Digital Factories for Capability Modeling and Visualization

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Abstract. This paper introduces the concept of Digital Factory (DF) that can be used for representing the technological capabilities of manufacturing facilities. The DF, as the digital twin of physical facilities, replicates the facility in terms of installed machinery, material handling equipment, and layout. DF is supported by a formal ontology that describes the capabilities of the factory in a formal and machine-understandable fashion and enables capability quantification and visualization. Through exploring and querying the Digital Factories, companies can develop a deeper and more precise understanding of the technological capabilities of prospective suppliers, thus making more informed decisions when building supply chain partnerships. By creating their digital twins, small to medium-sized manufacturers can significantly improve their visibility in the virtual space. Digital Factories also enable automated supply chain formation. DF is introduced and discussed from a conceptual perspective in this paper. Also, a mathematical model for quantifying the processing capabilities of Digital Factories is introduced.

Keywords: Digital factory · Manufacturing capability · Service ontology

1 Introduction

To remain competitive in today's volatile economy, manufacturing companies need to be provided with the decision-support systems that enable them to manufacture products more efficiently, less expensively, and more quickly. One of the key decisions that has a profound impact on the agility and responsive of manufacturing companies is the sourcing decision [1]. Sourcing is defined as the process of finding, evaluating, and engaging suppliers for acquiring goods and services [2]. Sourcing process, in its traditional form, is a lengthy and time-consuming process because it often entails visiting suppliers' facility or launching trial production runs in order to evaluate suppliers' true qualifications, capabilities, and capacities. However, when there is a need for rapidly responding to fast-changing market trends, traditional sourcing methods fail in meeting the strict time constraints of such projects.

An alternative solution for collecting information about suppliers' qualifications is to explore their web-based profiles to learn about the technological capabilities of suppliers. However, the online profiles are oftentimes outdated and incomplete and cannot accurately reflect the true capabilities of suppliers [3]. Also, the sheer size of the returned set in web-based searches makes supplier evaluation a costly and lengthy

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process [4]. Consequently, in fast-track production projects with stringent time constraints, sourcing decisions are often made based on superficial insights into the qualifications of prospective suppliers. To improve the intelligence and effectiveness of sourcing decisions, when the Internet is the only medium for interaction with the prospective suppliers, companies need to gain real-time, dynamic, and accurate insight into the capabilities and capacities of prospective suppliers [5].

In this paper, the problem of capability modeling and representation is addressed through introducing the concept of Digital Factory. Digital Factory provides a virtual representation of a manufacturing facility. It replicates the facility in terms of installed machinery, material handling equipment, and layout. It provides both visual and textual representation of the facility. Digital Factories, as the digital twin of physical facilities, can enhance the visibility of small and medium-sized manufacturers in the virtual space. The novel feature of the Digital Factory is that it is annotated by a formal ontology that is used for representing the capability model of the factory. Through exploring and querying the capability model of digital factories, companies can develop a deeper and more precise understanding of the technological capabilities of prospective suppliers, thus making more informed decisions when building supply chains. Some of the attributes of technological capability that can be captured by the Digital Factory include achievable tolerances and surface finishes, acceptable stock sizes, and available primary and secondary processes. The proposed model of Digital Factory perfectly meets the needs of the factories of the future, as they will be reconfigurable, adaptive, and evolving [6]. A Digital Factory can be quickly updated to reflect the changing nature of its associated physical factory in real-time. Digital Factories are developed on a web-based platform referred to as the Digital Manufacturing Market (DMM) [7]. DMM provides user-friendly interfaces and machine libraries for capability visualization and virtual factory modeling. This paper provides a conceptual perspective about Digital Factory, its utilities, development environment, and information backbone.

The paper is organized as follows. The next section describes the system architecture of DMM through introducing its main functional modules. The underlying ontology of DMM is introduced in Sect. 3. In Sect. 4, an example for a Digital Factory for a hypothetical machine shop is provided. The paper ends with the concluding remarks.

2 System Architecture

Manufacturing companies can create Digital Factories for advertising their capabilities in the Digital Manufacturing Market. The Digital Manufacturing Market (DMM) is a web-based market platform designed based on a service-oriented architecture (SOA) and supported by a formal ontology [7]. In DMM, units of manufacturing capacity are represented as standard service modules. Manufacturing service capabilities are described in a semantically rich fashion using a formal ontology called Manufacturing Service Description Language (MSDL) [8]. More details on MSDL is provided in Sect. 3. In DMM, participating suppliers can create digital twins of their facilities, dynamically update their digital factory through adding and removing

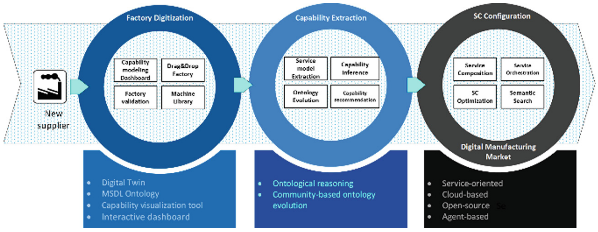

Fig. 1. The main modules of the proposed solution

machines and equipment to reflect the real conditions on the shop floor, and deploy software agents that represent them in the virtual space. Through building the digital factory, the service model associated with the factory is generated and published automatically. As can be seen in Fig. 1, the main functional modules of the DMM include Factory Digitization, Capability Extraction, and Supply Chain Configuration.

The service model is then used for capability quantification. DMM's functions and features enable manufacturing suppliers to: (i) Describe their technological capabilities in terms of manufacturing services in a machine-readable fashion using an open-source standard; (ii) Describe the parts produced in the past and the qualities achieved; (iii) Create a "digital twin" of their facility through selecting their installed equipment and machines from a given library of physical resources (*Drag & Drop Factory*); (iv) Update their capability model in real-time through updating the configuration and layout of the digital factory; (v) Find the right customers through using the automated matching utility provided by the platform; (vi) Evaluate their technological readiness and competencies based on the current demand through using the capability scoring utility provided by the platform.

DMM's functions and features enables manufacturing OEMs (customers) to: (i) Evaluate the technological capabilities of prospective suppliers through capability visualization and scoring utilities; (ii) Find the right suppliers through using the automated supplier search and evaluation tool; (iii) Deploy supply chains rapidly using the service composition and orchestration utility provided by the platform; (iv) Mitigate their risks through on-demand consumption of the pooled manufacturing capacities and capabilities available on the cloud.

2.1 Factory Digitization

Factory digitization entails creating the digital twin of the manufacturing facility owned by the supplier. Two user interfaces, namely, drag and drop factory and the capability modeling and visualization dashboard enables suppliers to interactively create the digital model of their facility and annotate it with explicit capability and capacity-related information. The user-friendly interface hides the complexities of the underlying knowledge models used in the platform's knowledge base. Also, it encourages rapid and regular update of the digital facility such that it accurately mirrors the physical facility. Any change in the digital facility will be reflected in the supplier's service and capability models in real-time. The digital factory is connected to a comprehensive library of manufacturing resources (machinery and equipment), allowing the user to populate the virtual facility with the right set of resources. The digital factory not only represents the type of resources used in the physical facility, but also it reflects the actual layout of the physical facility. The layout is used by the Capability Extraction module for inferring the system-level capabilities of the facility. System-level capabilities are characterized through properties such as throughput time, cycle time, and average in-process inventory level.

2.2 Capability Extraction

The Capability Extraction module builds the formal capability model of the digital factory coded in MSDL. It uses the explicit capability information provided by the supplier and expands upon it through discovering latent and implicit capability patterns. The extracted manufacturing capability is packaged as standard service units with well-defined input, output, and quality measures. Capability extraction is a knowledge-intensive process that capitalizes on the domain knowledge already encoded in the ontology. Capability extraction is a bottom-up process starting with device and machine-level capability model going up to supply chain level. The capability extraction module can create regional models of manufacturing capability and represent them through "capability heat map" thanks to the rigorous capability quantification algorithms embedded in this module (Fig. 2). This module also provides capability recommendation service which suggests new and supplementary capabilities to suppliers depending on the available work orders in the demand pool of the market.

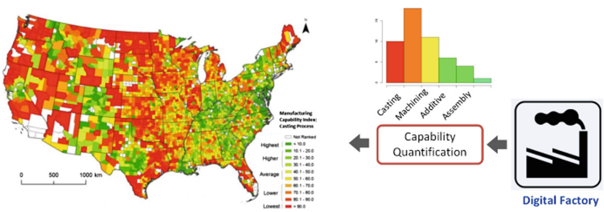

Fig. 2. The capability quantification techniques provided in this solution can be used for developing regional and national capability maps.

2.3 Supply Chain Configuration

Supply Chain configuration module provides the functionalities required for automated deployment of customized and short-lived supply chains for given work orders. In the Digital Manufacturing Market, supply and demand entities are translated into units of manufacturing service. Therefore, semantic matchmaking between requested services and provided services is one of the core functionalities of this module. The deployed supply chains are optimized in terms of the embedded capacity and capability in order to minimize underutilization of resources in the DMM. Suppliers and customers in the

DMM are represented by intelligent software agents with predefined goals and knowledge. One of the functions of a supplier agent in the DMM is to analyze the demand pool in order to identify the emerging trends and demand patterns in the market. This will enable manufacturing suppliers to gain insight into market conditions and react to changes in a timely manner through acquiring new capabilities and launching new services.

3 Manufacturing Service Ontology

In this section, the ontology of the digital factory is described and a method for quantifying the capabilities of the digital factories are described. The capability quantification method directly used the information that is provided by the service model of the factory that is represented ontologically.

3.1 Manufacturing Service Description Language (MSDL)

The recent advances in information technology, particularly in explicit knowledge representation using open-standards, provide a promising opportunity for enhancing the intelligence and automation capabilities of e-sourcing solutions through employing advanced knowledge modeling techniques for capability representation. In particular, creation of formal and standard ontologies for unambiguous description of manufacturing services can radically change the way manufacturing supply chains are configured and deployed [9]. Ontologies play a key role in any distributed intelligent system as they provide a shared, machine-understandable vocabulary for information exchange among dispersed agents [10]. A formal ontology with explicit semantics can provide the required building blocks for construction of a shared body of knowledge that can be understood and interpreted by all agents, machine or human, who subscribe to the ontology.

In the manufacturing domain, ontologies are at their early stage of development. Several ontologies have been proposed with the objective of facilitating knowledge management and information exchange across the extended enterprise. Most of the existing manufacturing domain ontologies are procedural in nature in a sense that they provide the required means for describing manufacturing transactions and operations within a manufacturing system. However, there are few ontologies that directly deal with declaration and characterization of a manufacturing system itself with respect to capabilities. Manufacturing Service Description Language (MSDL) is one of the few descriptive ontologies developed for representation of capabilities of manufacturing services. MSDL is used to build the ontological underpinning of DMM. MSDL decomposes the manufacturing capability into five levels of abstraction, namely, supplier-level, shop-level, machine-level, device-level, and process-level. The capabilities of every instance of the Digital Factory is formally described using MSDL ontology.

MSDL is based on Description Logic (DL) formalism that provides sufficient expressivity and extensibility for manufacturing knowledge modeling. A unique feature of MSDL is that it is built around a service-oriented paradigm, therefore, it can be used for representing a manufacturing system as a collection of manufacturing services. MSDL was initially designed to enable automated supplier discovery in distributed environments with focus on mechanical machining services. However, to address a wider range of services offered by small and medium-sized suppliers in contract manufacturing industry, the service ontology can always be extended systematically through active involvement of a community of ontology users. DMM contains an ontology evolution module that enables a wider range of stakeholders, including domain experts and ontology users, to contribute to extension of MSDL in various domains.

Web Ontology Language (OWL) is used as the ontology language of MSDL. OWL is recommended by the World Wide Web Consortium (W3C) as the ontology language of the Semantic Web. It uses XML as the syntax language, thus having enough portability, flexibility, and extensibility for web-scale applications. Furthermore, OWL is supported by the Semantic Web (SW), meaning that OWL-based Ontologies can be shared, parsed, and manipulated through open-source web-based tools and technologies. Figure 3 shows the Factory class diagram in together with the axiomatic description of End Milling process in MSDL.

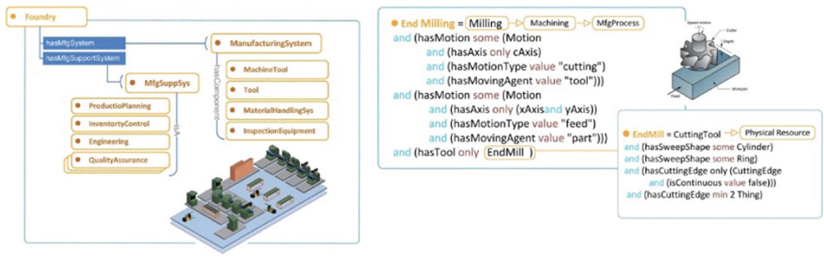

Fig. 3. MSDL describes different manufacturing processes and systems through ontological classes and logical axioms.

3.2 Capability Quantification

In the Digital Manufacturing Market, the capabilities of manufacturing companies can be objectively evaluated and quantified using the input provided by the ontological instances. Manufacturing capability is a multidimensional entity that depends on various factors such as production capacity, facilities, processing capabilities, quality, human resources, new product development systems, and production planning and inventory control techniques [11]. Since the Digital Factory mainly describes a manufacturing facility in terms of installed machinery and equipment, it can be used for assessing the processing capabilities of a manufacturing firm. For a Digital Factory composed of CNC machine tools, the attributes of processing capability include resolution, accuracy, surface finish, available machining power, part size, and part complexity. Every MSDL instance of the Digital Factory contains sufficient data for process capability measurement.

Table 1. Processing capability equations for machining process

Capability factor	Capability equation	Eq. number	Weight
Horsepower	$\frac{H}{H_{max}}$	1	W_H
Accuracy	$1 + \frac{1}{\log(A)}$	2	W_A
Resolution	$1 + \frac{1}{\log(R)}$	3	W_R
Automatic pallet changer	P	4	W_p
Number of axis	$\frac{X-3}{2}$	5	W_N
Working area	$\left(\frac{2}{Y_{max}^2}\right)(Y^2) + \left(\frac{-2}{Y_{max}}\right)(Y) + 1$	6	W_Y

Table 1 shows the equations that can be used for measuring the processing capability along different dimensions. In these equations, H = the machine horsepower for the CNC machine under study, Hmax = max horsepower provided by the CNC machines available in the market, A = machine accuracy, R = machine resolution, P is a boolean value indicating whether or not a machine has an automated pallet changer, X = number machining axes of the CNC machine, Y = size of the work area of the machine, Ymax = the largest work area available in the market. Each individual equation generates a capability score in [0, 1] range. For example, Eqs. 2 and 3 are formulated such that as the accuracy and the resolution of the machine improve, its capability scores along those dimensions increase exponentially. Equation 6, related to the working envelope of machine tool ensures that machine with very small or very large working envelop receive high score. The overall score of processing capability of the Digital Facility is the weighted average of the individual capability scores.

4 Digital Factory: Machine Shop Example

Consider a hypothetical machine shop (called Texas Precision Machining - TPM) that owns the machine tools shown in Table 2.

Because TPM is a member of the Digital Manufacturing Market, it needs to be represented digitally on DMM such that it can be discovered by potential customers. For this purpose, a TPM engineer uses the interfaces and libraries provided in DMM for replicating the physical machine shop on DMM. Out of five machine tools that TPM owns, four of them are directly available in the library. Using the drag & drop feature, the engineer adds those machines to the shop floor. The fifth machine, CNC

Table 2. The machines owned by TPM Company.

Machine type	Model	Quantity
Vertical machining center	Haas VF-5XT	1
Vertical turning center	Bridgeport Series 1	1
Precision grinder	Harig 612	1
Universal mill	Haas UMC-750	2
Swiss type lathe	Sprint 42	1

Swiss-type lathe, is not available in the machine library. Therefore, the engineer instantiates a generic CNC lathe class from the library and then adds the extra properties needed to create an instance of the specific Swiss-type lathe owned by TPM. A new class based on the newly created instance will be added to the DMM library such that other users can instantiate a similar machine if necessary in future. This is one of the methods used for extending DMM's underlying ontology. As the engineer adds new machines to the digital factory, the service and capability models of TPM are generated automatically in the backend. The score for the processing capabilities of each CNC machine owned by TPM can be calculated using the equations given in Table 1. For example, the processing capability score of the VF-5XT CNC machine is 0.73 as shown in Table 3.

Table 3. The processing capability score for VF-5XT milling center. The calculated score is based on $Y_{max} = 50,000$ cubic feet and $H_{max} = 100$ hp

Capability factor	Value	Weights		Score	Weighted score
Horsepower (H)	30	W_h	5	0.3	1.5
Accuracy (A)	0.0001	W_a	12	0.75	9
Resolution (R)	0.001	W_r	13	0.66	8.66
Pallet changer (P)	1	W_p	5	1	5
Number of axis (X)	5	W_x	7	1	7
Working area (W)	39000	W_w	6	0.65	3.94
	Total machine score				= 0.73

Because each of the machines available in TPM's digital factory is described ontologically, the capability inference engine can infer the overall processing capabilities of the digital factory automatically. Figure 4 shows the inferred capabilities of TPM.

Once the processing capabilities are extracted, the work order suggestion module of the DMM produces a list of work orders that are within the range of capabilities of

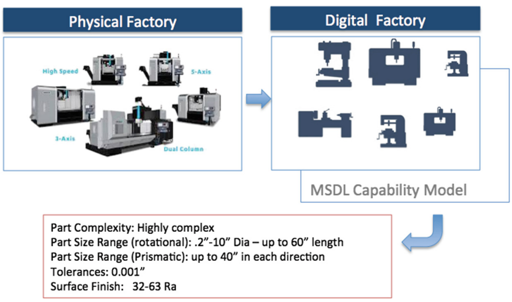

Fig. 4. The MSDL capability model of TPM is generated automatically based on the composition and types of machines available in the digital factory

TPM. Also, the system recommends TPM to acquire a new 5-axis milling center, because this machine tool would supplement and enhance the technological capabilities of TPM to a level that it can cover more than 75% of the parts available in the market. The supply chain configuration module recommends three potential supply chains in Central Texas for which TPM is a close match. Also, upon addition of TPM to DMM's supply pool, the capability model of Central Texas is updated to reflect the new capabilities introduced through TPM. The classification module of DMM classifies TPM as a high-complexity/high-precision/medium-production range supplier. Automated classification of suppliers improves the efficiency of the search process and also enhances the visibility of suppliers in the virtual space.

5 Conclusion

This paper presented a conceptual view of the Digital Factory in the context of the Digital Manufacturing Market. The DMM is a platform for building supply chain connections supported by semantic ontologies and data analytics tools and system. DMM create an ecosystem of manufacturing services that are formally described and can be discovered, evaluated, and integrated autonomously. Digital Factory, as a component of the DMM, is the virtual twin of a physical factory that is registered on DMM. There is no limit on the size and type of machines and equipment that can be included in a Digital Factory. Two models can be derived from the digital factory, namely, service model, and capability model. The service model described the primary and secondary manufacturing services that can be offered by a facility while the capability model describes the aggregate capabilities of the facility based on the available machinery and equipment. The main advantage of Digital Factory is real-time and accurate representation of the technological capabilities of manufacturing companies. Since Digital Factories are described semantically using MSDL ontology, they are amenable to automated search and reasoning. This will significantly enhance the intelligence of supply chain formation and sourcing tools in virtual space.

This research is part of an ongoing project in the broad area of intelligent supplier discovery. Some of the components of the described framework, such as the ontology, the search engine, and the agent based model, are already developed and validated in separate research projects [3, 7]. The Digital Factory is the next component that will be added to the DMM technology suite in near future. Also, the Digital Factories will be connected to MTConnect agents to collect operational information from the shop floor. This will enable further analysis and reasoning about operational capabilities of machine shops based on their actual production data. One limitation of the idea of Digital Factory is slow adoption rate particularly at the early stages of implementation. Since the envisioned users of this technology are mainly the SMEs that are accustomed to more traditional means of sourcing and marketing, they may exhibit resistance to migrating to the digital arena. To mitigate this risk and also learn about the behavior of manufacturing suppliers, the pilot implementation phase will involve a small number of select suppliers from Texas and Illinois who will voluntarily join the digital manufacturing market.

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