Smart Connected Digital Factories: Unleashing the Power of Industry 4.0

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Abstract. Recent initiatives such as the Industrial IoT, or Industry 4.0, as it has been dubbed, are fundamentally reshaping the industrial landscape by promoting connected manufacturing solutions that realize a "digital thread" which connects all aspects of manufacturing including all data and operations involved in the production of goods and services. This paper focuses on Industry 4.0 technologies and how they support the emergence of highly-connected, knowledge-enabled factories, referred to as Smart Manufacturing Networks. Smart Manufacturing Networks comprise an ecosystem of connected factory sites, plants, and self-regulating machines able to customize output, and allocate resources over manufacturing clouds optimally to offer a seamless transition between the physical and digital worlds of product design and production.

Keywords: Manufacturing networks · Industry 4.0 · Industrial internet · Cloud manufacturing · Digital twins · Smart manufacturing networks · Product and manufacturing network lifecycle

1 Introduction

Today, manufacturing is transforming from mass production to an industry characterized by mass customization. Not only must the right products be delivered to the right person for the right price, the process of how products are designed and delivered must be at a new level of sophistication.

Currently, manufacturing is becoming network centric with dynamic, complex interconnected supply and production chains. Traditionally linear supply chains are transformed into highly interconnected, continually changing systems that integrate information seamlessly to advance production and distribution. This implies a focus on core technologies and critical assets with Original Equipment Manufacturers moving toward digitally integrated systems and factories, autonomously running entire production processes, global outsourcing of product component fabrication, and a strategy

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that can more readily incorporate ecosystem partners and evolve to a more optimal state over time. We call this interconnected, open ecosystem a Manufacturing Network [1].

A manufacturing network integrates data from diverse sources and locations to drive the physical act of production and distribution. The result can be a "digital-twin" model of the connected 'smart' factory of the future where computer-driven systems create a virtual copy of the physical world and help make decentralized decisions with much higher degree of accuracy [2]. The digital-twin approach enables manufacturers to overlay the virtual, digital product on top of any physical product at any stage of production on the factory floor and analyze its behavior. This approach allows manufacturers to have a complete digital footprint of the entire manufacturing process - spanning product, production, and performance - so that product designers and engineers can make informed choices about materials and processes using visualization tools, e.g., 3D CAD/CAM tools, during the design stages of a digital product and immediately see the impact on a physical version of the product. This capability of digital products can be extended across multiple factories.

In networked manufacturing, we are moving from a push-driven model to a pull-driven model with the consumer becoming much more of a driver in the supply chain and where production systems are more flexible in terms of handling smaller volumes and individualized product portfolios that are part of discrete manufacturing [3].

The digital twin approach in networked manufacturing connects the digital to the physical world allowing visibility in the operations of production systems and manufacturing plants. It focuses more holistically on how end-to-end transparency can provide instant visibility across multiple aspects of the production chain all at once. This provides insights into critical areas by enabling firms to track material flow, synchronize production schedules, balance supply and demand, and production. There is also the increased demand for the individualization of mass production where manufacturers need to meet customer expectations for individualized products and need to collaborate with them and external stakeholders to design and manufacture these individualized products.

Industry 4.0 sets the foundations for completely connected factories that are characterized by the digitization and interconnection of supply chains, production equipment and lines, and the application of the latest advanced digital information technologies to manufacturing activities. Industry 4.0 can be perceived as the rapid transformation of industry, where the virtual world of information technology (IT), the physical world of machines, and the Internet meet, driving access to manufacturing data sources and systems. Paired with powerful tools, such as visualization, scenario analysis, and predictive learning algorithms, this access to data is fundamentally changing how manufacturers operate.

This paper examines the concept of manufacturing in the connected factories of the future and its enabling technologies. It first introduces the concept of Industry 4.0, and overviews standards and recent architectural developments. It then explains how Industry 4.0 technologies have the ability to efficiently extract meaningful data and insights from manufacturing systems and processes, and transform traditional plants into smart collaborative digital factories. This new direction is highly connected to knowledge-enabled factories, referred to as Smart Manufacturing Networks, where devices, production equipment, production services and processes spanning factories and firms are inter-connected - offering decision-making support on the basis of real-time production data – produce on-demand and are continuously monitored, and optimized.

The paper is organized as follows: Sect. 2 discusses the transition to Industry 4.0 by first outlining its basic characteristics and then focusing on the key enablers that facilitate moving to smart manufacturing. Section 3 describes security issues, outlines related standards and their role in support of Industry 4.0 and closes with presenting reference architectures and models. Section 4 makes a brief introduction to smart products and smart machines, while Sect. 5 focuses on Smart Manufacturing Networks analyzing their characteristics, the transformation roadmap, the digital product lifecycle, the knowledge related to product/production processes, and the digital twin lifecycle. Finally, Sect. 5 provides our conclusions.

2 Making the Transition to Industry 4.0

The Fourth Industrial Revolution – also known as Industry 4.0 – represents a paradigm shift to "decentralized" smart manufacturing and production, where intelligent machines, systems and networks are capable of autonomously exchanging and responding to information to manage and coordinate industrial production processes through edge analytics. It is rapidly transforming how companies interact with customers, develop and manufacture new products, and conduct operations by helping integrate systems across production chains.

2.1 Essential Characteristics of Industry 4.0

Currently, there is no consensus regarding the definition of Industry 4.0, rather it has a different meaning for each company depending on the company's production-domain and specific strategy. Moreover, this meaning is highly variable depending on the business process affected - manufacturing, logistics, and the like [2]. Nevertheless, Industry 4.0 in all of its forms and guises is marked by a shift toward a digital-to-physical connection.

Industry 4.0 demands production processes that are much more flexible as well as new machine-to-machine capabilities. It is not enough to have machines that flexibly and easily interconnect with each other; they also have to be geared towards adjusting production dynamically. Industry 4.0 - or Industrial Internet - offers new opportunities to harness manufacturing data so that manufacturers can use knowledge-based and advanced analytics techniques to structure, cross-correlate and gain insights from manufacturing data that originates from multiple systems, equipment, devices, sensors and processes. Subsequently, it automates and guides manufacturing accordingly to optimize planning and scheduling to produce higher quality manufactured products.

The definition of Industry 4.0 in this paper covers six important properties:

1. *Digitization of all physical assets and processes:* The first main characteristic of Industry 4.0 is the digitization of all physical assets and processes. Manufacturers expand their existing range of products with complete digital product descriptions as well as developing the capabilities they need to provide services and solutions

that supplement their traditional product offerings, e.g., embedded systems, sensors, aftercare and product support, etc., ensuring that customer needs are met while boosting the performance of the core product.

2. *Integration of vertical and horizontal value chains:* To enable production, vertical integration of production activities within smart factories, from product design and development and the various shop floor applications, devices, IoT, robot and equipment, is necessary. Furthermore, the increased data being generated throughout the plant floor also need to be accessible within higher-level enterprise systems, placing a new emphasis on seamless vertical network integration. Only by turning this data into meaningful information at the enterprise level can relevant production and business decisions be taken.

   Horizontal integration is combined with vertical integration to offer the prospect of coordination of orders, materials' flow and production data, with all geographically dispersed entities, e.g., customers, distributors and channel partners, materials and sub-product suppliers, contract manufacturers, and technology solution providers, to achieve end-to-end, holistic integration through the entire value chain.
3. *Control and Visibility*: As products move from ideation and development to end of life, the wealth of data produced at every stage of the manufacturing lifecycle can create a product's "digital thread," which denotes the aggregated, product-specific data stream that combines information from a variety of systems and sources. Purpose of the digital thread is to improve design and manufacturing processes by enabling real-time, data-driven actionable insights and decision-making, and control capabilities.

   Visibility denotes the ability to combine business transactional data with manufacturing operational data to gain full visibility and control and improve decision making and action taking. It can include visibility from order entry to inventory to finished product. It also includes real-time tracking and monitoring to prevent raw material, human or machine deviations or failures.
4. *Actionable insights*: The convergence of the IoT, processes and analytics is generating a new world of big data, which is enabling new capabilities such as tailored customer offerings, predictive solutions, streamlining production processes and adaptation to changes. The use of detailed analysis of manufacturing and sensor data from the plants combined with other critical data elements sets the foundation for greater optimization of overall business and control, better manufacturing and operations planning, greater improvement of production processes and product quality, and more efficient maintenance of production assets.
5. *Human-centered automation*: Industry 4.0 will lead to a structural shift towards an integrated digital and human workforce where the focus is on improving the user experience, so that information is presented in the context of manufacturing tasks performed, leading to better decision-making and new possibilities for improvement.
6. *Creation of innovative digital business models and strategic value propositions*: Digitization is eroding traditional barriers to entry in many sectors, creating opportunities for new product types and new value propositions through increased networking with customers and partners.

2.2 Key Enablers

Technologies such as IoT, Cyber-Physical Systems (CPS) and automation, big data and analytics, augmented reality, as well as new user interfaces, sit at the heart of Industry 4.0 and all of them run on the cloud. These technologies enable not just the creation of new value networks, but will also usher in a transition from product-as-a-service to anything-as-a-service models. Their purpose is to move discrete manufacturing activities towards the seamless collaborative and distributed sharing of smart manufacturing. Key enablers for Industry 4.0 include the following technologies:

Big Data Analytics. Industry 4.0 involves data analytics operations as a means of extracting knowledge that drives process optimizations. Gathering plant and supply chain data through a network of sensors and then processing such big data generates new insights, supports decision-making and helps to influence new product designs, streamlines system performance, and maximizes profitability. Some of these operations require advanced analytics that fall in the realm of deep learning and artificial intelligence. This is for example the case with the detection of failure modes in predictive maintenance, where sensors monitoring the operating temperature in mechanical components can track any abnormalities or deviations from an established baseline. This allows manufacturers to proactively address undesired behavior before crippling system failures can develop, which would otherwise lead to plant downtime and lost production revenue.

Augmented/Virtual Reality (AR/VR) and Novel User Interfaces. Product and user experience concepts are typically envisioned and shaped through sketching and CAD modeling and a broad range of options is visualized through virtual means.

AR/VR can change the way engineers design products, test scenarios and designs by using live demos and full immersion before the products are made. AR/VR offer the tools that have the ability to view accurate representations of finished products in real-world scenarios, review and evaluate concepts and alternatives, tweak and adjust and modify designs. AR supported CAD packages allow projection of objects on a real setting viewed for example through the camera of a smart device, as well as rotations in three dimensions, thus enabling the viewing of a designed object from any desired angle, even from the inside looking out on top of a live scenery.

VAR/AR can streamline development, especially when paired with prototyping methods. The result is a reduced technical risk, rapid repetition design cycles and ultimately innovative customized products.

Cyber-Physical Systems. These bring the virtual and physical worlds together using capabilities such as sensing, communication and actuation, to create a networked environment in which intelligent objects communicate and interact with each other. CPSs are transforming the manufacturing industry into its next generation through a closer relationship between the cyber computational space and the physical factory floor, enabling monitoring, synchronization, decision-making and control [4, 5].

Internet of Things. IoT has enabled devices and sensors of all kinds to connect with the Internet and each other to create, share, and analyze information, all without human intervention.

Industry 4.0 has taken IoT even further and applied it on a much grander scale leading to innovations like the smart factory and predictive technology. By outfitting industrial machines with sensors and equipping employees all across the supply and delivery chains with the tools to monitor and respond to the output from these sensors, manufacturers can streamline all production and business operations. Sensors along the production line lead to early detection of potential breakdowns. By relying on predictive maintenance to fix problems before they occur, companies avoid costly downtimes and breaks in production. All these applications improve efficiency, minimize unnecessary expenses, and maximize quality.

The purpose of IoT is "to connect objects", while CPSs aim "to integrate the cyber and physical worlds". Together, they construct a virtual world where sensors, controllers, and other devices are all connected through the network (the IoT-side), and implement this virtual world to the physical world by controlling and coordinating the things connected to this virtual world (the CPS-side).

Cloud-Computing. Cloud-based computing is an essential element of the smart manufacturing revolution. There are two types of possible cloud computing adoptions in the manufacturing sector, (i) Cloud-based manufacturing solutions with direct adoption of some Cloud computing technology, and (ii) Cloud-centered manufacturing - the manufacturing version of cloud computing.

Cloud-based solutions with direct adoption of some cloud computing technology target scalability; operational efficiency; the ability to leverage infinitely scalable computational resources on an on-demand, pay-as-you-go basis; application and partner integration; data storage and management; analytics; and enhanced security. They address isolated problems and fixes and unlike cloud-centered manufacturing they do not offer a more holistic approach.

Cloud-centered (or cloud) manufacturing, extends the concept of virtualization to a shared diversified collection of manufacturing resources e.g., machine tools and factories, offers those resources - primarily in the form of SaaS model - and deploys them at scale to form production lines in response to customer-demand. This manufacturing paradigm allows manufacturing service providers to engage in new, flexible arrangements leading to better utilization of manufacturing capabilities and aims to provide heightened levels of quality and value for consumers of third-party manufacturing services.

Fog Computing. Fog (or edge) computing is heralded by many as the next big thing in the world of Industry 4.0. Fog computing instead of transporting all data over the network and then processing it in the cloud, performs operations on critical data close to the IoT device (endpoint) and application, processing IoT data from a myriad of sensors much faster but also without wasting bandwidth.

"Edge analytics" greatly reduces the amount of raw data that must be stored on servers, either on premises or in the cloud, and reduces the amount of network traffic being generated [6]. Collecting and analyzing data close to the endpoints means that action can take place locally in real or near-real time. In this way, only meaningful information needs to be backhauled to the datacenter or cloud for storage, benchmarking or advanced statistical analysis.

Another important way fog computing will impact modern manufacturing is by facilitating integration - whether of widespread supply chains or of the data streaming – on the basis of IoT-enabled production-equipment on the factory floor [7]. Intelligently integrating data streams from numerous partners, platforms, and devices is challenging enough, but is much more difficult to achieve inside companies' own data centers as opposed to in well-networked data centers operating in the cloud.

Bringing it all Together. The merging of the above technologies, as well as the fusion of business processes and manufacturing processes, are leading the way to the new concept of smart factory [8]. The smart factory will enable highly customized and bespoke products to be produced at acceptable unit costs, using autonomous self-optimizing manufacturing processes and with much lower levels of emissions and environmental impact. The landscape of the smart factory will feature complex and extensive networks linking suppliers, manufacturers and customers.

3 Security, Standards and Reference Models

3.1 The Security Conundrum

Inadequately protected networks, data, processes and operations, and potential manipulation of the plants, pose huge threats to industrial plants and businesses. They are open to a range of attacks and cybercrimes, and threatened by interference, disruption or denial of process controls, theft of intellectual property, the loss of sensitive corporate data, hostile alterations to data, and industrial espionage [9]. Once attackers gain access to a critical application, they can manipulate machines or manufacturing processes remotely. The fact is that most existing industrial facilities were neither designed for connecting to the Internet nor developed with a special focus on IT security.

To assure adequate security, manufacturers must adapt by building in defensive measures to legacy equipment and systems that are now connected. Firms must, for one, ensure the security of the software, infrastructures, application and computer systems used. For another, they must deal with the effects of possible cyber-attacks on the operational safety of devices and plants that are connected to the Internet. This is exacerbated by the fact that firms open up their networks and systems for customers, suppliers and partners [10].

One approach of defense is to insert security measures into application programs, known as "security by design" [10]. Computational intelligence will play an important role by tracking, identifying, and analyzing digital security threats. This can be accomplished by strengthening applications and embedded systems and enabling them to self-protect against tampering, reverse-engineering, and malware insertion. Another solution could be online detection of threats, using machine learning and data analytics techniques for cybersecurity [11]. For instance, we can analyze the normal behavior for privileged users, privileged accounts, privileged access to machines and authentication attempts, and then identify deviations from the normal profile.

An innovative and customized encryption approach to support secure collaborative product development has been recently introduced [12]. Its goal is to maintain the security of the sensitive information in CAD models while sharing other information of the models in the cloud for effective collaboration. In addition, an approach that complements perimeter security by limiting and protecting information flows to internal and subcontracted factory floor devices has been introduced in [13].

Two security frameworks have been recently introduced to combat manufacturing cyber security threats. The NIST Cybersecurity Framework provides organizations with a structure to outline their current state of cybersecurity, considers cybersecurity risks as part of an organization's risk management processes and strengthen their security posture [14]. The Industrial Internet Consortium's 'Industrial Internet of Things, Security Framework' (IISF) identifies and positions security-related architectures, designs and technologies, as well as procedures relevant to trustworthy Industrial Internet of Things systems [15].

3.2 The Role of Standards

The ability of disparate systems to exchange, understand, and exploit product, production, and business data rests critically on standards. The Industry 4.0 developmental stage requires an unprecedented degree of system integration across domain borders, hierarchy borders and lifecycle phases. Today there exist several standards that can be used in the context of Industry 4.0. The standards landscape upon which future smart manufacturing systems can rely comprises integration standards within and across three manufacturing lifecycle dimensions [16]: product, production system, and business.

The standards in support of Industry 4.0 facilitate the delivery and exchange of manufacturing data, connect enterprise operations to plant operations, control systems and actual production and establish repeatable processes with common terminology and understandings of functionality.

Standards that Define Equipment Hierarchy. These standards include the ISA-95 (isa-95.com) standard that was developed to automate the interfaces to connect enterprise application systems with the control systems that operate a manufacturing plant's equipment. The ISO 15746 (www.iso.org/standard/61131.html) standard facilitates the integration and interoperability of process control and optimization capabilities for manufacturing systems that are based on the ISA 95 hierarchy. The IEC 62264 standard (www.iso.org/standard/57308.html) describes the manufacturing operations management domain and its activities, and the interface content and associated transactions within the Manufacturing Operations Management and Business Planning and Logistics view of ISA-95. The emerging IEC 62890 (www.vde-verlag.de/standards/1800343/e-din-en-62890-vde-0810-890-2017-04.html) defines standards for lifecycle management for systems and products used in industrial process measurement, control and automation, and is applicable to hardware and software of automation products and systems.

Standards that Model Manufacturing Processes. The most prominent of these standards is SCOR (www.supply-chain.org), a process reference model that identifies and promotes standardized methods for representing business processes and process interactions and easy communication between manufacturers and their partners.

Product Model and Data Exchange Standards. These include the ISO-1030 and the AutomationML standards. The ISO-10303 standard (www.steptools.com) describes how to represent and exchange digital product information to enable companies to have a proven single definition for all product information related to individual products throughout their lifecycle, independent of changes in process and information technology. And finally, the AutomationML data format (www.automationml.org), standardized in IEC-62714, is an open, neutral, XML-based, data exchange format which enables transfer of engineering data of production systems in a heterogeneous engineering tool landscape.

3.3 Reference Models

A reference architecture provides common and consistent definitions in the system of interest, its decompositions and design patterns, and a common vocabulary to discuss the specification of implementations so that options may be compared. A neutral reference architecture model is essential for further standards work in Industry 4.0 [15]. The two most popular reference smart manufacturing models are summarized below.

Reference Architecture Model for Industry 4.0. RAMI 4.0 [17] provides a common understanding of the relations existing between various individual components for Industry 4.0 by setting a comprehensive framework for the conceptual and structural design of Industry 4.0 systems.

RAMI 4.0 describes a reference architecture model in the form of a three-dimensional coordinate model that describes all the important aspects of Industry 4.0. The three-dimensional coordinate model of RAMI 4.0 includes three dimensions: Layers, Life Cycle and Value Stream, and Hierarchy Levels, as shown in Fig. 1.

The six layers of the vertical axis define the structure of the IT representation of an Industry 4.0 component. This axis represents the business applications, the functional aspects, information handling, communication and integration capability, and ability of the asset to implement Industry 4.0 features.

The *Business Layer* is composed of the business strategy, business environment, and business goals. This layer models the rules which the system has to follow, orchestrates services in the Functional Layer, provides a link between different business processes and receives events for advancing the business processes.

The *Functional Layer* is responsible for production rules, actions, processing, and system control. It also facilitates users as per product features like cloud services (restore/backup functionality). This layer provides a formal description of functions, a platform for horizontal integration of the various functions, and run-time and modelling environment for services which support business processes and applications.

The *Information Layer* structures data in an organized fashion. Its purpose is to provide information about the total number of sales, purchase orders info, suppliers, and location info. It carries information about all products and materials that are manufactured in the industry. It also gives information on the machines and components that are used to build products.

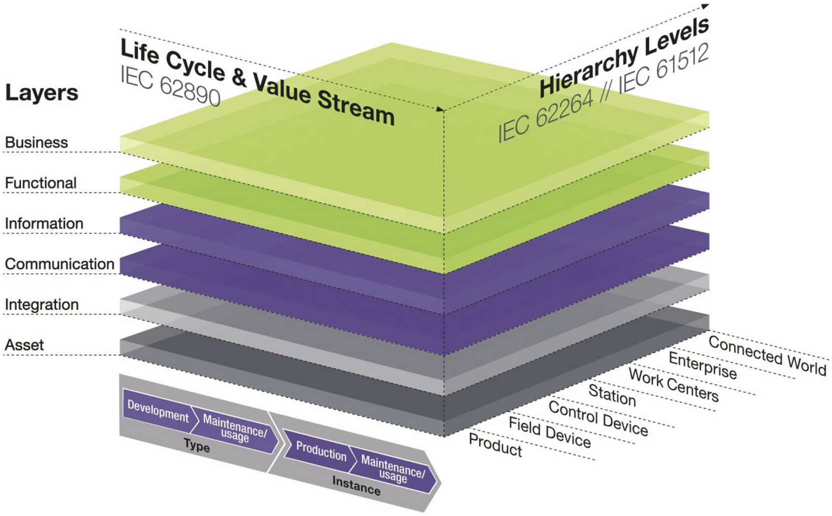

Fig. 1. Reference architecture model for Industry 4.0.

The *Communication Layer* provides standardized communication between the integration and information layers. It also provides services for control of the Integration Layer.

The *Integration Layer* deals with the effective processing of information and can be considered as a link between the physical and digital worlds. Interaction with humans also takes place at this layer, for instance via the use of Human Machine Interfaces.

The *Asset Layer* describes physical components such as motors, machines, documents, software applications, spare parts, system users, customers, suppliers, service providers, or any other physical entity.

The left horizontal axis of RAMI 4.0 represents the *Life Cycle of facilities and products*, based on IEC 62890 for life-cycle management. This axis offers potential for improvement throughout the life cycle of products, machines, factories, software, or even a factory.

The right horizontal axis of RAMI 4.0 represents different functions within factories based on *Hierarchy Levels* from IEC-62264 standards series for enterprise IT and control systems. The hierarchy levels within IEC-62264 are based on the classic ISA-95 standard. In order to represent the Industry 4.0 environment, these functions have been expanded to include workpieces, labelled “Product”, “Field & Control Devices”, “Enterprises”, and the connection to the Internet of Things and Services, labelled “Connected World”.

The Industrial Internet Reference Architecture (IIRA). IIRA is an open architecture for industrial internet systems to drive interoperability, to map applicable technologies, and to guide technology and standard development [15]. IIRA is not a standard, rather it provides guidelines on how a safe, secure and resilient architecture can help realize the vision behind the Industrial Internet. The IIRA contains architectural concepts, vocabulary, structures, patterns and a methodology for addressing design concerns. It defines a framework by adapting architectural approaches from the ISO/IEC/IEEE 42010-2011 Systems and Software Engineering - Architecture description standard. The IIRA framework includes viewpoints, lifecycle process, and industrial sectors.

At the core of IIRA are *viewpoints* (See Fig. 2) which identify the relevant stakeholders of Industrial Internet systems, determine the proper framing of concerns and enable architects and engineers to identify and resolve key design issues. These viewpoints provide a kind of checklist that breaks down the system design requirements into four categories, which include business, usage, functional and implementation elements. The *Business Viewpoint* identifies business stakeholders, their business vision, values and objectives. The *Usage Viewpoint* addresses the expected system usage and is represented as sequences of activities involving users that deliver intended functionality. The *Functional Viewpoint* focuses on the functional components in an Industrial Internet system, their structure and interrelation, the interfaces and their interactions, and the relation and interactions of the system with external elements in the environment. Finally, the *Implementation Viewpoint* focuses on technologies for implementing functional components. The IIRA also addresses specific system concerns, such as integration, interoperability and composability, connectivity, analytics and data management.

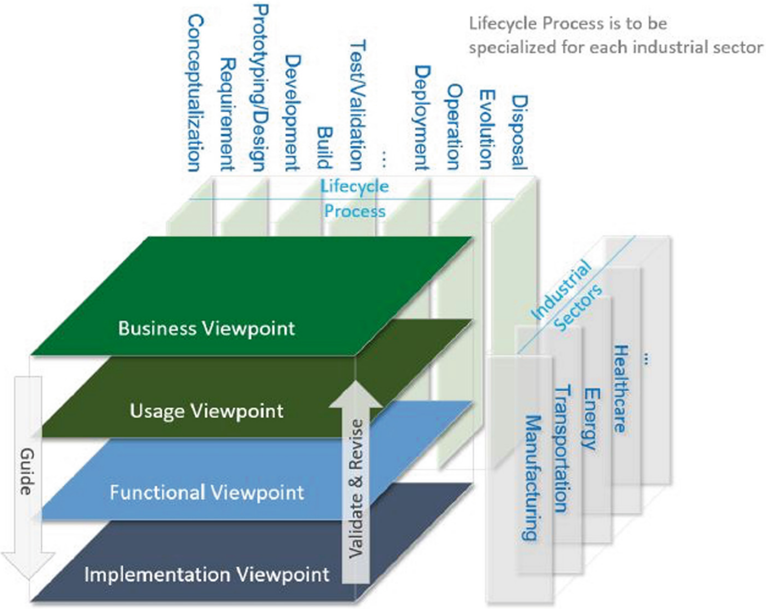

Fig. 2. The Industrial Internet Reference Architecture (IIRA).

As shown in Fig. 2, IIRA through its viewpoints provides guidance to *System Lifecycle Processes* from Industrial Internet system conception, to design, implementation, evolution and disposal. Its viewpoints offer a framework to system designers to think iteratively through important common architectural issues in industrial internet system creation. It also suggests common approaches (concepts and models) as views in each of these viewpoints to aid the identification and resolution of important architectural issues. IIRA is not a description of a system lifecycle process, which varies from one industrial sector to another. Rather, as shown in Fig. 2, this reference architecture is a tool for system conceptualization highlighting important system concerns that may affect the system lifecycle process.

IIRA purposely starts from a generic framework and seeks common architecture patterns to ensure wide applicability to Industrial Internet applications across a variety of *Industrial Sectors* (see Fig. 2). For this reason, the IIRA general framework stays at a high level in its architecture descriptions, and its concepts and models are at a high degree of abstraction. The application of this general architecture framework, as a reference architecture, to real-world usage scenarios transforms and extends the abstract architectural concepts and models into detailed architectures addressing the specificity of the Industrial Internet usage scenarios, e.g., manufacturing, transportation, logistics, etc. In this manner, the IIRA guides the next level of architecture and system design.

The general consensus was that certain aspects of IIRA and RAMI 4.0 intersect with each other, but more work is needed to precisely identify interoperability features between them.

4 Smart Products and Smart Machines

Industry 4.0 is progressively transitioning conventional factories to smart products and services, and networked production machines to enable the holistic digitalization of a supply chain, and an ecosystem of connected digital factories.

Products in Industry 4.0 are ‘smart’ - with embedded sensors for real-time data collection for measuring product state and environment conditions – connected, and incorporate communication capabilities. Smart products include self-management via the ability to monitor themselves and their environments and can enable remote control, optimization, and processing capabilities. Every smart product holds data about operating conditions, current use and product status. This data provides a virtual copy of each smart product. Such information is collected, updated and evaluated throughout the life of the product as needed, from product design, production to actual customer use and all the way to recycling. Connectivity provides smart products with the ability for machine-to-machine communication, and embedded interfaces enable interaction with human users.

Factory floor machines will evolve their level of intelligence in order to accommodate more knowledge-based processing and predictive planning. The term “smart machine” implies a machine that is better connected and can communicate with other machines and users, is more knowledgeable, flexible, more efficient and safer. The application of smarter control mechanisms to robots and artificial intelligence (AI)-

enabled machines will differentiate Industry 4.0 manufacturing. To date, robots have been restricted to repeatable step-based tasks without autonomy or self-control, or have been deployed in a restricted scope and not on the main assembly line. Industry 4.0 smart robots will work hand-in-hand with humans using human–machine interfaces.

Machine-to-machine communication can be considered the integral technology of the Internet of Things. Through advanced embedded sensor and actuator applications technology, the entire production floor can relay meaningful information, forming the interface between the physical and the virtual worlds. This provides a level of transparency that enables huge improvements in manufacturing performance. Other important aspects of smart machines include their ability to self-monitor and monitor the devices they are connected to, and ability to adapt on-demand. A smart machine is also capable of participating in predictive maintenance practices while minimizing its own environmental footprint and total cost of ownership.

5 The Advent of Smart Manufacturing Networks

Traditionally, manufactures structured their supply chains around siloed functions such as planning, sourcing, manufacturing, or distribution where the manufacturing site is typically not completely integrated. Stakeholders often have little, if any, visibility into other processes, which limits their ability to react or adjust their activities. In addition, many aspects of the production process, including design, manufacturing, and supply, are increasingly outsourced and remain widely fragmented. To succeed, firms need to eliminate these boundaries, by converging plant-level and enterprise networks and creating integrated, end-to-end production networks that are “always-on”.

Today, the trend is for networks of smaller, more nimble factories that are better able to customize production for specific regions and customers that will eventually replace large, centralized plants. This gives rise to the concept of Smart Manufacturing Networks (SMNs) [1], which epitomizes smart connected factories. SMNs require reconfiguring supply chains to integrate innovative and disruptive technologies and capabilities that align with overall business strategy. These technologies form the foundation of Industry 4.0 and are coupled with a trend towards highly customizable products that have smarter, dependable, and secure plug and play integration of digital and physical components.

5.1 Smart Manufacturing Network Characteristics

SMNs focus more holistically on how a network that consists of a permanent or temporal coalition of interoperating production systems - belonging to geographically dispersed manufacturing sites and factories - can better achieve joint production objectives. It also focusses on how this coalition can integrate manufacturing data from a variety of diverse sources, locations and manufacturing operations across connected manufacturing sites to drive physical production [1]. In the realm of Industry 4.0, an area of significant focus in SMNs is not only on the product, but on how the SMN capabilities integrate to enable the act of production.

On the technical level, an SMN comprises 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 a physical 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.

Production advantages in an SMN are not limited solely to one-off production conditions, but can also be optimized according to a global network of adaptive and self-organizing production units belonging to more than one operator [8]. Digital twins are used in an SMN during the development of a product or when planning production. They make the development process more efficient, improve quality and help to share information between stakeholders. By combining digital twins of a product and the production line, new production processes can be virtually tested and optimized before any physical work can start. In addition, when digital twin information (in the form of abstract knowledge types and structures, see Sect. 5.4) is shared with partners, they are better able to optimize and align their processes.

SMNs couple data and services with a wide range of performance metrics, and can achieve visibility across the extended manufacturing network such that critical manufacturing operations are intercepted, analyzed and executed by applying the best manufacturing practices.

High levels of automation come as standard in an SMN: this is made possible by a flexible network of production systems which, using Industry 4.0 technologies (see Sect. 2.2), can, to a large extent, automatically control and coordinate production processes.

SMNs are increasingly dynamic and complex, and require increasingly more sophisticated information integration. Two important elements of an SMN are vertical and horizontal integration (see Sect. 2.2).

Vertical integration means that demand changes that are recorded in enterprise-level systems can be fed into manufacturing schedules to ensure quantities of products manufactured are more closely aligned with demand for leaner and more efficient manufacturing. Shop-floor machinery is now powered by embedded sensors and control mechanisms that allow via IoT for in-progress production adjustments on the factory floor.

Smart Manufacturing Networks accentuate the shift in horizontal integration towards a flexibly defined extended enterprise thus supporting the evolution into dynamic, global, production networks. Such manufacturing networks enable manufacturers to focus on core competences yet allowing them to offer customized products in any market. A true Smart Manufacturing Network can integrate data from system-wide physical, operational, and human assets to drive manufacturing, maintenance, production planning, scheduling and digitization of operations across the entire manufacturing network.

To achieve their purpose, SMNs rely on domain-specific manufacturing knowledge (see Sect. 5.4). We refer to the collective manufacturing knowledge in an SMN as *manufacturing smartness*. Manufacturing smartness signifies the ability of an SMN to:

1. gain line of sight and provide unobstructed visibility of dispersed production data and coordinated production operations across the entire SMN,
2. optimize use of dispersed data, resources and (human)-expertise,
3. provide help and guidance for making efficient and effective holistic decisions, and
4. plan a coordinated response to individual and collective manufacturing needs.

SMNs aim to improve manufacturing by connecting people to the right information, over the right device at the point of need and cross company boundaries to include suppliers, maintenance partners, and distribution chains. The human role will progress from operators of the machines ("human-in-the-loop") to partners of the machines ("human-in-the-mesh") with the potential for humans and machines to operate more seamlessly and systems to interconnect better than ever before (see Sect. 2.2).

Every SMN could look different due to variations in line layouts, products, automation equipment, and other factors. Despite all potential differences, the components needed to enable a successful SMN are largely universal, and each one is important: data, technology, manufacturing knowledge and processes, security and people engagement.

In the following, we examine first the concept of digital transformation, digital product lifecycle, and then focus on the concept of manufacturing smartness and the process of managing an entire SMN.

5.2 Digital Transformation Roadmap

According to expert reports [18], manufacturing companies expect by the year 2020 to reduce operational costs by 3.6% p.a., while increasing efficiency by 4.1% annually (see Fig. 3). High levels of cost reduction are expected in every industry sector (e.g., aerospace, automotive, industrial manufacturing, metals, etc.).

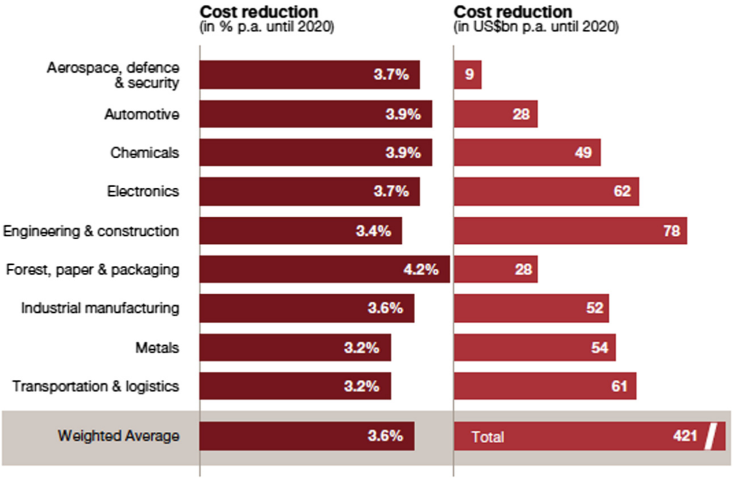

Fig. 3. Industry 4.0 induced reduction of operational per industry sector (source: [18]).

Industry 4.0 will lead us not only to greater industrial productivity, but also to greater commercial creativity by driving digital transformation. Transforming to a digital Industry 4.0 manufacturing model requires a re-estimation of manufacturing sector capacities, processes, operations, policies and frameworks [19].

Digital transformation in the context of Industry 4.0 is the profound transformation of manufacturing and organizational activities, processes, competencies and models to fully leverage the changes and opportunities of a mix of digital technology innovations and their accelerating impact across production and manufacturing, with present and future shifts in mind. Technology innovations - including cloud computing and platform technologies, big data and analytics, mobile solutions, social and collaborative systems, IoT, and AI (see Sect. 2.2), are fueling and accelerating a new era of digital business transformation. Digital transformation in the Industry 4.0 era and the digitization of the enterprise lead to huge leaps in performance and improve digital relationships with customers who contribute to the productivity of the organization.

Many industrial firms have already begun digitizing their business, but often the process has started in organizational silos, rather than following a holistic approach. This will eventually lead to pitfalls. Instead, firms need to take the time to evaluate their maturity level in all areas of Industry 4.0 and develop a digital transformation roadmap. A typical digital transformation roadmap may include the following steps:

Readiness Check and Digital Maturity Assessment: Companies need to determine their current business position and then start their digitalization initiative. They need to conduct a readiness check to determine the following five aspects: viability of business model, human expertise and cultural adoption readiness, technology-levels (the current state or their organization's technology), sophistication levels of data health, and sophistication of processes. This should be followed by undertaking a comprehensive digital maturity assessment in all areas of Industry 4.0 to understand their current strengths and weaknesses throughout all relevant assessment domains (business model, digital practices, management practices and digital capabilities, and which systems/processes they may need to integrate into future solutions). Companies like PWC and CapGemini have developed maturity models to assess how well companies are positioned for digital success [18, 20].

Identifying Opportunities and Threats: Once organizations have a clear perspective on their digital maturity, they need to explore the corporate environment for opportunities and threats triggered by the digital transformation. They need to look into altering customer demands, competition dynamics and digital best practices across all relevant business domains. Opportunities and threats will need to consider five strategic dimensions: business model, human expertise, technology, data health and processes.

Defining Digital Vision and Agenda: Based on the identified opportunities and threats, manufacturing firms need to develop a clear digital vision. This vision needs to provide a comprehensive view on how the firm aims to conduct digital business. A recent trend is for an industry to forge technology partnerships to create a rich ecosystem to achieve their digital ambitions. These partnerships set the stage for open innovation platforms and some manufacturers are already envisioning future as a continuous process of breaking out of traditional molds to spark new ways of producing and moving goods and services, better, faster, and with increasing efficiency.

Prioritization of Transformation Business Segments and Piloting: The next step after defining the digital agenda is to prioritize specific business segments for transformation and select within these pilots based on the perceived business benefits and ease of implementation. Digital transformation introduces complex, systemic challenges, which manufacturers can address by architecting initiatives to connect disparate operations and siloed systems and processes, starting with smaller, focused, department-level pilots and growing them gradually to a unified end-to-end manufacturing ecosystem. The complexity of the implementation will depend on the required level of integration with the existing core business processes and systems. Pilots can help address these issues by targeting a confined scope, but highlighting the end-to-end concept of Industry 4.0.

During this step it is important to pick the right projects. Possible options include vertical integration within one or two manufacturing sites including digital engineering and real-time data integrated manufacturing planning. This can be followed by gradual horizontal integration with selected key suppliers. For instance, enhanced track and trace capabilities and dynamic connections with Enterprise Resource Planning systems at the enterprise-level can make it possible to apply data analytics to optimize supply chain planning end-to-end.

Developing a Digital Transformation Blueprint and Adoption Strategy: Once the transformation domains and pilot initiatives have been selected, prioritized, successfully performed and completed, a digital roadmap has to be created containing transformation details for each of the preceding steps and lessons learned. The digital roadmap provides a comprehensive plan designed to achieve value specific to manufacturing organization outcomes, inclusive of an adoption roadmap, benefit estimate, actions that will deliver those benefits, and monitoring of those benefits. The roadmap will also identify opportunities to improve user experience of the most widely-used manufacturing processes services. The digital transformation journey has to build on a consistent vision shared by all relevant stakeholders. Cultivating a digital environment can only happen with committed leadership. As a result, the digital factory strategy must be placed squarely at the center of the C-suite agenda and become a top priority.

5.3 Digital Product Lifecycle

In discrete manufacturing every manufactured product passes through a standard lifecycle on its path from product concept, through engineering development, to production. The digital product lifecycle in discrete manufacturing usually encompasses the following stages.

Product Ideation/Analysis: This stage includes interaction with customers, and brainstorming, collaboration and ‘ideation’ of a digital product potential and possibility with product designers and strategists. Objective is to determine and analyze the different product characteristics usually by improving an existing product or design a new product from scratch and variants as part of requests for quote for customized products.

Product Design: covers the techniques, digital tools and expanded mind-set used to design, simulate, and plan a product in an SMN setting. Its objective is to provide a virtual version of a product and all of its variations that can be run through wider ranging tests. The concept of a digital twin is central to product design as it includes design and engineering details describing the product's geometry, materials, components and behavior, individual parts and assemblies that make up the product. A digital twin of a connected product can provide insight into how the product is behaving in the field, helping to steer product design and provide intelligence for successful service calls. During product design engineering teams see not just static mock-ups of a product or system (the traditional 3D digital mock-up driven by CAD), but rather provide insights into its physical behavior, like stress and vibration, as well as behavior associated with software and control systems. A product is first visualized with an engineering design, followed by the creation of a Bill of Materials (BOM). The BOM is a list of parts and materials needed to make a product and shows "what product" to make, not "how" to make it.

Product Planning: During this stage, the design concepts are turned into product requirements and production plans. Planning enables manufacturers to manage manufacturing data, process, resource, and plant data in an integrated product and production environment. Planning bridges the connection between the product centric view of building a product and the plant centric view of building a product in the plant. Planning enables the development of three models critical to manufacturing:

- Manufacturing process model that provides an accurate description as to how the product will be produced.
- Production facility model that provides a full digital representation of the production and assembly lines needed to make the product.
- Production facility automation model that describes how the automation and industrial control systems, such as Supervisory Control and Data acquisition (SCADA) systems, Distributed Control Systems (DCS), and other control system configurations, such as skid-mounted Programmable Logic Controllers (PLC), will support production.

Planning consists of detailed plans explaining the manufacturing process. Within these plans resides in-depth information on the above three models including machinery, plant resources, equipment layout, configurations, tools, and instructions. It also provides a bill of manufacturing processes that contains components and subassemblies and the recipes of operations and resources needed to build the product and stations and cells with the list of operations that can be performed at a particular factory floor station.

Production Execution and Management: Production execution oversees production operations, including functions to control material and product flow between equipment. It includes digitally controlled/sensed equipment, factory floor tools/systems/software, infrastructure systems, and simulations used to optimize production and product quality. It supports production schedule execution and product tracking against scheduled completion times, with adjustments to optimize efficiencies.

Service and Maintenance: Services are seen as an approach to create competitive advantage and market differentiation [21]. The process through which this is achieved is commonly known as servitization. With servitization traditional products can incorporate additional value services, such as maintenance, upgrades in functionality, condition monitoring, remote communications to resolve issues from a distance, consumption monitoring, pushing information to line workers, production outputs, etc. Servitisation is being accelerated by the IoT sensors that can collect huge volumes of data which can be used to improve product quality, reliability, and customer satisfaction.

5.4 Manufacturing Smartness

Currently, manufacturing knowledge is not completely captured in a digital, searchable form in all phases of the manufacturing lifecycle. For example, design drawings, process capability graphs, equipment pictures, manufacturing operation tables, production schedules, statistical-process data interpretations, and engineering change requests are not fully integrated. Furthermore, engineering knowledge is embedded in various stages in the product lifecycle in forms of rules, logical expressions, predictive models, statistics, and information extracted from sensors, such as production, inspection, product use, supplier networks, and maintenance [22]. To circumvent this problem, manufacturing knowledge must be captured, streamlined, structured, interrelated, and curated by means of a formal manufacturing knowledge model.

An SMN can efficiently elicit knowledge from distributed resources and form a coherent body of knowledge that can be analyzed by automated tools to create insights that are used by analysts, engineers and customers alike to optimize product design and production processes. In the following we focus on product, production and quality knowledge related to product/production processes in an SMN setting.

Product structure knowledge should provide a hierarchical classification of the items which form a product. Product knowledge should include all the details about individual parts which compose a product, as well as their attributes and their relations with each other, and is typically released in the form of assemblies, sub-assemblies and components that are organized in a function-oriented structure.

Production knowledge is typically related to the parts in a specific order that can be sourced and combined to manufacture a product. It describes numerous plant level activities and workflows involving equipment (definition, usage, schedule, and maintenance), materials (identification, properties, location, and status), personnel (qualifications, availability, and schedule) and the interaction between them. The production knowledge model is driven by production schedules containing production work orders that are sent to production. These describe the manufacturing operation sequences coupled with manufacturing task time, space, tooling and other resources that include material, equipment, or personnel needed to manufacture the product.

Quality assurance knowledge helps streamline production and ensure that the final products meet the company's quality criteria and ensure customers receive products free from defects and meet their needs. Quality Assurance knowledge includes knowledge about the following aspects of manufacturing:

- *Customer experience and responsiveness*: includes knowledge and metrics about on-time delivery of a completed product on the schedule that was committed to customers.
- *Quality manufacturing*: includes knowledge and metrics about yield, which is the percentage of products that are manufactured correctly, and specifications regarding the manufacturing process and metrics about customer rejects and returns.
- *Production performance*: regards knowledge about the collection of activities that analyze and report performance including production unit cycle times, resource utilization, equipment utilization, equipment performance, procedure efficiencies and production variability. Production performance knowledge typically relies on production throughput, capacity utilization, and production attainment.

In a recent development the authors describe how manufacturing smartness in an SMN is captured in a digital, formal manufacturing knowledge model that classifies it, and encapsulates it in five inter-connected, programmable abstract knowledge types, referred to as manufacturing blueprint images [23]. Manufacturing blueprint images (or simply blueprints) 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. The blueprint images below are programmable abstract knowledge types that classify product and production knowledge achieving separation of production concerns.

Supplier Blueprint: defines a partner firm's business and technical details in an SMN constellation, such as production capabilities, production capacity details, and stakeholder roles.

Product Blueprint: this knowledge type is the "digital record" of a product, which is continuously updated as the product itself passes through its life cycle. The Product Blueprint defines the details of a standard or configurable product, product hierarchy, product parts, materials, and product-related 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. Such information helps the manufacturer understand how the product behaves in different production environments and provides traceability from inception to retirement.

Services Blueprint: defines and represents all services corresponding to a product (e.g. maintenance, repair, upgrades, spare parts, etc.).

Production Plan Blueprint: defines standard assembly and production solutions, as well as a suitable production plan via a workflow linking the events of discrete activities associated with all aspects of actual production on the factory-floor. It facilitates planning at all levels - plant, region, division and enterprise. It empowers local planners to "own" their production schedules, while allowing line planners to view both individual plant schedules and the aggregate production schedule across all plants.

Quality Assurance Blueprint: ensures 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.

The five manufacturing blueprints described above enable the sharing of a common understanding of manufacturing information among people and software tools; enable the reuse and extension of manufacturing knowledge; make assumptions regarding the manufacturing domain explicit; separate manufacturing from operational knowledge; can be combined in end-to-end constellations describing entire supply chains and process; and can, finally, enable the analysis of manufacturing knowledge leading to improved decision making. The five manufacturing blueprints are generic in nature to ensure wide applicability to Industrial Internet applications across a variety of Industrial Sectors. They can be extended and specialized to address sector-specific requirements. The previous characteristics are necessary to realize Industry 4.0 tenets.

Blueprint images can be stored in a marketplace repository (see Fig. 4), are discoverable, can be queried, compared, interrelated and composed pair-wise into end-to-end constellations defining a composite digital product and its component parts, as well as its associated production plans and schedule.

5.5 Digital Twin Lifecycle

A significant emerging trend in SMNs is the unified, end-to-end digital twin lifecycle that extends from digital product design through production execution, and production monitoring.

To illustrate the SMN digital twin lifecycle process we consider a scenario in which an OEM outsources a portion of its manufacturing operations to either a single or multiple manufacturing partners who manufacture the necessary product parts and then ship them for final processing and assembly at the OEM's facility. In this scenario, we assume that the OEM can obtain a digital representation of components through an industry domain-specific digital marketplace repository (see Fig. 4) and augment them via value-added digital services to meet specific customer needs.

The digital marketplace provides domain-specific manufacturing service offerings rich in diversity and a shared, secure, open-access infrastructure, and functionality to ease service interoperation and composability, and to allow users or a variety of third parties to develop customized solutions.

To effectively deal with heterogeneity manufacturing partners can harmonize their offerings by describing them in a common standardized knowledge model (see Sect. 5.4) and by storing them in the marketplace repository for discovery purposes. The repository provides harmonized digital services that can be combined with other such services to perform a desired task. Production units will then become modules, featuring 'Plug & Produce', enabling fast reconfiguration and optimization of production lines. Figure 4 also shows the SMN digital twin lifecycle stages, which include:

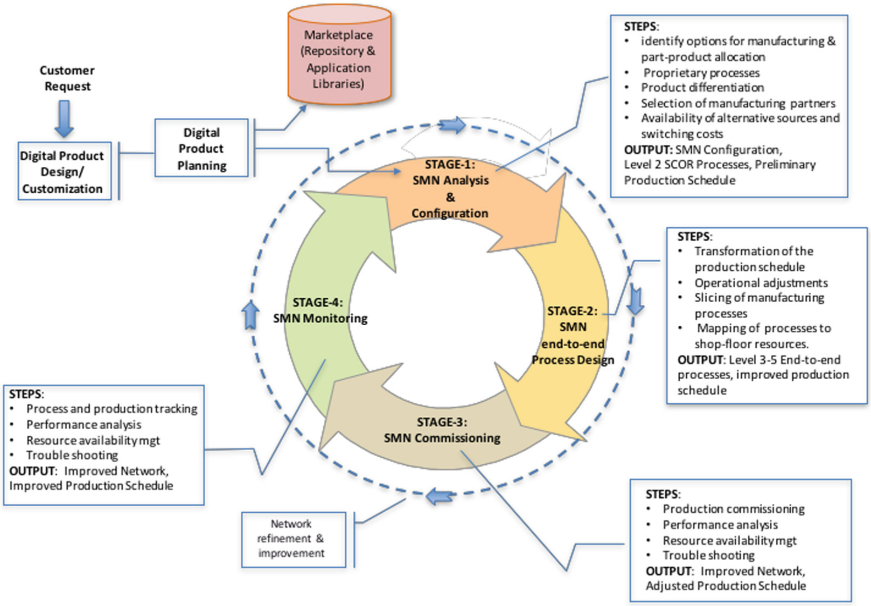

Fig. 4. SMN digital twin lifecycle stages.

SMN Analysis and Configuration: During this stage, the OEM identifies manufacturing options and allocates the production of product parts to potential external partners selected from the marketplace in Fig. 4 that were chosen for outsourcing purposes. By examining entries in the marketplace repository, an OEM determines which product parts can be produced by a third-party supplier. It then assesses the selected partners by examining key indicators, such as manufacturing and engineering capabilities, design and innovation skills, costs, ability to scale, capacity utilization, and the policies of the potential partner. At this stage, the OEM uses simulation and visualization tools to estimate and display alternative network configurations with regards to partners, variants, partner availability, quantities and delivery dates to determine the partners that can jointly contribute to the construction of the final product. In this way, a final set of partners is determined and the SMN is fully configured (see Fig. 4).

SMN Process Design: This stage enables the digitalization of a broad spectrum of production-related functions, including advanced planning and scheduling, quality management and manufacturing intelligence to coordinate processes and systems within and across factories and standardize production across the entire SMN. This stage connects the automation layer with product planning and design, enabling companies to execute according to the plan and schedule. This affords improving the full product and production lifecycle.

Design provides end-to-end visibility into production operations and quality management, connecting the automated operations, equipment, and systems on the shop floor to the decision makers in product development, manufacturing engineering, production and enterprise management. With full visibility into production, decision makers can readily identify areas to be improved within both the product design and associated manufacturing processes, and make the necessary operational adjustments for smoother and more efficient production.

In this stage, it is possible to distribute workloads across multiple suppliers. This phase adopts a vertical slicing (decomposition) of the OEM production process into outsourced parts manufacturer processes, which need to be synchronized and coordinated.

During SMN Design a digital “thread” of local processes and data flows continuously, creating a virtual replica of a manufacturing process that reveals significant insights. Results of this stage are apportioned and stored in the five blueprints described in Sect. 5.4. A detailed example of how this procedure is performed can be found in [23].

SMN Commissioning: is the stage that involves testing the entire production system, including equipment, plant and facility, and handing off the production system for operation. This could be performed on the basis of information contained in the five blueprints in Sect. 5.4.

SMN commissioning covers the digitally enabled tools, technologies, and work concepts that aid in the execution of manufacturing, processing, or assembly of a product. Technologies that influence execution and processing include digitally controlled/sensed equipment, shop floor tools/systems/software, infrastructure systems, and simulations used to optimize production and product quality. SMN commissioning provides up-to-date visibility of all Work in Process (WIP) orders for product lines and production areas.

After commissioning, the production system enters operations and maintenance - a steady state of tactical operations and strategic maintenance activities.

SMN Monitoring: provides real-time visibility, enables traceability of both materials and products throughout their lifecycles, optimizes workflow to ensure lower lead times, facilitates corrective actions for defective products, and optimizes plant operations for effective use of resources and assets. It detects abnormal conditions, machine failures or KPI deviations, e.g., by inspecting end-to-end Quality Assurance and Production Plan blueprints in an SMN, changing consumer demands, laws and regulations (e.g., carbon emission). Its aim is to monitor production processes and either automatically correct them or provide insights to human operators to improve product design and processes, discover deficiencies though analytics and simulation, and provide support to operators for correcting and improving process activities to ensure that the processes supporting a given manufacturing task are performing in accordance with service-level objectives.

During this stage, IoT-based systems distributed throughout the plant floor can capture data along a wide array of dimensions, from behavioral characteristics of the production machinery to characteristics of works in progress (thickness, hardness, torque, and so on) and environmental conditions within the factory itself. By combing performance data from the sensors with predictive analytics simulations, engineers can examine and address performance issues, foresee the need for product maintenance or repair, and ensure that future versions of the product are optimized for day-to-day operating conditions

6 Conclusions

Industry 4.0 is driven by disruptive technologies which promote connected manufacturing solutions that link the supply chain directly to the production line by triggering integrated, automated, autonomous manufacturing processes that make better use of raw materials, and human resources to produce higher-quality products at reduced costs. This is made possible by workpieces and means of production which are digitally networked and are able to communicate. This end-to-end digitization and integration are improving process efficiency, quality management, and productivity, along with real-time insights into the whole manufacturing landscape, building a digital business model that supports data-driven decision-making and integrated platform-based services.

A critical element is the evolution of Industry 4.0 toward a connected, smart, and highly efficient manufacturing network ecosystem that integrates data and processes from many different sources and locations to drive the physical act of production and distribution. This gives rise to the concept of a Smart Manufacturing Network that extends the vertical integration of all corporate functions to the horizontal dimension, knitting together relevant stakeholders - the suppliers of raw materials and parts, external support firms, outside service organizations, the production process itself, and finally the customer - through a network of sensors and digital services managed through an overarching knowledge-driven environment and data analytics engine. The result can be a virtual world, which mirrors and informs the physical world by replicating what is happening on the factory floor.

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