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Toward Portable Cloud Manufacturing Services

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In cloud manufacturing, a product bill of materials (BOM) uses distributed manufacturing services for production purposes. Modeling BOMs poses challenges as regards distributed manufacturing plans, production policies, and the BOM's portability among multiple manufacturers. The authors' mechanism lets producers model and build BOMs by composing diverse manufacturing services and resources using the OASIS Topology and Orchestration Specification for Cloud Applications standard.

Cloud manufacturing provides a cooperative work environment for enterprises and individuals, enabling collaboration among the entire manufacturing ecosystem.[1] With the cloud, resource pools can use virtualization to abstract away the heterogeneousness and regional distribution of manufacturing resources. Cloud manufacturing aims to orchestrate and allocate such distributed resources and render production services for clients to seamlessly enable manufacturing on demand.

Cloud-based design and manufacturing refers to a product realization model supported by three core technologies: cloud computing, the Internet of Things (IoT), and collaborative engineering. The cloud computing paradigm provides a virtualization layer on top of shop-floor devices and resources envisaged in the IoT. These manufacturing resources can elastically scale with on-demand access among distributed regions, leading to an automated IoT application deployment.[2] Collaborative engineering addresses the orchestration and collaboration side of manufacturing workflows, in which resources (such as devices, sensors, materials, and drivers) are virtualized and encapsulated into a product *bill of materials* (BOM; http://en.wikipedia.org/wiki/Bill_of_materials). Manufacturers can access, configure, invoke, deploy, and orchestrate this BOM on distributed production lines in a near real-time manner. BOM data must go to the right manufacturer at the right time for the right cost.

Our proposed mechanism deals with the provisioning, portability, and management of all types of manufacturing resources as services, for all phases of the production lifecycle. This mechanism incorporates the Oasis Topology and Orchestration Specification for Cloud Applications (TOSCA)[3] policies, plans, and templates as a mechanism for dynamic configuration, portability, and management of product BOMs across multiple collaborating manufacturers. Once virtualized on the cloud, we can refer to a product BOM as a *bill of manufacturing services* (BOMS).

We use TOSCA as a unified manufacturing language, exposing its grammar to describe a manufacturing service and product templates. Last but not least, the mechanism provides a set of abstraction levels for various manufacturing services and resources that encapsulate and address specific requirements and satisfy stakeholders' needs. Manufacturing resources such as physical resources, software services, and data units are dynamically configured and composed in the TOSCA-based BOMS for use via manufacturing services. Portable cloud manufacturing services enable elastic, reconfigurable, and portable production lines, manufacturing services, and resources among collaborating manufacturers. This enhances efficiency, reduces product time to market and costs, and enables optimal resource allocation in response to demand changes and market dynamics.

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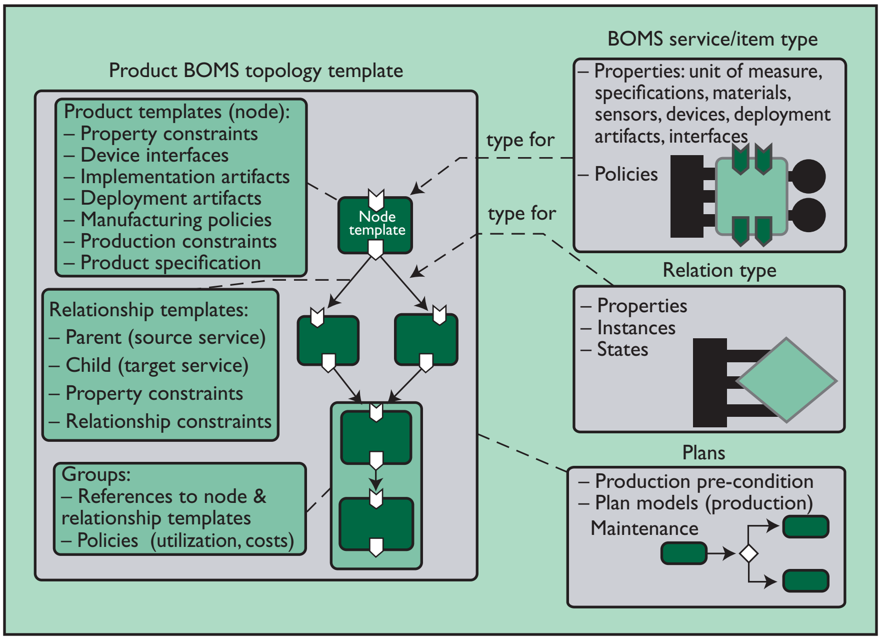

Figure 1. Core elements of a TOSCA-based product bill of manufacturing services (BOMS).

TOSCA-Based Bill of Manufacturing Services

A configurable product BOMS comprises a comprehensive list of raw materials, components, services, and assemblies required to build or manufacture the product. The BOMS is usually represented in a hierarchical format, with the topmost level showing the end product, and the bottom level displaying services, individual components, resources, and materials. Each item in a BOMS describes the relationship between a parent (assembly) item and a child (component) item. To establish cross-factory manufacturing governance and ultimately integrate distributed production lines, we need a standard to define the product structure covering the relationship between production services, components, and their configuration recipes.

Web-scale workflows based on cloud computing in the manufacturing domain could lead to an evolution in production service delivery models. Cloud-enabled BOMS should be designed, composed, configured, and manufactured on demand. We can view the BOMS as a cloud-manufactured virtual product, applicable for deployment in multiple production lines and resulting in actual "as-built" assets. In this respect, the need for a cloud standard or specification to represent BOMS seems vital.

The TOSCA language introduces a grammar for describing service templates via *topology templates* and *plans*, which we can use to define the BOMS as well. The focus is on design-time aspects — that is, the description of services, resources, and materials (in a broader view, "things") to ensure their exchange. TOSCA also addresses runtime aspects by providing a container in which to specify plan models. In the cloud manufacturing case, these models can address supply chain, production, and maintenance plans, which can support the management of manufacturing service instances. In fact, designers will be more focused on the BOMS topology design, which is a logical relationship between product components, equipment, and assembly items. The BOMS topology defines an item's specification regardless of any explicit development and manufacturing operation details. With this approach, a product's manufacturing operations can change without affecting its BOMS design. Hence, both the manufacturer and the customer can compare various actual manufacturing solutions in terms of cost, quality, and timely production to make a reasonable choice.

Figure 1 shows the meta model of a TOSCA-based BOMS. At the root is the *product template*, which contains a directed graph representing the product's structure called a *product BOMS topology*. Every product template has at least one product BOMS topology. The topology graph is composed of nodes and edges. In a directed graph, edges are links with a direction from node to node. The edges in a product BOMS topology graph are binary relationships between nodes. The nodes represent the product's logical components, items, or objects. These nodes and relationships are patterns for the actual resources, objects, or materials and their relationships as instantiated in a deployed manufacturing service. Relations capture, represent, and quantify associations between objects.

The product topology's manufacturing process is realized via TOSCA plans, which orchestrate various aspects of a manufacturing service lifecycle. The TOSCA specification defines *build plans* and *termination plans*. Build plans orchestrate a product BOMS's deployment, installation, and production operations. Termination plans orchestrate decommissioning a production line. Designers of TOSCA-based BOMS can add plan types as needed, so the BOMS encapsulates the required information for product lifecycle management. Such BOMS maximize the portability of manufacturing documents, and guarantee a smooth dataflow.

TOSCA Plans as Manufacturing Workflows

Plans define manufacturing process models — that is, a workflow of one or more steps that is deployed on production lines to instantiate and terminate a manufacturing operation and manage a product during its whole lifecycle. These plans specify the manufacturing service's operational behavior — in particular, how to instantiate, terminate, or manage the product flow. TOSCA basically supports two main build and termination plan types used to instantiate and terminate manufacturing services and associated operations. In TOSCA, manufacturers can define any number of plans, such as resource supplement, production, delivery, and maintenance plans, or furnish their requirements. Manufacturers can define these plans using any preferred process modeling language, including the Business to Manufacturing Markup Language (http://en.wikipedia.org/wiki/B2MML), Business Process Model and Notation, and the Business Process Execution Language. Manufacturing process models basically contain tasks referring to the operations of manufacturing service interfaces from collaborating manufacturers, making these models interoperable.

The build plan provides actual values for various BOMS item properties, including itemID, vendor, unit of measure, and amount. Manufacturers operating on a TOSCA-based BOMS can adapt the build plan to their specific, concrete production line environment. Each manufacturer would map the specified product BOMS topology to its available concrete resources and materials to support specific instances of the manufacturing service and adapt management plans accordingly. Manufacturers can achieve this mapping by running a corresponding instantiating management plan. This approach is applicable to all plans.

Manufacturers can make a concrete instance of a product topology template by running a corresponding plan (for example, a build plan). This build plan could come from the manufacturing service developer, who also creates the *service template*. Service providers can adapt the build plan to their specific concrete environment. A service template can also specify other management plans useful in various states of the service lifecycle. As with build plans, service providers can adapt these management plans to their specific environment.

TOSCA-Based Manufacturing Policies

Nonfunctional behavior and quality of service (QoS) are defined in TOSCA policies. In cloud manufacturing, for instance, a policy can express such diverse features as monitoring production operations, order and payment conditions, scalability, shop-floor fault tolerance, and energy efficiency in green manufacturing.[4]

Each TOSCA-based BOMS node can be associated with a set of policies collectively expressing the actual properties of nonfunctional behavior or quality of manufacturing service that each resource instance will expose. One example is the quality of raw materials used in each manufacturing step, which ensures healthy device operation and energy-efficient consumption. All policies are AND-combined, meaning they must be enforced by TOSCA-based manufacturing build plans. We can define policies in TOSCA independent of a policy language. For instance, we can use a policy definition language called Ponder2 (www.ponder2.net), which enables us to define both obligation and authorization policies. As a concrete example, sensors on production lines monitor device operations and send the events to the TOSCA container, where an obligation policy agent interprets the event's meaning and correlates it to a running instance. The agent then identifies the model from which this instance was derived to get the policy, evaluates the product's nonfunctional behavior against this policy, and invokes the corresponding actions.[5]

Portable cloud manufacturing incorporates TOSCA topology templates, nodes, and interfaces along with orchestration specifications including deployment, build, and management plans. This solution will transform manufacturing processes such as supplement, consumption, and production models over the Web. These models are inspired by the idea of provisioning elastically scalable manufacturing resources and efficiently integrating diverse manufacturing services. This provisioning strategy provides an initial impetus for sharing domain knowledge and collaborating about intended usage scenarios; an example is real-time traceability and interoperability for distributed shop-floor planning, execution, and control. This idea facilitates inter- and intra-factory communication and collaboration in cloud manufacturing environments, enabling the distributed execution of shop-floor jobs.

A portable cloud manufacturing system serves multiple factories as an integrated manufacturing ecosystem, helping to govern the manufacturing process and support product design. It also enables overall dynamic configuration, production lifecycle management, and team collaboration. It makes production planning and manufacturing work in progress (WIP) distributable, controllable, composable, and portable over the Web, leading to an even broader definition for the concepts of "design anywhere and make anywhere (DAMA)," manufacture on demand, and manufacturing as a service. Our proposed TOSCA-based BOMS manufacturing mechanism realizes these concepts.

As a potential benefit, employing TOSCA in cloud manufacturing enables valuable use cases such as portable manufacturing services among collaborating manufacturers to achieve scalability and manufacturing in an on-demand fashion. This elevates the manufacturing process to be more resistant against failure and defects detected in one production line, because the manufacturing service can be ported to other certified production lines. Meanwhile, the TOSCA-based BOMS product modeler can include deep domain knowledge in its associated manufacturing plans that other stakeholders can reuse simply by "invoking" the plans. This abstracts the complexity of the underlying manufacturing operations away from the client. All in all, our mechanism will realize the concept of virtual factories formed via dynamic composition of distributed manufacturing services and resources. Last but not least, we can now consider manufacturing services to be marketable entities in the industrial world, opening up opportunities for novel manufacturing-based business models such as manufacturing as a service.

References

1. L. Wu and C. Yang, "A Solution of Manufacturing Resources Sharing in Cloud Computing Environment," *Cooperative Design, Visualization, and Engineering*, LCNS 6240, Y. Luo, ed., 2010, pp. 247–252.
2. F. Li et al., "Towards Automated IoT Application Deployment by a Cloud-Based Approach," *Proc. IEEE 6th Int'l Conf. Service-Oriented Computing and Applications* (SOCA 13), 2013, pp. 61–68.
3. *Topology and Orchestration Specification for Cloud Applications version 1.0*, Oasis committee specification, Mar. 2013; http://docs.oasis-open.org/tosca/TOSCA/v1.0/os/TOSCA-v1.0-os.html.
4. D. Dornfeld et al., "Introduction to Green Manufacturing," *Green Manufacturing*, Springer, 2013, pp. 1–23.
5. S. Keoh et al., "Policy-Based Management for Body-Sensor Networks," *Proc. 4th Int'l Workshop on Wearable and Implantable Body Sensor Networks*, S. Leonhardt, T. Falck, and P. Mähönen, eds., 2007, pp. 92–98.

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