component parts relatively easy, there still remains the even greater challenge of producing bespoke devices and machines that represent an assembly of many individually tailored components. Such products will require a complex supply chain involving different specialist manufactures whose outputs are coordinated to deliver the sub-components that are required to construct a given design. It is obvious that the creation of such a flexible production network demands a sophisticated IT infrastructure which is able to map (i.e. translate) *customer-specific product configurations* to specific process plans which are executed in a flexible manufacturing network. As a consequence, a two-way exchange is needed between the supplier’s manufacturing capability (i.e. functionality, cost, availability) and the specific manufacturing services that are required for the creation of a custom product. In other words, the custom product must describe the component parts it requires in a language analogue to the capability of the individual suppliers.

The system envisaged can be illustrated by the following scenario: If a company wishes to produce a tablet computer with specific dimensions, the designer would have to specify many components: some standard and other components like e.g. the casing and the screen one-offs. However, in the advanced manufacturing environment envisaged there is no point in allowing the designer to specify sizes larger than the production systems available can currently manufacture. Consequently, it is essential that the underlying limits (i.e.

capabilities) of the manufacturing resources available to a product designer are reflected in the design environment and limit the range of sizes that can be used.

The feasibility of such dynamic supply networks for the retail of consumer products has been demonstrated by many online retailers. So if you purchase e.g. a book or customized sports shoes online, the supply chain used to deliver the order is invisible; only time and price are explicitly shown. The research question asked by the authors is “Could such an approach be used in the manufacturing of complex products?” In other words, could the physical creation of various bespoke components be invisible to a designer or customer in the same way that many “cloud”-based applications provide high-level interfaces to complex logistical operations. The “cloud computing” paradigm is now more than a decade old and defined by key characteristics like scalability (flexible increase or decrease of capacity and/or capability) or location transparency (i.e. the physical location of resources are invisible to the user). The work reported here is motivated by the desire to demonstrate a realization of a “cloud manufacturing environment” which transfers the key characteristics of cloud-based applications to the manufacturing domain. While the resulting system will be similar to the paradigms established by Software-as-a-Service (SaaS), Infrastructure-as-a-Service (IaaS), or Platform-as-a-Service (PaaS) systems in conception, the Manufacturing-as-a-Service (MaaS) system involves unique challenges that will require new technological solutions for its realization.

This paper gives an overview of these challenges and reports how the characteristics of cloud computing can be implemented in the manufacturing domain to make MaaS applicable to SMEs to produce customizable (i.e. small batch) products which are feasible in terms of costs and integration effort. The goal is to dynamically combine various manufacturing services in such a way that customers can access them as if they were one facility. Such a virtual value chain established by the aggregation of certain services acts as one virtual factory. The customers will not be aware of the physical location or nature of the infrastructure providing the service.

2. Objectives

During the conceptualization of the flexible production network infrastructure two main users have been identified:

- *Manufacturing Service Providers* (MSP, who manufacture or process products or component parts) could use a MaaS infrastructure to participate in cloud manufacturing networks and in this way increase their production or extend their production portfolio. This could increase the profitability of participating organizations as they are not only able to provide final products but also single production steps and sub-components. The resulting volumes should present more advanced or cost-effective products.
- *Manufacturing Service Consumers* who purchase products or sub-products from MSPs. For example, this could enable product designers or engineers to push new concepts into production without direct access to manufacturing expertise, capabilities, or capacities. Additionally, they could verify the manufacturability of new designs.

Both stakeholders demand a flexible, configurable manufacturing system that is able to manufacture small amounts of customer-specific products (small series, single pieces, prototypes, etc.) in a cost-effective way.

One prerequisite for executing distributed manufacturing services is an appropriate IT infrastructure which must, among other things, include a specification, management and runtime environment for manufacturing services which is introduced in this paper as Manufacturing-as-a-Service infrastructure. A basic principle the whole MaaS infrastructure has to follow is that the effort required to join a manufacturing network (providing or consuming manufacturing services) needs to be as small as possible.

3. Methodology and Core Concepts

In order to provide such a MaaS infrastructure, a cloud manufacturing marketplace needs to be established where manufacturing services are registered. In this way, the infrastructure is capable of managing and supplying those services that are provided by manufacturers and requested by service consumers in order to run the production networks within a manufacturing cloud (including the secure exchange of data between all parties, joint specification management, product configuration infrastructure, etc.). Such manufacturing services are analogue to the distributed software systems found in cloud computing infrastructures. They are provided by MSPs who generate the service descriptions from their internal facilities and publish them to a service repository. Manufacturing service consumers with ideas about new products but without the full portfolio of manufacturing facilities needed for their production are able to search and select the services from the repository and to combine them to configurable process plans. By doing this, they are able to build up virtual value chains consisting of MSPs to execute the production of customized products. The service consumers have the opportunity to configure their products depending on the degree of freedom that is provided by the related manufacturing services and their interdependencies. Based on this, concrete process plans which are to be executed in the cloud manufacturing network are instanced and parameterized.

One of the most important virtualization concepts used to set up a manufacturing cloud as described above is the description of the associated manufacturing services. The paper focuses on this aspect, as all other cloud-based manufacturing components depend on the description of production and product-related information.

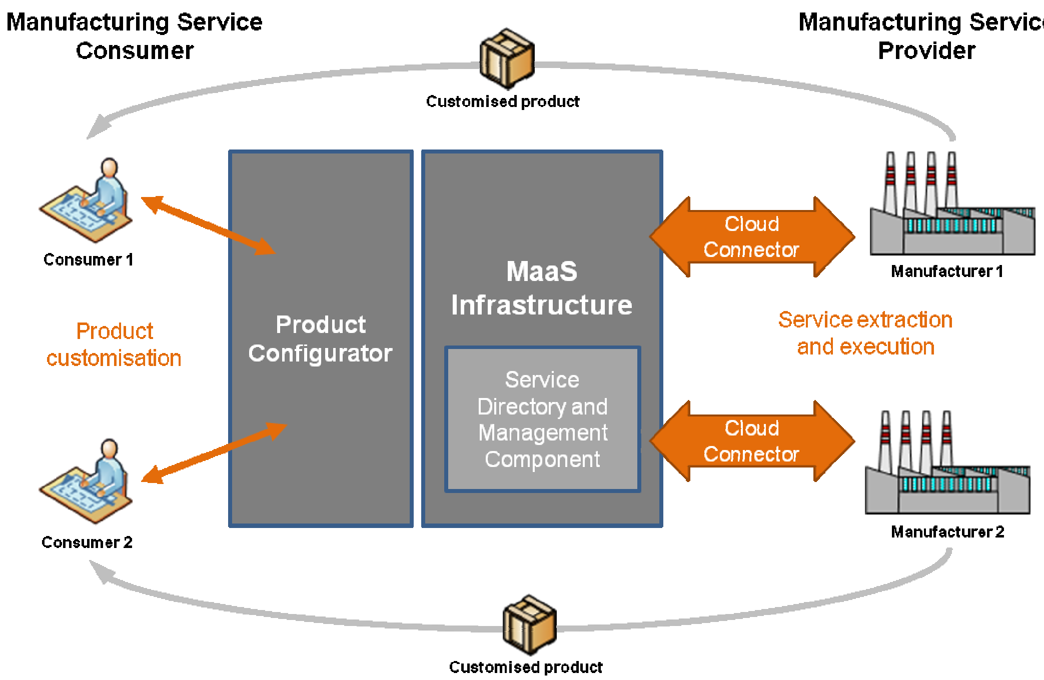

Figure 1: Processing of Manufacturing Service Descriptions in the MaaS Environment

Figure 1 shows the processing of manufacturing service descriptions (MSD) within the MaaS infrastructure. Two main directions can be identified:

1. *From manufacturer to cloud to customers* (publishing new products and related manufacturing services): MSPs are able to publish a new product and its associated services in the cloud. The MSD document is used to register product information, its manufacturing service and its customization limitations. From a front-end perspective, customers can use a web-portal to browse new products and its services. In using the

product configurator component, the customer can customize a product on the basis of a product template which is an instance of the associated MSD document.

2. *From customer to cloud to manufacturer* (delivering requested customized products to the customer): Once the customer customizes the product according to his/her requirements, the product template is sent back to the cloud and processed by the Service Directory and Management Component. All relevant information for the delivery of the product is updated and provided as feedback to the customer. Lastly, the MSD document is passed to MSPs to execute the production of the customized product.

Based on this communication flow, the multiple roles an MSD has to play in the cloud-based manufacturing environment can be extracted:

- It must be extendable to not restrict its usage to pre-defined manufacturing facilities.
- It must ensure the producibility of the generated product configurations and therefore has to approve the matching of depending manufacturing services.
- It must be able to model and represent different types of data required for the various key components of the marketplace cloud infrastructure such as product configuration, sample product presentation, manufacturing service directory and discovery as well as the execution level of the manufacturing services.
- It must support the aggregation and management of the manufacturing services in order to create manufacturing networks that act as virtual organizations.
- A manufacturing service directory and management component must enable manufacturing services to be published, searched, and retrieved via the marketplace.
- The MSDs must be interlinked to be able to reason in response to customized product queries such as delivery dates and costs.

The overall goal of the proposed Manufacturing Description Service Language (MSDL) is to provide a formal description of the manufacturing services in consideration of the representation of the product domain knowledge and product management aspects.

4. State-of-the-Art Review

There exist many ideas, approaches, and concepts of how to use services and their descriptions within manufacturing networks. Yan *et al.* [1] and Lilan *et al.* [2] suggest the usage of Service Oriented Architectures due to the synergies, which can be used there since manufacturing service concepts focus on resource sharing and SOA provide distributed architecture concepts which enable interoperability, easily integration, simplicity, extensibility and properties of secure access [2]. However, common software service technologies such as WSDL (Web Service Description Language), UDDI (Universal Description, Discovery and Integration), DAML (Darpa Agent Markup Language), and OWL-S (Web Ontology Language for Web Services) are not sufficient for describing, publishing, discovering, and applying manufacturing services [3]. Hence, approaches need to extend existing, widely used, and well-proven web technologies with ontologies. For example, Jang *et al.* [3] extended UDDI to support semantics-based service advertisement and discovery, and Cai *et al.* [4] added ontologies to web services via annotations. Due to the importance of those ontologies, various related research activities [1; 5; 6; 7] focus on the development of appropriate ontology concepts and compositions. There exist several approaches for service search, match-making [4; 7], discovery [3], selection and composition, the appropriate network structures and performance evaluation [8], and service granularity and aggregation [2].

The applications of the reviewed manufacturing service description concepts and the associated ontologies mainly focus on machining processes which include the description of tools, sub-components like e.g. spindles and axes, and associated motions and process capabilities such as grinding, milling, or drilling [3; 4; 6; 7].

Due to the fact that the previous work in describing manufacturing services does not consider the aspect that manufacturing services are configured automatically via product customization, product models and product modeling methods were also included into the research for the sake of completeness:

Product models and product modeling methods have been researched extensively in different domains and applications to support the product development process [9]. In particular, much research efforts have been made in developing product models for the configuration of customizable products. This has involved various approaches to develop generic product structures representing product variants within a product family [10-12].

Many of the previous approaches to product modeling are based on object-oriented concepts to describe configurable products. The Product Variant Master (PVM) method discussed by Hvam *et al.* [13] illustrates this. Zhang *et al*. present a configuration-oriented product model based on an object-oriented knowledge representation, too [14].

Other works focus on the adaption of existing standard product modeling languages. The Unified Modeling Language (UML) was applied by Felfernig *et al.* [15] for the modeling of configuration knowledge. This approach uses UML class diagrams to describe the composition of parts, attributes and their relations. Also as a part of UML, the Object Constraint Language was used to describe the configuration constraints. In a recent review, UML/OCL, SysML and STEP/EXPRESS modeling languages were evaluated [16].

The limitations of each technology and modeling language were highlighted and it turned out that there remains enough scope to propose a new modeling language to satisfy the demand for a combined product configuration and manufacturing service description.

5. Project Approach

Due to the review of previous work, it is clear that there are key challenges to be addressed in the development of the proposed MSDL concept and structure. The approach envisaged in this work aims at developing an extendable MSDL structure, which achieves the interoperability of collaborative product specification and manufacturing of customized products within the MaaS infrastructure. Against this background, three main requirements of manufacturing service descriptions have been identified to ensure applicability to SMEs and generality of a service description at the same time:

- They must be able to represent several aspects ranging from product characteristics (shape, size, mechanical, electrical, optical characteristics, etc.) to manufacturing process specific details (resources and associated capabilities, technology and material characteristics), organizational and management related information (logistics, costs).
- They must be able to represent complex structures and interdependencies between the services or specific aspects and their aggregations.
- They should be easily extractable from existing production IT systems and should propagate the necessary level of information demanded by the manufacturing cloud.

Based on the main MSD requirements, the initial development of the proposed MSDL was iteratively approached from two main perspectives – the consideration of product-related aspects and manufacturing technology aspects of the service descriptions. The following section describes the work in the development of an appropriate manufacturing description document.

6. Work in Progress

The current work focuses on the definition of product and production-relevant information (e.g. bill of material, process plan, and adjustable settings) of the MSD. To describe this aspect, the MSP has to provide the definition of a product it can provide to the cloud. It will provide this within an MSD as a “product template” (see Figure 2, left diagram).

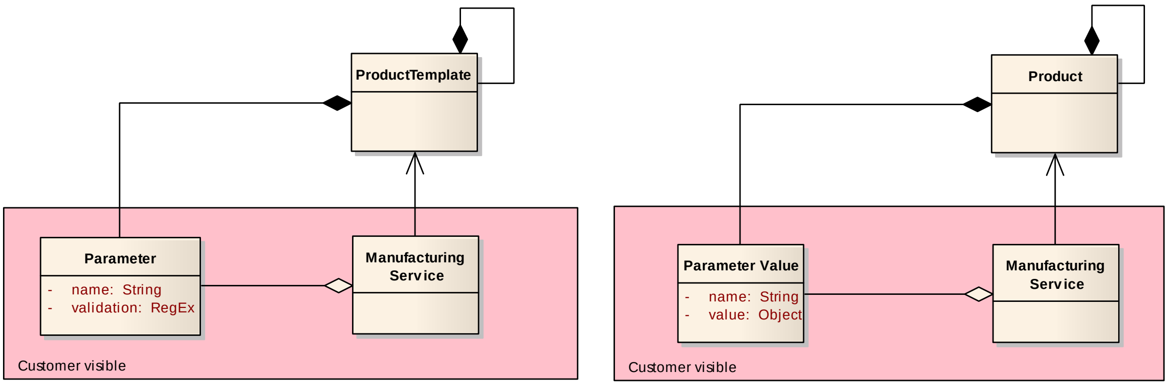

Figure 2: Product Template Definition (left) and Concrete Product Request (right) in an MSD

The product template itself contains internal production-relevant information (e.g. equipment usage, recipe, detailed process plan, etc.) which remain hidden to the customer. Therefore, only a reference to the product template will be available inside the open section of the MSD which will be visible to others. The adjustable settings of the product are defined inside the customer-visible part of the MSD by the MSP. They describe each parameter by its name and the allowed values in the form of regular expressions, which can be configured by the customers (see also chapter 3). The customer will use a MSD published by the MaaS infrastructure to configure the customized product he wants to order (see Figure 2, right diagram) by specifying concrete values for the predefined parameters, based on the valid value settings. As a result, a configured product template, i.e. a concrete product definition will be generated, which can be directly used for downstream production process at the MSPs' facilities.

The ongoing creation of the MSD document is accompanied by investigation of how to represent the complex MSD structures and related documents in the MaaS cloud. As explained in section 4, OWL/RDF is a promising technology to be used for managing and processing MSD documents in the cloud. Besides this, the MSD structure will be represented within the associated data storage by applying graph-based database solutions.

Further implementation issues related to MSDs are the representation of product configuration rules and dependencies. This includes the integration of product visualization information, which will be implemented by references to rules and associated rule engines and CAD file formats.

7. Business Case

The described MSDs, together with the marketplace infrastructure mentioned, enable to share manufacturing capabilities, facilities, and capacities. As mass production is relocated to low-wage countries, manufacturers from other regions have to increasingly focus on providing high-value and customized products by means of flexible supply infrastructures.

As the introduced concept provides a solution especially for the customization and distributed production of small series, single pieces, or specimen, it is able to support manufacturing of sophisticated high-value and low-number products. For this reason, the production of building-integrated OLED (Organic LED) and OPV (Organic Photovoltaic) elements was chosen to be the initial application context for the Manufacturing-as-a-Service environment. Based on the customer specification, a facade element is built which consists of solar cells and OLEDs with e.g. a specific size, shape, and color in addition to common components like glass elements.

Both, the OLED and the OPV industry are still niche markets characterized by a huge number of newly founded companies, mainly SMEs. The introduction of MaaS principles into these industries will enable the easy integration of the associated technologies into manufacturing networks. This will support the development of new and innovative products on the basis of new manufacturing capabilities and the commercial success of organic semiconductor technologies.

8. Results

By defining a first version of a MSDL which contains a basic production-relevant aspect, the principle concept of the MaaS cloud can be proved. The MSP is able to publish a predefined MSD to the MaaS infrastructure, which can be used by a customer to configure and order a concrete product.

For example, it could provide information about products and sub-products, manufacturing service(s), 2D/3D images of products, configurable data like CAD, constraints, dependencies, etc. To get a better understanding of this MSD document, Figure 3 gives an example which shows a MSD document for a combined OPV and OLED facade element customization in a MaaS environment.

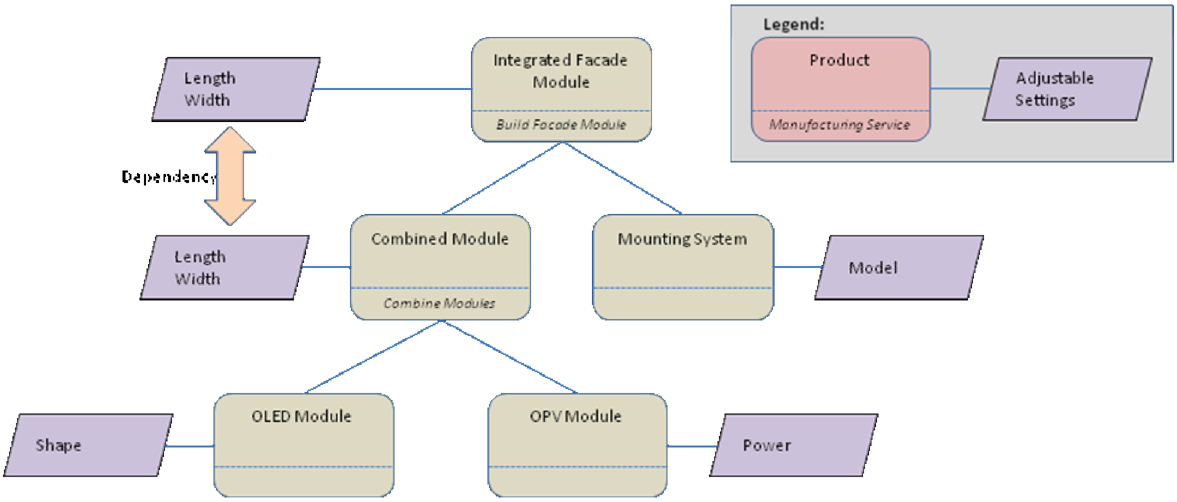

Figure 3: Sample Structure of an MSD Document

The rectangular boxes in Figure 3 show the products with their associated manufacturing services. These services can be provided from any location and will potentially be registered in the cloud. The corresponding customization parameters and their values (parallelograms in Figure 3) are also part of the MSD document.

9. Future Work

In order to continue the work described and to achieve further results, the related research activities will be extended to include service aggregation. This will enable the combination of various manufacturing services from different providers in order to support the design and configuration of new product ideas. Furthermore, the MSDs will be extended to cover additional aspects such as material characteristics and logistics.

In parallel, the development of the product configurator and Manufacturing Execution System components within the MaaS environment will play a major role. Future work will concern the investigation of concepts and technologies supporting the extraction of MSDs from factory internal IT systems in order to ensure their actuality and maintainability, as well as integrating appropriate security functionalities to the overall MaaS infrastructure.

10. Conclusion

This paper describes the functionality of an emerging class of manufacturing networks exploiting the technologies of cloud computing and the representational power of industrial ontologies to create a product delivery system that brings “Internet speed” to the configuration of component supply chains. The work reported seeks to produce a system that not only coordinates the production of complex customized components across many physical locations but also allows the limitations and capabilities of the supply chain to be explicitly available during the product design process. This form of bespoke "design for dynamic supply chain configuration" is implemented by building a MaaS infrastructure that includes a manufacturing service management as well as product configuration capabilities in order to provide and process MSDs associated with each individual participant in the network. The major work undertaken to date by the project consortium includes:

- A comprehensive technology review which highlights there are no fundamental technological problems to prevent the implementation of such a system.
- The draft of a system architecture describing the key elements to support the MSDL, MES, and product configuration, which are to be combined in a web-portal.

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