On the advances of the Industry 4.0 Manufacturing Planning and Control system architectures

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Abstract: During the last decades, the Material Resource Planning system has been considered an essential management tool for facing the manufacture of complex and highly customised products. Nowadays, the recent innovations brought from the Industry 4.0 push for a strong evolution of the Manufacturing Planning and Control System (MPC) architectures, aiming to a new class of control architectures. Among these, the intermediate (i.e., the semi-heterarchical and oligarchical) ones are taking considerable interest from the manufacturing firms due to their increased flexibility degree and productivity enhancement. However, the current scientific literature is still focused on the 'hierarchical' approach of these architectures while the 'horizontal' bargaining among entities and architecture modules need to be further investigated. After a narrative literature review of MPC architecture, this paper will focus on the development of such intermediate architectures. In particular, referring to a semi-heterarchical MPC architecture, this work extends the contributes to the design of the horizontal aspect of the higher level, evaluating the possible advantages of such an application.

Keywords: Industry 4.0; Cyber-physical system; Decentralized production planning and control; Manufacturing Planning and Control

1. Introduction

The ability to meet highly personalised market demand in a short amount of time can be considered a fundamental principle for businesses seeking to compete in today's production environment (Fogliatto, Da Silveira and Borenstein, 2012). To fulfil the challenge of this dynamic production scenario, it is essential to acquire the capability to allocate and relocate production resources with a flexible approach (Dolgui *et al.*, 2019a; Derigent, Cardin and Trentesaux, 2020).

The increasing digitalization of production systems (i.e. the use of automated data collection, data management and data analytics, as well as cloud technologies) is seen as the key to higher productivity standards, more reliable procedures, and improved coordination and monitoring of production systems to achieve greater reliability and robustness (Bendul and Blunck, 2019). This strategy has such a significant impact on the production and distribution systems that it has led to the establishment of a new industrial paradigm, the Fourth Industrial Revolution, known as Industry 4.0 (Hermann, Pentek and Otto, 2016).

Like the other industrial revolutions, Industry 4.0 carried out the adoption of new enabling technologies. Terms such as "Internet of Things" (IoT), "Smart Factory" and "Cyber-Physical System" (CPS) reflect the vision of such highly efficient production processes, where smart devices, cannot only calculate and determine their situation but also coordinate and make decisions based on local and global knowledge (Moeuf *et al.*, 2018).

These technologies improve the machines coordination and awareness. The machines are no longer merely automatic in the operational sense of the term, but they are capable of interacting and making decisions (Riedl *et al.*, 2014; Herterich, Uebernickel and Brenner, 2015; Monostori *et al.*, 2016; Guizzi, Vespoli and Santini, 2017).

Until recently, the Material Resources Planning (MRP-II; regarded as the sequel to MRP) system was considered the best system to be adopted when facing a highly personalised production. It was created to solve the growing difficulty of manufacturing goods and lowering average inventory costs, as this would free up a large number of immobilized resources while also increasing plant versatility. Unfortunately, those aspirations were not achieved in the years that followed (Hopp and Spearman, 2011).

Here is where the adoption of the Industry 4.0 technologies takes the scene, enabling to the introduction of new Manufacturing Planning and Control (MPC) models and architectures capable of managing the productive activity while providing highly customised products with short response time and high production standards of efficiency and effectiveness (Grassi *et al.*, 2020c). The network of interconnected machines (i.e., a CPS network) facilitates MPC architectures focused on delegating a portion of the decision-making process to the shop floor level, instead of taking a unique central decision-making system (MRP-like). This method of delegating decision-making authority has already begun, and there are several references in the literature (Ivanov *et al.*, 2018; Rossit, Tohmé and Frutos, 2019; Vespoli *et al.*, 2019; Grassi *et al.*, 2020b).

However, a completely distributed decision-making system, based on local knowledge and limited computing resources, often has negative consequences, since decision-making objects cannot incorporate the complete visions of the environment into their decision-making process. As a consequence, the productivity operations are more difficult to forecast and the overall efficiency can deteriorate (Riedl *et al.*, 2014).

Summarising, without global knowledge, completely decentralized decision-making methods converge to a local optimization, leading to a process scheduling "reactive" to manufacturing disturbance (e.g. machine failure or unforeseen product rescheduling), sacrificing performance. Conversely, centralized decision-making methods, which tend to "proactive" process scheduling, converge to a global optimization, leading to the maximization of machine utilization, sacrificing the response rate (which is the typical behaviour of the MRP-like system) (Jeken *et al.*, 2012; Grundstein, Freitag and Scholz-Reiter, 2017).

However, the current scientific literature is still focused on the "hierarchical" approach of these architectures while the "horizontal" bargaining among entities and architecture modules need to be further investigated.

After a review of the advances on the MPC architecture of the last years in which the advantage and the disadvantages of these are presented, this paper proposes a narrative literature review of the most-promising hybrid semi-heterarchical MPC architecture, extending the contributes to the design of the horizontal aspect of the higher levels and exploring the possible advantages of such an application.

The remainder of the paper is structured as follows: in Section 2, the advances on the MPC architecture with a short review of the latest advances in product digitalization are presented. Section 3 propose a critical review and extension of the most-promising hybrid MPC architecture, while Section 4 conclude the paper.

2. Advances on the Manufacturing Planning and Control (MPC) Architectures

The Manufacturing Planning and Control (MPC) system plans and manages the manufacturing process (including materials, machines, people and suppliers). Essentially, it provides information for the efficient management of material movement, the efficient use of equipment and resources, the coordination of operations with vendors and the communication of business needs with consumers (Hopp and Spearman, 2011).

Figure 1 displays a coherence diagram in which the various manufacturing methods are optimally placed concerning the required customisation level of the production and the ratio between the requested market response time and the production Cycle Time (CT). Short response times are expected by the market in the left region of Figure 1, meaning the need for finished product inventories and forecast-based production planning.

This method is consistent only if the production are significantly standardised, due to the need to achieve reliable demand forecasts and minimize obsolescence risk. Here the MPC simply defines load plans, which are organized as a collection of resources (i.e. flow lines) allocated to products/product families, while respecting capacity plan and seeking to reduce total costs (Jacobs *et al.*, 2010).

At the centre of the diagram, the Just-In-Time (JIT) paradigm is found. Here the aim is to ensure a steady and consistent flow through the whole system. The JIT strategy, which ranges from Toyota's "pure pull" kanban method (bottom left side of the JIT block in the diagram) to the CONstant Work-In-Progress (CONWIP), aims to keep CT reduced and stabilized by minimizing WIP in the production flow, whilst continuously delivering at demand rate (Spearman, Woodruff and Hopp, 1990). Limits on the minimum volume of WIP that can be released into the production system are enforced by the need to compensate for fluctuations caused by both internal (such as configurations, breakdowns, and so on) and external variables (i.e. demand mix, customisation).

The region with the highest degree of customisation can be seen by moving to the right in Figure 1. The manufacturing in this region is highly customized, and inventories must be transferred upstream as production management is shifted on an "on request" basis. Since the supply flows in this field are very difficult to manage, with each order having its path on the shop floor, the standard method used by firms to schedule and manage production in the past was to try to optimize the utilization of each resource rather than looking at the whole flow (Panetto *et al.*, 2019).

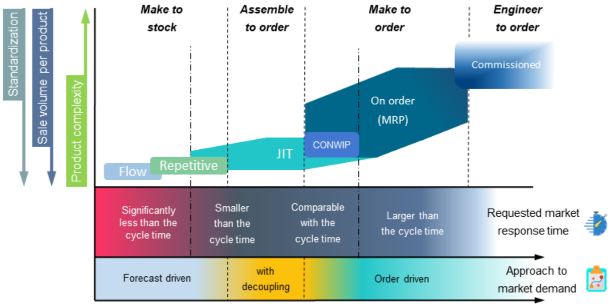

Figure 1: Coherence diagram through different production system approaches

As a result, the MRP was born, to identify an efficient production planning based on an estimate of available production resources over a discretized time horizon. Although the MRP solution seems to be successful in managing customised output, on the one hand, it is plagued by several issues, the most serious of which are its sharp behaviour and increased CT. This latter, which is becoming extremely necessary as a result of customers' demands for quicker response times, is a direct result of the MRP's effort to compensate for the variability generated by order customisation (Knollmann and Windt, 2013). As a matter of fact, the MRP in order to increase the production, starts to push a large amount of WIP into the system, to avoid starvation phenomena in the production flow. Doing this, the CT of the system increases and this is why, in MRP, the planner introduces fixed, and in general larger, lead times between production phases.

The result is a system capable of maximizing resource usage even in a highly variable flow setting, but showing, as a counterpart, a system with large and unstable CTs, resulting in a less predictable system (Knollmann and Windt, 2013; Bendul and Knollmann, 2016).

Moving on to the Industry 4.0 case, where improved customisation and short time-to-market are viewed as added value by the consumer, it becomes critical to take advantage from the introduced technology to increase the flexibility and responsiveness of the MPC system. Since (i) the consumer is willing to pay more for a highly personalized product delivered in a limited period and (ii) the sale will be missed if the productive system is not adequately responsive in terms of delivery time, the newer MPC have to focus not only on minimising manufacturing costs, as conventional methods imply, but also to take advantage of the potential to maximize sales (Grassi *et al.*, 2020a).

Given a certain degree of customization, a device that can consistently run with a lower CT while keeping the Throughput (TH) of the production line in line with the demand rate can yield the most revenue. Furthermore, if the device can achieve a high degree of resource usage, costs are minimized, and benefits are maximized. As a result, in the current business environment, the CT, like the TH, becomes an output parameter to be optimized. In relation to Figure 1, the result is that modern Industry 4.0-oriented MPC architectures should be able to shift the high customization zone as far to the left as possible in the diagram, i.e., be able to sustain a steady output rate with short and consistent CT even when customization is high. This is made possible by the collaborative use of both introduced Industry 4.0 technologies (i.e., Internet of Things and Cyber Physical System), which allow for the exploration of various types of MPC architecture.

Regarding the currently MPC architecture, to the best author knowledge, three possible architectures structure are found in the literature: the first, hierarchical, described by ANSI/ISA 95; the second, mostly theoretical, heterarchical, with a fully autonomous decision-making architecture; the third, currently under research by the literature, semi-heterarchical [Figure 2].

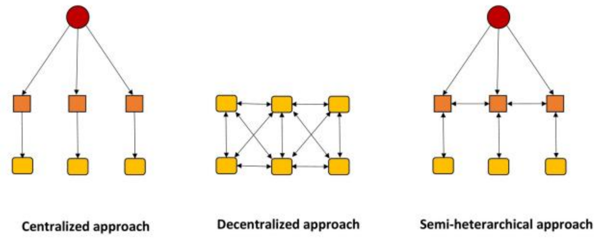

Figure 2: MPC architectures

In particular, the hierarchical ANSI/ISA 95 [Figure 3] had been born to streamline the various competencies of the production plant management level, clarify the competences and knowledge that each of the different assets (e.g. ERP, MES, PLC) could share with the others. The action of such an architecture contributes to the concentrating of much of the high functional levels on a single asset, while the lower levels (i.e. PLC/SCADA and MACHINES), instead, are heavily constrained in their iteration with higher levels, since they can only inherit knowledge from them, with a limited role in the MPC architecture. As a result, the ANSI/ISA95 standard gives a highly hierarchical view of the MPC structure which is likely to be the origin of the behaviour of the MRP systems.

Regarding the fully heterarchical ones, the vast majority of the research works are focused on modelling the behaviour of such as autonomous entities (Jeken *et al.*, 2012; Bendul and Blunck, 2019; Derigent, Cardin and Trentesaux, 2020). Some of these strategies include autonomous and independent control principles, like decision-making methodologies originating from biological examples, such as bees (Scholz-Reiter, Jagalski and Bendul, 2007) or ants (Scholz-Reiter *et al.*, 2008; Rowlings, Tyrrell and Trefzer, 2015). Similarly, Dolgui et al. implemented a research branch (Dolgui *et al.*, 2018, 2019b) focused on the application of the classical control theory within the MPC framework.

Then, unlike the common vision of Industry 4.0, for which decentralized MPC architecture is always proposed within the literature, it could be of interest to investigate a different approach for the MPC system architecture: this is the aim of the hybrid MPC architecture, like the semi-heterarchical ones. In this case, such architectures are focused on the scalability of the control system among different management levels, each of them with a different quota of decision-making autonomy concerning specific objectives. Then, they are differentiated by their functionality and not by simple subdividing the scheduling problem through different autonomies. The peculiarity lies in the separation between the physical entities and the logical ones since the distinction among the levels is based upon their management responsibility.

In the following paragraph, the advances of the semi-heterarchical architecture in literature are investigated, enhancing the advantages and the limits of the current implementation and state of the art.

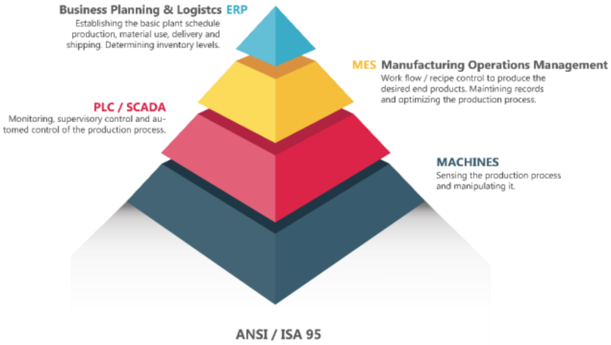

Figure 3: The hierarchical ANSI/ISA heterarchical architecture

3. The MPC intermediates architecture: the semi-heterarchical one

The current scientific literature agrees to consider that a fully distributed control architecture has to be recommended for short-term optimization, whereas a centralised one is advised when facing a long-term optimisation (Bendul and Blunck, 2019). In particular, it should be noted that to overcome the rigidity of the classical hierarchical architecture, the MPC architecture had to evolve to a new architecture that combines both the vertical and the horizontal aspect of the production.

In the literature, some first attempts of architectures on these intermediate approaches can be identified and all are directed to the semi-heterarchical structure (Gonzalez, Zambrano and Mondragon, 2019; Jairo, Jimenez and Zambrano-Rey, 2019; Grassi *et al.*, 2020a, 2020b).

Focusing on the Grassi et al. architecture (Grassi *et al.*, 2020a), different management levels by both their physical identity and functional scope are recognised. In particular, they identified three level in their architecture: 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) [Figure 4].

All these level are characterised by a specific degree of autonomous decision-making capabilities integrating both vertical aspects and horizontal ones. The problem is that the horizontal aspect is only cited and not investigated by the authors. Here the aim is to reconsider their structure, enhancing the functionality of each proposed level, with a particular focus on the horizontal point of view of such an architecture.

The first level, known as Knowledge-based Enterprise Resource Planning (KERP), is an extension of the traditional ERP structure that accepts orders and determines whether or not they should be accepted. It is responsible for the overall management of operations in the factory, as well as constantly monitoring and managing order cycle time and machine throughput (i.e., controlling output profitability), but it is no longer responsible for comprehensive production preparation. It determines the corresponding orders to be issued in production and the target outputs to be accomplished by tracking production system performances (TH and CT) and orders in progress at lower stages.

The production is no longer expected by imposing lead times but rather began in conjunction with other tasks in the production flow (i.e. reliable prediction of TH and CT). Due to an accurate estimate of their CT, orders for corresponding manufacturing processes (i.e. part development and product assembly) may be properly organized.

From the horizontal point of view, the KERP level has a key function when dealing with other KERPs from different firms. In the future cloud-based production environment, in fact, its function will be crucial for the negotiating process of the orders among a unified production platform. One limit to be further investigated at this level is that it is necessary to have a comprehensive knowledge of the production capabilities and the production output (in terms of TH and CT).

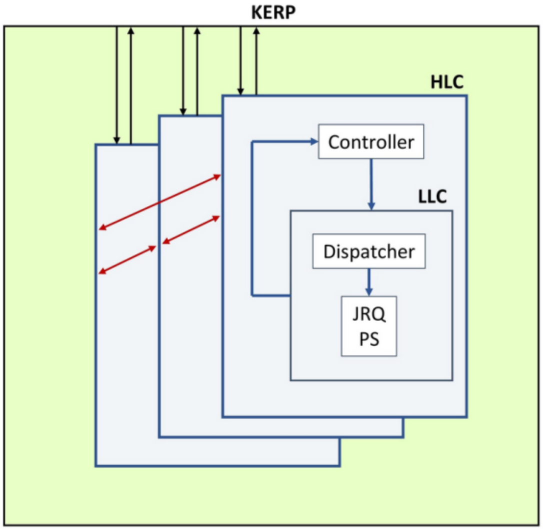

Figure 4 The semi-heterarchical architecture (inspired by (Grassi et al., 2020))

Following, the second level, known as High-Level Controller (HLC) is found. It inherits from the upper level (i.e., the KERP) the orders to be accepted into production as well as the planned goal outputs (in terms of TH and CT), and combines them with its unique knowledge of the controlled production sub-system (i.e. production line, cell, shop, etc.).

Knowing the sub-system at a higher level of detail, the HLC can monitor the general dynamics of the managed system, attempting to obtain the desired results in a suitable amount of time by operating primarily on the released WIP level. It may also be used to identify the best trade-offs between TH and CT, delivering recommendations to the higher level if the desired results are not fully realized.

As a result, the HLC operates as a sort of CPS in communication with the plant's upper level and other HLCs, using two separate management strategies:

- A *vertical* one in which the HLC sets the conditions for managing the subsystem in which it operates;
- A *horizontal* one in which the HLC cooperates with the other HLCs of the plant to resolve contingent conditions proactively without involving the upper floor;

To this extent, to the best knowledge of the author, the current literature about semi-heterarchical architecture is mainly focused on the vertical aspect of it (Vespoli *et al.*, 2019; Grassi *et al.*, 2020b) without a lack of research on the horizontal aspect of such a level. However, it should be noted that the HLC is the stage at which the benefits of the semi-heterarchical architecture become evident. It was intended to create both vertical and horizontal coordination at the level of performance abstraction, i.e. at the level of detail at which decision-making and negotiating techniques are implemented based on mid-to short-term performance analysis and forecasting.

One example may be the need to arrange order swaps with other HLCs that are likely to result in workload unbalancing difficult to handle at the lower level. Hence, this is the level at which the future research has to particularly focus on, with the introduction of a bargaining mechanism able to facilitate the HLC in making quick decisions and resolving unexpected operational problems autonomously, without involving the KERP.

The basic idea may be to take advantages of the traditional game-theory (particularly the cooperative games (Halpern and Rong, 2010)) in which, if an HLC has a particularly uncomfortable job to be processed, it can try to negotiate that job with other HLCs. Among the traditional possible games to be used, the auction ones, that are games with incomplete information, coherently with the fact that each HLC has private information, are the most promising for the considered problem. In fact, information such as performances and costs may consists of prediction or individual value inappropriate to be shared with the others entities. The mechanism may involve the use of a second-price sealed-bid auction with the hypothesis of private values, in which the HLC that wins the auction and therefore takes over the job pot up for auction, must be rewarded for the help provided with a payoff, thought in terms of credits. Of course, such a bargaining mechanism has to involve further research that aim to investigate the benefits with a focus on the production performances estimation algorithm needed for its execution.

Finally, the Low-Level Controller (LLC) is found. It includes the physical component of the subsystem and the conceptual actors responsible for managing the device in the very short term. This level knows the production in the greatest possible depth and, for this reason, it is the level at which the scheduling problem is resolved.

Given the WIP-based control technique implemented by the HLC, scheduling is approached here through a dynamic approach, first of all by a logical entity, the Dispatcher, which determines which order stored in the Job Ready Queue (JRQ) is the best to be released in the output subsystem every time one is completed. About the logic to be implemented on the Dispatcher, a lot of work has been already done (Grassi *et al.*, 2020b; Rolf *et al.*, 2020) within the literature.

From the vertical point of view, the LLC, operating as CPS, work to produce the desired outcomes by addressing local and dependent problems autonomously. Given the flow-based control approach of the HLC, the LLC dynamically preserve the conditions that maximize the complexities of the output flow — for example i) decreasing the variability of the workload, ii) smoothing the workload between resources when the variability is minimal, iii) preventing the creation of bottlenecks, iv) acting to impose overcapacity on the part of the LLC. This is done with a proper work of sequencing of the order store in the JRQ.

From the horizontal point of view, instead the LLC is liable for recognising possible disturbances to the output of the system due to unexpected events (machine breakdowns, unpredictable late or events, etc.) notifying the problem to the HLC and shifting all the already sequenced jobs on the other available machines. The HLC, from its side, is then encouraged to locate new solutions for the upcoming jobs, starting the bargaining mechanism with other available HLCs.

4. Conclusions

Industry 4.0 represents the solution to maintaining competition in today's industry, characterized by increased customisation demands and shorter response times. However, in an Industry 4.0-enabled world, a thorough understanding of the dynamics involved in the complex interactions taking place in a manufacturing system is still needed. To this aim, this works proposed a narrative literature review of the state of the art of MPC advances with particular regard to the Industry 4.0 implementations.

Among the reviewed MPC architectures, it has been shown that the most viable options for the Industry 4.0 production scenario are the hybrid ones (i.e., neither centralised nor decentralised), like the semi-heterarchical, able to take advantages from the learned lesson from the past and to introduce the required sequencing flexibility. The behaviour of such an MPC architecture has been reviewed, with a particular focus on its overall structure and vertical/horizontal point of view, enhancing the advantages and the limitation. In particular, the literature gap identified is referred to the horizontal (i.e. collaboration) aspect of these architecture that is only present from a theoretical point of view in all the considered paper.

We hope that the future development efforts will be focused on developing this aspect, taking advantages of the classical cooperative game-theory, like the auction mechanisms, and on continue developing architectures that go beyond the limits and problems associated with a strict hierarchical scheme, avoiding the full delegation of control to plant organizations.

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