The Manufacturing Blueprint Environment: Bringing Intelligence into Manufacturing

Michael P. Papazoglou
European Research Institute in Service Science (ERISS)
Tilburg University
Tilburg, The Netherlands
mikep@uvt.nl

Amal Elgammal[1]
Faculty of Computers and Information
Cairo University
Cairo, Egypt
amal@servtech.info

***Abstract*—Manufacturers today are rapidly moving into a business climate that is characterized by the ability to fulfill orders on demand by doing business through short-term networks where they negotiate value-adding processes dynamically – taking into account quality, time, price, viability, sustainability, and other dimensions. This necessitates the use of novel technologies to help manufacturers connect their data, processes, systems, personnel and equipment to enable smart factories. This paper proposes a new manufacturing paradigm, called manufacturing blueprints, which allows manufacturers to move from a traditional product-centric business model to a fully digital, knowledge-based and service-centric one. Using this paradigm, manufacturers are able to combine manufacturing and equipment data and knowledge, production systems and processes to form a smart manufacturing network to diversify products and build new markets.**

Keywords—collaborative & networked factories; human-centred manufacturing; smart manufacturing; manufacturing marketplaces; manufacturing knowledge; CPS; manufacturing domain-specific langauge; digital manufacturing; manufacturing interoperability.

I. Introduction

Today, the trend in manufacturing is for increased connectivity and more sophisticated data-gathering and analytics capabilities empowered by Cyber Physical Systems (CPS), big data technologies and the Internet of Things (IoT). These usher in tandem a new era of smarter supply and production chains, smarter production processes, and even end-to-end connected manufacturing ecosystems.

An end-to-end connected manufacturing ecosystem signifies a permanent or temporal coalition comprising production systems of geographically dispersed firms that conduct collaborative manufacturing in a shared value-chain. “Smart manufacturing” is a vision of the world in which such open networks connect people, manufacturing data, operational processes, various kinds of devices, sensors, and machines for joint production [1].

Smart Manufacturing Networks (SMNs) focus more holistically on how the full supply chain can better achieve business objectives, how it can integrate data from a variety of different sources and locations, and manufacturing operations across connected manufacturing sites to drive the physical production [2]. SMNs promote a paradigm shift from centralized manufacturing units towards decentralized and geographically dispersed production units.

On the technical level SMNs comprise production systems of geographically dispersed enterprises (supplier networks, external support firms, and outside service organizations) that collaborate in a shared value-chain to design and jointly produce an end product. Parts of this product can be manufactured by dispersed subcontractors running their own production systems in an end-to-end, plug and produce manner. In this way, a specialist factory can fill excess capacity by collaborating with other such like entities, increasing flexibility and reducing costs whilst improving quality of the product for the end consumer.

To accomplish its objectives, an SMN relies on smart use of networked information; integrated computational materials; enterprise and supply chain performance and broad-based workforce engagement; and manufacturing robotics that work safely with people in shared spaces [1]. It also requires coupling data and services with a wide range of performance metrics and achieving visibility across the extended manufacturing network such that critical manufacturing operations are intercepted, analyzed and executed by applying the best manufacturing practices.

An SMN typically relies on domain-specific manufacturing knowledge which we call *manufacturing smartness* (see Section VI). Manufacturing smartness signifies the ability of an SMN to:

- gain line of sight and provide unobstructed visibility of dispersed production data and manufacturing operations across the manufacturing network,
- optimize use of dispersed data, resources and (human)-expertise,

[1] Also affiliated to the Scientific Academy for Service Technology (ServTech), Bürgerstr. 54a, Hagen D-58097, Germany.

- provide help and guidance for making efficient and effective holistic decisions, and
- plan a coordinated response to individual and collective manufacturing needs.

This paper introduces a reference architecture for SMNs, explains how the modules in this architecture ensure interoperability for complex data, processes and resources within local and remote manufacturing sites. Subsequently, the paper concentrates on the knowledge representation and processing facilities of this architectural platform and explains how these can receive and processes customer requests and product design parameters which they transform into concrete operations that aid in the production of manufactured products.

II. OVERVIEW OF THE SITUATION AND RELATED WORK

Currently, traditional manufacturing factories continue to operate as "black boxes" within very localized environments. They typically do not have adequate, timely status information on the external events that affect their own operations and costs. SMNs approach these drawbacks from the perspective of distributed manufacturing, and CPS. Related work in these fields is briefly examined below.

Distributed manufacturing has been touted as the natural evolution in manufacturing to replace traditional centralized factories where raw materials are brought together, assembled and fabricated in large centralized factories into identical finished products. In distributed manufacturing - unlike traditional manufacturing - the raw materials and methods of fabrication are decentralized, and the final product is manufactured very close to the final customer. This happens usually by leveraging large numbers of ‘partner’ factories to create agile supply chains [3]. An essential characteristic of distributed manufacturing is to replace as much of the material supply chain as possible with digital information.

In distributed manufacturing literature emphasis is placed on distributed manufacturing systems and its operations [4], on assessing interdependencies between product design and the choice of manufacturing site [5], and in identifying supply chain partners evaluated on their capabilities, ability to provide a variety of products and services toward the satisfaction of the customer demands and their capacity [6].

In [7] an axiomatic approach is proposed for a three-level distributed manufacturing framework for designing a franchise production system made of several geographically distributed, changeable, scalable as well as replicable manufacturing unit. Another example of distributed manufacturing can be found in [8] where the authors present a holistic framework for configuring manufacturing networks able to effectively and efficiently deal with a mass customized production.

Manufacturing CPS can be defined as novel transformative technologies for managing interconnected systems between their physical assets and computational capabilities on and across all levels of production from processes through machines up to production and logistics networks [9]. In manufacturing CPS communication is between many world-wide distributed production lines requiring IoT based communications. In [10] the authors propose an approach whereby CPSs are fundamental units that have almost instant access to relevant information and parametrization of machines, production processes and the final product itself.

Recently, authors have researched the connection between manufacturing CPSs and analytics. In [11] the authors propose a cloud manufacturing paradigm by considering a manufacturing CPS in which each sensor-based process or equipment makes available event and status information for advanced Big Data analytics. Finally, in [12] the authors present a methodology for the pattern-based development and realization of business models in the context of Cyber-Physical Production Systems.

III. BUILDING THE CONNECTED MANUFACTURING ECOSYSTEM

One of the primary roles of an SMN is to ensure interoperability and thereby reduce integration time for complex devices and subsystems within local and remote manufacturing sites. Overall SMNs must provide the following functionality:

- Capabilities to solve problems end-to-end to improve decision making on the individual plant floor and across the entire manufacturing network;
- Greater visibility and control into manufacturing operations that span and manage manufacturing sites; and
- Capabilities to turn massive amounts of production data into actionable information by using advanced analytics to identify bottlenecks, troubleshoot issues, understand asset interdependencies, and reduce costs.

To enable a holistic product/production view, an SMN must support three types of interoperability:

- *Horizontal interoperability:* which signifies the ability for high-level integration of manufacturing sites to implement demand-oriented production creating transparency and flexibility across entire process chains.
- *Vertical interoperability:* which means seamlessly integrating features and functionality of enterprise top-floor with factory-floor, and production systems (robots, conveyor belts, smart meters, generators, substation equipment, transformers and the like).
- *Mixed interoperability:* the combination of horizontal and vertical interoperability in an SMN to enable effective holistic product/production decision making.

An effective way to deal with wide-ranging interoperability requirements of applications in different manufacturing sectors is the use of a Manufacturing Reference Architecture (MRA) for SMNs. An MRA is the fundamental organization of a manufacturing system on the basis of model-based architecture and systems engineering approaches to provide manufacturers with an integrated framework for optimizing their resources to integrate existing and future plant data, processes simulations and systems across manufacturing functions [13].

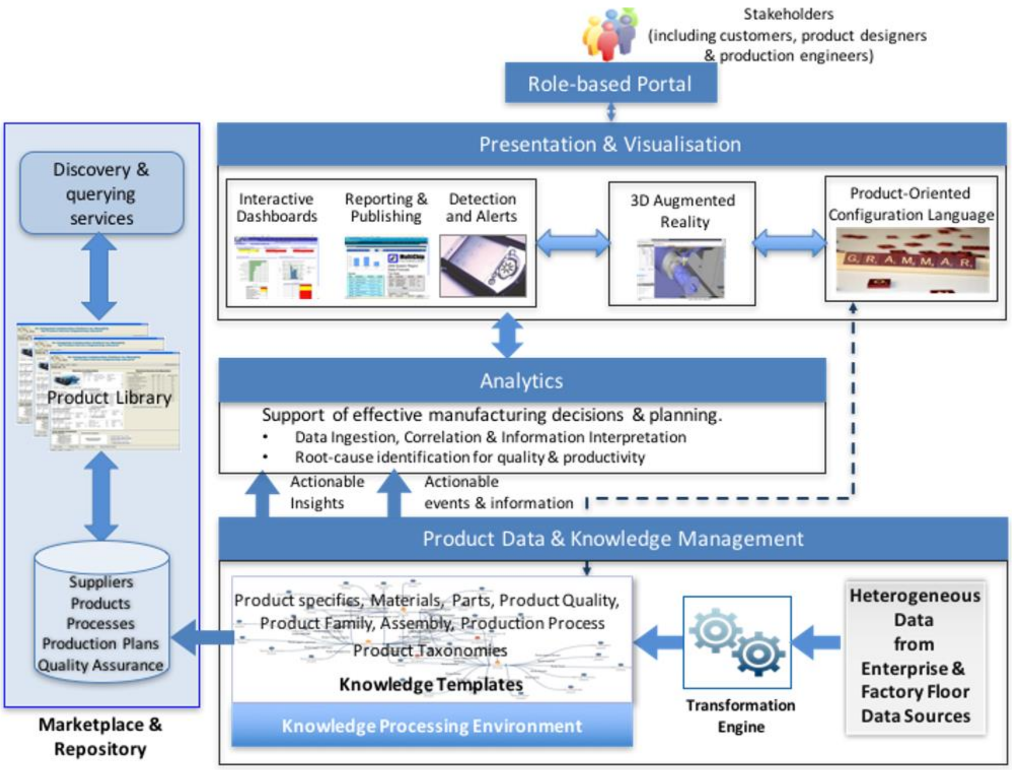

Fig. 1. Manufacturing Reference Architecture (MRA) for smart manufacturing networks

A core aspect of the MRA is service-oriented technologies (SOA), which help convert products, processes and resources into digital services and trigger a shift towards service platforms and digital ecosystems.

Digital services in manufacturing can be defined as Internet-connected standardized SOA-enabled product, process, and resource descriptions that can offer innovative, value-added manufacturing services and can enact manufacturing processes and end-to-end solutions.

The key to a successful MRA lies in properly balancing the inherent tradeoff between commonality and distinctiveness: designers must balance the commonality of its generic structure with the specific distinctiveness of each domain-specific extension to yield manufacturing sector-specific variability [2].

Based on previous experience with platform-based development for smart manufacturing applications in sectors, such as aeronautics, and automotive domains [2], we postulate that a generic MRA incorporates the software modules shown in Fig. 1. Modules of the MRA are briefly described below.

1. ***Product Data & Knowledge Management*** module that includes the following four main sub-modules:

   - *Product specific knowledge templates*: These represent and inter-link product data, product and manufacturing process information (both its content and context), product portfolios and product families, manufacturing assets (personnel, plant machinery and facilities, production line equipment), production processing requirements and production workflows.
   - *Knowledge processing environment*: This operates on the knowledge templates mentioned above and provides the *knowledge services* that discover, query, correlate and make sense of the collections of massive data, and processes which are described in knowledge templates.
   - *Heterogeneous data sources*: These include traditional enterprise data from operational systems such as data from ERP, CRM systems, as well as production, demand, supply, and product related data from PLM systems. They also include production, process engineering and plant data from machines, equipment, and sensors as well as plant/equipment maintenance and quality assurance data.
   - *Data transformation* services: Data mapping and transformation facilities that transform manufacturing data (described above) and map them to appropriate knowledge templates for further processing and analysis.

2. ***Manufacturing Marketplace***: An on-line Manufacturing Marketplace is an efficient online sector-specific manufacturers directory and repository, e.g., multi-axis laser machine products, plastic injection molding, metal fabrication, injection molding, castings, metal stamping and so on. The Marketplace combines search and discovery of manufacturing data and services, products, suppliers, potential customers, data and so on, with facilities for increased security, collaboration and intellectual property

protection. In a Marketplace philosophy manufacturers, suppliers and potential customers of products and services are brought together to collaborate, partner and produce more efficiently. For example, potential customers can use this Marketplace to source and procure laser product offerings, to look for potential suppliers to manufacture metal, injection molding plastic or rubber parts and obtain quotes. The product library and repository in Fig. 1 is used for storing the retrievable Marketplace information about registered suppliers, products, services, etc.

3. ***Analytics services***: The manufacturing analytics module in Fig. 1 employs knowledge templates and the knowledge processing environment to manage production operations in which the data needs to be turned into information that provides actionable intelligence. This module performs the following functions:

- provides enhanced manufacturing-network visibility, transparency, and analytical insights,
- optimizes use of dispersed resources and human expertise, and
- plans a coordinated response to individual and collective manufacturing needs.

To accomplish its functions this module provides the foundation for a wide range of analytics, which include:

- *Data Ingestion, Correlation and Information Interpretation*: These services are required for ingestion, correlation and interpretation of information found in the knowledge templates.
- *Root-cause identification for quality and productivity*: Analytics techniques include identification of root cause and predicting part and production failures.

4. ***Presentation and Visualization***: This module has a dual purpose. Firstly, it provides services for collaboratively creating, visualizing, validating and optimizing product designs, by identifying and resolving issues. In addition, it provides a visual, graphical domain-specific language that allows users express their request and preferences as regards customized products. This module includes the following sub-modules:

- *3D Augmented Reality*: This module comprises a 3D virtual reality design studio and showroom that helps product co-design and modular manufacturing solutions by projecting a digital product for refinement and optimization.
- *Interactive Dashboard*: The dashboard provides real-time visibility for decision making using advanced graphic representations of product, production and event data, alarms, thresholds, KPI status, and performance levels.
- *Product-Oriented Configuration Language (PoCL)*: this module furnishes an intuitive, graphical language that enables different stakeholders to formulate product requests in an abstract and user -friendly manner. This module also includes a transformation engine to automatically transform the graphical PoCL model of a complete and consistent end product information stored into the knowledge templates. The dashed lines in Fig. 1 illustrate this.

5. ***Role-based Portal***: provides users with a single dedicated, personalized point of access to relevant authoritative information (e.g., product details, production, and planning) and manufacturing services in the Marketplace, and role-based use of the PoCL and the augmented reality and visualization studio tools.

The basic flows in the MRA below explain how manufacturers and potential customers can use the MRA.

Basic Flows in the MRA: The intention of the Marketplace in the MRA is to simplify and speed up the process of ordering and fulfilling solutions, enabling collaborative development of customized products. The basic flows in the MRA are described using the following simplified steps.

1. Manufacturers and suppliers store their product offerings in the form of modular knowledge templates (called manufacturing blueprints in this paper, see Section VI) in the Marketplace repository.
2. Manufacturers, suppliers and potential customers are brought together in the Marketplace to collaborate, partner and produce new product offerings more efficiently.
3. Potential customers can discover and inspect product offerings of interest form the Marketplace, then they can specify specific requests/preferences using the PoCL.
4. Customers are able to visualize the customization of an existing product in their environment and see how it fits in it using the 3D virtual reality design studio and showroom. Based on the visualization of the product the customer can further modify it until the outcome fulfils her/his requirements coming from the real environment.
5. An order is then put to an OEM (selected from the Marketplace) who will produce the end product.
6. The contract OEM may focus on its core competencies and outsource parts of the production to contract manufacturers or procure these product parts and materials by finding suppliers that supply them from the Marketplace. The OEM will eventually assemble these product parts, subassemblies, into the final product.
7. To achieve collaborative production, the OEM partners with contract manufacturers or part/material suppliers that it knows or locates from the Marketplace after retrieving their knowledge templates. These knowledge templates describe fully the outsourced product parts, subassemblies, materials and the competencies and capacities of the manufacturers/suppliers that supply them.

Fig. 2. GUI for the Product-Oriented Configuration Language

8. Once the OEM has partnered with contract manufacturers or suppliers and has produced the end product, it describes the new value offering in terms of composable knowledge templates, which it places in the Marketplace for future discovery purposes.

In the following we shall focus on how requests are expressed by means of the Product-Oriented Configuration Language and on the Product & Knowledge Management features of the MRA.

IV. Pilot Case

In this section, we give a brief overview of a make- to- order scenario for configurable laser machine products. We assume that a tier- one supplier (OEM) receives an order for a cutting and welding laser machine from a customer (aerospace engine manufacturer). In this use-case we assume that the customer is interested in a multi-axis laser processing system for manufacturing turbine engines for aircrafts and associated services for their maintenance, repair, and overhaul. Further, we assume that OEM product designers and production engineers co-design the product (laser processing system) together with the customer using the Product-Oriented Configuration Language in the MRA.

The laser processing system must be suited for operations with relatively high volume applications of precision 3D laser cutting, welding, and drilling and high power fiber laser capability. It must offer great flexibility and options and multiple configurations for processing parts in aerospace market segments requiring manufacturing flexibility, rapid prototyping and quick change overs. To maximize throughput the laser processing system must feature two completely independent 3D laser processing units located next to each other that can be operated by a single person.

For the purposes of this paper we assume further that the OEM engages a number of tier-two suppliers who deliver specialized parts for the laser processing system, such as angle-torch, acetylene valve, plasma cutter, and optical focus control parts in a collaborative SMN arrangement.

V. Product-Oriented Configuration Language

PoCL is a model-based graphical user-friendly Domain-Specific Language (DSL) that helps customers to collaboratively create, validate and optimize manufacturing design plans concurrently with product designers [14]. This language allows a variety of stakeholders, such as customers, product designers and engineers, to create conceptual drawings for final assessment and approval of a digital product. In essence, PoCL allows customers to imagine and gradually create a virtual product, amplifying their ideas and clearing the way to better design and innovate.

PoCL interacts with users depending on their level of expertise ranging from customers with design engineering knowledge who are closely involved in the co-design of products to lay-users. The language employs easily combinable graphical representations of product shapes and combines product quality characteristics with product design artefacts [14]. Different stakeholders are supported by different interfaces with varying abstraction levels that accommodate the user perspectives. To enforce standard product and process descriptions and ensure wide applicability, the language constructs are based on common manufacturing and supply-chain standards such as the ISA-95 (www.isa-95.com) [14].

Extensions of PoCL are underway to include 3D parts and assembly modeling through which the design intent of a part or assembly will be accurately and unambiguously described by a 3D virtual model. Using PoCL 3D designs will be developed quickly using imported images, simple sketches, or scanned 3D data, and then more details will be added as the design evolves. Direct model editing–manipulate and modify 3D design plans will be supported by adding or subtracting functionality and parts working directly on the 3D CAD model.

Here, we assume that the aerospace engine manufacturer is interested in a multi-axis laser processing system and specifies its requirements and preferences and co-designs the product with the help of OEM production personnel, product designers and production engineers using the PoCL. The customer may specify using the PoCL interface and 3D CAD model (using graphical drawings for fabrication with standardized symbols for mechanical, welding, construction, electrical wiring and assembly and accompanying textual explanations) the product and its characteristics. For example, the aerospace engine manufacturer may specify that the laser processing system features should include new generation beam director laser beam positioning capability combined with high-accuracy rotary table motion to enable new manufacturing processes while improving existing ones. The work area should be X 600 mm – Y 600 mm – Z 600 mm, the beam director should provide rotary axis motion of 900o, and tilt axis motion of 300o and an axis speed of 90 rpm. The aerospace engine manufacturer may also specify that during processing, sensors should measure multiple parameters, including the actual laser output, motion, process gases, and process control in both workstations.

Fig. 2 illustrates a simplified GUI for PoCL. This figure shows a screenshot of the PoCL for the customized multi-axis laser processing system. In particular, the screenshot shows a “Laser Machines” palette (left hand-side of the screenshot) that is being constructed in a drag-and-drop fashion by adding or subtracting functionality and parts working directly on the 3D CAD model (not shown in the figure) for customization purposes. The PoCL parameters that specify the customer requirements and preferences in our example are illustrated on the pop-up windows shown at the right-hand side of the screenshot.

The PoCL example above involves a sheer volume, diversity of fragmented manufacturing data (e.g., product, part, sensor, equipment, technical performance, quality, etc) that are widely dispersed over a number of systems and tools. It also involves operations that span connected manufacturing sites to drive the physical production and trigger complex production activities that influence product customization and yield. It is precisely this type of information that is stored in the knowledge templates in Fig. 1 and is used to steer resources (machines, devices, sensors, robots, etc) on the factory floor and enables construction of the properly designed customized multi-axis laser processing system.

To construct a customized product (like the one specified in PoCL above) dispersed data such as, desired product characteristics, material type, product dimensions, tolerances, quality characteristics, material callouts, product-services, assembly directions, and so on, must be organized, related to operational processes that span SMN partners and stored in the knowledge templates in the MRA. This information comprises the virtual reflection of the actual product and actual manufacturing processes that will eventually be used to construct the end product. This is explained in the next section.

VI. Manufacturing Blueprint Environment

The purpose of the knowledge environment in the MRA is to provide manufacturers with a more granular, composable knowledge structures and approach to correlate and systematize vast amounts of dispersed manufacturing data, associate the “normalized” data with manufacturing operations, and orchestrate manufacturing processes in a more closed-loop performance system that delivers continuous innovation and insight. Such knowledge is crucial for creating manufacturing smartness in an SMN.

The source of manufacturing smartness in an SMN are the knowledge templates that we introduced earlier in the MRA in Fig. 1. These knowledge templates are collectively called manufacturing blueprints [2].

Manufacturing blueprints provide a complete digest of a product, by juxtaposing its characteristics with its operational and performance features, with how it is manufactured, with which processes are being used and which manufacturing assets (personnel, plant machinery and facilities, production line equipment) are used to produce it, and with the suppliers that provide/produce parts and materials. Manufacturing blueprints also provide a succinct description of suppliers, their competencies and their capacity. Finally, manufacturing blueprints also describe how manufacturers and suppliers collaborate, how they orchestrate manufacturing processes, streamline hand-offs and produce the end product.

In this section, we put manufacturing blueprints within a broader representation and operational context, called a Manufacturing Blueprint Environment (MBE). The MBE is shown in Fig. 3.

Purpose of the MBE is to represent and inter-relate products, product parts and materials, high manufacturing data volumes, manufacturing assets and operational characteristics and performance by employing compositional meta-modeling and knowledge representation and processing techniques. Besides improving productivity, the MBE provides and inter-relates data that can be used to assess the long-term performance of processes and equipment models and to make predictive recommendations.

The MBE is shown in Fig. 3 to comprise two interrelated parts:

- *A Knowledge representation framework* that currently provides a set of five inter-connected knowledge templates (called blueprint images), and a
- *knowledge processing environment* that provides services that operate on blueprint images to help inter-relate product parts, quality KPIs, production requirements, and relevant processes that are used as the means to achieve customer and production demands.

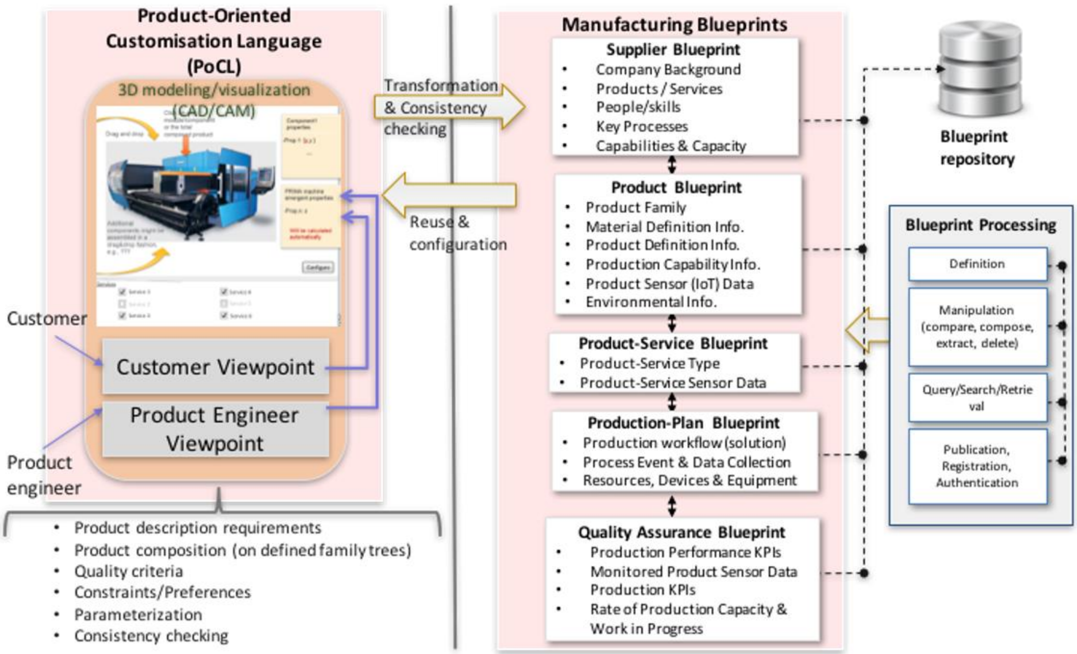

Fig. 3. The Manufacturing Blueprint Environment.

A. Blueprint Represntation Frameowork

Manufacturing blueprints use knowledge representation and model-based design techniques to represent, inter-link product and process data, product and manufacturing process information (both its content and context), product portfolios and product families, manufacturing assets (personnel, plant machinery and facilities, production line equipment), production processing requirements and production workflows.

Manufacturing blueprints codify, integrate, and contextualize manufacturing data and processes [2]. They provide parameterized solution-aware patterns that represent operational processes and inter-relate a variety of data of diverse data types, critical functional, sensor and performance factors in production. Manufacturing blueprints help meet the requirements (functional, performance, quality, cost, physical factors, interoperability, time, etc.) of an entire manufacturing network.

They gather manufacturing "intelligence" from every point of an integrated production line and faithfully represent multiple manufacturing aspects (e.g., functional, behavioral, timing, quality of service, and control) and production-flows. In this manner, manufacturing blueprints support a move toward more fact-based manufacturing decisions.

Manufacturing knowledge is encapsulated in the five inter-connected knowledge-based templates described below, referred to as blueprint images (or simply blueprints). Blueprint images compartmentalize product and production knowledge and achieve separation of production concerns as follows:

1. Partner/Stakeholder Blueprint: defines a partner firm's business and technical details, such production capabilities and production capacity details and stakeholder roles.
2. Product Blueprint: represents the details of a standard or configurable product, product parts, materials, product-related. Such information is coupled with other relevant data, such as machine parameters or customer order data, machine and tool data, personnel skills, and all entities necessary to faithfully represent a complete product and ease production work.
3. Product-Services Blueprint: This blueprint defines and represents all services corresponding to a product (e.g. maintenance, repair, upgrades, spare parts, etc). Instances of this blueprint describe the services that are coupled with a physical product to meet customer requirements. This type of bundling allows the convenient purchase of several products and/or services from one manufacturer.
4. Production Plan Blueprint: this knowledge-structure represents standard assembly and production solutions as well as a suitable production execution plan via a workflow linking the events of discrete activities associated with all aspects of actual production on the factory-floor.
5. Quality Assurance Blueprint: objective of this blueprint image is to increase process efficiency and asset utilization, process performance, equipment health, and energy consumption levels. It defines process performance and product quality metrics (KPIs) to monitor production operations and solve operation problems across supply and production-chains. Its purpose is to alert human operators when an important event occurs, and enable them to take appropriate corrective action, if necessary.

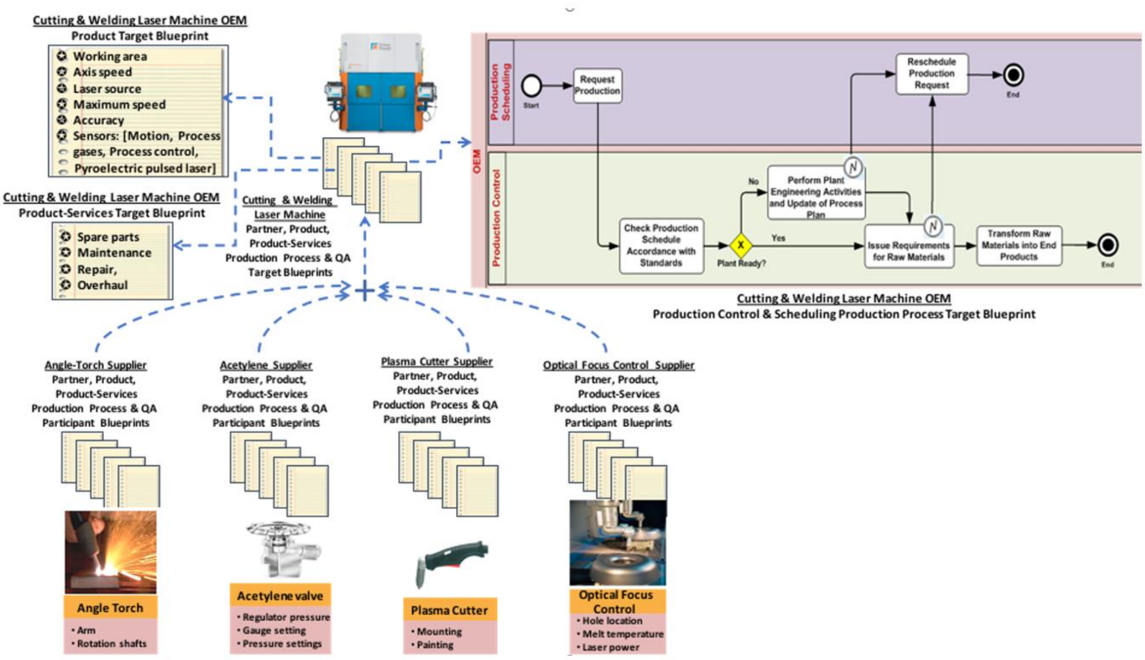

Fig. 4. Merging blueprints into a full manufacturing solution

The above set of blueprint images (or simply blueprints) is stored in a blueprint repository, which is part of the Marketplace in Fig. 1, for discovery and eventual composition to provide a complete picture of all aspects of customized products. As will be discussed later in the implementation and validation section (Section VI), the blueprinting model is implemented using the Ontology Web Language (OWL) standard.

B. *Blueprint Processing Environment*

The catalysts for the blueprinting approach in manufacturing are the emergence of the inter-connected data, product, product parts and product-services, processes, devices, sensors, machines, and people communicating together in unprecedented ways to improve productivity and optimize supply and production chains

The MBE provides processing operators that infuse seamlessly manufacturing knowledge from all five blueprint images to the supply and production chain and ensure that all ensuing actions are integrated in time and fully synchronized. The MBE blueprint processing operators are as follows:

1. *Declarative blueprint definition operators*: these provide the necessary constructs to define the four knowledge-templates shown in Fig. 1, namely partner/stakeholder, product, production-plan and quality assurance blueprints.

2. *Simple blueprint manipulation operators*: these provide a set of operators for users and stakeholders to *retrieve* existing blueprints representing products or production-plan plans, to *compare* them and compose a product from individual parts, or a production schedule by composing schedules for individual activities.

   The blueprint manipulation operators exhibit a closure property: each operation takes one or more compatible blueprints and returns a higher-level blueprint. Compatible blueprints are blueprints of the same kind (e.g., product-to-product or production-plan-to-production plan). This allows for *blueprint composition* using the *merge* operation that interconnects a set of blueprints end-to-end by describing all the characteristics, parts, services, quality and operational aspects of a customized product.

3. *Simple query services*: to query blueprints or zoom into individual blueprints to extract valuable information for decision-making purposes.

Operators for publishing, registering and authenticating blueprints are also provided.

Fig. 4 illustrates the use of the merge operator (+ symbol), which merges in a compatible pairwise manner the blueprints of tier-two suppliers who deliver specialized parts for the laser processing system designed by the aerospace engine manufacturer (customer) that used the PoCL in Section V. In Fig. 4 the blueprints of the tier-two suppliers who provide partial solutions are called *participant blueprints*. In this figure, the participant blueprints are provided by the angle-torch, acetylene valve, plasma cutter, and optical focus control parts tier-two suppliers who deliver these specialized parts in a collaborative SMN arrangement.

Here, we assume that the participant blueprints of the tier-two suppliers in Fig. 4 were stored in Manufacturing Marketplace for laser machines and spare parts and were chosen by the OEM to jointly manufacture the multi-axis laser processing system order placed by the aerospace engine manufacturer and assembled by the contract OEM and its SMN partners.

The four participant blueprints in Fig. 4 are merged by the contract OEM with its own blueprints into a set of end-to-end blueprints that represents the final product and specifies the manufacturing operations that are needed to construct it. In Fig. 4 the set of merged blueprints is constructed dynamically and is referred to as *target blueprints*.

In Fig. 4 virtual production processes are part of target blueprint and are represented as the simplified BPMN SCOR Level 4 processes for "Production Scheduling" and "Production Control". These operations communicate directly with physical factory floor resources to drive production of the desired laser processing system. This figure also illustrates the product-services for the cutting and welding laser machine target blueprints, which include attributes, such as maintenance, repair, upgrades, and spare parts.

The inter-linking of target and participant blueprints by means of the MBE operations described above provides the end-to-end visibility necessary for an OEM to drive effective supply chain performance and improve operational effectiveness across the entire SMN. It provides the instrument to guide manufacturers to make efficient and effective holistic decisions and for planning a coordinated response to individual and collective manufacturing needs in an SMN.

The manufacturing blueprints and the MBE serve as a replica for the actual production flow by infusing the production organization earlier in the product design processes in order to facilitate and optimize the manufacturing process (e.g., process parameters, tool selection, material flow and workstation balancing) in an early stage. In addition to enabling total control of the production processes, the MBE also facilitates best practice sharing between production sites. The next step is to then build a physical product that meets the specifications of this controlling virtual product and production operations described in the target blueprints.

A physical product can be manufactured by relying on the knowledge encoded in the participant, product, product-service and QA blueprint images and by implementing the operations specified in the production plan blueprint image that are used to steer resources (machines, devices, sensors, robots, etc) on the factory floor.

VII. Implementation and Validation

A first step towards the validation and evaluation of the approach presented in this article is the development of a comprehensive prototype system implementing the PoCL and the MBE. The identified functional requirements (pilot case and features) have been validated and prioritized to reflect the complex requirements of a leading manufacturer of laser and sheet metal machinery, namely Prima Industries (www.primapower.com) which acts as the contract OEM in the pilot case.

Piloting, prototyping and testing are ongoing into two parallel directions realizing the model-driven smart manufacturing approach presented in Fig. 3 and discussed throughout this article. Specifically, they focus on the:

- Design and development of a web-based product configurator environment that integrates in its core the PoCL language. Details are presented next in Section VII.A.
- Design and development of the Manufacturing blueprint environment as discussed in Section VI. Details are given next in Section VII.B.

Validation activities conducted so far ensure the novelty, validity, usability and applicability of the proposed approach.

A. Product Configurator Subsystem

PoCL adopts a view-based model-driven engineering approach, where various stakeholders, e.g., customers, advanced customers, product designers, product engineers, etc., collaborate in configuring a customized product design/manufacturing equipped with different GUIs that accommodate various views/needs. This enables collaborative product customization supported by an integrated environment based on formal knowledge structures (blueprints images discussed in Section VI and their implementation in Section VII.B)

Fig. 2 presented a screenshot of the implementation product configurator component. PoCL is implemented as a graphical DSL; the main technologies used are: (i) Front-end: Liferay portal (https://www.liferay.com/) and GoJS (https://gojs.net), which is a powerful model-driven JavaScript framework, and (ii) Back-end: Java servlets.

The screenshot in Fig. 2 supports the pilot case in Section 0. As shown in this figure, the contract OEM's "PRIMA Machines" palette (left hand-side of the screenshot) dynamically shows the available PRIMA multi-axis laser processing system for manufacturing of turbine engines for aircrafts by retrieving its parts from the blueprints repository. PRIMA's customer (aerospace engine manufacturer) can then select the base machine from the "PRIMA Machines" palette, which it can gradually customize to include desired features, such as for example, few sensors and supporting services.

B. Blueprint Manufacturing environment Subsystem

The blueprint manufacturing environment as presented in Section VI has been fulling implemented using the Ontology Web Language (OWL) standard.

The OWL implementation provides semantic support to the blueprint knowledge-base, which is vital requirement to bring intelligence to manufacturing, and enables dynamic consistency checking of the blueprint knowledge-base. It also enables simple forms of automated reasoning and verification techniques based on Description Logic to verify customers' requirements, constraints and preferences; an essential feature that is still under design and development. The manufacturing blueprint environment has been developed using the Protégé tool-suite (http://protege.stanford.edu/), a free, open-source ontology editor and framework for building intelligent systems.

VIII. CONCLUSIONS & FUTURE WORK

This paper proposed a paradigm shift from optimizing physical manufacturing assets to a collaborative digital manufacturing approach that optimizes how data, knowledge and processes are leveraged along all the channels of product and production lifecycle. This approach, called manufacturing blueprints, equips manufacturers with capabilities for designing and evaluating their products and processes virtually.

The manufacturing blueprint approach builds on an end-to-end data/knowledge and process digital flow running through the entire product and production lifecycle. It starts with eliciting user requirements, followed by the digital design of the product, and passes on through digitally steered and controlled manufacturing processes. At each of these steps, the digital thumbnail of the manufacturing knowledge, called manufacturing blueprints, operates as an enabler for leveraging, sharing and exchanging data, information and processes that come together as a fully integrated, automated, and optimized production flow along the process of digital production.

The approach proposed in this paper enables stronger cross-functional integration of data and processes leading to greater efficiencies. It employs the blueprint model as the digital reflection of the physical product that takes gradually shape on the factory floor. This new digital reality and the unprecedented capabilities it embodies in terms of integrability, interoperability, and more composability of products and processes gives rise to great challenges in smart manufacturing. It also fundamentally changes the traditional production relationships among suppliers, producers, and customers. The focus reverts now from one single production site to production networks that encompass multiple sites belonging to a manufacturing firm as well as its suppliers and customers.

The ultimate goal of this work in the not-too-distant future targets the concept of “self-organizing manufacturing processes for highly customizable products”. It is expected that the blueprinting approach will evolve towards autonomic, reconfigurable manufacturing systems where a manufacturer receives a digital blueprint model of a new product, and based on the information in the model, the production environment will configure itself to produce that product. Autonomic, re-configurable manufacturing takes all the manufacturing to the next level by combining flexibility and self-adaptability of the production systems, self-optimization of adjustable smart production resources across all functions, paving the way for new product and more agile service platform schemes.

ACKNOWLEDGMENT

This research is partially funded by the European Commission Horizon 2020 project ICP4Life, which is financed under grant agreement number 636862. We wish to thank Prima Industries (www.primapower.com) for providing the essentials of the pilot study in this paper.

REFERENCES

[1] J. Davis, T. F. Edgar, J. Porter, J. Bernaden, and M. Sarli, "Smart manufacturing, manufacturing intelligence and demand-dynamic performance," Computers & Chemical Engineering, vol. 47, 2012, pp. 145-156.

[2] M. Papazoglou, W. J. Heuvel, and J. Mascolo, "Reference architecture and knowledge-based structures for smart manufacturing networks," IEEE Software, vol. PP, 2015, pp. 1-1.

[3] K. H., Distributed manufacturing: paradigm, concepts, solutions and examples: Springer, 2010.

[4] D. McFarlane and A. Farid, "A design structure matrix based method for reconfigurability measurement of distributed manufacturing systems," *International Journal of Intelligent Control and Systems,* vol. 12, 2007, pp. 118-129.

[5] Grauer M., "Globally distributed manufacturing networks: interdependencies between product design and choice of production site," the World Congress on Engineering and Computer Science (WCECS 2007), USA, 2007.

[6] W. HP and L. S., "Production in networks," *CIRP - Annals of Manufacturing Technology,* vol. 5, 2002, pp. 573–586.

[7] D. T. Matt and E. Rauch, "An ad based design and implementation approach for franchise," *Networks With Distributed Manufacturing Units,* 2013, pp. 1-9.

[8] D. Mourtzis and M. Doukas, "Decentralized manufacturing systems review: challenges and outlook," *Logistics Research,* vol. 5, 2012, pp. 113-121.

[9] L. Monostori, "Cyber-physical production systems: roots, expectations and R&D challenges," *Procedia CIRP,* vol. 17, 2014, pp. 9-13.

[10] B. S., "Intelligent manufacturing based on self-monitoring cyber-physical systems," The Ninth International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, 2015.

[11] R. F. Babiceanu and R. Seker, "Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook," *Computers in Industry,* vol. 81, 2016, pp. 128-137.

[12] V. Rudtsch, J. Gausemeier, J. Gesing, T. Mittag, and S. Peter, "Pattern-based business model development for cyber-physical production systems," *Procedia CIRP,* vol. 25, 2014, pp. 313-319.

[13] B. Batke and P. Didier, "The importance of reference architectures in manufacturing networks," the CIP Networks Conference, 2007.

[14] A. Elgammal, M. Papazoglou, B. Krämer, and C. Constantinescu, "Design for customization: A new paradigm for product-service system development," the The 9th CIRP IPSS Conference: Circular Perspectives on Product/Service-Systems, Denmark, 2017.