Advances in Production Management Systems: Issues, Trends, and Vision Towards 2030

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Abstract. Since its inception in 1978, the IFIP Working Group 5.7 on Advances in Production Management Systems (APMS) has played an active role in the conception, development, and application of innovative strategies, frameworks, architectures, processes, methods, and tools for the advancement of the field of production and production management in academia and industry. In this field, the IFIP WG5.7 has helped to shape the progress of both scientific theories and industrial practices. This achievement is driven by an emphasis on the continuous development and refinement of research inspired by excellences in industrial practices while maintaining academic sophistication and scientific rigour. More recently, in light of the Fourth Industrial Revolution (4IR), the field has been experiencing a remarkable (r)evolution and disruptive changes. This triggered by the fusion of advanced operational and information technologies, innovative operating and business models, as well as social and environmental pressures for more sustainable production systems. This chapter reviews past and present issues and trends to establish a coherent vision and research agenda for the IFIP WG5.7 and its international community. The chapter covers a wide range of production aspects and resources required to design, engineer, and manage the next generation of sustainable and smart production systems.

Keywords: Production Management, Cyber-Physical Production Systems, Smart Manufacturing, Industry 4.0, Operator 4.0, Product-Service Systems, Product Lifecycle, Lean Manufacturing, Servitization, Gamification, Customization.

1. Introduction

Many social, environmental, economic, as well as technological trends, are shaping the new production[*] environment towards 2030 (WEF, 2020). This is driven not only by traditional discrete manufacturing but also by "edge" manufacturing such as farming, food, and biopharmaceutical manufacturing among others. The objective of this book chapter is to identify the socio-technical challenges and enabling technologies relevant for production managers to remain competitive in 2030 and beyond. To do so, we conducted an investigation for developing a coherent vision and research agenda for production and production management based on information gathered from industry whitepapers, forward-looking manufacturing studies (e.g. WMF (2018)), and extensive discussions in the IFIP WG5.7 community.

This chapter is structured as follows: First, we take a brief look at the IFIP WG5.7 today and introduce our vision for 2030. Second, we introduce *Seven Grand Challenges* that pertain to the group's focal research areas. We discuss each grand challenge and reflect how the IFIP WG5.7 will address it. Each challenge's discussion is structured by first providing a brief overview of its current status, followed by introducing relevant enabling technologies, before elaborating on the related IFIP WG5.7 Special Interest Group (SIG) efforts to address it, to finally presenting a research agenda and future outlook. The last two sections of this chapter include barriers and enablers for addressing the presented grand challenges and concluding remarks.

2. IFIP WG 5.7 – Advances in Production Management Systems

The aim of IFIP Working Group 5.7 on Advances in Production Management Systems[†] is to globally promote and facilitate the advancement of knowledge, theory, technology, and industrial practice in the field of sustainable and smart production management systems. In this field, the focus of IFIP WG5.7 addresses topics such as advancement and integration of operational and information technologies, operations management, and Industry 4.0-infused innovative business models development. The IFIP WG5.7 takes an interdisciplinary approach to define the next generation of production systems, especially when exploring the future role of human ingenuity and the human workforce within a manufacturing setting. This broad aim is achieved by the continuous development and refinement of an "industry-based" research agenda, focusing on industrial excellence for assessing best practices and stimulating young researchers seeking careers in production management. The IFIP WG5.7 emphasizes a collaborative research culture that nurtures state-of-the-art research motivated by taking into account current industrial needs while maintaining academic excellence and scientific rigour. The communities' R&D contributions and best practices are disseminated globally to both academics and practitioners through the annual flagship *APMS International Conference*[‡], the flagship journal *Production Planning & Control (PPC)*, as well as workshops and additional activities organised by *Special Interest Groups (SIGs)*.

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[*] *Production* is defined as the processes and resources required to design, engineer, manufacture, deliver, servitize, and recover a product to/from the market.

[†] https://www.ifipwg57.org/

[‡] https://www.apms-conference.org/

2.1 A Production and Production Management Vision Towards 2030

Our shared IFIP WG5.7 vision is: "*As elements of production systems continue to be more connected across the layers of operations from shop-floor to supply chain, by 2030 production managers will become the orchestrators of the ever more complex and collaborative cyber-physical production systems (CPPS)*". Such advanced CPPSs will be characterized by their self-aware intelligence and can achieve a balance between engineering, social, environmental, and economic objectives. They will rely on a vast amount of digitally connected knowledge to make such balancing decisions using AI technologies. These CPPS will be highly-configurable at the physical and control level such that individualized products can be produced with similar or even improved cost, quality, lead-time, and safety compared to mass-produced products. For this to become a reality, "interoperability" will be key.

The subsequent sections of the chapter show that a significant amount of conceptual work on CPPSs has been completed and that a large range of enabling technologies are readily available for implementation. At the same time, the *Grand Challenges* that production and production management will be facing in the future are extending beyond simple technologies adoption. The *Grand Challenges* are reflective of changing customer expectations and the new realities of global, tightly intertwined digital supply networks (Sinha et al, 2020) and their implications on production management. Each *Grand Challenge* is interdisciplinary and crosses domains – which is a reflection of the future work environment in manufacturing and beyond. The utilized industry reports deriving the *Grand Challenges* present successful implementations of advanced digital technologies in production, maintenance, and logistics operations, and showcase the potential inherited in aggressively exploring new opportunities to expand technology applications and human ingenuity.

The fact that smart technologies play an important role in our daily life, as private consumers, is a cause for optimism. Today, office staff and operators of production companies are very familiar with digital technology on a personal level. This will naturally expand to the work environment and become second nature in the next decade. Manufacturing will look very different from today's dark, dirty, dangerous myth.

3. Grand Challenges for Production & Production Management

Transcending the current status of advanced production and production management, 2030 targets present major socio-technical challenges for production managers, which are referred to as "Grand Challenges" or fundamental goals in order to realize sustainable and smart production systems. The *Seven Grand Challenges* are:

1. Agile Product Customization Processes
2. Proactive and Socially Intelligent Products and Assets
3. Data-Driven Operations Management
4. Digital Lean Manufacturing Systems
5. Human Cyber-Physical Production Systems
6. Immersive Learning and Virtual Training Environments
7. Servitization of Manufacturing

3.1 Grand Challenge 1: Agile Product Customization Processes

Grand Challenge 1 is to develop *agile product customization processes* with particular attention to “pure-personalized products” known as Engineer-to-Order (ETO) solutions and “mass-customized products” that fall under the category of Make-to-Order (MTO) or Build-to-Order (BTO) solutions. The goal for this grand challenge is to achieve the Industry 4.0 vision of small-batches and item-level productions (i.e. batch-size-1) using agile engineering and production systems that enable efficient mass-customization and pure-personalization through customer- and product-specific coordination of design, engineering, configuration, ordering, planning, production, and logistics operations (Rudberg & Wikner, 2004; Duchi et al, 2017; Vellmar et al, 2017).

3.1.1 Current Status

There is an increasing market demand for mass-customized and personalized products. As a result, manufacturers are moving away from Make-to-Stock (MTS) and shifting towards Make-to-Order (MTO) or Engineer-to-Order (ETO) fulfilment strategies. The growth in product mass-customization and pure-personalization drives an increased complexity and uncertainty in production systems (Duchi et al, 2017). In this context, highly customized engineering and production in ETO environments have traditionally been characterized by a large extent of manual work, a low level of data availability, and a large extent of value creation performed by suppliers, which put extra stress on the coordination of value chain actors (Wikner & Rudberg, 2005). *Mass-customization* typically works around the alignment of engineering and production activities by implementing modularity, product platforms, and other techniques to manage a large variety of designs, while at the same time decrease lead times and costs (Bonev, 2015). Most mass-customization research focuses on how mass-producers (i.e. both MTS and ATO (Assemble-to-Order)) can increase variety and customization while maintaining high efficiency (Duchi et al, 2017). Moreover, *ETO* manufacturers need a different perspective, including shifting the time of differentiation closer to the time of delivery through partial standardization and modularization of both engineering and production (Cannas, 2019). The *ETO perspective* on “efficient customization processes” is lacking in contemporary research on mass-customization and order fulfilment of personalized products with a high degree of engineering content (Vellmar et al, 2017).

3.1.2 Enabling Technologies

Some *technologies* that companies could use to enable efficient customisation are:

- *Configure, Price, Quote (CPQ) Software* – as an enabler of sales of customized products in minutes, allowing real-time responses to customer inquiries.
- *Knowledge-Based Engineering (KBE) Systems* – as computer systems allowing to capture and reuse engineering knowledge to automate CAD/CAE-based engineering design and simulation activities, allowing an automated engineering process from sales to the programming of robots and machines.
- *Software Connectivity* – as an interoperability solution for real-time, reliable data/information integration between supporting systems including ERP, CRM, Pricing, MES, PLM, CAD/CAM, SCM, and Service.

- *3D Information Models and Visualization Tools* – as enablers for real-time planning, monitoring, and evaluation of processes, site layout, and material handling for large complex products (e.g. Building Information Models (BIM)).
- *Augmented Reality* – as simplifier of complex assembly/installation procedures for engineers and manufacturers by replacing static work instruction documents with AR solutions, and making possible for engineers to provide operators with instant direction and image/voice instructions.
- *Smart Scheduling Techniques* – as new techniques featuring the use of cyber-physical systems that yield flexible and efficient production schedules on the fly. Such smart techniques can be used for resource-constrained multi-project scheduling, time and pricing determination in tendering, and for rescheduling in the face of unforeseen events at the shop-floor (see Rossit et al, 2019).
- *Internet of Things* – as an enabler for the tracking of customers' products or assets (i.e. equipment) and predicting what they need in advance. It can also help in reinventing site management since it is possible to know where every tool and part is, and what area of the site that is likely to be free soon.
- *Autonomous and Collaborative Robots* – as robots that can load and unload resources, and start, stop, load, and unload machines, and enable a more automated flow in production systems supporting customized products.
- *Additive Manufacturing* – as a facilitator for the integration of the engineering and production processes with fast feed-forward and feedback between the two processes. It can also increase the effectiveness of an efficient customization process in ETO operations.
- *Digital Twins and CAD Parametric Design* – as facilitators of the integration between design/engineering and production processes employing sensor data and reality capture methodologies (e.g. point clouds) that can create model-based parametric designs. Furthermore, when including the production line perspective in this, real-time 3DCE (3D-dimensional concurrent engineering) can be integrated into the digital twin to not only model the product but also the production processes.
- *Machine Learning and Artificial Intelligence* – as solvers of constraint-based problems such as improving production efficiency while defining the best possible workflows for producing highly configurable, customized products.

3.1.3 IFIP WG5.7 SIG – Operations Management in ETO Manufacturing

The IFIP WG5.7 SIG on "Operations Management in ETO Manufacturing" welcomes research contributions and industrial best practices on Operations Management (OM) enabling effective Engineer-To-Order (ETO) manufacturing, including Industry 4.0 technologies, Supply Chain Management (SCM) practices, lean operations, production planning and control techniques, production strategies, and product platforms. ETO is a manufacturing approach where design and engineering activities are included in the order fulfilment process. ETO manufacturing is used when engineering specifications of products are not known in detail upon receipt of the customer order, and is common in mechanical industries, construction sector, shipbuilding, offshore supplier industries, and other types of project-based manufacturing; industries typically facing several unique challenges as the products are often one-of-a-kind and/or highly customized.

3.1.4 Research Agenda & Future Outlook

The following *trends* are seen of particular relevance for changing the way of working towards the efficient design and engineering of mass-customized and pure-personalized products (Vellmar et al, 2017):

- *Increasing Complexity* – as products complexity continues to increase in terms of their number of components and sub-systems, and the intensity of their interactions, appropriate balance between modular/flexible composition and agile engineering of a product solution will be needed to quickly respond to mass-customization and even mass-personalization market demands.
- *Increasing Competition* – as cost-competitive pressures demand reductions in engineering costs, innovative methods and tools (e.g. model-based engineering, virtual prototyping, digital mock-ups) will be required to improve the way of working in engineering projects.
- *Digitalization & Industry 4.0* – as time-to-market pressures continue to increase, agile product development processes will make more and more use of software and automation systems to support the visualization of engineering data and the automation of engineering processes and decisions.
- *Glocalization* – as "being global and acting local" becomes a new source of competitive advantage when it comes to responsiveness and specialization, new strategies to achieve better market proximity to customers and suppliers and for rationalizing the value chain will be needed.

3.2 Grand Challenge 2: Proactive and Socially Intelligent Products and Assets

Grand Challenge 2 is to design and engineer *proactive and socially intelligent products and assets* aligned to the requirements of circular lifecycle management options and collaborative multi-agent production management approaches. The next generation of intelligent products and assets will be more proactive, and even socially intelligent. Products and assets will be supported across their multiple possible lifecycles in the emerging Circular Economy and as part of collaborative multi-agent cyber-physical production systems.

In this sense, *proactive intelligent products or assets* refer to those smart, connected entities capable of using Just-In-Time (JIT) information about needs, circumstances, preferences, life events, conditions, locations, etc. to anticipate and automate relevant tasks for themselves or their operators or users (Wuest et al, 2018). Whereas, *socially intelligent products or assets* allude to those smart, connected entities capable of sharing status information and cooperating via a social network to achieve a common or compatible goal using context-aware capabilities and cooperative initiatives (Li et al, 2018). Therefore, *circular lifecycle management of products or assets* refers to a strategy focused on gathering and analysing the data of a product or asset from the perspective of enabling and supporting its circular systems (Kiritsis, 2011; Freitas de Oliveira & Soares, 2017; Macchi et al, 2018). Moreover, *collaborative multi-agent production management approaches* represent a "production control strategy" where production resources, as assets of the production system, are understood as collaborative agents sharing the common or compatible goal to manufacture a product within certain quality, time, and cost constraints (Scholz-Reiter et al, 2009).

Overall, the goal of this grand challenge is to achieve optimal system-level performance by making a product or an asset more reliable and productive by itself, for its operator or user, and for the network of "things" to which it may belong; enabling value-oriented decision-making. Advanced approaches to predictive maintenance and quality control (Guillén et al, 2016; Cho et al, 2018; Psarommatis et al, 2019; 2020), as well as impact analysis at factory-level and risk-oriented strategic decision-support systems (Roda & Macchi, 2018; 2019; Roda et al, 2019; Polenghi et al, 2019a), are required to this end. Furthermore, data needed to support different circular systems and services during a product's or asset's multiple lifecycles should be transformed and integrated to make available information and knowledge relevant for more sustainable products and assets (Nezami et al, 2019; Polenghi et al, 2019b).

3.2.1 Current Status

From an evolutionary perspective, products and assets have evolved from mechatronic to smart, connected entities embedded with sensors, actuators, processors, and software. Their connectivity allows data to be exchanged with their environment, manufacturer, operator or user, as well as with other products or assets and systems. In this context, the next evolutionary stage will require the development of cybersecurity, pervasive connectivity, interoperability, and advanced data analytics solutions towards proactive and socially intelligent products and assets. Besides, the current capabilities of product and asset lifecycle management systems need to be extended to deal with the multitude of these connected entities.

3.2.2 Enabling Technologies

Some *enabling technologies* that companies could incorporate into their proactive and socially intelligent products or assets are:

- *Smart Sensors* – as the "eyes-and-ears" that IoT/IIoT devices provide to their applications through novel telemetry systems that monitor their mechanisms and environment.
- *Machine-to-Machine (M2M) and Human-Machine Interfaces (HMIs)* – as the automation of communications and data exchange among networked devices and between the operator and the system, enabling the IIoT.
- *Edge Computing* – as the local data processing power that is closer to the source of the data for faster response time, increased reliability, and cybersecurity.
- *Cloud Computing* – as the global data processing power that builds on access to data from anywhere as well as the provision of additional data-driven services for production systems, also enabling the enlargement to a network of computing resources from suppliers.
- *Machine Learning* – as the operational data analytics to descriptive, diagnostic, predictive, and prescriptive equipment behaviour for higher levels of reliability and efficiency.
- *5G-Connectivity* – as a more reliable wireless connection offering high-speed (>1 Gbps), low-power, and low-latency (<1ms) for the IoT/IIoT world(s).

- *Industrial Ontologies*[§] – as integrated data models of products, processes, and production systems for semantic interoperability, and knowledge sharing and reuse along the lifecycle of products or assets.
- *Cybersecurity Standards*[**] – as protection from malicious intrusions aiming at modifying the intended behaviour of a smart, connected product or an asset will become a new design requirement for devices in the IoT/IIoT world(s).
- *Circular Technologies*[††] – as resource-efficient production technologies aiming at minimising waste and emissions, and maintaining the value of products and resources for as long as possible so that circular products and their raw materials can be recycled and recreated in a circular production system.

3.2.3 IFIP WG5.7 SIG – Product and Asset Lifecycle Management

The IFIP WG5.7 SIG on "Product and Asset Lifecycle Management" aims at promoting collaborative research and networking activities among researchers and practitioners with a shared interest on the key aspects of product and asset lifecycle management within advanced production systems. The "lifecycle" is the cornerstone based on which the SIG explores innovative ways for the development, coordination, and control of activities undertaken on products and assets. In particular, the SIG encourages research exploring how to design, engineer, implement, and improve systems for circular lifecycle management of products and assets, and collaborative multi-agent production systems management. To this end, the SIG is interested in merging academic rigour with practical applications on topics such as the effective management and use of data, information, and knowledge among the different lifecycle phases of a product or asset, enabling closing the loops of information as well as knowledge sharing and reuse required by product/asset-related decisions; the adoption of Zero Defect Manufacturing (ZDM), and Prognostics and Health Management (PHM) strategies to support the optimization of performances along the lifecycle; the adoption of "intelligent" products and assets for a smart lifecycle management; the exploitation of the (Industrial) Internet of Things (IIoT), Big Data, Predictive Analytics, Semantic Technologies, as well as advanced Human-Machine Interfaces (HMIs) in order to build an Industry 4.0-infused innovative lifecycle management. The purpose of the SIG is (i) to identify and share best practices in order to consolidate the knowledge in the field, (ii) to explore the existing gaps in practice and theory in order to identify new research paths, and (iii) to establish interdisciplinary collaborations in international projects and research activities.

3.2.4 Research Agenda & Future Outlook

Some *emerging paradigms* enabled by proactive and socially intelligent products and assets are:

- *Zero Defect Manufacturing (ZDM)* – as intelligent assets (i.e. smart machines) become able to harvest data from both their processes and products and use advanced data analytics tools in real-time, quality control will gain a new edge

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[§] https://www.industrialontologies.org/

[**] https://www.nist.gov/cyberframework/

[††] https://www.ellenmacarthurfoundation.org/

by detecting and correcting a defect or fault either in a machine or production process of a product before it happens (Psarommatis et al, 2019; 2020).

- *Prognostics and Health Management (PHM) Systems* – as intelligent assets (i.e. smart machines) start using real-time data and historical information, they will be able to provide actionable information for improving their performance – as safety, reliability, and maintainability – through fault detection, fault isolation and identification, and fault prognosis abilities, enabling advanced approaches to predictive maintenance with overall benefits along the asset lifecycle phases (Lee et al, 2006; Sun et al, 2012; Guillén et al, 2016; Cho et al, 2018; Fumagalli et al, 2019).
- *Cyber-Physical Product Lifecycle Management (CP-PLM)* – as intelligent products become “cyber-physical”, new data-driven and circular value-added services for augmenting and extending a product lifecycle will become possible (Romero et al, 2020).
- *Digital Twinning (DT)* – as intelligent products and assets acquire their digital twins, they will be able to perform self-simulations and use prediction models to proactively identify and correct software and hardware performance issues (Negri et al, 2017; Ashtari Talkhestani et al, 2019; Romero et al, 2020).

3.3 Grand Challenge 3: Data-Driven Operations Management

Grand Challenge 3 is to develop *data-driven operations management* approaches for production planning, control, and management. A *data-driven approach* stands for the use of data rather than intuition or personal experience for decision-making at the shop-floor and supply chain (Gölzer & Fritzsche, 2017). This paradigm is closely associated with the rise of *smart manufacturing systems* with an increasing degree of automation at the decision-making level using real-time data availability and automated monitoring and control (Mittal et al, 2017; Romero et al, 2019b).

The scope of Operations Management (OM) is extended from the pure management of processes involved in the creation and delivery of goods to those of services. This is due to the progression from mass-produced products to personalized solutions, through integrating products and services. Such trend increases the complexity of OM (Gölzer & Fritzsche, 2017; Christensen et al, 2019). New capabilities are required to handle this complexity, including digitally enabled tools like advanced data analytics supporting human decisions.

The grand challenge in *data-driven operations management* extends into several dimensions, horizontally across the supply chain, vertically through the manufacturing system, and along the life cycle of the product (Medini et al, 2019). Decentralized value creation activities require a decentralized exchange and processing of “smart data[‡‡]” as well, in order to predict changes and adapt accordingly. Diverse data repositories have to be included in data analytics.

[‡‡] *Smart Data* is defined as high-quality, accurate, up-to-date, and contextualized data targeted to assist specific business needs such as supporting a more confident AI and human decision-making.

The goal for this grand challenge is to evolve to a data-driven decision-making culture in OM tasks like processes planning & scheduling, layout planning, part/family formation, production ramp-up, quality management, and production logistics.

3.3.1 Current Status

The proliferation of data-driven operations management is hindered by uncertainties regarding the potential of technology and return on investment (Wiesner et al, 2018). Furthermore, interoperability issues prevent a seamless integration of the whole supply chain (Kulvatunyou et al, 2016). However, data gathered in processes like design, engineering, production, maintenance, and after-services is increasingly used to support the management of operations (Freitag & Wiesner, 2018). The connection of previously independent data sources, together with the increasing availability of raw data makes data quality an issue. It must be monitored to strengthen trust and support the human operator.

3.3.2 Enabling Technologies

Some *enabling technologies* that companies could use to create data-driven systems are:

- *Machine Learning and Artificial Intelligence* – as reasoning methods to assess the current status of an operation and predict future situations that can help OM to support the analysis of available manufacturing data (Nieto et al, 2019).
- *Machine Vision Systems* – as computer systems supporting the visualization of complex manufacturing information as an important vehicle to communicate data analytics results to stakeholders for OM (Hwang & Noh, 2019). Because of the different requirements for data visualization, sophisticated visualization solutions must be capable of breaking down abstract sensor-based data and provide value-added, applicable information (Thoben et al, 2017).
- *Data Flow and Standards* – as a major issue to achieve interoperable data flows, different interoperability approaches need to be developed to enable data-driven OM. Machines, transport systems, and human interface devices from different vendors need to be able to collaborate. Commonly respected standards are needed to facilitate the operation of successful smart manufacturing systems (Kulvatunyou et al, 2018). Open-source big data management systems promise to enable affordable data-driven operation management even in the small and medium-sized manufacturing organization (Radhya et al, 2020).

3.3.3 IFIP WG5.7 SIG – Smart Manufacturing Systems & CP Production Systems

The IFIP WG5.7 SIG on “Smart Manufacturing Systems & Cyber-Physical Production Systems” is formed by experts from science and industry dedicated to foster the adoption of smart technologies in manufacturing systems, factories, and supply chains. This objective is supported by research and networking activities on models, methods, and tools across the lifecycle of these systems. The scope of the SIG comprises agile development methods and approaches to choose, prioritize, and integrate smart technologies. The SIG encourages new ideas related to “smart manufacturing” characterization, maturity analysis, interoperability, industrial ontologies, smart data, OM, HMI, aligning technology with performance goals, or for the creation of new visions of smart systems such as new business models based on smart products and services. Thus, the SIG aims to analyse the state-of-the-art in the above topics, as well as to provide guidance for basic and applied research to close the existing gaps in the theory and practice through international and interdisciplinary collaboration.

3.3.4 Research Agenda & Future Outlook

Some *emerging paradigms* enabled by data-driven operations management approaches are:

- *Data-driven Decision-Making Culture* – as the proactive use of the available data and data analytics tools in OM to enable human decisions makers to act on a reliable basis (Polenghi et al, 2019b).
- *Industrial Data Space*[§§] – as a reliable and secure platform for data exchange and trade, leveraging existing standards and technologies, as well as accepted governance models for the Data Economy (Boris et al, 2019).
- *Data-driven Optimized Industrial Value Networks* – as the data analytics efforts conducted to achieve an inter-organisational optimisation of the supply chain, dynamically adapting to individual customer requirements (Schuh et al, 2018; Tien et al, 2016).
- *Model-based and Ontology-based Data and Knowledge Interoperability* – as more data need to be tracked and interpreted by a computer; cost and speed in which data from various sources are integrated and made computationally understandable need to be more attractive. Model-based standard makes data from the transactional data exchange available faster; ontology-based standard *p*romises to make heterogeneous data more understandable by computers in a coherent manner (Kulvatunyou et al, 2018).
- *Integration between AI Approaches and Knowledge-Bases* – as potential usage of data-driven decision-making through AI becomes more apparent, research on how to integrate this with the traditional and tacit knowledge will increase the trustworthiness and performance of such fuzzy decision-making approaches (Brundage et al, 2017).

3.4 Grand Challenge 4: Digital Lean Manufacturing Systems

Grand Challenge 4 is to update, develop, and demonstrate new lean concepts, methods, and tools that can enable the *Digital Lean Transformation* (Romero et al, 2019a) of production systems towards *Digital Lean Manufacturing (DLM) systems* (Romero et al, 2018; Powell et al, 2018). Such an approach seeks to maintain the *people-centricity* of traditional lean production but adds the “digital” dimension by using Industry 4.0 technologies as “enablers” for a new frontier of processes improvement. In a DLM system, business processes are strategically (re-)engineered using the *lean thinking* principles of value, value stream, flow, pull, and perfection (Womack & Jones, 1996) when adopting digital technologies to develop new, digital lean capabilities (Romero et

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[§§] https://www.internationaldataspaces.org/

al, 2018; 2019b). The goal for this grand challenge is to develop and deploy *digital lean solutions* that contribute towards establishing a cyber-physical waste-free Industry 4.0 (Romero et al, 2018; 2019b).

3.4.1 Current Status

In the Fourth Industrial Revolution, there is a missing link between the methods-driven approach to *lean production* and the technology-driven vision of *Industry 4.0* that has led to many unsuccessful digital transformations. Hence, production managers must not be led to believe that digital technologies will simply render lean practices unnecessary and that digital technologies can be successfully adopted without proper lean methods. Both are complementary and necessary for the development of DLM systems (Romero et al, 2018; 2019a) that combine the benefits of digital technologies with a proper (lean) implementation methodology. In this sense, DLM promises (i) to further facilitate the application of lean practices, and (ii) to enhance their scope and direction (Romero et al, 2018; Powell et al, 2018). Moreover, production managers must not underestimate the *people-centricity* of both approaches, particularly the fundamental importance of *leadership & learning*, as well as the adoption of a *long-term perspective* for succeeding with a digital (lean) transformation (Netland & Powell, 2017; Romero et al, 2019a). The production managers of the near-future will require an awareness of both the traditions of lean thinking and the new digital capabilities that can be added by the emerging Industry 4.0 technologies. The following section describes a sample of such concepts and enabling technologies, suggesting how they might enhance the traditional lean production practices.

3.4.2 Concepts and Enabling Technologies

Some *concepts* and *enabling technologies* that promise to enhance the future capabilities of manufacturing companies that apply a “digital lean thinking” are:

- *Concepts:*
    - *Digital Waste* – as lean managers go beyond the identification and reduction or elimination of waste (Muda) in the physical world, DLM recognises the existence of “digital waste” as part of the new cyber-physical production environments. Both in the form of missing digital opportunities to unlock the power of existing data or as a result of over-digitalization and/or poor information management (Romero et al, 2018; 2019b).
- *Methods & Tools:*
    - *Digital Quality Management System* – as real-time monitoring and reporting of intelligent assets performance becomes a reality in manufacturing cells and production lines, proactive alerting of potential deviations from quality standards as and even before they materialize will be possible, improving in-process quality control and, as a result, product quality (Romero et al, 2018; 2019c).
    - *Digital Kanban Systems* – as ‘pull’ signalling systems become real-time at the shop-floor with the use of digital technology (both in and between organisations), the “Just-In-Time” movement of materials and electronic

    information will help to eliminate overproduction by becoming even more responsive to the actual demand instead of forecasts (Romero et al, 2018).
  - *Jidoka 4.0 Systems* – as novel human-machine cooperation systems that are characterized by cyber-physical-social interactions, knowledge exchange, and reciprocal learning, which go beyond error catching to facilitate mutual human-machine learning for quality improvement (Romero et al, 2018, 2019d).
  - *Heijunka 4.0 Systems* – as all production resources get networked in an IIoT environment, the support of a truly holistic production scheduling or re-scheduling approach will become possible in real-time using just-in-sequence logic (Romero et al, 2018).

3.4.3 IFIP WG5.7 SIG – The Future of Lean Thinking & Practice

The IFIP WG5.7 SIG on "The Future of Lean Thinking and Practice" seeks to deepen the academic foundations of lean by promoting collaborative research on future and emerging trends in lean production systems. The SIG is composed of researchers and practitioners who are committed to contributing to our understanding of how to reduce waste, unevenness and overburden along the entire value streams. Group members are also encouraged to improve and advance this exciting research field by investigating areas such as lean management, lean production, lean shop-floor control, lean and green, and lean services; as well as digital lean manufacturing systems and lean digital transformations. The SIG places a particular emphasis on research that merges academic rigour with practical applications of lean thinking and practice in Industry. The objectives of the SIG are (i) to create a platform for exchanging ideas and learning, (ii) to organize Gemba walks and industrial best practice visits for its members, (iii) to organize special sessions/tracks at APMS conferences, (iv) to create special issues in leading international journals, and (v) to publish joint position papers among the SIG members. In realizing these objectives, the purpose of the SIG is to consolidate state-of-the-art knowledge in the lean production field and explore gaps in theory and practice in order to identify new research paths and to establish further collaboration in international projects and research activities throughout the SIG.

3.4.4 Research Agenda & Future Outlook

The emerging paradigm of *digital lean manufacturing* aims to become an extension of the lean philosophy, now considering the cyber-physical nature of production (systems) and operations management, incorporating "digital tools" as in integral part of lean transformations in pursuit of new digital levers to realize safer working environments with higher productivity levels, higher quality, improved delivery performance, optimized resource-usage, and increased production throughput (Romero et al, 2018).

3.5 Grand Challenge 5: Human Cyber-Physical Production Systems

Grand Challenge 5 is to design, engineer, and implement *Human Cyber-Physical Production Systems (H-CPPSs)* as human-automation symbiosis work systems. Such systems emphasize and keep the human-in-the-loop and are able to get the best of humans and machines capabilities, as production resources that can achieve new production efficiency levels neither can achieve on their own (Romero et al, 2016a; 2016b). The goal for this grand challenge is to achieve socially sustainable cyber-physical production systems, in which a new generation of operators named "Operators 4.0", explores new roles and tasks in the future's smart and social factory environments where humans, machines, and software systems cooperate (socialise) in real-time to support manufacturing and services operations (Romero et al, 2016b; 2017).

In this context, an *Operator 4.0* is defined as a smart and skilled operator performing not only cooperative work in unison with software, hardware, as well as social robot companions and helpers but also work aided by enterprise wearable technologies such as smart glasses, helmets, headsets, watches, handhelds, and exoskeletons (Romero et al, 2016a; 2016b).

Furthermore, the *Operator 4.0 vision* aims for factories of the (near-)future that accommodate workers with different skills, capabilities, and preferences towards the social sustainability of manufacturing (Romero et al, 2020; Kaasinen et al, 2020; WMF 2019). Such vision proposes the adoption of human-centred design approaches aimed at demonstrating the social and productivity benefits of "balanced automation systems" (Romero et al, 2015; Romero et al, 2020).

3.5.1 Current Status

According to present research (Romero et al, 2020; Rauch et al, 2020; Kaasinen et al, 2020), the *Operator 4.0 vision* – explores newly available technological means for supporting and aiding the physical, sensorial, and cognitive work of the operators in smart production environments in three possible ways: (i) *Assisted Work* – where the operators perform the key tasks and make the key decisions, but a wearable device, a collaborative robot, or an AI application (i.e. intelligent personal assistants) executes the repetitive and standardized tasks or decisions on their behalf to reduce their cognitive and physical workload, (ii) *Collaborative Work* – where the operators work side-by-side with collaborative robots (cobots) and AIs (virtual assistants and chatbots), each performing the tasks they are best at and supporting each other on eye-level, and (iii) *Augmented Work* – where operators use technology (i.e. enterprise wearable devices) to extend their physical, sensorial, and cognitive capabilities (Romero et al, 2015; 2016a; 2016b).

3.5.2 Enabling Technologies

Some *enabling technologies* for "The Operator 4.0" are (Romero et al, 2016b; Ruppert et al, 2018):

- *Exoskeletons* – as light wearables suits powered by a system of electric motors, pneumatics, levers, hydraulics, or a combination of these technologies to add additional strength and endurance to operators movements.
- *Augmented Reality* – as a digital assistance technology enriching the real-world factory environment with relevant information for the operator that is overlaid in real-time in his/her field of view to improve the "hands-free" information transfer from the digital to the physical world and reduce human errors.

- *Virtual Reality* – as a multi-purpose, immersive, interactive-multimedia, and computer-simulated reality for the operator to explore in a risk-free environment the outcomes of his/her decisions with real-time feedback.
- *Wearable Trackers* – as wearable smart sensors designed to measure activity, stress, heart rate, and other health-related metrics, as well as location, to support the occupational health and safety of the operator.
- *Intelligent Personal Assistants* – as AI-based chatbots supporting the operator in his/her interfacing with smart machines and robots, computers, databases, and other information systems to support him/her in the execution of different tasks in a human-like interaction.
- *Collaborative Robots (Cobots)* – as robots designed to work alongside and in direct cooperation with the operator without compromising his/her safety and supporting him/her to perform repetitive, non-ergonomic, and dangerous tasks or enabling him/her to perform more precise or force-requiring operations.
- *Enterprise Social Networks* – as mobile and social collaborative methods to connect (smart) operators on the shop-floor with other smart factory resources (e.g. smart operators, machines, robots, computers, software systems, etc.).
- *Big Data Analytics* – as automated data analysis approaches for discovering useful information and predicting relevant events to support the operator in a smart (big data) factory environment in the monitoring, control and optimization of a cyber-physical production system.

3.5.3 IFIP WG5.7 SIG – Smart Manufacturing Systems & CP Production Systems

The IFIP WG5.7 SIG on "Smart Manufacturing Systems & Cyber-Physical Production Systems" has been putting special attention over the last years to emerging physical and cognitive Human-Machine Interfaces (HMIs) contributing to more inclusive, human-centred cyber-physical production systems. The SIG encourages the *Operator 4.0 vision* of human + technology rather than human vs. technology for the factories of the future.

3.5.4 Research Agenda & Future Outlook

Current and further research efforts for materializing the *Operator 4.0* vision include:

- *Modelling the Human-in-the-Loop* (Munir et al, 2013; Romero et al, 2017):
    - *Human-in-the-Loop (HITL)* – as we further develop our understanding of the spectrum of the types of HITL controls, techniques to derive models of human behaviours, and determine how to incorporate human behaviour models into the formal methodology of feedback control to leverage both human and machine intelligence.
- *Collaborative and Aiding Systems Engineering* (Romero et al, 2015; 2016b; Ruppert et al, 2018; Rauch et al, 2020):
    - *Physical Systems* – as smart automation, collaborative robots, and enterprise wearables are further developed to safely and ergonomically interact with humans decreasing their physical efforts and increase their comfort during their work and aid for their occupational health and performance. In this context, "safety" in human-robot collaboration and ergonomically well-designed wearables are state-of-the-art research venues.

- *Sensorial Systems* – as joint sensor systems become a reality by combining human senses with smart sensors (e.g. infrared-, olfactory-, microphone-, visual-, location-, wearable-sensors) in advanced “sensor networks” for discovering and predicting events, capturing voices and noises, machine vision systems, image processing, mapping and location, etc. In this sense, special care is being put into avoiding the overwhelming human senses.
- *Cognitive Systems* – as joint cognitive systems enable the combination of human and AI cognitive capabilities creating a form of superior intelligence for complex decision-making. In this case, special attention is being put into cognitive ergonomics for proper “cognitive” human-AI interfacing design (Jones et al, 2018).

3.6 Grand Challenge 6: Immersive Learning and Virtual Training Environments

Grand Challenge 6 focusses on developing *immersive learning and virtual training environments* for the current and future workforce development (see Herrington et al, 2007). *Immersive learning* places individuals in an interactive and engaging learning environment, either physically or virtually, to replicate possible situations or to teach particular skills or techniques, using simulations, game-based learning, Augmented Reality (AR) or Virtual Reality (VR) (Baalsrud Hauge et al, 2012; Pourabdollahian et al, 2013; Dempsey et al, 2014; Garbaya et al, 2014; Stefan et al, 2019; Hallinger et al, 2020). Furthermore, *virtual training* is a training method to perform certain tasks by repeatedly executing them in a VR environment to induce the transfer of procedural knowledge and technical skills (Ordaz et al, 2015). The goal for this grand challenge is twofold: (i) to address companies demand for industry-ready engineering graduates who can contribute quickly to their business, and (ii) to provide workers with the effective means for skill(s) upgrading, re-skilling, and acquisition of new (digital) skills to maintain their employability, and enterprise competitiveness (Cerinšek et al, 2017; Vergnano et al, 2017).

3.6.1 Current Status

Overall, employers from manufacturing industries continue to complain that the supply of skilled labour is declining and that they must provide their employees with basic training to make up for the shortcomings of education systems (Taisch et al, 2019; Hořejší et al, 2019). Furthermore, today’s industry training programmes continue to be inefficient as they require diverting production resources away from production. So the research question that arises from both situations is how new digital technologies can contribute to speed-up learning curves of new hires and allow retraining without huge effort and disruption to the ongoing production?

3.6.2 Enabling Technologies

Some *enabling technologies* that higher-educational institutions and companies could incorporate into their learning and training programmes are:

- *Simulations* – as the learner can take control of a character that is expected to perform a certain task correctly in a controllable virtual learning environment that facilitates repetition and retention.
- *Virtual Reality (VR)* – as VR technologies can take advantage of previously learned knowledge in several simulated situations to ensure a deeper level of understanding of how to perform, e.g. a dangerous task where learning rules and regulations may not be enough.
- *Augmented Reality (AR)* – as AR offers an immersive, guided training platform in a quasi-virtual environment by overlaying digital instructions onto the real world.
- *Game-based Learning* – as “games” create an engaging learning environment where the learners perform certain tasks by following certain rules and gain rewards for doing things correctly. Also, competition between learners can accelerate learning.
- *Gemba Walks* – as the learner can “go-and-see” the task (in a real industrial environment), understand it, ask questions, and learn.

3.6.3 IFIP WG5.7 SIG – Serious Games in Production Management Environments

The IFIP WG5.7 SIG on “Serious Games in Production Management Environments” focuses on the convergence of three relevant developments within the advances in production management systems: Industry 4.0, Gamification, and Mixed Reality (MR) (i.e. AR/VR variations) (Erol et al, 2016; Hantono et al, 2018; Wolf et al, 2019). The SIG predicts that the evolution and synergetic interaction of these three developments will produce new paradigms in teaching, research, and how knowledge is generated and used within the disciplines of industrial engineering, industrial management, and operations management. The SIG envisages the emergence of complex virtual learning environments combined with “interactive” and “collaborative” educational processes. The SIG also foresees the development and adoption of novel technologies via gaming and AR/VR/MR. Pioneering research projects will use the practice of AR/VR/MR-supported gamification as an exploration of new solutions. The SIG purpose is (i) to identify the state-of-the-art of this convergence from conceptual, practical, and technological points of view, (ii) to recognize the trends, gaps, and opportunities emerging from this convergence, and (iii) to establish collaborations between the interested international researchers and practitioners.

3.6.4 Research Agenda & Future Outlook

Looking into the near future, some learning and training *emerging paradigms* are:

- *Personalized Learning & Training* – as multiple generations will coexist at the workplace, personalized learning and training will be required according to job requirements, learning preferences, and pre-existing workers’ knowledge.
- *Lifelong Learning & Training* – since the only thing we know about the future is that it will be “different”, the workforce will need to continuously adapt to changing technologies and organisational structures.

- *Accelerated Learning & Training* – as the pace of knowledge change accelerates, keeping skills up-to-date will require new methods and technology-means for accelerated learning and training processes.

3.7 Grand Challenge 7: Servitization of Manufacturing

Grand Challenge 7 is to support the *servitization of manufacturing* as an evolutionary phenomenon implying a complete change of the traditional product-based business models towards a new approach promoting the sale of the “performance” associated with a product use (Gaiardelli et al, 2015). Such a change foresees the provision of the so-called *Product-Service System (PSS)* as a system of products, services, networks of players, and supporting infrastructure, which continuously strives to be competitive, satisfies customer needs, and has a lower environmental impact than traditional business models (Goedkoop, 1999).

The significance of *servitization* phenomenon developed over the last decades has been underlined by a perceptible upsurge of relevant studies (Smith & Wuest, 2017; Cavalieri et al, 2018; Marjanovic et al, 2018). Different schools of thought, related to a multitude of disciplines, have tried to investigate its various facets, often embracing different genesis, motivations, cultural, and methodological approaches (Cavalieri et al, 2012; Gaiardelli et al, 2015; Baines et al, 2017).

Recent research has underlined that dynamics behind such a journey cannot be understood without considering the role of technological innovation in product, process, and service entities (Romero et al, 2019c; Marjanovic et al, 2019). The reasons behind is a growing interest towards the development of what is being referred as “digital servitization” (Baines et al, 2017; Boucher et al, 2019; Romero et al, 2019c), which concerns with the numerous operational, marketing, and business benefits that can be obtained through the integration of technology into PSSs (Freitag & Wiesner 2018; Wiesner et al, 2019; Sala et al, 2019; Moser et al, 2019; Boucher et al, 2019).

However, the understanding of how and to what extent such integration is steered and fostered by technological development, where technology could act as an enabler, a mediator or a facilitator is still lagging-behind (Sala et al, 2017). In particular, while the majority of studies have been developed around applications and benefits of technologically-based PSSs taking a strategic perspective, only a few works have sought to understand day-by-day actions that have to be addressed to accomplish an effective digital servitization transformation (Baines & Shi, 2015).

Hence, the development of frameworks, methods, and approaches addressing what (i.e. content), where and when (i.e. context), and how and to what extent (i.e. process) technological innovation supports operational adaptation to “servitization” strategies emerge as mandatory. In this perspective, this grand challenge refers to the design, engineering, management, and delivery of the next generation of technologically-enabled *Product-Service Systems (PSSs)* equipped with the ability to collect and record a large quantity of data about how the products are used and how their associated services are delivered. Specifically, this grand challenge concerns a complete rethinking of current operational processes, organization structures, skills and competences, management approaches, communication tools, as well as measurement and control systems, according to a multi-prospective and interdisciplinary view. At the same time, new methods and tools to review, design, develop, visualize, operationalize, manage, and evaluate smart PSSs are needed to enable companies to create smart, integrated, robust, and flexible solutions, able to deliver the maximum value to the needs and desires of a diverse set of customers.

3.7.1 Current Status

Notwithstanding significant advantages featured from the literature, most organizations that have set out a servitization journey have found quite problematic to deal with this transition (Kowalkowski et al, 2017). Develop new client value propositions, re-design operations and value chains, enlarge competences, people expertise and skills, as well as increase systems integration capabilities, are just some topics that research has explored over the years to identify effective and efficient servitization journey (Wiesner et al, 2013; Pirola et al, 2014; Rondini et al, 2015; Alexopoulos et al, 2017; Orellano et al, 2019; Boucher et al, 2019).

Recently, the growing interest in the topic has been further increased with the introduction of new technologies, the use of which makes it possible to amplify the availability and intensity of information and to speed up the collection and processing of data. In this sense, it has been recognized that "the service revolution and the information revolution are two sides of the same coin" (Rust, 2004).

In this context, the next evolution stage will require a further understanding of the impact that the new digital technologies would have on the operational management of PSSs. In particular, it will be essential to comprehend the extent to which technological innovation will influence relationships among all the actors within the PSS ecosystem to design, engineer and operationalize effective and efficient technologically-enabled PSSs.

3.7.2 Enabling Technologies

Some *enabling technologies* that companies could use to create technologically-enabled PSSs (Romero et al, 2019c):

- *Internet of Things* – as a new channel for the delivery and provisioning of new services to smart, connected products and assets.
- *Big Data Analytics* – as insights integration with human, assisted, or automated service delivery processes can ultimately improve customer experience.
- *Augmented / Virtual Reality* – as enabling means to improve customer support agents training, enrich services tangibility, and thus customer experience.
- *Cloud Computing* – as "elastic resources" that can offer at each point in time the needed computing resources to match the current service demand as closely as possible.
- *Horizontal and Vertical Integration* – as a way to improve service delivery processes and services quality by enriching the value creation capabilities of a service value chain.
- *Simulations* – as support for the design of new product-service solutions.
- *Machine Learning and Artificial Intelligence* – as an enabling mean to improve the availability of customer service and support and for supporting decision-making processes along the service delivery process.

3.7.3 IFIP WG5.7 SIG – Service Systems Design, Engineering and Management

The IFIP WG5.7 SIG on "Service Systems Design, Engineering and Management" promotes collaborative research on future and emerging innovative ideas and networking activities related to new models, methods and tools to support service systems along their lifecycle. The SIG is composed of researchers and practitioners who are committed to improving and advancing the investigation of Service Systems. In particular, the SIG is focused on exploring how service solutions developed within the manufacturing industry (i.e. Product-Service Systems (PSSs)) and/or pure oriented service industries (i.e. healthcare, finance, entertainment, logistics) can be designed, engineered and managed. Moreover, due to the Fourth Industrial Revolution, it aims to exploit how new digital technologies can be applied to rethink operational processes, organizational structures, skills and competencies, management approaches, communication tools, as well as measurement and control systems in the Service Systems field. The purpose of the SIG is (i) to identify and share best practices in order to consolidate the knowledge in the field, (ii) to explore the existing gaps in practice and theory to identify new research paths, and (iii) to establish collaborations in international projects and research activities.

3.7.4 Research Agenda & Future Outlook

Some *emerging topics* characterizing future research at ecosystem and company level are:

- *Ecosystem Collaboration* – as an evolution of the technological capabilities for value creation together with new value creation interactions that highlight the necessity to explore new collaboration models and tools to monitor and support decision-making within the ecosystem.
- *Risk and Revenue Sharing Mechanisms* – as new kind of ecosystems emerge with their respective value (co-)creation interactions, new methods and tools enabling risk and revenue sharing mechanisms will be needed.
- *Data Sharing and Security* – as new forms of "win-win" collaborations appear based upon information sharing, and featuring a high degree of uncertainty and risk, additional research will be needed to understand these new collaborations forms. Moreover, as data sharing involves data privacy and security inside the ecosystem, future research will also focus on understanding the factors that foster or inhibit data sharing in the emerging Data Economy.
- *Decision-Making* – as digital technologies adoption increases, the relevance of the monitoring and analysis of the whole lifecycle of a product or an asset will be fundamental to support decision-making. The solution (i.e. a product-service system) together with its evolution throughout its entire lifecycle will need to be properly monitored and managed. This would be of primary importance if the solutions will become "intelligent" (i.e. AI-supported).
- *Interoperability Standards* – as technology interoperability gains relevance as a key topic in the analysed scenario, the need to spur additional research on the topic of standards emerges as essential. Explorative research, for example, in the available ISO global community could be a starting point to address this issue.

4. Discussion: Barriers & Enablers Towards Production 2030

Production systems and production managers for 2030 will require to pass different social, environmental, economic, as well as technological sustainability tests.

From a *social sustainability perspective,* creating an adequate, safe, inclusive, and attractive work environment will be required to overcome the lack of awareness of the benefits of developing "human cyber-physical production systems" (Romero et al, 2015; 2016a). In such systems, humans constitute the most flexible production resource and are the root source of competitive advantage in a smart enterprise because of their creativity, ingenuity, and innovation capabilities. Furthermore, a socially sustainable workforce will require to adopt continuous and multi-faceted learning and training strategies, for example, in "immersive learning and virtual training environments", to cope with the accelerated rate of skills obsolescence and sustain their competitiveness in the labour market (Romero & Stahre, 2019).

From an *environmental sustainability perspective,* "green" products and production systems will become insufficient, calling for "circular" products and production systems capable of not only minimising waste and emissions, and making the most of any resource present in the production system, but also becoming restorative or regenerative industrial systems. For doing so, the design and engineering of "proactive and socially intelligent products and assets" will play a key role to close the information loops needed for their proper maintenance, repair, reuse, remanufacturing, refurbishing, and recycling (Wuest et al, 2018; Khan et al, 2018; Romero et al, 2020). Moreover, the emergence of "digital lean manufacturing systems" will contribute towards establishing a cyber-physical waste-free Industry 4.0 by making physical and digital production processes resource-efficient (Romero et al, 2018; 2019b).

From an *economic sustainability perspective,* new business models such as the "servitization of manufacturing" (Cavalieri et al, 2012; Gaiardelli et al, 2015) will need to decouple the economic development from resources depletion and be able to meet customers' demands for mass-customized and pure-personalized products and services using "agile product customization processes" (Duchi et al, 2017; Vellmar et al, 2017).

Lastly, from a *technological sustainability perspective,* technological innovation and new digital technologies will enable novel "data-driven operations management" approaches at advanced production management systems that will contribute to control and optimize products and assets behaviours, improve customer value, and enable new business models (Gölzer & Fritzsche, 2017; Medini et al, 2019).

5. Conclusions

"Production in 2030 will be sustainable, dynamic, and competitive". For achieving such a bold vision, future production managers will require the integration of information, technology, and human ingenuity to promote the rapid evolution of manufacturing, service, and logistics systems towards sustainable and human-inclusive cyber-physical production systems.

Policymakers, governments, and funding agencies are making funding available for research and technology development to address the *Grand Challenges* globally. At the same time, academia and industry need to collaborate closely and as equal partners on implementing the vision of Production 2030. Given the interdisciplinary nature of the

Seven Grand challenges put forth in this chapter, we need to come together and put aside animosities to work towards the joint goal. This is not a localized development but a global one. The World will look very different in 2030, and if the sketched out innovation is successful – and remains agile and adaptive – the World will be a more sustainable place with manufacturing being a driving factor for this positive change.

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