On the development of innovative Manufacturing Planning and Control system architectures for the Industry 4.0

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Abstract: Despite the technological growth brought from the previous industrial revolutions, a strong delay in the evolution of the Manufacturing Planning and Control system (MPC) logic and architectures has been observed. With the advent of Information Technology (IT) and Industry 4.0, the concepts of Cyber-Physical System and Internet of Things arise, proposing to change the classic centralised approach, typical of Material Requirements Planning (MRP and then MRP-II) systems, with a new class of more decentralised control architectures. Hence, in this work, the state of the art of Industry 4.0 architectural implementations is explored, with particular attention to recent proposals of reference architectures, such as Reference Architectural Model Industrie 4.0 (RAMI 4.0). The aim is to analyse how intermediate MPC architectures (i.e., neither centralised nor decentralised) can be classified from an ontological and taxonomic point of view within modern reference architecture models. In particular, a semi-heterarchical MPC architecture will be presented, analysing functional relationships among the decisional components/levels within the RAMI 4.0 reference architecture.

Keywords: Industry 4.0; Manufacturing Planning and Control system; Scheduling; RAMI 4.0;

1. Introduction

In recent years, the evolution of the manufacturing industry has been mainly driven by the development of new technologies leading to big improvements both from a production point of view, increasing throughput and lowering costs, then from a product point of view, increasingly technologically advanced. With the strong development and consequent integration of Information Technologies (IT) in all aspects of a company, an increasing number of new production paradigms are emerging, showing the design of new factories of the future.

In particular, we are assisting to a production shift vision from a "mass production" scenario, typical of the previous century, towards "mass customisation" one (Fogliatto, Da Silveira, & Borenstein, 2012; Kamble, Gunasekaran, & Gawankar, 2018). Hence, instead of achieving a production focused on a mere cost reduction, it is desirable to create value while meeting customers' customisation and speed of delivery requirements. In this new, extremely dynamic context, it becomes fundamental to acquire and evolve the management capabilities of a manufacturing plant, pushing the researches of new management solutions for Manufacturing Planning and Control (MPC) systems, able to allocate production resources quickly and more efficiently.

The impact of such a strategy is so critical to justifies the creation of a new industrial paradigm: the "fourth industrial revolution" with the introduction of the Cyber-Physical System (CPS) and Internet of Thing concept (Hermann, M.; Pentek, 2015). The CPSs are systems in which the "cyber" part, sum of computational and communication capabilities, and the physical part are tightly integrated either as project that as operations. This brings to a collaborative system of elements linked through the Internet of Thing paradigm.

In particular, the network of CPS, make it possible new type of MPC approaches, based on the delegation of a part of the decision making process to the shop floor level. This process of decision-making delegation has already started and there are plenty of examples in the literature (Di Nardo, Madonna, & Santillo, 2016; Grundstein, Freitag, & Scholz-Reiter, 2017; Guizzi, Revetria, Vanacore, & Vespoli, 2019; Leusin, Frazzon, Uriona Maldonado, Kück, & Freitag, 2018; Panetto, Iung, Ivanov, Weichhart, & Wang, 2019; Riedl, Zipper, Meier, & Diedrich, 2014).

Various strategies, based on the shift from a centralised approach (MRP-based) to a decentralised one as a way to cope with more dynamic contexts have been proposed and developed (Bochmann et al., 2015; Converso, Ascione, Di Nardo, & Natale, 2014; D. A. Rossit, Tohmé, & Frutos, 2019; D. Rossit & Tohmé, 2018; B Scholz-Reiter, 2004).

Some of these paradigms imply autonomous and independent control concepts, including decision-making methodologies derived from biological examples, such as bees (Bernd Scholz-Reiter, Jagalski, & Bendul, 2007) or ants (Rowlings, Tyrrell, & Trefzer, 2015; B. Scholz-Reiter, De Beer, Freitag, & Jagalski, 2008). Others, instead, are based on the implementation of the traditional Control Theory within an MPC system (Dolgui, Ivanov, Sethi, &

Sokolov, 2019, 2018; Ivanov, Dolgui, Sokolov, Werner, & Ivanova, 2016; Ivanov, Sethi, Dolgui, & Sokolov, 2018).

Among them, Jeken et al. in (Jeken et al., 2012) developed the concept of independent production. These last ones' approach is characterised by local and autonomous decision-making of smart objects, such as workstations that adjust production rates and parts that decide which products they will become and which orders they will fill. The authors analysed the dynamic interaction between the entities, evidencing how the introduction of decision-making autonomy within the shop-floor could lead to more efficient production activity and more robustness against any production disturbances. Their proposal represents a first vision of autonomous control in manufacturing, that is a heterarchical control of highly distributed manufacturing systems.

Nevertheless, Jeken et al.'s heterarchical approach (Jeken et al., 2012), based on complete independence among the autonomous entities, entails a limited decisional degree of entities, since them can rely only on the knowledge of their neighbour to set their objectives. In fact, without global information, fully decentralised decision-making strategies converge to a local optimum (Philipp, Böse, & Windt, 2006) rather than a global one, driving to a machine scheduling "reactive" to production disruptions (e.g. machine breakdown or unexpected product rescheduling), losing efficiency. Conversely, centralised decision-making approaches, driving to a "proactive" machine scheduling, converge to a global optimum, leading to the maximisation of machines utilisation but losing a quota of responsiveness (which is the typical behaviour of an MRP System) (Grundstein et al., 2017).

Based on the considerations mentioned above, this work intends to analyse the current state of the art of the Industry 4.0 architectural implementations, taking particular attention to recent proposals of reference architectures, such as Reference Architectural Model Industrie 4.0 (RAMI 4.0). The aim is to show the possibilities of the Industry 4.0, analysing intermediate MPC architecture approaches while trying to propose a first classification of them from an ontological and taxonomic point of view within modern reference architecture models. In particular, a semi-heterarchical MPC architecture will be presented, analysing functional relationships among the decisional components/levels within the RAMI 4.0 reference architecture.

2. The Industry 4.0 Reference Model Architecture

Based on advanced digitisation, the combination of Internet technologies and technologies in the field of "smart" objects (machines and products) seems to lead to a new fundamental paradigm shift in industrial production. The vision of future production contains modular and efficient production systems and characterises scenarios in which products control their manufacturing process. This is supposed to enable the manufacture of customised products in individual batches while maintaining the economic conditions of mass production. (Fogliatto et al., 2012).

According to Industry 4.0 objectives, the change of current production practices leads to a transition of production systems from highly centralised to a delegated decision-making one. Hence, in order to support such a transition in its organisational and management principles, appropriate architectures are required.

An architecture is a blueprint that "provides current or future descriptions of a 'domain' composed of components, and their interconnection actions or activities those components perform, and the rules or constraints for those activities" (Levis, 2009). In this regard, it is possible to identify a multitude of 'reference models', 'reference architectures', and 'architectures' in the literature (Bendul & Blunck, 2019; Moghaddam, Cadavid, Kenley, & Deshmukh, 2018). Before going on to mention some of the most important ones, we want to clarify the differences between the definitions, from a taxonomic perspective, considering the various interpretations available in the literature.

It is assumed that a "reference model" is based on a small number of unifying concepts and can be used as a basis for the development and explanation of standards to a non-specialist. Hence, a reference model should not be linked directly to any standards, technology, or other concrete implementation details, but should try to utilise conventional semantics that can be used unambiguously through different implementations. It is a stable model, universally recognised and recommended, based on which architectural reference models (e.g., reference architecture) can be derived for an assigned specific area.

Differently, it is assumed that a "reference architecture" is a fundamental structural model, but applicable in a particular domain, accepted as a starting point for the definition of new system-specific architectures. To this extent, it must be a sufficiently abstract framework that includes a set of basic concepts, axioms, and descriptions of the main interactions between entities in the internal and external application domain.

Finally, we will refer to an "architecture" as a well-defined system structure with greater detail regarding its elementary components, principles and relationships between its components. Hence, wanting to give a concrete example: a typical reference model may be the Industry 4.0 one, able to define with a few elementary concepts the fundamental principles of a very wide production paradigm, applicable to different concepts. Within such a reference model, therefore, no reference should be made to a pre-existing standard and no attempt to implement it.

Regarding the manufacturing field, reference models available in the literature are Industry 4.0, cloud manufacturing, and the Internet of Things. Liu and Xu (2016) conducted a comparative analysis of Industry 4.0 and cloud manufacturing, highlighting the similarities and differences between them (Liu & Xu, 2016). As an example, in [Figure 1] the Industry 4.0 reference model, inspired by the previously cited work, has been reported.

It should be noted that, in Industry 4.0 reference model, the Cyber-Physical System (CPS) plays the central role, since it is able to summarise all the technological aspects and the main concepts of Industry 4.0 within it, including the machine-to-machine (M2M) communication, horizontal, vertical and end-to-end integration concepts. In this environment, machines and, hence, CPSs, must be able to interact with their digital counterpart (digital twin) to evaluate their operating conditions (e.g., estimating their state of health with prognostics techniques) and with other CPSs to facilitate cooperation while achieving production objectives (i.e., schedule activities).

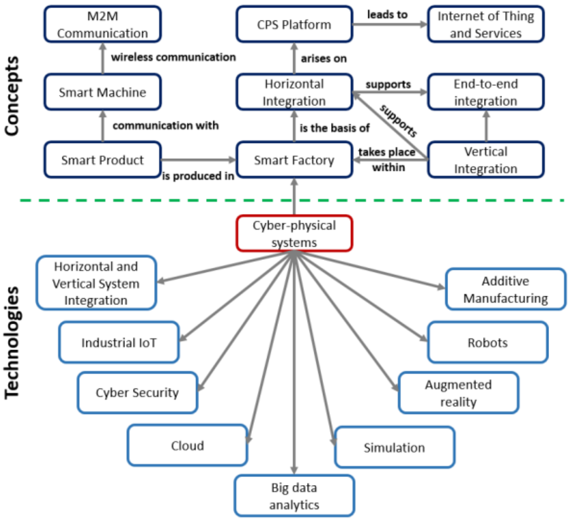

Figure 1 - The Industry 4.0 reference model, inspired by (Liu & Xu, 2016)

Regarding the reference architecture, instead, a consistent number of examples can be found in the literature. Many of these examples are based on the evolution and development of previous models related to the IoT area, now an essential paradigm for Industry 4.0.

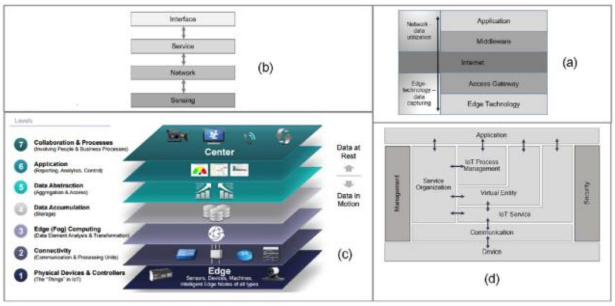

Figure 2 – Internet of Things reference architectures

Figure 2 shows some of the reference models for the IoT, and it is possible to see how these proposals converge into models based on the communication of information on different functional levels.

Focusing our attention to the Industry 4.0 reference model domain, in literature are identifiable three emerging reference architecture:

- Reference Architectural Model Industrie 4.0 (RAMI 4.0) (91345:2016-04, 2016);
- The IBM Industry 4.0 architecture (IBM, 2018);
- The NIST Service-Oriented Smart Manufacturing System Architecture (Lu, Morris, & Frechette, 2016);

The objective of a reference architecture is to focus on a particular reference domain (and therefore to be based on a particular reference model), specifying the possible functional levels and application domains, without outlining the possible iterations between them. However, the last two models go beyond the simple definition of the application domain and the different possible functional levels, outlying also the iterations and the information exchange between the different levels. At the same time, the last two models are of interest because they propose different approaches to the same domain of application, providing then a specific architecture for the problem.

The "IBM Industry 4.0 architecture" (IBM, 2018) introduces the division of manufacturing system architectures into three functional layers (i.e., edge, plant, and enterprise), with enhanced flexibility to deploy and move similar functionality between the three layers. The "NIST Service-Oriented Smart Manufacturing System Architecture" (Lu et al., 2016), instead, introduces the "Smart Manufacturing Ecosystems" concept, integrating for the first time in the same paradigm all the manufacturing competences, like production, management, design and engineering function.

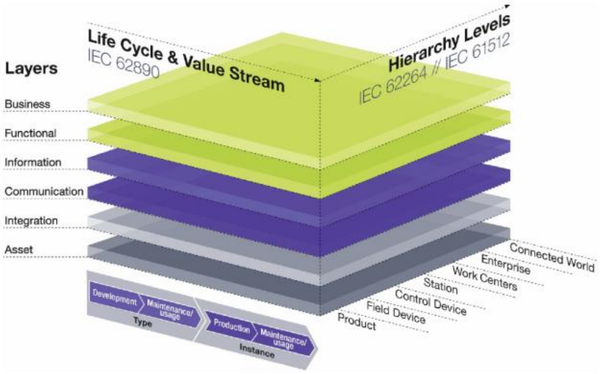

Figure 3 – The Reference Architecture Model Industry 4.0 (reprint from (91345:2016-04, 2016))

Finally, the "Reference Architecture Model Industry 4.0" (91345:2016-04, 2016), derived from the CENELEC model for the Smart Grid Architecture Model (CEN, CENELEC, & ETSI, 2014), is found [Figure 3]. At the current state, it represents the most comprehensive Industry 4.0 reference architecture, considering the wide number of functional levels that a manufacturing "asset" may have. And the asset concept is the first definition to be clarified, referred to it as I4.0 component. It can be a simple sensor or a set of simple components, expressions of a processing machine, and it may be referred to as a component or a set of components of the factory. It may be physical (e.g., an industrial machine or a product), as well as logical (e.g., a management system). In turn, once the asset has been positioned on the baseline, it is then possible to characterise its "functionalities" among the different provided layers.

The baseline of the RAMI 4.0 consists of two axes: (i) the life cycle and the value stream, defined with respect to the IEC 62890; (ii) a second one characteristic of the hierarchical managerial level, expanded from IEC 61512. For the third axis, instead, the model shows seven levels of functional interaction able to describe all the structural properties that an asset may have: business, functional, information, communication, and integration, as well as the asset itself.

The real strength of RAMI 4.0 lies in its spatiality. The general concept of I4.0 components and assets, makes it possible to consider as asset also logical elements such as the component of an MPC system. Therefore, the future MPC architecture of an Industry 4.0 may be examined from a taxonomic and ontological point of view through the RAMI 4.0 reference architecture, going to define the different logical assets while clarifying their degree of iteration between the different functional levels of the architecture (e.g., defining the information that different functional and physical levels may exchange between them).

3. Industry 4.0 MPC Architecture

Above, the reference architecture concept and the examples available within the literature has been reported. The discussion now focuses on the analysis and definition of the possible architecture that an MPC system may have. To this extent, it should be noted that there are not many examples to be presented and, more importantly, none of them has been derived from a specific reference architecture.

Currently, for the manufacturing paradigm, there are two main structures for an MPC system: a first one, hierarchical, defined by the ANSI/ISA 95 ("ANSI/ISA-95.00.06-2014, Enterprise-Control System Integration," 2014) [Figure 4]; and a second one, heterarchical, with a complete autonomous decision-making architecture.

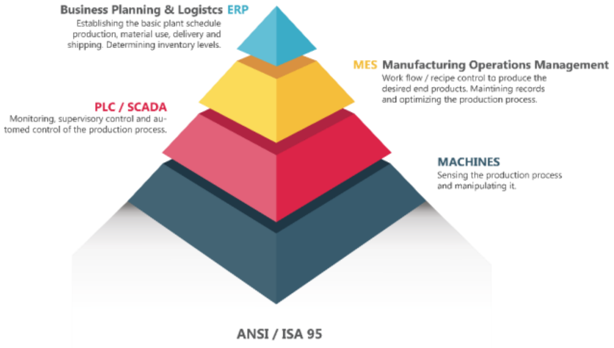

Figure 4 – The ANSI/ISA 95 hierarchical architecture

In particular, the ANSI/ISA 95 standard falling into the category of RAMI 4.0 specifications, represents its specific application, also if it was developed before the reference architecture. In fact, the ANSI/ISA 95 was defined with the aim to rationalise the different competencies of a production plant managerial levels, clarifying the competencies and information that each of the different assets (e.g., ERP, MES, PLC) should exchange with the others. The behaviour of such architecture leads to concentrate most of the high functional levels on a single asset. In particular, the structure proposed by the ANSI/ISA 95 standard concentrates the functionalities of "Business", "Functional", "Information" within the ERP level, leaving only the "Communication" functionality at the MES level. The lower levels (i.e. PLC/SCADA and MACHINES), instead, are strongly limited in their possible iteration with the higher levels, as they can only inherit information from them, with a limited role within the MPC architecture. The result is that the ANSI/ISA95 standard provides a strongly hierarchical view of the MPC system and, probably, it represents the cause of the behaviour of the current MRP systems.

RAMI 4.0 is structured to include the hierarchical organisational system and also the heterarchical ones as a particular case. In this last case, it should be noted that a heterarchical MPC architecture leads to a scenario in which, a wide number of RAMI 4.0 functional level are concentrated and duplicated in all the autonomous entities. The result is that all the autonomous entities of a heterarchical MPC system need to be informed about the status of the overall manufacturing system. The heterarchical structure leads to a situation in which entities can only chase local optimisations, trying to solve a complex problem by dividing it into several little problems.

Then, differently from the common vision about the Industry 4.0, for which a decentralised MPC architecture is advisable, it may be of interest to overcome the rigidity of these two scenario, exploring a different solution for the MPC system architecture. Duffie et al. (1996) in (Duffie & Prabhu, 1996) alredy in 1996 proposed four possible structures that an MPC system may have: hierarchical, oligarchical, semi-heterarchical and heterarchical [Figure 5].

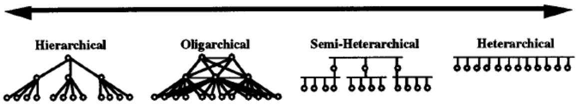

Figure 5 - Spectrum of distributed MPC systems

As above discussed, the hierarchical structure has been widely tested (ANSI/ISA95), showing its potential and, above all, its limits. The same has also been shown for the strongly decentralised architectures that, although not yet fully operational, is limited by the degree of complexity to be transferred to autonomous entities.

Hence it is of interest to analyse the possible advantages of the intermediate approach in an Industry 4.0 scenario: i.e., the oligarchical and the semi-heterarchical architectural structure. These types of architectures face with the complex problem of the MPC system not by dividing it into many smaller problems but dividing it by functionality and decision-making skills.

In the literature, some first attempts of architectures on these intermediate approaches can be identified: for example (Grassi, Guizzi, Santillo, & Vespoli, 2020) proposed a semi-heterarchical for Industry 4.0 recognising different management levels by both their physical identity and functional scope. Their objective was to overcome the rigidity of the classical hierarchical architecture, based on functional verticalisation while avoiding the loss of systemic vision typically involved by a complete decentralisation of the decision-making process. In their description, however, it is missed a reference to the RAMI 4.0, also if this link is to be derived.

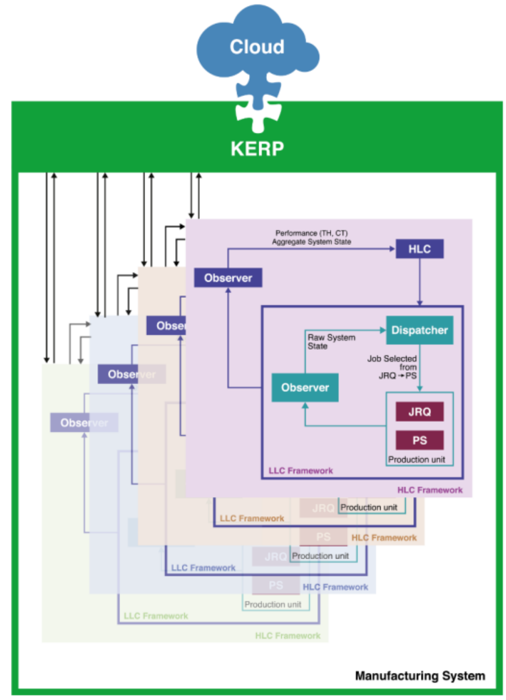

Figure 5 – The semi-heterarchical architecture (inspired by (Grassi et al., 2020))

They proposed a three-level architecture: (i) the Knowledge-based Enterprise Resource Planning (KERP) (i.e., the business level, also accountable for cloud interaction); (ii) the High-Level Controller (i.e., the general performance level); (iii) the Low-Level Controller (i.e., the operative level); characterised by a specific degree of autonomous decision-making capabilities integrating both vertical aspects and horizontal ones [Figure 6]. Each of the three components can, therefore, be considered an asset within RAMI 4.0, with its specific functional skills and information exchange. In particular, the KERP level may be accountable of the "Business" and "Functional" level of the RAMI 4.0, leaving at the High-Level Controller the liability of the "Information", "Communication" and "Integration" functionality. In this way, only the higher functionalities are centralised. At the same time, the mid of the RAMI 4.0 functionalities are demanded to the lower levels of the MPC system, considering an acceptable duplication of them among several but limited High-Level Controllers within the manufacturing plant, liable of the performance of a particular production line. Finally, the Low-Level Controller should be liable of the "Integration" and "Asset" functionality, duplicating it on every CPSs of the plant.

It should be noted that an important limitation of the showed architectures lies in their static nature. They are, in fact, structures that do not provide changes during the production cycle. However, RAMI 4.0 makes it possible also to change the asset structure. As a matter of fact, in RAMI 4.0, each asset involved during the Production phase may have a homologue in the development phase. Hence, by means of advanced simulative tools, the MPC architecture of a manufacturing system may be foreseen from time to time, according to the required plant flexibility, allowing to change the MPC architecture itself when the production requirements change.

4. Conclusions

Industry 4.0 represents the answer to deliver competitiveness in modern market contexts characterised by increased customisation requirements and reduced response times. However, even in an Industry 4.0 empowered environment, it is still necessary to gain a clear understanding of the dynamics involved in the complex interactions taking place in a manufacturing system.

In this work, the state of the art of Industry 4.0 architectural implementations compliant with the RAMI 4.0 has been explored. The findings showed that the intermediate MPC architectures (i.e., neither centralised nor decentralised) are the most feasible solution to be followed up for the Industry 4.0 production scenario. In particular, the behaviour of a semi-heterarchical MPC architecture has been analysed, showing the functional relationships among the decisional components/levels within the RAMI 4.0 reference architecture.

Considering RAMI 4.0 as a commonly accepted and established reference architecture for Industry 4.0, future research effort could be focused on formulating architectures that go beyond the limits and problems associated with a strict hierarchical scheme while attempting to avoid the complete delegation of autonomy to entities within the plant.

References

91345:2016-04, D. S. (2016). *DIN SPEC 91345 - Reference Architecture Model Industrie 4.0 (RAMI4.0).*

ANSI/ISA-95.00.06-2014, Enterprise-Control System Integration. (2014). ANSI.

Bendul, J. C., & Blunck, H. (2019). The design space of production planning and control for industry 4.0. *Computers in Industry*, *105*, 260–272. https://doi.org/10.1016/j.compind.2018.10.010

Bochmann, L., Gehrke, L., Böckenkamp, A., Weichert, F., Albersmann, R., Prasse, C., … Wegener, K. (2015). Towards decentralized production: A novel method to identify flexibility potentials in production sequences based on flexibility graphs. *International Journal of Automation Technology*, *9*(3), 270–282.

CEN, CENELEC, & ETSI. (2014). Report on Smart Grid Coordination Group: Smart Grid Information Security, (November), 1–107. Retrieved from ftp://ftp.cen.eu/EN/EuropeanStandardization/HotTopics/SmartGrids/Security.pdf

Converso, G., Ascione, M., Di Nardo, M., & Natale, P. (2014). An optimisation model in health care processes by lean energy approach. In *20th ISSAT International Conference Reliability and Quality in Design2014* (pp. 20–24).

Di Nardo, M., Madonna, M., & Santillo, L. C. (2016). Safety management system: A system dynamics approach to manage risks in a process plant. *International Review on Modelling and Simulations*, *9*(4), 256–264.

Dolgui, A., Ivanov, D., Sethi, S. P., & Sokolov, B. (2019). Scheduling in production, supply chain and Industry 4.0 systems by optimal control: fundamentals, state-of-the-art and applications. *International Journal of Production Research*, *57*(2), 411–432. https://doi.org/10.1080/00207543.2018.1442948

Dolgui, A., Ivanov, D., Sethi, S., & Sokolov, B. (2018). Control Theory Applications to Operations Systems, Supply Chain Management and Industry 4.0 Networks. In *16th IFAC Symposium on Information Control Problems in Manufacturing*. Bergamo.

Duffie, N., & Prabhu, V. V. (1996). Heterarchical control of highly distributed manufacturing systems. *International Journal of Computer Integrated Manufacturing*, *9*(4), 270–281. https://doi.org/10.1080/095119296131562

Fogliatto, F. S., Da Silveira, G. J. C., & Borenstein, D. (2012). The mass customisation decade: An updated review of the literature. *International Journal of Production Economics*, *138*(1), 14–25. https://doi.org/10.1016/j.ijpe.2012.03.002

Grassi, A., Guizzi, G., Santillo, L. C., & Vespoli, S. (2020). A Semi-Heterarchical Production Control Architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*.

Grundstein, S., Freitag, M., & Scholz-Reiter, B. (2017). A new method for autonomous control of complex job shops - Integrating order release, sequencing and capacity control to meet due dates. *Journal of Manufacturing Systems*, *42*, 11–28. https://doi.org/10.1016/j.jmsy.2016.10.006

Guizzi, G., Revetria, R., Vanacore, G., & Vespoli, S. (2019). On the open job-shop scheduling problem: A decentralised multi-agent approach for the manufacturing system performance optimisation. In *Procedia CIRP* (Vol. 79, pp. 192–197). Elsevier B.V. https://doi.org/10.1016/j.procir.2019.02.045

Hermann, M.; Pentek, T. (2015). Desingn principles for industrie 4.0 scenarios: a literature review, (01), 15. https://doi.org/10.1109/HICSS.2016.488

IBM. (2018). *IBM Industrie 4.0 Architecture - SmartFactoryXL*.

Ivanov, D., Dolgui, A., Sokolov, B., Werner, F., & Ivanova, M. (2016). A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0. *International Journal of Production Research*, *54*(2), 386–402. https://doi.org/10.1080/00207543.2014.999958

Ivanov, D., Sethi, S., Dolgui, A., & Sokolov, B. (2018). A survey on control theory applications to operational systems, supply chain management, and Industry 4.0. *Annual Reviews in Control*, *46*, 134–147. https://doi.org/10.1016/j.arcontrol.2018.10.014

Jeken, O., Duffie, N., Windt, K., Blunck, H., Chehade, A., & Rekersbrink, H. (2012). Dynamics of autonomously acting products and work systems in production and assembly. *CIRP Journal of Manufacturing Science and Technology*, *5*(4), 267–275. https://doi.org/10.1016/j.cirpj.2012.09.012

Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2018). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Safety and Environmental Protection*, *117*, 408–425. https://doi.org/10.1016/j.psep.2018.05.009

Leusin, M., Frazzon, E., Uriona Maldonado, M., Kück, M., & Freitag, M. (2018). Solving the Job-Shop Scheduling Problem in the Industry 4.0 Era. *Technologies*, *6*(4), 107. https://doi.org/10.3390/technologies6040107

Levis, A. (2009). *Handbook of systems engineering and management*.

Liu, Y., & Xu, X. (2016). Industry 4.0 and Cloud Manufacturing: A Comparative Analysis. *Volume 2: Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing*, *139*(March 2017), V002T04A016. https://doi.org/10.1115/MSEC2016-8726

Lu, Y., Morris, K., & Frechette, S. (2016). *Current Standards Landscape for Smart Manufacturing Systems. National Institute of Standards and Technology, NISTIR,* (Vol. 8107). https://doi.org/10.6028/NIST.IR.8107

Moghaddam, M., Cadavid, M. N., Kenley, C. R., & Deshmukh, A. V. (2018). Reference architectures for smart manufacturing: A critical review. *Journal of Manufacturing Systems*, *49*(October), 215–225. https://doi.org/10.1016/j.jmsy.2018.10.006

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., & Wang, X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control*, *47*, 200–213. https://doi.org/10.1016/j.arcontrol.2019.02.002

Philipp, T., Böse, F., & Windt, K. (2006). Evaluation of Autonomously Controlled Logistic Processes. *Proceedings of 5th CIRP International Seminar on Intelligent Computation in Manufacturing Engineering*, (April), 347–352.

Riedl, M., Zipper, H., Meier, M., & Diedrich, C. (2014). Cyber-physical systems alter automation architectures. *Annual Reviews in Control*, *38*(1), 123–133. https://doi.org/10.1016/j.arcontrol.2014.03.012

Rossit, D. A., Tohmé, F., & Frutos, M. (2019). Industry 4.0: Smart Scheduling. *International Journal of Production Research*, *57*(12), 3802–3813. https://doi.org/10.1080/00207543.2018.1504248

Rossit, D., & Tohmé, F. (2018). Scheduling research contributions to Smart manufacturing. *Manufacturing Letters*, *15*, 111–114. https://doi.org/10.1016/j.mfglet.2017.12.005

Rowlings, M., Tyrrell, A., & Trefzer, M. (2015). Social-Insect-Inspired Networking for Autonomous Load Optimisation. *Procedia CIRP*, *38*, 259–264. https://doi.org/http://dx.doi.org/10.1016/j.procir.2015.07.062

Scholz-Reiter, B., De Beer, C., Freitag, M., & Jagalski, T. (2008). Bio-inspired and pheromone-based shop-floor control. *International Journal of Computer Integrated Manufacturing*, *21*(2), 201–205. https://doi.org/10.1080/09511920701607840

Scholz-Reiter, B. (2004). Autonomous logistic processes: New demands and first approaches. In *Proceedings of 37th CIRP International Seminar on Manufacturing Systems* (pp. 357–362). Retrieved from http://www.sfb637.uni-bremen.de/fileadmin/SFB_Files/PDF_Download/SFB637_CIRP_2004.pdf

Scholz-Reiter, Bernd, Jagalski, T., & Bendul, J. C. (2007). Autonomous Control of a Shop Floor Based on Bee's Foraging Behaviour. In *Dynamics in Logistics* (Vol. 52, pp. 415–423). https://doi.org/10.1007/978-3-540-76862-3