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 (WG) 5.7 on Advances in Production Management Systems (APMS) has played an active role in the fields of production and production management. The Working Group has focused on the conception, development, strategies, frameworks, architectures, processes, methods, and tools needed for the advancement of both fields. The associated standards created by the IFIP WG5.7 have always been impacted by the latest developments of scientific rigour, academic research, and industrial practices. The most recent of those developments involves the Fourth Industrial Revolution, which is having remarkable (r)evolutionary and disruptive changes in both the fields and the standards. These changes are triggered by the fusion of advanced operational and informational technologies, innovative operating and business models, as well as social and environmental pressures for more sustainable production systems. This chapter reviews past, current, and future 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

Current social, environmental, economic, and technological “trends” will shape the evolution of new production environments towards 2030 [1] [2]. These trends are impacting not only traditional, discrete manufacturing but also “edge” manufacturing such as farming, food, and biopharma among others. This book chapter identifies those trends. their impacts on production managers, and the help they need for them to remain competitive in 2030 and beyond. To do so, we investigated 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. The WMF Report [2]) 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 the 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. The IFIP WG5.7 emphasizes a collaborative culture that nurtures state-of-the-art research, which is motivated by current industrial needs, academic excellence, and scientific rigour. Its 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)*.

The goals of IFIP WG5.7 are to define the next generation production systems and provide methods and algorithms to implement those systems. Achieving those goals requires an interdisciplinary approach that includes topics such as (i) the advancement of, and the integration of, both operational and informational technologies, (ii) the new, Industry 4.0-infused, innovative, business model development methods, (iii) the future role of the ingenuity of humans and their interactions with both of the above, and (iv) the new requirements of the human workforce as part of future manufacturing settings. Successfully addressing these four topics can be achieved only by the continuous development and refinement of an “industry-based,” research agenda. An agenda that focuses on improving the industry’s best practices in, and stimulating young researchers seeking careers in, production management.

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[*] 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 Human Cyber-Physical Production Systems (HCPPSs)*". Such advanced HCPPSs will be characterized by their dynamic "self-awareness" of the physical world, and their intelligent decisions in the cognitive world. Decisions that must achieve a balance between engineering, societal, environmental, and economic objectives.

In the future, more and more of those decisions will (i) be based on several existing and emerging AI technologies and (ii) rely on a vast amount of real-time, digitally connected information, and (iii) use the stored knowledge inferred and deduced from that information. To make those decisions more "intelligent", these CPPS will need to be highly configurable in both the physical and cognitive worlds. This is the only way, in our view, that future, customized products can be produced with similar or even improved cost, quality, lead-time, and safety. For these improvements to become a reality, "interoperability" will be a key issue.

The subsequent sections of the chapter show that (i) a significant amount of conceptual work on CPPSs has been completed, and (ii) a large range of enabling technologies are readily available for implementation. At the same time, the *Grand Challenges* that lie ahead will require new concepts, methods, algorithms, and technologies. The *Grand Challenges* and their implications on production management are reflective of the changes in both individuals customer expectations, and global supply networks [3]. Each *Grand Challenge,* which was derived from numerous industry reports, is interdisciplinary in nature and domain agnostic. These reports present examples of successful implementations of advanced digital technologies in production, maintenance, and logistics operations. Such industrial examples showcase the potential inherent 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

To date, seven "Grand Challenges" – sometimes called fundamental goals – have been identified. 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 on (i) “pure-personalized products”, known as Engineer-to-Order (ETO) solutions, and (ii) “mass-customized products”, which fall under the category of Make-to-Order (MTO) or Build-to-Order (BTO) solutions. If successful, these solutions will help achieve the Industry 4.0 vision of small-batches and item-level productions (i.e. batch-size-1) using agile engineering and production systems. Systems that enable efficient mass-customization and pure-personalization through customer- and product-specific coordination across the entire life cycle [4-6].

3.1.1 Current Status

There is an increasing market demand for mass-customized, personalized products.

Mass-customization requires the alignment of engineering and production activities. Typically, this alignment is achieved by implementing modularity, product platforms, and other techniques that manage both the increase in the number of designs and the decrease in lead times and costs [7]. Most mass-customization research focuses on how mass-producers can increase product variety and customization while maintaining high efficiency [5].

As a result, manufacturers are moving away from Make-to-Stock (MTS) strategies and shifting to Make-to-Order (MTO), routinely called “Engineer-to-Order (ETO)”, fulfilment strategies. These strategies are not new [8]. In this context, highly customized engineering and production systems in ETO environments have been characterized traditionally by mostly manual work, poor data availability, and value creation performed by suppliers. In a recent paper, however, the authors strongly argued that these strategies increase both the complexity of, and the uncertainty in, modern, production systems [5].

To utilize these modern systems effectively, *ETO* manufacturers need a different viewpoint than the one described above. That viewpoint involves two activities. First, shifting the “time-of-differentiation” closer to the “time-of-delivery” by more closely linking engineering and production. The linking is done using both standardization and modularization [9]. Second, addressing the lack of contemporary research associated with the new *ETO perspective* on “efficient mass-customization processes” [6]. Those processes start from design and engineering and run through production and inspection.

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 which capture and reuse engineering knowledge to automate CAD-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 among 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 evaluating manufacturing processes, site layout, and material handling for large complex products (e.g. Building Information Models (BIM)).
- *Augmented Reality (AR)* – as a simplifier of complex assembly and installation procedures for engineers and manufacturers by first replacing static, work-instruction documents with AR solutions and then giving engineers the ability to provide operators with instant direction and image/voice instructions.
- *Smart Scheduling Techniques* – as techniques focusing on the use of cyber-physical systems that generate flexible and efficient production schedules on the fly. Such smart techniques can be used for (i) resource-constrained, multi-project scheduling, (ii) rescheduling in the face of unforeseen events at the shop-floor, and (iii) time and pricing determination in tendering (see [10]).
- *Internet of Things (IoT)* – as an enabler for tracking of customers' products or assets (i.e. equipment) and predicting what they need in advance. IoT can also help in reinventing site management since it is possible to know where both the locations of every tool, part, and soon-to-be-free site areas.
- *Autonomous and Collaborative Robots* – as robots/cobots that can load and unload resources; start, stop, load, and unload machines; and enable a more automated workflow in production systems supporting customized products.
- *Additive Manufacturing (AM)* – as a facilitator of the integration of engineering and production processes with fast feed-forward and feedback information going between the two processes. AM can also increase the options when choosing an efficient customization process in ETO operations.
- *Digital Twins and CAD Parametric Design* – as facilitators of the integration of design, engineering, and production processes with the data captured by sensors and other reality-capture methodologies (e.g. point clouds) that can create model-based parametric designs. Furthermore, when including a digital twin of the production line, real-time 3D-dimensional concurrent engineering (3DCE) information should be integrated into that digital twin. That information includes models of both the product the processes.
- *Machine Learning and Artificial Intelligence (AI)* – 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

Engineer-to-Order (ETO) is a manufacturing approach where design and engineering are included in the normal activities associated with the order fulfilment process. ETO is used when engineering specifications of products or services are not known in detail upon receipt of the customer order. This situation is common in mechanical industries, the construction sector, shipbuilding, offshore supplier industries, and other types of project-based manufacturing industries. These industries are typically facing several, unique challenges as the products are often one-of-a-kind and/or highly customized.

The IFIP WG5.7 SIG on "Operations Management in ETO Manufacturing" welcomes research contributions and industrial best practices on Operations Management (OM). These contributions can enable more effective use of ETO manufacturing strategies, Industry 4.0 technologies, Supply Chain Management (SCM) practices, lean operations, production planning and control techniques, production strategies, and product platforms.

3.1.4 Research Agenda & Future Outlook

The following *trends* are of importance when developing methods and algorithms that will lead to more efficient ways to design and engineer mass-customized and pure-personalized products [6]:

- *Increasing Complexity* – as products continue to increase the number of digital components and modules, the intensity and types of their interactions will also increase. As a result, the complexity of the final products will also increase. Moreover, from a production perspective, dealing with such complexity requires an appropriate balance between modular and flexible composition and the agile engineering needed to implement that composition in the real world. Finding that right balance is essential to quickly respond to mass-and-personalized customizations.
- *Increasing Competition* – as competition increases over time, cost reductions in engineering, innovative methods, and software tools (e.g. model-based engineering, virtual prototyping, digital mock-ups) will be required to improve the way engineering projects are executed.
- *Digitalization and Industry 4.0* – as "time-to-market" pressures continue to increase, agile product development processes will make more and more use of advanced digital information, AI-tools, and Industry 4.0 technologies to support the visualization of engineering data, and the automation of engineering processes and decisions.
- *Glocalization* – as "being global and acting local" becomes the new mantra for having a competitive advantage when it comes to responsiveness and specialization, new strategies will be needed (i) to achieve better market proximity to customers and suppliers, and (ii) for rationalizing new designs and structures for the value chain.

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* that (i) meet the requirements of circular lifecycle management options and (ii) use collaborative, multi-agent, cyber-physical, production-management approaches. In this sense, *proactive intelligent products or assets* refer to those smart, connected entities capable of using Just-In-Time (JIT) information to anticipate and automate relevant tasks for themselves or their operators or users [11]. Whereas *socially intelligent products or assets* refer to those smart, connected entities capable of (i) sharing status information, context-aware capabilities, and cooperative initiatives, and (ii) cooperating via a social network to achieve a common or compatible goal [12]. 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 [13-15]. 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.

These agents share a common or compatible goal to manufacture a product within a certain quality, time, and cost constraints [16].

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 – for itself, for its operator or user, and for the network of "things" to which it may belong. Several authors have looked at different performance metrics. Guillén et al [17] and Cho et al [18] focused on predictive maintenance and quality control; Psarommatis et al [19] [20] focused on impact analysis at factory-level. Roda & Macchi [21] [22], Roda et al [23], and Polenghi et al [24] focused on risk-oriented, strategic, decision-support systems. Moreover, the data needed to estimate these performance metrics should be transformed and integrated to make available information and/or knowledge relevant for more sustainable products and assets [25] [26].

3.2.1 Current Status

From an evolutionary perspective, mechatronic products and assets have evolved into 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 improved cybersecurity, connectivity, interoperability, and data analytics. Also, 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 analyses data from anywhere. It includes additional "data-driven services" for production systems and supply chains.
- *Machine Learning* – as the operational data analytics approach 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, knowledge sharing and reuse across the lifecycle of products or assets.
- *Cybersecurity Standards*[§] – as protection from malicious intrusions aimed at modifying the intended behaviour of a smart, connected product or an asset.
- *Circular Technologies*[**] – as resource-efficient, production technologies aimed 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" (PALM) promotes 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 collaborative, multi-agent systems. Systems that manage the circular lifecycle of products and assets with particular emphasis on production aspects of that lifecycle.

The purposes of the SIG are (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. To achieve these purposes, the SIG is interested in merging academic rigour with practical applications. Suggested topics include (i) the effective management and use of data, information, and knowledge across the different lifecycles, (ii) closing the loops of information as well as knowledge sharing and reuse required by product/asset-related decisions, (iii) the adoption of Zero Defect Manufacturing (ZDM), and Prognostics & Health Management (PHM) strategies to support the optimization of performances along the lifecycle, (iv) the adoption of "intelligent" products and assets for a smart lifecycle management, (v) using 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.

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 potential quality problems are detected in products and corrected either in a machine or a process before those problems happen [19] [20]. As these machines and processes become more intelligent,

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

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

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

detecting in real-time will require the abilities to harvest all relevant data and to use advanced analytics to investigate that data.

- *Prognostics & Health Management (PHM) Systems* – as advanced systems and approaches to predictive maintenance with overall benefits along with an asset lifecycle phases [17-18] [27-29]. Such systems typically include capabilities such as fault detection, fault isolation and identification, and fault prognosis abilities. These capabilities will rely on intelligent assets to provide actionable, real-time data and historical information as needed.
- *Cyber-Physical Product Lifecycle Management (CP-PLM)* – as intelligent products/assets become "cyber-physical", new data-driven and circular, value-added services for augmenting and extending a product lifecycle will become possible [30].
- *Digital Twinning (DT)* – as intelligent products and assets acquire their digital twins, they will be able to use advanced simulations and other prediction models to proactively identify and correct software and hardware performance issues [30-32].

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* uses data, intuition, or personal experience – rather than first principles – for decision-making at both shop-floor and the supply-chain levels [33]. This change in paradigm is closely associated with the rise of *smart manufacturing systems* [34] [35] because they have an increasing degree of automated, real-time, monitoring, control, and decision-making.

The scope of Operations Management (OM) has been extended from just the local management of processes involved in the creation and delivery of goods to the cloud and other global services that provide that management. This extension is due to the progression of mass-produced products to highly personalized products that are capable of using those services.

Such capabilities increase the "complexity" of OM [33] [36]. According to those authors, new decentralized capabilities are required to handle this complexity, including digitally enabled tools like advanced data analytics supporting human decisions. To predict changes and adapt dynamically, decentralized, value-creation activities will require a decentralized exchange and processing of "smart data[††]" as well. Diverse, data repositories must be included in that smart data.

The grand challenge then 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 [37]. The goal for this grand challenge is to evolve to a data-driven decision-making culture in OM. A culture that focuses on tasks like processes planning and scheduling, layout planning, part/family formation, production ramp-up, quality management, and production logistics.

[††] *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.

3.3.1 Current Status

The proliferation of data-driven operations management tools is hindered by uncertainties regarding their potential and their ROI [38]. Furthermore, interoperability issues prevent a seamless integration of operations across the entire supply chain [39]. However, data gathered in processes like design, engineering, production, inspection, maintenance, and after-services is increasingly used to support the management of operations [40]. The connection of previously independent data sources, together with the increasing availability of new data sources, makes data quality an issue. The data must now 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 (AI)* – as automatic reasoning methods to support the analysis of available manufacturing data to help OM to assess the current status of and predict the future status of any operation [41].
- *Machine Vision Systems* – as computer systems supporting the visualization of complex manufacturing information, becoming in this way the vehicle to communicate data analytics results to stakeholders for OM [42]. Moreover, 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 [43].
- *Data Flow and Standards* – as interoperable data flows will be needed to enable data-driven OM. Data will need to originate from each intelligent process and asset. From them, the data flows to other collaborating, intelligent processes and assets. Hence, data-flow standards can facilitate such collaborations [44]. Open-source, big-data-management systems promise to enable the same kinds of collaborations – even among SMEs [45].

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” comprises science and industry experts dedicated to facilitating the penetration of smart technologies into manufacturing systems, factories, and supply chains. This dedication has resulted in research and networking activities on models, methods, and tools across the lifecycle of these systems. The research scope of the SIG comprises agile, development methods and approaches to choose, prioritize, and integrate smart technologies. The SIG encourages new ideas related to that scope such as smart manufacturing characterization, maturity analysis, interoperability, industrial ontologies, smart data, OM, and HMI. These ideas can help (i) align technology with performance goals, (ii) create new visions for current smart systems 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. Research that can close the existing gaps in the theory and practice through both international and interdisciplinary collaborations.

3.3.4 Research Agenda & Outlook

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

- *Data-driven Decision-Making Culture* – as the proactive use of available data and (big) data analytics tools in OM to enable human decisions makers to act on a reliable basis [26].
- *Industrial Data Space*[‡‡] – as a reliable and secure platform for data exchange and trade. This platform leverages existing standards and technologies, as well as accepted governance models for the Data Economy [46].
- *Data-driven Optimized Industrial Value Networks* – as (big) data analytics will achieve an inter-organisational optimisation of the supply chain, dynamically adapting to individual customer requirements [47] [48].
- *Model-based and Ontology-based Data and Knowledge Interoperability* – as model-based standards will make data from the transactional data exchange more interoperable. Ontology-based standards will make heterogeneous data more understandable by computers in a coherent manner [49]. More and more of the data needed to build these models and ontologies will be tracked and interpreted automatically by a computer. Therefore, the cost and speed associated with automatically and correctly integrating and understanding that data must be considered.
- *Integration of AI Approaches with Knowledge-Bases* – as AI-tools are becoming the new approach to data-driven decision-making in OM. There will be a need to integrate these AI-tools with existing, traditional, and tacit OM knowledge bases. “Integration” will increase the trustworthiness and performance of such fuzzy, decision-making approaches [50].

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 necessary transformation [51] of traditional production systems towards *Digital Lean Manufacturing (DLM) Systems* [35] [52]. Such a transformation should maintain the current people-centric view of traditional, lean, production systems. Additionally, this transformation must now include the “digital” dimension, preferably by using Industry 4.0 technologies as “enablers” as the foundation for these new DLM systems. In such systems, business processes will be strategically (re-)engineered using the *lean thinking* principles – value, value stream, flow, pull, and perfection [53] – when adopting digital technologies [35] [54]. 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 [35] [54].

3.4.1 Current Status

There is a link between the methods-driven approaches to *lean production* and the technology-driven approaches envisioned by Industry 4.0 [51]. There have been many

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

unsuccessful attempts to build this link and implement such a transformation. Hence, production managers must understand that digital technologies (i) will not simply render current lean practices unnecessary, and (ii) cannot be successfully adopted without proper lean methods. Both are complementary and necessary for the development of DLM systems [35] [51]. In this sense, DLM promises (i) to further facilitate the application of lean practices, and (ii) to enhance their scope and direction [35] [52].

Moreover, current production managers must not underestimate the people-centric view of both approaches, that view stresses the fundamental importance of *leadership & learning*, as well as the adoption of a *long-term perspective* for succeeding with a digital (lean) transformation [51] [55]. As part of that perspective, future production managers will need an awareness of both the old, the new, and the emerging Industry 4.0 technologies.

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. Digital waste comes in two forms: (i) as missing digital opportunities to unlock the power of existing data and (ii) as a result of over-digitalization and/or poor information management [35] [54].
- *Methods & Tools:*
    - *Digital Quality Management System* – as real-time monitoring and status reporting of intelligent assets will become a reality. Proactive alerting of potential deviations from quality standards, even before they materialize, will be needed. Alerting will improve both in-process control and, as a result, product quality [35] [56].
    - *Digital Kanban Systems* – as digital technologies will enable smart 'pull' signalling systems to operate in real-time at the shop-floor. The "Just-In-Time" movement of materials and electronic information, which will be even more "responsive" to the actual demand instead of forecasts. This responsiveness will help to eliminate overproduction [35].
    - *Jidoka 4.0 Systems* – as novel, human-machine, cooperation systems will be characterized by cyber-physical-social interactions, knowledge exchange, and reciprocal learning. These smart capabilities go beyond "error catching" to facilitate mutual, human-machine learning for quality improvement [35] [57].
    - *Heijunka 4.0 Systems* – as all production resources will be connected in future in IIoT environments, the support of a truly holistic production scheduling or re-scheduling approaches will become possible in real-time using just-in-sequence logic [35].

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 stream. 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, lean services, digital lean manufacturing systems, and lean digital transformations.

The purposes of the SIG are to consolidate state-of-the-art knowledge in the lean-production field, explore gaps in theory and practice, to identify new research paths, and to establish further collaboration in international projects and research activities. The SIG places an emphasis on research that merges academic rigour with practical applications. 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.

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 [35].

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 symbiotic, human-automation, work systems. Such systems emphasize and keep the human-in-the-loop and can get the best of humans and machines capabilities, as production resources that can achieve new production efficiency levels neither can achieve on their own [58] [59]. The goal for this grand challenge is to achieve socially sustainable, cyber-physical production systems, which includes a new generation of operators named “Operators 4.0. The new operators will have new roles and execute new tasks. They will work in environments where humans, machines, and software systems cooperate in real-time to support manufacturing and service operations [59] [60].

In this context, an *Operator 4.0* is defined as a smart and skilled operator who can perform cooperative work in unison with software, hardware (including social robots), as well as isolated work aided using wearable technologies such as smart glasses, helmets, headsets, watches, handhelds, and exoskeletons [58] [59].

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 [61] [62]. This vision proposes the adoption of human-centred design approaches aimed at demonstrating the social and productivity benefits of "balanced automation systems" [61] [63].

3.5.1 Current Status

According to present research [61] [62] [64], the *Operator 4.0 vision* explores newly available technological means for supporting and aiding the work of the operators in smart production environments. Three types of work aid are being discussed: assisted work, collaborative work, and augmented work. *Assisted Work* is where the operators perform the key tasks and make the key decisions; but, a wearable device, a cobot (collaborative robot), or an AI application (i.e. intelligent personal assistants) executes the repetitive and standardized tasks. In assisted work, operators can reduce their cognitive and physical workload. *Collaborative Work* is where the operators work side-by-side with cobots (collaborative robots) and AIs (e.g. virtual assistants and chatbots). Each worker type performs the tasks it is best at executing and supports other workers as needed. Lastly, *Augmented Work* is where operators use technology (i.e. enterprise wearable devices) to extend their physical, sensorial, and cognitive capabilities [58] [59].

3.5.2 Enabling Technologies

Some *enabling technologies* for "The Operator 4.0" are [59] [65]:

- *Exoskeletons* – as light, wearables suits powered by a system of electric motors, pneumatics, levers, hydraulics, or a combination of these technologies to add strength and endurance to operators movements.
- *Augmented Reality (AR)* – as a digital-assistance technology enriching the real-world factory environment with relevant information for the operator. This information can be overlaid in real-time in the operator's field of view. The resulting "hands-free" information transfer from the digital world to the physical world will 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 and to see the likely outcomes of decisions in real-time.
- *Wearable Trackers* – as wearable, smart sensors designed to measure location, activity, stress, heart rate, and other health-related metrics. Metrics that support the occupational health and safety of the operator.
- *Intelligent Personal Assistants* – as AI-based chatbots supporting the operator when interfacing with smart machines and robots, computers, databases, and other information systems. These chatbots can support the operator in the execution of different tasks using human-like communication and interaction.
- *Collaborative Robots (Cobots)* – as robots designed to work alongside and in direct cooperation with, but without compromising the safety of, the operator. Cobots can support the operator in performing (i) repetitive, non-ergonomic, and dangerous tasks, and (ii) 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 such as smart operators, machines, robots, computers, and software systems.
- *Big Data Analytics* – as a variety of tools for discovering useful information and predicting relevant events from collected data. Those tools support the operator in monitoring, controlling, and optimizing the performance 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 recently putting special attention to the emerging Human-Machine Interfaces (HMIs) with physical and cognitive systems. These HMIs are 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* [60] [66]:
  - *Human-in-the-Loop (HITL)* – as our understanding of the spectrum of the activities involving humans and other processes and assets deepens, new techniques will be needed to derive models of human behaviours and to determine how to incorporate those models into the formal methodology of feedback control to leverage both human and machine intelligence.
- *Collaborative and Aiding Systems Engineering* [59] [63-65]:
  - *Physical Systems* – as smart automation, collaborative robots, and enterprise wearables will be further developed to (i) safely and ergonomically interact with humans, (ii) decrease their physical efforts, (iii) increase their comfort during their work, and (iv) aid in their occupational health and performance.
  - *Sensorial Systems* – as multi-sensor network systems that combine human senses with smart sensors (e.g. infrared-, olfactory-, microphone-, visual-, location-, wearable-sensors, etc.) will soon become a reality. Data from these networks can be used 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.
  - *Joint Cognitive Systems* – as systems that comprise human, OR, AI, and other cognitive capabilities creating a form of highly cooperative intelligence for complex decision-making. In this case, special attention is being put into cognitive ergonomics for proper "cognitive" human-AI interfacing design [67].

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 [68]). *Immersive learning* places individuals in an interactive and engaging learning environment, either physically or virtually. This environment can replicate possible situations to teach particular skills or techniques. Teaching can be based on using simulations, game-based learning, Augmented Reality (AR) or Virtual Reality (VR) [69-74]. *Virtual training*, on the other hand, is a training method where individuals perform certain tasks repeatedly by executing them in a VR environment. This method induces the transfer of procedural knowledge and technical skills [75].

There are two goals for this grand challenge. First, is to address the demand from companies for industry-ready engineering graduates who can contribute quickly to their business. Second is 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 [76] [77].

3.6.1 Current Status

Overall, employers from manufacturing industries are continually concerned about the declining supply of skilled labour and the number of basic training employees needed to make up for the shortcomings of education systems [78] [79]. Furthermore, in today's industry, training programmes continue to be inefficient since they require employees to divert time and resources away from production. So, the research question that arises from both situations is how new, digital technologies can contribute to (i) speed-up the learning curves of new hires, and (ii) allow retraining without the current 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 learning tools that 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 the previously learned knowledge from several simulated situations to ensure a deeper level of understanding of how to perform assigned tasks, especially dangerous tasks 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 predetermined rules and gain rewards for doing things correctly. Also, competition between learners can accelerate learning.

- *Gemba Walks* – as the learner to “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) [80-82]. The SIG purposes are (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 supported gamification as an exploration of new solutions. emerging from this convergence, and (iii) to establish collaborations between the interested international researchers and practitioners.

The SIG predicts that the evolution and synergetic interactions of these three developments will produce new paradigms in teaching and research. Moreover, they will provide answers to questions related to how knowledge is generated and used within the disciplines of industrial engineering, industrial management, and operations management. The SIG envisages the emergence of advanced/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.

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* – as 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.* The significance of the *servitization* phenomenon has been developed over the last decades It has been underlined by a perceptible upsurge of relevant studies [83-85]. 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 [86-88].

Servitization is an evolutionary journey that will completely change the traditional product-based, business models. That change will result in a new approach promoting the “performance” associated with a product use [87]. 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. This new system, which will have a lower environmental impact than traditional businesses, will continuously strive to be competitive and to satisfy customer needs [89].

Recent research has underlined that the dynamics behind such a journey cannot be understood without considering the role of technological innovation in product, process, and service entities [90] [91]. The reasons behind is a growing interest towards the development of what is being referred as "digital servitization" [88] [90] [92], which concerns with the numerous operational, marketing, and business benefits that can be obtained through the integration of technology into PSSs [40] [92-94].

However, there is little understanding of (i) how and to what extent such integration is steered and fostered by technological development, and (ii) where technology could act as an enabler, a mediator, or a facilitator [96]. While most 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 [97].

Hence, the development of frameworks, methods, and approaches addressing what (i.e. content), where, when (i.e. context), how, and to what extent (i.e. process) technological innovation supports the operational adaptation needed for "servitization" strategies to 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).* Systems that are 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. 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. Solutions that can deliver the maximum value across the diverse needs and desires of a varied and global set of customers.

3.7.1 Current Status

Notwithstanding significant advantages featured from the literature, most organizations that have set out on a servitization journey have found the transition quite problematic [98]. Developing new, client, value propositions; re-designing operations and value chains; increasing the competencies, expertise and skills of people; as well as increasing systems-integration capabilities. These are just some of the research topics being explored over the years to identify effective and efficient servitization journey [92] [98-103].

Recently, interest in the topic has increased with the introduction of new technologies. These technologies make it possible to amplify the availability and intensity of information and to speed up the collection and processing of data. It is in this sense, that Rust [104] said: "the service revolution and the information revolution are two sides of the same coin".

In this context, the next evolutionary stage will require a further understanding of the impact that the new digital technologies would have on the operational management of PSSs. 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 [90]:

- *Internet of Things (IoT)* – as a new channel for the delivery and provisioning of new services to smart, connected products and assets.
- *Big Data Analytics* – as insights about the interactions between human, human-assisted, or automated service-delivery processes. Such insights can ultimately improve the customer experience.
- *Augmented / Virtual Reality (AR/VR)* – 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 the delivery and quality of services by enriching the value creation capabilities of a service value chain.
- *Simulations* – as support to evaluate the designs of new product-service solutions.
- *Machine Learning and Artificial Intelligence (AI)* – as enabling means 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 purposes of the SIG include (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.

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 these service systems are developing in several industries including the manufacturing industry (i.e. Product-Service Systems (PSSs)) and several service-oriented industries (i.e. healthcare, finance, entertainment, logistics). The SIG's research answers question about how to design, engineer and manage these domain-specific systems. Moreover, due to the Fourth Industrial Revolution, that research is also answering questions about how new digital technologies can be applied to rethink operations management approaches, processes, structures, skills, competencies, control, communication, and performance.

3.7.4 Research Agenda & Future Outlook

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

- *Ecosystem Collaboration* – as a collaborative form needed to use the evolving technological capabilities to improve both value creation and the interactions needed for that creation. To support such collaborations, new models and tools that monitor activities and support decision-making will be needed.
- *Risk and Revenue Sharing Mechanisms* – as new kind of collaboration-based ecosystems emerge, new methods and tools enabling risk and revenue sharing mechanisms will be needed in value co-creation schemas.
- *Data Sharing and Security* – as new forms of these collaborations appear; additional research will be needed to understand how they operate. That research will depend upon information sharing and will feature a high degree of uncertainty and risk. Moreover, since data sharing involves internal data privacy and security, future research will also focus on understanding the factors that foster or inhibit data sharing in the emerging Data Economy.
- *Decision-Making* – as digital-technology adoption increases, the need to monitor and analyse the whole lifecycle of both products and assets will arise. Addressing that need will be fundamental to support decision-making across that lifecycle. Decisions that will be made in the new product-service systems. Decisions that, more and more, will be made by data-driven and AI-tools.
- *Interoperability Standards* – as technology interoperability is required to realize the new collaborative and product-service systems. Consequently, there is an essential need to spur additional research on the topic of standards. 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

In this section, we consider barriers and enablers from four, sustainability perspectives: social, environmental, economic, and technological.

From a social sustainability perspective, creating an adequate, safe, inclusive, and attractive work environment will be required to build the proposed “human cyber-physical production systems” [58] [63]. In such systems, humans constitute the most flexible production resource; and, they are the root source of competitive advantage in a smart enterprise. The advantage comes from their creativity, ingenuity, and innovation capabilities. Furthermore, a “socially sustainable workforce” will require continuous and multi-faceted learning and training strategies. As noted in Romero & Stahre [105], in “immersive learning and virtual training environments”, humans must be able to (i) cope with the accelerated rate of skills obsolescence, and (ii) sustain their competitiveness in the labour market.

From an environmental sustainability perspective, current “green” products and production systems will soon become “circular” products and production systems. These new systems will be capable of (i) minimising waste and emissions, (ii) making the most of any resource present in the production system, (iii) becoming restorative or regenerative industrial systems. To have these capabilities, it will be necessary to design and engineer new “proactive and socially intelligent products and assets” so that they can close all information loops. Loops that are needed for their proper maintenance, repair, reuse, remanufacturing, refurbishing, and recycling [11] [30] [106]. Moreover, the emergence of “digital lean manufacturing systems” [35] [52] will contribute towards establishing a cyber-physical waste-free Industry 4.0 by making physical and digital production processes resource-efficient.

From an economic sustainability perspective, new business models such as the “servitization of manufacturing” [88] will need to decouple the economic development from resources depletion. Additionally, those models must be able to meet customers' demands for mass-customized and pure-personalized products and services using “agile product customization processes” [5] [6].

Lastly, from a technological sustainability perspective, technological innovation and new digital technologies will enable novel “data-driven operations management” approaches. Approaches that advanced, production management systems can use to control and optimize products and assets behaviours, improve customer value, and enable new business models [33] [37].

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. This integration will 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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