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Information systems and knowledge management in industrial engineering: recent advances and new perspectives

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EDITORIAL NOTE

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1. Context

Production Research is foundational for advancing theories, methods, technologies and practices in manufacturing industries, production systems and related service industries. Over the last five decades, tremendous scientific and technical progresses have been made in all areas of production of goods and services, ranging from the birth of Computer-Aided tools (CAx, where x stands for Design, Manufacturing, Process Planning or Engineering), Computer Numerically Controlled (CNC) machines and industrial robotics in the 60s, then to Flexible Manufacturing Systems (FMSs), Automated Guided-Vehicles (AGVs) and concept of unmanned factories in the 70s, to Computer-Integrated Manufacturing (CIM), quality management, value chains and lean management in the 80s, to mass customisation, distributed warehousing and networked organisations governed by integrated Enterprise Resource Planning (ERP) packages in the 90s, then to service-orientation (or 'servitization'), global supply chains and interoperable and knowledge-based systems in the 2000s and, finally, to emerging smart, sensing and sustainable production systems today culminating with the concept of smart factories and Industry 4.0 since 2011, and the emerging cyber physical production.

Within this framework, and not to forget significant advances made on materials, production and machining processes, numerous optimisation methods, new manufacturing paradigms, various systems engineering methods and organisational and management theories, Information & Communication Technologies (ICTs) have played a crucial role in the progress of manufacturing and production systems. Therefore, advances on modern production systems are to a large extend bound to progresses in ICT domains.

To celebrate the 55th anniversary of *International Journal of Production Research*, which has been a forefront witness and an active vector in the progress of production research since 1961, it has been decided to publish a series of special issues. The present one continues the series and concentrates on recent advances and new perspectives in the thematic field of Information Systems and Knowledge Management of the journal enlarged to ICTs and management methods, including performance evaluation, from an Industrial Engineering perspective.

As far as information systems and knowledge management in particular and ICT in general are concerned, there are three major interrelated thrusts in production research to which they provide essential contributions. Namely, these are Industry 4.0, S^3 (Sensing, Smart and Sustainable) Enterprises and Cloud Manufacturing.

- **Industry 4.0**, or technologies for the factories of the future as defined by the 'Industrie 4.0' Working Group set up by the German federal government (Kagermann, Wahlster, and Helbig 2013; Hermann, Pentek, and Otto 2015), is often presented as the 4th manufacturing revolution (after the mechanisation revolution due to water power and steam power, followed by the mass production revolution thanks to assembly lines and electricity, and then the more recent computer and automation revolution). The goal is to provide high connectivity and cooperation between humans, machines, and systems within production systems, but also across production systems and with their environment to build so-called smart factories. Machines must become smart devices and products smart connected products, meaning that they should exhibit some behaviour, be able to interpret information, and have some degree of autonomy. Information must be available anywhere, anytime, for any user using any device, and be accessible in different formats. The idea is to provide human workers with more accurate and relevant information, support them with smart technologies, and give them more responsibility and freedom with higher mobility perspective at work while delegating routine and low-level decision-making tasks to machines and systems. Stated this way, Industry 4.0 and the emerging Cyber-Physical Production Systems (CPPS) are the logical progression from the CIM and integrated manufacturing trends that started at the beginning of the 80s, but they go one step further by taking advantage of recent technologies such as IoT (Internet of Things) and IoS (Internet of Services), Cloud Computing, Cyber-Physical Systems (CPSs), Artificial Intelligence (AI) and cyber technologies, smart products, broadband and wireless networking, and Big Data Analytics to move to fully decentralised, agile and collaborative manufacturing enterprises.

- **S^3 Enterprises** consist in enhancing sensing, smart and sustainability capabilities of manufacturing or service companies (Weichhart et al. 2016). Indeed, they must be able to collect and sense relevant and useful data and information about their statuses, processes, components, partners and environment, they must be provided with advanced mechanisms for performance measurement, situation assessment, action planning and decision-making to control and optimise their day-to-day operations, anticipate risky situations and react to unexpected changes, and they must be sustainable in the economic, environmental and social sense. In other words, they must be knowledge-driven, interoperable, and reactive enterprise systems and they will rely on Artificial Intelligence (AI) tools and techniques, semantic interoperability, manufacturing ontologies, Complex Adaptive System (CAS) theory, as well as advanced Enterprise Modelling (EM) and Enterprise Architecture (EA) principles such as Model-Driven Architectures (MDA) or Service-Oriented Architectures (SOAs) for their design and implementation. The goal is to move to knowledge-based, context-aware and adaptable enterprises.
- **Cloud Manufacturing** (CMfg) is a recent manufacturing paradigm that takes full advantage of networked organisation and Cloud Computing (CC) (Zhang et al. 2014; Ren et al. 2015). Xu (2012) has defined CMfg as 'a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction'. In other words, it transforms a traditional manufacturing system into a decentralised modular system of (physical and software) components (or *system of systems* using a *modularisation* principle), complemented by a set of shareable services accessible on-demand over Internet as SaaS (Software as a Service) solutions (*servitisation* principle). The main advantage will be *higher agility* of the new system (i.e. it can be quickly and more easily reorganised or even reshaped in the case of changing market conditions or adoption of new manufacturing strategies. Another major advantage, especially for SMEs but also for larger companies, is potentially a substantial reduction of cost in terms of software acquisition and maintenance as well as data centre operations because software modules for CAD, CAE, CAPP or ERP, for instances, can be remotely used on a pay-per-use basis and no more need to be the property of the company as part of large software packages. The same idea can apply to some manufacturing facilities or processes leading to the concept of MaaS (Manufacturing as a Service).

Advancement and practical development along these major trends rely on several more specific technologies that need to be further investigated and developed. For better understanding of articles of the special issue, some of the major ones are listed hereafter with a brief definition and one or a few key references for further reading:

- Internet of Things (IoT): IoT (Gubbi et al. 2013) is believed to be foundational for Industry 4.0 and CPPS. It enables objects and machines, ranging from small devices such as sensors to actuators or larger devices such as robots or customer devices and to control systems or mobile devices (e.g. mobile phones, tablets, or connected watches), to 'communicate' with each other as well as with human agents in order to carry out tasks or to work out solutions. This technology relies on network structures based on worldwide standards (e.g. IPv6, Ethernet-TSN/DSN and 5G), RFID and micro-Web (or µWeb) servers. µWeb servers are small add-on devices that provide the object or the machine with an IP address and an Internet connection (Ethernet plug or WiFi access) so that the object or the machine can become pluggable and accessible over the Internet network.
- Internet of Services (IoS): In the IoS context (Soriano et al. 2013), a service is intended as a commercial transaction where one party gets temporary access to resources of another party to perform a prescribed function at a certain cost. Resources may be of different nature (human workforce or skills, technical operations, IT-based operations, and others). In the case of IoS, services can be found, contracted and obtained over Internet. Registries of services are therefore mandatory to be able to locate relevant services when one wants to satisfy a given need and contract a service.
- Cloud Computing (CC): Cloud Computing (Buyya, Broberg, and Goscinski 2010) 'is an information technology (IT) paradigm that enables ubiquitous access to shared pools of configurable system resources and higher level services that can be rapidly provisioned with minimal management effort, often over the Internet. Cloud computing relies on sharing of resources to achieve coherence and economies of scale, similar to a public utility' (Wikipedia 2018). Clouds can be private (i.e. for restricted use of a single enterprise or a group of enterprises), public (i.e. accessible by everyone) or hybrid (i.e. a cloud computing service that is composed of some combination of private, public and community cloud services, from different service providers). SaaS services are commonly offered on public clouds operated by service providers. They can be free of charge or subject to a fee.
- Cyber Physical Production Systems (CPPS): In production systems, CPPSs are made of humans, IT systems and smart devices (i.e. connected technical agents such as machines, robots, transportation systems, storage systems

and production facilities) capable of autonomously exchanging information, triggering actions and controlling each other independently (Kyoung-Dae and Kumar 2012). CPPS provide an infrastructure aiming at the integration of physical and computational components, facilitating fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage, logistics, supply chain and life cycle management (Yoon and Nof 2011). Stated differently, CPPS couple the cyber-world with the physical world to create synergy. In terms of abstraction, they are one level above IoT, IoS and CC and are essential components in implementing Industry 4.0 compliant solutions.

- Big Data Analytics: All the objects (including products and devices) of the enterprise, connected as things on the IoT and services on the IoS, are going to generate massive volumes of data. To discover new facts or extract relevant information or knowledge from these data sets, big data analytics techniques are required. Big data analytics is where advanced analytic techniques operate on big data-sets, for instance using data analysis, statistical, data mining, knowledge discovery and machine learning techniques, possibly coupled with data warehousing solutions as well as data visualisation techniques (Russom 2011; Hwang and Chen 2017).
- Systems Interoperability: Interoperability happens anytime that two or more systems want to exchange information or work together. It is the ability of peer entities involved in a communication to exchange information on the basis of mutual understanding and to successfully use functionalities or services of the other (Vernadat 1996; Panetto 2007; Chen, Doumeingts, and Vernadat 2008). Interoperability is essential for interactions and exchanges amongst (technical, IT or human) agents of smart factories or Industry 4.0 environments (Panetto et al. 2016). Interoperability can happen at the technical level (or *technical interoperability,* dealing with the 'plumbing' aspects of linking systems through networking and data exchange methods), the semantic level (or *semantic interoperability*, addressing the 'meaning' and the use of data/messages exchanged, possibly referring to ontologies for semantic unification of concepts), and at the business level (or *organisational interoperability*, focusing on organisation and business process alignment issues).
- Manufacturing Ontologies: In IT, ontology concerns the specification of a shared conceptualisation in a certain domain (Gruber 1993). An ontology is a formal description (using formal logic languages for knowledge representation such as First Order Logic, Common Logic or OWL – the Web Ontology Language) of entities and their properties, relationships, constraints and behaviours. To hinder the diversity in the semantics of concepts and information structures used in manufacturing, and to relieve from inconsistency of concept semantics across technical domains or industrial systems, the concept of formal reference ontology for manufacturing has been proposed (Usman et al. 2013). It should prove to be a key component in future interoperable manufacturing systems as found in smart manufacturing, cloud manufacturing, the S^3 Enterprise or Industry 4.0.
- Enterprise Modelling/BPM: Business Process Modelling (BPM) in particular (van der Aalst 2013) and Enterprise Modelling (EM) in a broader sense (Sandkuhl et al. 2014) are essential prerequisites for the analysis, design, reengineering, structuring, integration, optimisation, monitoring and even control of manufacturing and production systems and their supply chains as well as for their move towards Industry 4.0. Enterprise Modelling is the 'art of externalizing knowledge about the enterprise to bring value to the enterprise' (Vernadat 1996). The goal is to model the structure, the behaviour, and the organisation of the enterprise, or network of enterprises, in terms of its components, actors, resources, and various flows (product/material flows, data and information flows, decision flows, control flows or value chains). Models produced can be either descriptive (i.e. static such as object class diagrams), can be enacted (i.e. executable such as workflow diagrams), or can be subject to computer simulation.
- Knowledge Management (KM): Knowledge Management is essential for building all the 'smart' components usually mentioned when referring to Industry 4.0 or the S^3 Enterprise (e.g. smart products, smart devices, smart factories or smart manufacturing). A smart entity must have some 'awareness or familiarity' of its status, environment or possible actions. Well, according to the Oxford Dictionary, knowledge can be defined as 'awareness or familiarity gained by experience'. Two types of knowledge must usually be differentiated: tacit (i.e. subjective or intuitive insights) versus explicit (i.e. formalised and validated) knowledge as defined by Nonaka (1994, 2007). KM is a discipline that provides strategy, process, and technology to share and leverage information and expertise that will increase the level of understanding to more effectively solve problems and make decisions (Harigopal and Satyadas 2001). Knowledge management is best defined by its life cycle that involves the following generic activities: knowledge creation, knowledge capture, knowledge organisation (based on knowledge representation) and knowledge dissemination and sharing (Satyadas, Harigopal, and Cassaigne 2001).
- Smart Connected Products & Devices and their Avatars: Smart products are physical products augmented by digital data/knowledge about themselves. These data can be bundled with the product or kept separately. Data can be dynamic to reflect the state of the product all over its life cycle. Smart connected products are smart products that can communicate with other products or devices or with their environment (for instance, via RFID or IoT).

Examples are connected cars or aircraft engines connected with their manufacturer. Similar definitions can be given for smart devices. Avatars of smart products or devices exist when a digital image (or dual entity) exists in the cyber-world for each physical instance of these products or devices. Avatars are directly connected with their respective physical instances to keep data up-to-date, preferably synchronously but sometimes asynchronously. They can be provided with a data base, a knowledge base and planning or reasoning capabilities to make local decisions on behalf of their real-world artefact (Hribernik et al. 2006).

- Cyber-Augmented Interaction and Collaboration: In networked and connected production systems, cyber augmentation goes beyond communication devices, which engage and overload human interactions and workload. Combining ICT and real-time control, cybernetic brain models operate at a parallel cyber-space with multi-agent systems, task administration protocols and algorithms to provide streamlined, harmonised and optimised workflows for humans' and machines' autonomous interactions (Nof et al. 2006, 2015). With machine learning, adaptive and predictive planning and control, such cyber augmentation enables collaboration amongst humans, sensors, robots and autonomous systems for better quality, effectiveness and sustainability (Filip and Zamfirescu 2016; Reyes Levalle 2017).
- Augmented Reality (AR): Augmented reality is a technology that complements real data (usually live direct or indirect video images) with computer-processed data (sound, 2D or 3D images, videos, charts, etc.) and using various sensory modalities, including visual, auditory, haptic, somatosensory and olfactory sensations (Azuma et al. 2001). AR is dedicated to human agents who wear AR glasses or other sensory devices. For instance, in smart manufacturing, AR can be very useful to assist human operators in various tasks such as diagnosis, repair and maintenance, control, etc.

2. The special issue

The goal of the special issue is to make a state-of-play of some recent advances and to discuss some future perspectives related to the three main trends mentioned in the first section with a focus on ICT, information system, knowledge management and performance assessment perspectives. It cannot be exhaustive because a thorough state-of-the-art of all sub-domains mentioned above applied to production research would have made a too large scope.

Submissions have been solicited on the basis of a call for papers published on the IJPR website but also on personal invitations by the associate and guest editors. The call was quite successful with 49 papers submitted. Finally, 17 papers have been accepted for publication. All papers have been peer-reviewed by 2 to 4 reviewers and have been subject to 2 to 3 revision rounds.

Starting from a management perspective, the special issue opens with a paper on performance measurement and management (PMM) by Bourne, Franco-Santos, Micheli and Pavlov. After reviewing the current dominant paradigm in PMM (viewing organisations as 'monolithic' systems made of interconnected parts), the paper advocates for a novel perspective that considers PMM from a 'system of systems' (SoS) point of view, whose essential characteristics are autonomy, belonging, connectivity, diversity, and emergence. The move towards collaborative, smart, decentralised and more agile manufacturing systems should justify the approach in a near future.

The special issue continues with a block of two papers dealing with Enterprise Modelling (EM). Both emphasise the ability of EM to externalise knowledge about the function, behaviour and structure of the enterprise or network of enterprises. The first one by Vallespir and Ducq first presents a survey of the evolution of enterprise modelling approaches over the last thirty years. Then, the paper discusses recent advances in the use of enterprise models in model-driven approaches, solving manufacturing interoperability problems and performing simulation of enterprise processes, which all require model transformations. The next paper, by Weichhart, Stary and Vernadat, also starts with a survey of enterprise modelling evolution but with a focus on the convergence with knowledge representation in the context of enterprise integration and interoperability and organisational learning. The novelty of the paper is to propose a framework for organisational learning and the management of active knowledge for the smart enterprise of tomorrow (the S^3 enterprise) illustrated by case studies from industry.

The next two papers more specifically address the manufacturing interoperability problem still in relation with enterprise models but considering their enactment. The first paper of this block, by Palmer, Usman, Canciglieri, Malucelli and Young, presents advances obtained from the EU FLEXINET project on semantic interoperability of manufacturing enterprises. It formulates enterprise models in the form of a manufacturing reference ontology that can be used for semantic unification across technical domains, supporting information sharing across interacting software applications, or configuring knowledge bases to support manufacturing systems interoperability. The other paper, by Youssef, Zacharewicz, Chen and Vernadat, paves the way for the development of novel infrastructures, called Enterprise Operating Systems (EOSs). Their aim is to support real time monitoring and control of enterprise operations based on enterprise models in the context of interoperable enterprise systems. Requirements and a generic architecture for EOS are presented to foster further research on this topic.

The sixth paper of the special issue by Moghaddam and Nof makes a nice transition from previous manufacturing interoperability and integration concerns to the topics of Cloud Manufacturing, Industry 4.0, and Collaborative Control Theory (CCT). Starting from the need to bridge the gap between the cyber and physical worlds with a clear articulation between the Internet of Things (illustrating the modularisation principle of physical components) and the Internet of Services (applying the servitisation principle to computational elements) in Cloud Manufacturing, the paper presents an innovative framework for dynamic integration of services and components in collaborative network manufacturing organisations. The problem has been mathematically formulated as a bi-objective mixed-integer programming (BOMIP) formulation which, due to its computational complexity, is solved by means of an efficient socio-inspired tabu-search heuristic algorithm.

With the seventh paper by Xu, Xu and Li, the special issue moves to more focused topics on Industry 4.0. The paper provides a state-of-the-art review of the domain, first recalling industrial evolution and rationale for Industry 4.0, and then reviewing underlying technologies and disciplines required to carry out Industry 4.0 research and industrial projects. Finally, the paper analyses major obstacles for exploiting the full potential of Industry 4.0, especially the lack of formal methods, and the impact on enterprise information systems (such as ERP), before concluding by suggesting some research trends.

The next paper by Buer, Strandhagen and Chan discusses the link between Industry 4.0 and lean management, which both share the same general objectives of increased productivity and flexibility. This novel topic is analysed through a systematic literature review. From this analysis, four research streams are identified and key research findings are presented in each area. Based on this, a research agenda for future studies is proposed.

The next two papers concentrate on Internet of Things technologies. First, the ninth paper, proposed by by Zdravković, Aubry, Moalla, Guedria and Sarraipa, investigates the scientific disciplines which could contribute to the development of IoT platforms for industrial eco-systems, namely requirements engineering, change management/continuous improvement, model-based systems engineering, system architecture design, interoperability and policy and regulatory aspects. Challenges of these contributions in the context of IoT are discussed. Finally, related research directions with important impact are tentatively identified. The tenth paper, by Lee, Lv, Ng, Ho and Choy, provides an original contribution illustrating the use of IoT technology in the design of a warehouse management system platform for smart logistics. Indeed, considering the increasing complexity and variety of customer orders (highly customised orders, which tend to be of small batch size but with high variety and are subject to frequent changes), and the need for real-time data and contextual information to synchronise purchase orders to support production, an IoT approach based on RFID tags seems a viable alternative solution to the traditional approaches for the design and operation of a warehouse management system (WSM). The paper describes an IoT-based WMS with an advanced data analytical approach using computational intelligence techniques to enable smart logistics for Industry 4.0. The approach is illustrated by a case study.

The eleventh paper by He, Aggarwal and Nof, continues with smart warehouse management. The problem addressed by the authors concerns a novel policy, called Differentiated Probabilistic Queuing (DPQ), developed for servicing customers' orders by Automated Guided Vehicles (AGVs) in the context of smart warehouse automation to face the increasing demand for physical storage and distribution services with minimal latency. The DPQ policy is proposed as a novel order picking planning policy of warehouse automation system developed for differentiating service levels for different classes of paying customers. To solve numerical examples, the problem is formulated as a joint optimisation of the storage assignment and the queueing policy. Numerical experiments show the validity of the approach.

Then comes a block of three contributions dealing with knowledge management. The first paper is by Arena, Tsolakis, Zikos, Krinidis, Ziogou, Ioannidis, Voutetakis, Tzovaras and Kiritsis. It proposes an innovative engine for human resource optimisation, which employs semantically enhanced information and probabilistic models with knowledge derived from the industrial shop floor level. The goal is to propose the right person for the right job in real-time for shop floor operations to optimise decisions on how to schedule either repeatedly or non-occurring tasks. The static and dynamic information used by the engine is semantically enriched by the inclusion of semantic tags defined in an ontology model. Experimental results are given for shop-floor operations. The second paper by Li, Jiang, Liu, and Song analyses empirical engineering knowledge, i.e. specific technical know-how about solving engineering problems, and especially its evolutional motivation and evolution patterns. The research is motivated by the rapid evolution of this type of knowledge because of the intense business competition. The paper identifies four kinds of evolution patterns and implements a knowledge management system for empirical engineering knowledge in a CAD application. The third paper by Chen touches big data analytics. It deals with knowledge-based analytics for massively distributed networks with noisy data. The goal is to find pathways of interest in large data sets organised as graphs. To this end, a novel search algorithm using optimisation techniques for data mining in large networks with noisy data is proposed.

The last three papers are technical research papers tackling specific industrial engineering problems in production research. The one by He and Jiang is about a new belief Markov chain model and its application to inventory prediction. The new model combines Dempster-Shafer evidence theory and discrete time Markov chains. The model is applied to do the prediction of inventory demand of products in a supply chain. The following paper by Etgar, Gelbard and Cohen presents a novel technique for improving the run-time of metaheuristic search optimisations. Because modern products are frequently subject to replacement by new versions, the technique is applied to the so-called several-release problem (SRP). The problem is proved to be NP-hard. So, a near-optimal technique for determining the feature content of all version releases over a given planning horizon is presented, discussed, and validated against different other heuristics. Finally, the last paper by Despoudi, Papaioannou, Saridakis and Dani addresses the problem of partner collaboration in fruit agricultural supply chains. Different types of collaboration between producers and cooperatives are analysed and it has been found that some types of collaboration such as 'goal congruence' can play a significant role in reducing postharvest fruit loss and improving the quality of fruit production.

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