A Reference Architecture and Knowledge-Based Structures for Smart Manufacturing Networks

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// Researchers and practitioners have developed a reference architecture for developing a highly connected, knowledge-enabled manufacturing network that decentralizes production control. This network will enable collaborative product manufacturing and response to product demand, allowing for greater production flexibility and product variability. //

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SMART MANUFACTURING NETWORKS (SMNs) will fundamentally change product manufacturing, customization, and delivery. An SMN is a collaborative arrangement that disperses production to a dynamic agglomeration of production facilities belonging to diverse organizations that conduct joint manufacturing activities as part of a shared value chain. This value chain is enabled by the Internet and service-oriented architecture (SOA) to facilitate value-added production services.[1]

SMNs have their roots in cyber-physical-systems technologies.[2] They're also inextricably associated with *demand-driven manufacturing*, which requires that manufacturing occurs when demand is confirmed, to reduce overproduction. Key aspects of effective SMN management are enhanced manufacturing-network visibility, information sharing, manufacturing process integration and variability, and informed decision making so that the overall production runs according to plan.

Through SMNs, manufacturers can leverage the opportunities arising from a globalized marketplace of expertise to develop novel, domain-specific smart applications and penetrate new service manufacturing markets. For instance, a midsize original equipment manufacturer (OEM) would be able to decide which activities to perform in-house and which to outsource to deliver solutions tailored to its needs. Through a shared SMN platform, the OEM could collaborate with third-party subcontractors or suppliers to develop specific finished parts, such as transmissions or axial steel pinions. These parts would then be assembled into the final product, such as a transmission system.

MANUFACTURING REFERENCE ARCHITECTURES

A software reference architecture describes a software system's fundamental organization, embodied in its modules and their interrelationships. It helps achieve understanding of specific domains and provides consistency of technology implementation for solving domain-specific applications.[1] Manufacturing reference architectures (MRAs) are built on technology and manufacturing standards. Here we describe four important MRA initiatives.

Manufacturing 2.0 integrates manufacturing operations in a demand-driven value network.[2] It supports multiple manufacturing operating modes and operations based on a service-oriented-architecture approach combined with Web 2.0.

The Smart Manufacturing Leadership Coalition (SMLC) is a US initiative on next-generation manufacturing. It involves companies, manufacturing consortia, academia, and government agencies including the National Institute of Standards and Technology. The SMLC's goal is seamless manufacturing execution through a cloud-based, open-architecture manufacturing infrastructure and marketplace that supports real-time applications that optimize manufacturing production systems.[3]

Industrie 4.0 is a German initiative based on the technical integration of cyber-physical systems (CPS) in production and the application of Internet of Things services in industrial processes.[4] Its basic principle is that manufacturers can create intelligent networks with significantly reduced operator intervention by connecting machines that communicate with and control one another autonomously.

Microsoft's *DiRA* (*Di*screte Manufacturing *R*eference *A*rchitecture) is a cloud-based framework that connects smart devices across manufacturing networks.[5] DiRA emphasizes user interfaces, enterprise-class social-computing solutions, smart connected devices, and security-enhanced solutions.

Although each of these initiatives might emphasize different technologies, advanced manufacturing architectures—such as SMLC, Industrie 4.0, and our SMN reference architecture (see the main article)—share several concerns. These include integration of CPS in production, manufacturing intelligence, and analytics for implementing open platforms. They also have notable differences. For example, Industrie 4.0 emphasizes smart products and machine-to-machine communication. In contrast, our SMN reference architecture concentrates on smarter production processes, advanced knowledge representation mechanisms, and manufacturing-specific languages. Unlike the SMLC, it places less emphasis on cybersecurity and optimization techniques for supply chain performance.

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We've developed an SMN reference architecture and platform that machine part manufacturers, manufacturing-software developers, and third-party service providers can use to develop new products or improve existing ones. This reference architecture can lower the barrier for entrepreneurs to design novel products and processes and develop manufacturing software that could be plugged into the SMN platform for access by multiple users. Our findings can also help researchers innovate manufacturing practices and improve production processes.

Challenges to achieving the SMN vision include a lack of

- common modeling formalisms,
- configuration and deployment strategies,
- software product line development methods, and
- advanced knowledge representation mechanisms for enabling dynamic yet controlled collaboration across manufacturing systems.

To address these challenges, we propose an architectural framework for coordinating disparate production systems and physical assets (such as machines and equipment) and aligning processes in a shared production

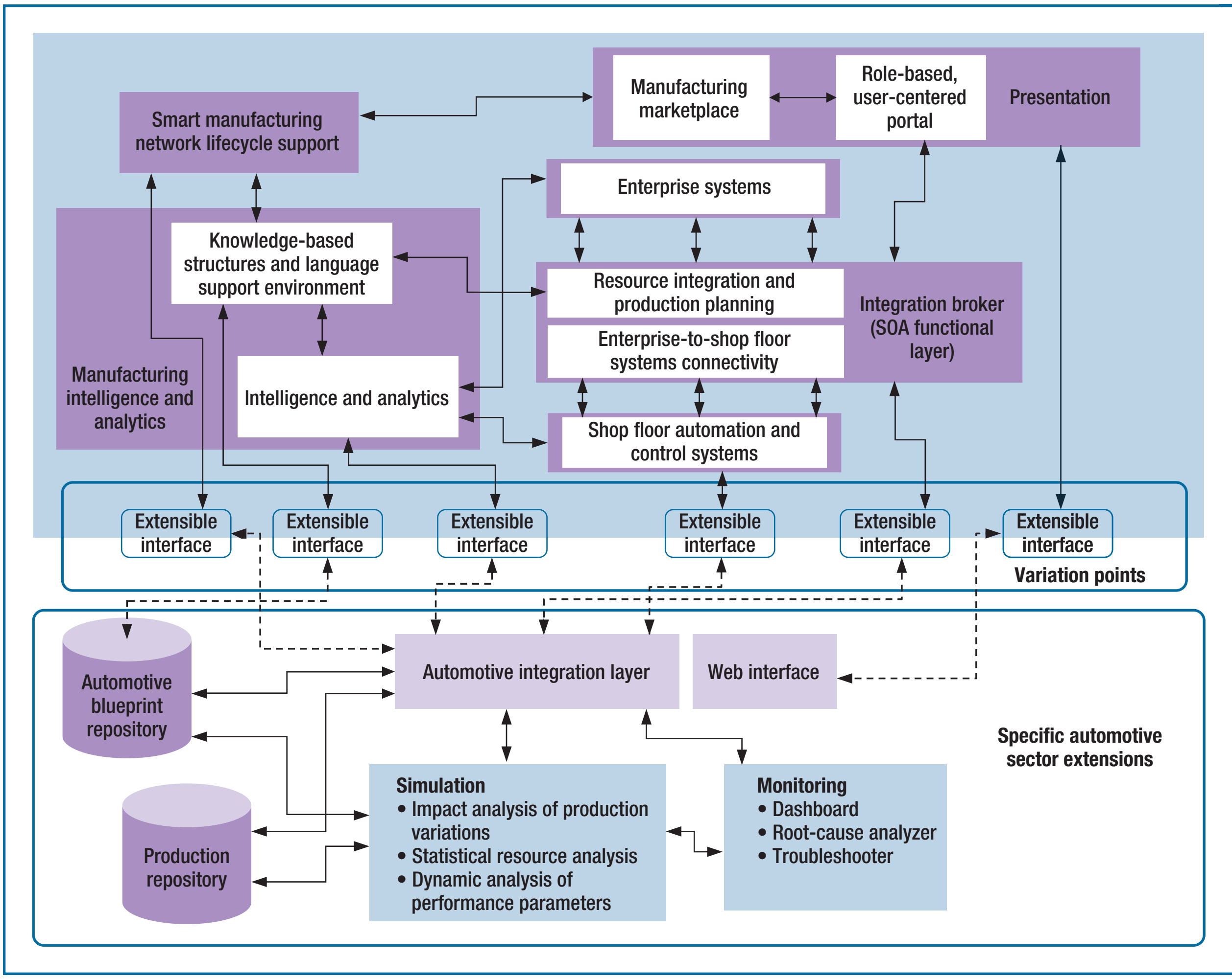

FIGURE 1. A manufacturing reference architecture. The solid lines represent connections and control flow between modules. The dashed lines represent service-based functional extensions of the generic architecture structure to yield manufacturing variability. SOA stands for service-oriented architecture.

chain. We've also developed a domain-specific language for describing and manipulating the knowledge embodied in a manufacturing network. An example from the automotive sector illustrates this architectural model's implementation.

Our Reference Architecture

Developing a *manufacturing reference architecture* (MRA) for SMNs is an effective way to deal with wide-ranging requirements of applications in different manufacturing sectors. An MRA is the fundamental organization of a manufacturing system that provides manufacturers with a framework for optimizing their technical resources to support their business and product development requirements.[3] (For a look at related research on MRAs, see the sidebar.)

The key to a successful MRA is similar to that for product platforms:[4] properly balancing the inherent tradeoff between commonality and distinctiveness. That is, designers must balance the commonality of the generic MRA with the distinctiveness of each domain-specific extension to yield manufacturing-sector-specific variability.

Figure 1 illustrates our MRA. As the top part of the figure shows, the MRA provides structure and overall logical organization, and a set of common software modules for implementing a generic, industry-shared platform. This platform enables the development of smart manufacturing applications for related product families to satisfy a variety of market niches. The bottom part of Figure 1 illustrates how domain-specific extensions of the generic plug-and-play MRA promote manufacturing system variability by addressing specific domains' needs.

We determined what software modules to incorporate in our MRA on the basis of extensive experiments with service-based platform development in sectors including aeronautics, automotive manufacturing, and semiconductors.[5]

Our MRA leverages SOA across integrated manufacturing operations to provide added flexibility. The MRA modules offer manufacturing operations functionality across the organizational boundaries of OEMs, subcontractors, and material suppliers through software services. Moreover, knowledge-based and analytics capabilities are service-enabled to support more streamlined processes ranging from product descriptions to production.

To enforce standard process descriptions and ensure wide applicability, our MRA relies on common manufacturing and supply chain standards. ISA-95 (www.isa-95.com) supports the MRA in integrating enterprise and control systems. SCOR (Supply Chain Operations Reference model; www.apics.org/sites/apics-supply-chain-council/frameworks/scor) supports architecting business processes and benchmarking against standardized performance measurements. Finally, STEP (the ISO Standard for the Exchange of Product; www.steptools.com) provides standard descriptions of product data for the MRA knowledge structures.

Next, we describe the MRA modules; a more detailed description appears elsewhere.[5]

The Presentation Module

The *presentation* module in Figure 1 comprises the *manufacturing marketplace* and the *role-based, user-centered portal*.[5]

The MRA follows a manufacturing-marketplace philosophy that brings together developers, suppliers, and potential customers to collaborate, partner, and produce more efficiently. A manufacturing marketplace is an efficient online sector-specific (such as automotive manufacturing) repository that combines search and discovery of manufacturing services with facilities for increased security, collaboration, and intellectual-property protection.

The role-based, user-centered portal provides users with a single dedicated, personalized point of access to relevant authoritative information (such as for production and planning) and manufacturing services in the marketplace.

The Integration Broker

The *integration broker* provides advanced features through innovative service offerings based on vertical and horizontal connectivity.

A key driver of the vertical-integration strategy is to connect enterprise floor systems, such as enterprise resource planning and product lifecycle management, with shop floor automation systems such as a manufacturing execution system. These are collectively called *core systems*. The *enterprise-to-shop-floor systems connectivity* submodule achieves data integration from core systems ranging from detailed product descriptions and production schedules to quality and configuration data with shop floor equipment data. In this way, the module instructs machines, equipment, and people in an SMN application to manufacture the requested product on time and in compliance with the agreed-upon criteria.

The *resource integration and production planning* submodule focuses on the horizontal integration of data and processes across entire production chains, achieving complete visibility of production and materials. This module manages all manufacturing resources in an SMN, such as partner equipment, materials, and human resources, effectively linking product parts and processes to deliver a single unified product. It also projects production schedules and plans material requirements, capacity requirements, and renditions of the final product.

To bridge the heterogeneous data gap between core systems and MRA modules, the integration broker employs extensible adapters.

We developed an open SOA-based platform implementing the generic MRA using Software AG's webMethods Integration Platform (www.softwareag.com/corporate/products/webmethods_integration/integration/overview/default.asp) and Java-based adapters. We based the marketplace and portal on the Liferay portal (www.liferay.com).

SMN Lifecycle Support

Our SMN lifecycle management method ensures connectivity, communication, and smooth operation of the manufacturing application implemented on the SOA-based realization of the MRA. To achieve this, the *SMN lifecycle support* module provides marketplace onboarding, SMN configuration, SMN design, SMN deployment, and monitoring.[5]

Manufacturing Intelligence and Analytics

Owing to the distributed nature of production, knowledge about products, processes, production resources, and plant facilities is widespread and disjointed. A serious challenge is transforming information from a vast array of diverse sources into useful knowledge to support effective decisions and planning.

Representing manufacturing knowledge. Our MRA approach promotes knowledge exchange with partners to achieve maximum operations visibility over the production chain by relying heavily on knowledge-intensive structures. These knowledge structures are the source for manufacturing intelligence.

Ontologies have traditionally been used for disambiguating and defining classes of manufacturing resources, representing industrial machinery, and supporting interoperability.[6,7] Ontologies rely on heavyweight logic and are cumbersome in industrial settings. They also fail to represent, interrelate, and manipulate essential manufacturing knowledge. Such knowledge includes partner expertise and capacities, manufacturing processes and operations, and comprehensive quality–performance metrics and quantity–quality aspects for products in a single representation framework.

To circumvent ontology problems, our MRA uses expressive knowledge-based structures to categorize, organize, represent, and interrelate knowledge associated with machinery, manufacturing resources, and operations. It also employs a lightweight, compositional manufacturing-specific language to manipulate the knowledge-based structures.

Figure 2 provides a more detailed description of the *knowledge-based structures and language support environment*, which comprises the *knowledge structures* and *knowledge structure operations* submodules.

The knowledge structures submodule contains the *manufacturing blueprints*, which codify, integrate, and contextualize manufacturing processes and data. They provide a foundation for representing and interlinking plant-level system requirements, manufacturing-operations-management activities, and operations-to-enterprise integration. They gather manufacturing intelligence from every point of an integrated production line and faithfully represent multiple manufacturing aspects (such as functions, behavior, timing, quality of service, and control) and production flows. To help manufacturers develop a range of applications, blueprints support established software-engineering methods such as separation of concerns, modularization, and reuse.

Blueprints encapsulate manufacturing knowledge from diverse sources, including product-lifecycle-management and bill-of-materials data, which is stored in the *production repository* (see Figure 2). Blueprints also include partner profiles and production capabilities, process and critical-manufacturing-event descriptions, schedules and deadlines, and product quality characteristics.

There are four types of manufacturing blueprints:

- The *partner blueprint* defines a partner company's business and technical details, such as production capabilities and capacity details.
- The *product blueprint* shows the details of a standard or configurable product or product part, such as materials, machines, tools, personnel skills, and all entities necessary to complete production.
- The *process orchestration blueprint* links, through a workflow, the events of discrete processes associated with all aspects of part development. It also defines how end-to-end manufacturing operations are executed and where responsibility is handed off between overall SMN operations and individual partner capabilities.
- The *quality assurance blueprint* defines performance and product quality metrics for manufacturing operations across supply relationships between and within individual partner services. It alerts human operators when an important event occurs, enabling them to take corrective action if necessary.

The knowledge structure operations module uses these four facilities:

- The declarative *definition language* provides the constructs to define the four types of blueprints.
- The *manipulation language* provides a set of operators for manipulating, comparing, and achieving mappings between compatible blueprints (blueprints of the same kind, such as process-to-process or product-to-product). This language's operators exhibit a closure property in which each operation takes one blueprint or multiple compatible blueprints and returns a blueprint. This allows for blueprint composition.
- A *query, search, and retrieval language* that queries blueprint collections or zooms in on individual blueprints.
- *Operators for publishing, registering, and authenticating blueprints* in the *marketplace repository*.

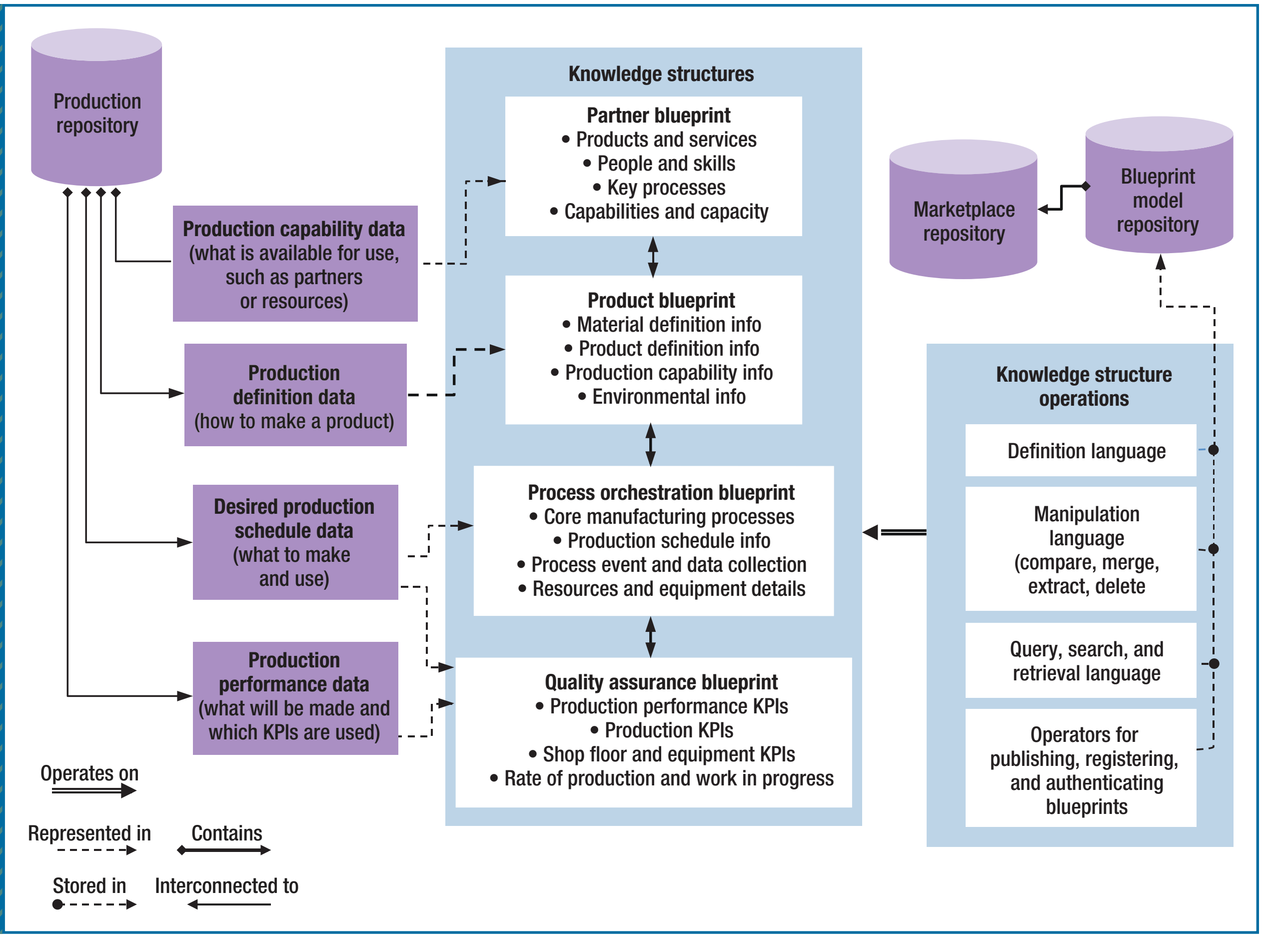

FIGURE 2. The knowledge-based structures and language support module. Knowledge-based structures comprise a family of knowledge representation mechanisms that describe and inter-connect production capability data, product data, production plans and routes, and product performance data. Such information is stored in a repository and then is retrieved, queried, and manipulated, providing analytical insights to end-to-end production processes in a manufacturing network. KPI stands for key performance indicators.

We defined the blueprints in Figure 2 in RDF (Resource Description Framework) Schema and used SPARQL for querying.

Intelligence and analytics. Manufacturing intelligence signifies the capability to

- provide enhanced manufacturing-network visibility, transparency, and analytical insights,
- optimize use of dispersed resources and human expertise,
- analyze and cross-correlate production data across organizations in an SMN to manage production operations, and
- plan a coordinated response to individual and collective manufacturing needs.

The *manufacturing intelligence and analytics* module employs the blueprint model as a source of intelligence to provide visibility of and analytical insight into global manufacturing operations in an SMN. This module makes sense of large datasets originating from core systems, sensors, computerized controls, and production management software. It also provides data analytics capabilities to help production managers understand where improvement measures might be necessary. To achieve this, it organizes production capacity across plants and monitors relevant processes against specified *key performance indicators* (KPIs) associated with productivity and quality.

We implemented the analytic capabilities by extending the Esper complex-event-processing engine (www.espertech. com). To realize anomaly detection, we used machine-learning and data-mining tools.

Smart Automotive Manufacturing

Smart-automotive-manufacturing solutions involve all the stages of vehicle assembly, from material and part tracking to online assembly and rework. These solutions benefit from the production status visibility and process control provided by the SMN and blueprints.

Here, we provide a brief overview of a make-to-order scenario for configurable products in which manufacturing starts only after the OEM receives a customer's order. We assume that a tier-one supplier receives an order for luxury car doors from the OEM and engages a number of tier-two suppliers in a collaborative SMN arrangement.

To produce car doors, different tier-two suppliers typically perform these steps:

1. Steel sheets are cut according to the door's size and then bent and cut in a stamping machine. The inner and outer door panels are then produced.
2. The door panels are folded and welded together. Other metal components, as well as holding fixtures, can also be welded.
3. The entire metal assembly is painted.
4. The door is assembled, including interior wiring and assembly and panel installation.

This scenario has two goals. First, it demonstrates how the manufacturing knowledge stored in blueprints enables the transition from car door specifications to production. Second, it demonstrates how OEMs gain insights from production data and react to critical events by coordinating human-assisted actions necessary to reach KPIs related to volume, time, and quality.

To illustrate this scenario and the two goals, we next describe a prototype vehicle-part production system we developed for the Fiat Group.

The SMN

Our SMN platform enables smart-application development based on blueprinting. It achieves manufacturing variability by customizing the generic blueprints with sector-specific (automotive) data and by extending the generic architecture functionality with new domain-specific service plug-ins. The bottom of Figure 1 shows the extension of the generic platform with the *automotive blueprint repository* and *simulation* and *monitoring* modules.

Developers of smart-manufacturing applications, such as in this scenario, create blueprint agglomerations to describe the entire production process, material flows and dataflows, and the participants' responsibilities. This enables a seamless transition from design to production.

Second-tier suppliers and material providers first give descriptions of their profiles, capabilities, capacity, products, and service offerings. Partner, product, process, and quality assurance blueprints capture this information and store it in the blueprint or marketplace repository. We call these *participant blueprints*.

Prospective clients, such as the OEM, use the query language to find registered partners' blueprints in the marketplace repository that describe the materials and operations necessary to assemble a car door. The OEM acts as an SMN contractor. It forms an SMN configuration involving the second-tier suppliers and material providers whose blueprints have been selected and can perform process steps such as stamping, welding, painting, and assembling. The OEM merges the participant blueprints into *master blueprints*, which orchestrate and configure a global production process. The result is a new or improved product such as a luxury car door.

The central instrument of production control in an SMN is a production schedule. Figure 3 illustrates a production schedule containing information about what must be produced, how and when to produce it, and who will produce it. The figure also shows that the production schedule drives the entire SMN application by describing product routings and work sequences that connect equipment and resources. This information is contained in the master and participant blueprints. In this way, an entire networked production environment is instantiated, and all its aspects—including timing, participant responsibilities, product routings, and resources—are described in detail.

The production schedule in Figure 3 specifies how the process steps—such as stamping, welding, painting, and assembling—are performed and sequenced and how they're composed into the corresponding process that produces a car door. The blueprints associated with the production schedule also specify which participants execute process steps. In addition, they specify operation–equipment combinations such as edge wrapping, laser trimming, ultrasonic welding, hot-wire cladding, and sanding for spray painting.

The master orchestration process blueprint at the top part of Figure 3 is a working canvas for the entire SMN application that produces luxury car doors. It specifies all work-plan dependencies and flows between all other blueprint images. It associates

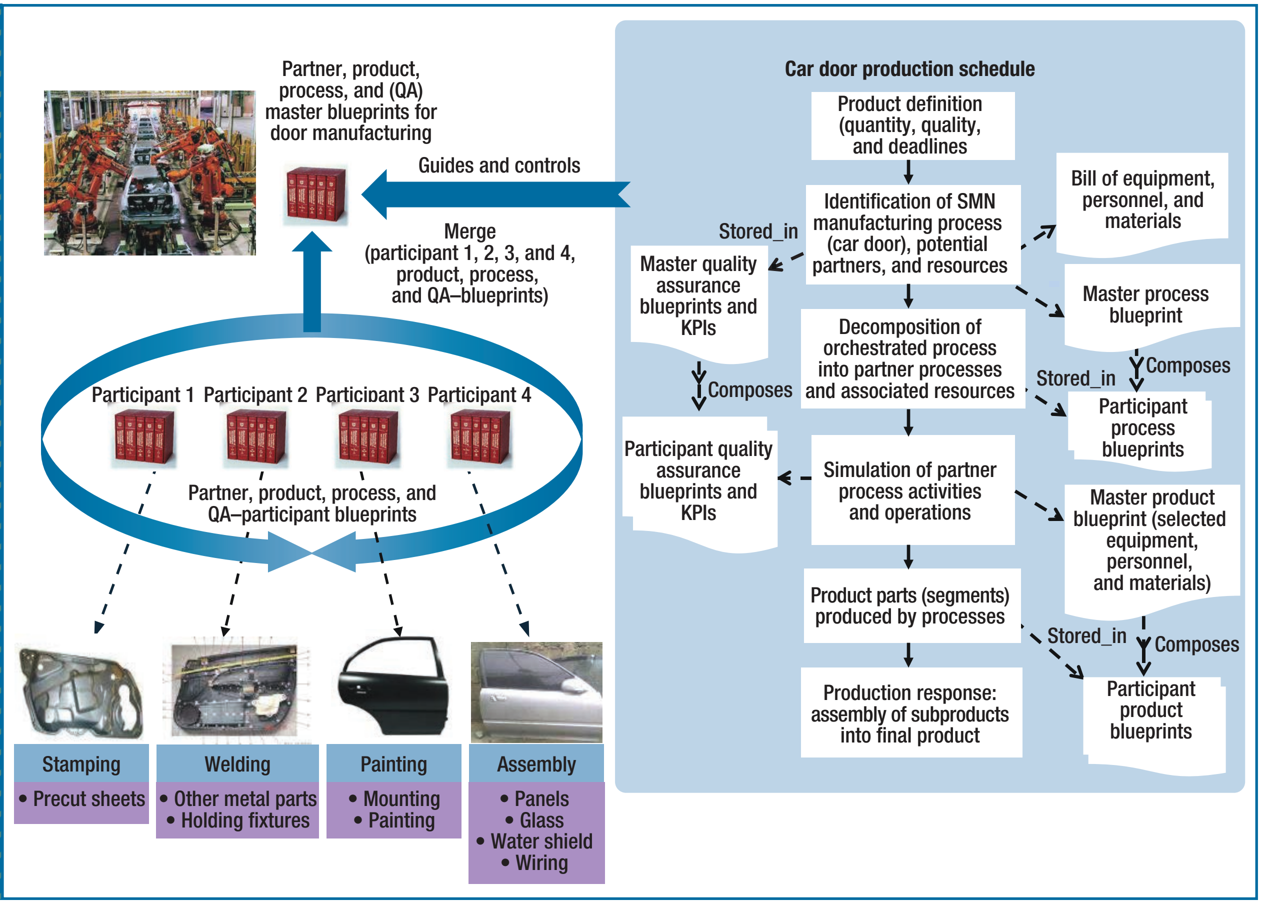

FIGURE 3. A simplified production schedule for luxury car doors. This schedule drives the smart-manufacturing-network application by describing product routings and work sequences connecting equipment and resources. The double-headed arrows illustrate composition; the solid arrows signify control and material flows. Solid rectangles specify activities; curved rectangles represent knowledge structures such as various types of blueprints and data structures such as bills of equipment, personnel, and materials. Dashed arrows represent the storage of relevant data in blueprints.

partners, product descriptions, and quality assurance data with work steps, routings and timing, capacity, equipment, and material specifications to ensure KPI compliance and create the end product.

Process Tracking and Product Quality Management

This part of the scenario requires providing quantitative visibility and transparency in manufacturing operations by consistently tracing processes and preventing anomalies from spreading into production. To gain insights from production, equipment, machine, quality, and performance data, which is associated with the KPIs in the quality assurance blueprints, we require simulation and monitoring tools. We integrated these third-party tools with the engineering data stored in blueprints using the generic MRA services.

The simulation module in Figure 1 employs the Siemens Tecnomatix Plant Simulator, a standard Fiat Group tool. This tool simulates the SMN and provides decision criteria to help production managers evaluate and compare approaches regarding new production facilities and global production networks. It does this by showcasing the dataflow between production sites and the SMN platform. Statistical-analysis graphs display material flows and resource utilization patterns. They provide a holistic view of SMN global production (described in the master blueprints) and its relation to local plant facilities, machines and personnel, and performance parameters including line workload, breakdowns, supplier interruptions, and idle and repair times (described in the participant blueprints).

The monitoring module manages optimized production and adjustment to changing demands by using KPIs to allow production monitoring. It captures the critical tracking events of a given unit or assembly.

The master and participant quality assurance blueprints help the monitoring module detect potential violations in terms of measurable KPIs. The module tracks production completion, material usage, and quality metrics, and gains visibility into work in process, real-time quality, and production notifications. Correlating this information to a specific manufacturing unit or assembly line provides both historical and real-time product records.

The monitoring module contains the *dashboard*, *troubleshooter*, and *root-cause analyzer*, and historical and real-time product record data repositories. The dashboard provides real-time visibility for decision making using advanced graphic representations of event data, alarms, thresholds, KPI status, and performance levels. The troubleshooter enables analysis of logged versus historical or simulated data and creates reports of the alert status. The root-cause analyzer identifies the root cause, predicts part and production failures, and identifies process improvements. We based this module's implementation on the Nagios open source monitoring tool (www.nagios.org).

Smart manufacturing combines technology, knowledge, information, and human ingenuity to develop and apply manufacturing intelligence to every aspect of applications. It could fundamentally change how products are manufactured and delivered. We expect that product innovations will arise from the creative use of manufacturing knowledge gathered from every point of an SMN value chain, ranging from consumer preferences to production and delivery mechanisms.

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