Synchro-push: a new production control paradigm

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Abstract: The paper aims at proposing a new production control paradigm, the *Synchro-push*, that offers a step forward with respect to the traditional push and pull production paradigms as for plant re-configurability power and quick reaction to demand changes: in fact, theoretically, it offers the advantages of the two traditional approaches without suffering their drawbacks. This could be of advantage for any manufacturing company and especially for SMEs (Small-Medium Enterprises), acting as a support against worldwide competition. The paper presents a brief history of the evolution of the push and pull approaches, the comparison between them and among the different alternatives that have been proposed in literature for their implementation. It presents the new approach, its theory and the subsequent industrial implications. The new approach is now made possible by the development of innovative smart technologies that allow the close-to-real-time decision making in scheduling and a higher level of modularity in the plant.

Keywords: Push production, Pull production, SMEs, Re-configurability, Modularity, Synchro-push

1. Introduction

Manufacturing companies, especially SMEs, are nowadays facing a fierce pressure to cope with rapidly changing market demands for high product variety, small lots of customized products, and quick delivery requirements (McCutcheon et al. 1994; Meredith & Akinc 2007; Salvador & Forza 2004; Hasan et al. 2014). Indeed, while for big companies manufacturing is evolving from mass production to mass customization, SMEs are instead pushed to produce repetitive, but small production lots, when acting as suppliers of big companies, or short-life personalized products, when they directly serve the final market (Hopp & Spearman 2011). These new trends are generating many big challenges: in fact, from an operations management viewpoint, high variety induces complexity, which may negatively affect operations by increasing costs and slowing down the velocity of the supply chain. Furthermore, complexity increases shop floor inefficiency because of the increased of product changeovers, many routing alternatives, larger quantities of work in progress, balancing problems in assembly lines for mixed-model operation, higher process variability, etc. (Blecker & Abdelkafi 2006). All in all, the complexity induced by increase in variety adversely influences the costs and lead-times. But this should be limited: therefore, taking into account the current turbulent global economy context, companies, and especially SMEs, require delivering customized products rapidly and cost-effectively to stay competitive. For this reason, a higher manufacturing responsiveness can strongly improve the European SMEs competitiveness on the market. To this concern, this paper wants to contribute to answering these needs by allowing companies to realize manufacturing and logistics systems featuring high capability of responsiveness, being based on the concept of *Synchro-push* approach. The approach will be defined in this document as a new proposal for production management worth being further analyzed.

The paper is structured as follows. Section 2 states the research scope and objective of the paper. Section 3 shows the relevant theoretical background both from the production management discipline and from the technological advancements point of view. Section 4 presents the theory of the innovative concept of *Synchro-push*, defined and presented for the first time in this paper; this section is also devoted to showing the comparison of the innovative concept with the state-of-the-art approaches. Finally, section 5 reports some concluding remarks and discusses the industrial implications of the application of *Synchro-push*.

2. Research statement

Several approaches for production management have emerged in the last 15 years (Cavalieri et al. 2000; Cavalieri et al. 2007). However, the setting up of a successful approach, which could be valid also for SMEs, requires tools allowing a close but simple interaction between the high level control software, the low level control of shop floor devices, and the man in the loop. This vision has led the research work whose main concepts and approaches are presented in this paper.
More specifically, the research objective of this paper is to present an innovative production control approach whose purpose is to support both the re-configurability and the responsiveness of production system. The approach relies on the modularity of production systems and new smart technologies that allow close-to-real-time decision making (figure 1). In particular, the hardware- and software-based

modularity in production systems acts as the founding basis that supports long term re-configuration capabilities of the systems. The use of smart components that bring near field intelligence in the system is built on such modularity and is the means to reach short-term responsiveness of the system. These two aspects are pre-requisites to have close-to-real-time decision making in the shopfloor, thus generating the possibility to have a responsive production system that quickly adapts to changes in particular with the use of data models that support intelligence, such as ontologies (Garetti & Fumagalli 2012; Garetti et al. 2013).

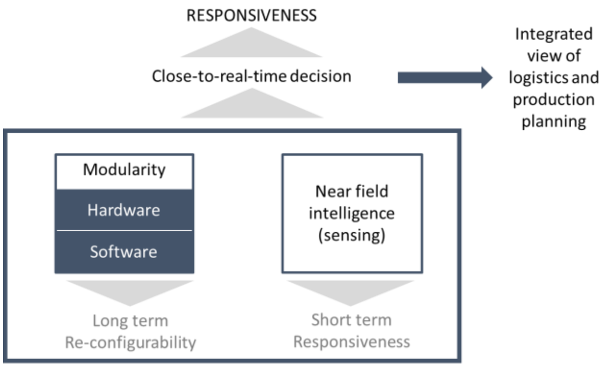

Figure 1 - Conceptual background

By implementing the proposed approach, companies will be able to develop a lean and flexible system, allowing prompt re-configurability and responsiveness to scenario changes. Indeed, today the lead time from the design to the market placement of a new product is becoming shorter and shorter, requiring a fast adaptation of the production system in terms of typology of components, re-configurability of the system and reactivity of production control.

3. Theoretical Background

3.1 Push and pull production paradigms

Traditionally, production management may be divided into push and pull production paradigms, which lead to different PP&C (Production, Planning & Control) system implementations. The fundamental difference between the push and the pull approaches is the mechanism that triggers the movement of work in the production system: the trigger for job releases comes "from outside" in a push system, while "from inside" in a pull system (Hopp & Spearman 2011). The difference can be explained based on the policy under which the jobs are released into the production system to be processed and assembled.
In the push policy, a short-term plan is elaborated to decide what to produce and when. The term "push" is created to underline the fact that this pre-definite plan "pushes" the jobs into the system. After jobs enter the system, they queue at the first required resource; they wait in queue according to a selected scheduling rule until they are processed; on completion of a process the jobs proceed to the following resources on the designated routing. In this way, the jobs flow in the system until all processes in the routing are completed, so that they exit the system. Jobs to be produced are generally identified according to orders and demand forecasting (i.e. trigger "from outside"). For what concerns implementation, push systems are traditionally associated to the world of MRP (Material Requirements Planning), that came to life in the 60s. In the 80s, new technology advancements enabled the evolution of MRP systems to the MRP II (Manufacturing Resources Planning), which combined the MRP with other planning tools in the company (such as the Capacity Requirements Planning), and to the ERP (Enterprise Resources Planning) that integrated all company's applications into a common database, exploiting the evolution of the client/server information technology architecture.
In the pull systems, there is not pre-defined plan that pushes the production: each job is moved from the previous resource only when the subsequent resource requires the material to be processed (i.e. trigger "from inside"). A well-known mechanism in order to implement the pull system is the depletion of the Kanban stock that constitutes the trigger to process a queue unit at the relative resource (Hopp & Spearman 2004; Kumar & Meade 2002; De Toni et al. 1988; Dawson & Henley 2012). Pull production systems –and Just In Time (JIT) as specific implementation of pull systems in the early 70s – were introduced to overcome the great issues of the batch production systems: long lead times and high WIP (Work In Process) inventory (Lee 1989). In fact, as demonstrated in the study by Lee, pull methods produce better job throughput and are able to maintain a lower level of inventory, especially under higher demand levels (Lee 1989).
Push and pull paradigms present different advantages and drawbacks. The pull systems appear to offer smoother production flows, improved quality and reduced costs (due to the less congestion in production systems), easier control (WIP is more easily controlled than throughput, since it is directly observable) and bounded WIP (Hopp & Spearman 2004). On the other side, while the pull systems are not impacted by errors in forecasting as push systems are, the pull systems feel the effects of production fluctuation, present higher probabilities of process "starvation" due to low in-process inventory, resulting in more disruptive effects due to reduced safety margins. Moreover, as the job mix increases, the pull methods appear disadvantaged with respect to the push ones. The pull systems also require a total quality control and reduced setup procedures, because the batch sizes are minimized (Lee 1989).
Within the pull paradigm, there are different variants of implementation, which try to overcome some of the disadvantages of the pure pull implemented by Kanban systems. To name a few, some of these are the DBR (Drum – Buffer – Rope), described by Gilland; the PFB (Pull – From – Bottleneck) by Hopp and Spearman; the CONWIP (CONstant Work In Process) by Spearman, Woodruff and Hopp; the POLCA (Paired-Cell Overlapping Loops of Cards with Authorization) by Fernandes and do Carmo-Silva (Gilland 2002; Hopp & Spearman 1996; Spearman et al. 1990; Tubino & Suri 2000; Fernandes & do Carmo-Silva 2006). They envision different release rules of new jobs into the production system: for example, the DBR and PFB limit the number of jobs in the upper portion of the production system

before the bottleneck resource (i.e. a new job can enter the system only when a job completes the service at the bottleneck). The CONWIP sets a limit on the total WIP in the system (i.e. a new job can enter the system only when a job completes the last process). It is possible to see here the difference of these pull alternatives with respect to the pure Kanban systems, where the limit is on the number of jobs between each adjacent resources. In this sense, it is worth also remarking that some of these approaches could be understood as hybrid push/pull systems. As examples: in CONWIP the first resource in the production system requires a pull trigger but the other resources do not (to move job through the system), while in POLCA the first authorization is provided by MRP and then cards limit the amount of WIP into the system (Hopp & Spearman 2004).

Literature is very rich in papers comparing and simulating different policies also within the push or pull approaches, different alternatives of pull systems, different rules for releasing, for serving and for managing queues, tested in order to find the optimum or to see whether under certain parameters an approach is better than another. Indeed, researchers do not agree on what is the best between push and pull, and also among pull alternatives, as their comparisons do not show the same results also when assessing the same performance indicators, finding that the comparison results are strongly affected by different contextual factors (Gilland 2002; Huang & Kusiak 1996; Framinan et al. 2003; Ovalle & Marquez 2003; Geraghty & Heavey 2004; Gonçalves et al. 2005).

3.2 Enabling technological advancements

Technological advancements that have been registered in the last years represent a huge step forward in the trend to making the production environment smart and to addressing the need of real-time information management from field. In fact, innovative production systems are composed of two main elements: the interconnection of intelligent systems and the unprecedented access to data. These elements allow production systems to be characterized by (Lee et al. 2015):

i. a tighter collaboration between human and machines (and especially robots) sharing the same workspace;
ii. the fact that the entire production chain is controlled and documented;
iii. the remote access to control elements;
iv. the interaction among machines in the production system;
v. high levels of self-awareness and self-prediction of health conditions.

These characteristics potentially open the door to self-configuration, self-maintenance and self-organization of networked systems (Lee et al. 2015).

These potentials are achievable thanks to the introduction into the production systems of the Cyber Physical Systems (CPS). CPS are evolution of embedded systems that are able to control physical entities and to expose their computation capabilities on a network communication in order to act as modules of a production system (Garetti et al. 2015; Baheti & Gill 2011; Lee et al. 2013). Therefore, a network of modular CPS, which have their own embedded controller, ensures easier re-configuration capabilities than in custom-designed systems (Energetics Incorporated - NIST 2012). In fact, CPS are perceived as enablers for efficient smart manufacturing, providing efficient, reliable and interactive control. Subsequently, a lot of discussion on benefits derived from CPS is today on the research agenda. The main benefit for some authors is the high level of efficiency achievable (see e.g. (Wolf 2009)). According to NIST (National Institute of Standard and Technology), some of the possible practical benefits of CPS in factory automation are manifold: reduced time to market; agile response to consumer demand; integrated energy management; optimized plant operations and safety; asset management through predictive maintenance and improved reliability; detection of anomalies to prevent catastrophic events; improved productivity and flexibility leading to reduced production costs (Energetics Incorporated - NIST 2012).

Another essential element to reach the above modern production systems characteristics are flexible and modular control systems, that allow to support the easy re-configuration and changes on CPS-based production system (Martinez Lastra & Delamer 2008). In fact, modularity in software systems, for the control and monitoring of the physical elements in the factory, must come parallel to the modularity of the physical components in order to reach the desired flexibilities and fast re-configuration capabilities. In other words, to support physical reconfigurations, the control software must also be changed accordingly and, without software-enabled modularity, the control system should be re-coded, hindering fast reconfigurations of the production system (Fumagalli et al. 2014). The hardware modularity has already been thoroughly investigated and has reached high levels; instead, the software-based modularity (i.e. modularity of software components integrated into hardware modular units) is still under research, and the development of CPS is the first step to achieve it, leading to the creation of intelligent modules that could be easily coordinated (Delamer & Lastra 2006; Energetics Incorporated - NIST 2012; Derler et al. 2012; Caridi & Cavalieri 2004; Negri et al. 2016).

On the whole, the CPS-based production systems have a two levels control architecture: on the one side the local control level managed by the intelligent CPS, and on the other side the systemic control that coordinates and orchestrates the various CPS modules (Garetti et al. 2015). These factors – CPS modules, built on hardware and software modularity – allow real-time monitoring and access to data related to the field, thus opening the door for close-to-real-time decision making related to the shop-floor operations.

4. The synchro-push approach

The discussion about production management, and in particular control policies, has its origin and development in the past years (as reminded in section 3.1). The authors of the present paper esteem that the time is ripe for a further research investigation on the topic, thanks to the enabling technologies recently developed, allowing the creation and implementation of innovations in push-pull production paradigms. Considering the trend towards close-to-real-time decision making, production control is today assuming a higher prominence: we believe that we have to concentrate at this level – according to our research statement (section 2) – in order to innovate the paradigms to a greater extent.

This paper proposes to come closer to the shop floor operations, through the innovation concept of *Synchro-push* approach, as a lever in order to improve and enhance both directions relying on an integrated view of the logistic flow (on the shop floor) and the planning of production. This kind of integration may represent a relevant opportunity, especially for SMEs, since the trend is to operate in a customized market, while not reaching the overall higher and more stable production volumes typical of big companies.

The proposed approach is hereafter described also illustrating the fostered advancement in comparison to the state of the art of "traditional" solutions.

The *Synchro-push* approach can be explained starting from the well-known Just In Time (JIT) model for production control, based on the *pull* production control mechanism. In the *pull* approach, production orders are generated in a reactive way, when the level of components in intermediate buffers between workstations drops down, due to the withdrawal of the finished product from the final buffer (in practice this rule is implemented through the Kanban mechanism). This is a very nice and simple mechanism in theory, however it requires in practice that all intermediate inventories are provided with the components of the various products belonging to the planned production mix (in fact buffers are the triggers of the replenishment orders). Furthermore, the production mix must remain stable, otherwise the content of buffers needs to be updated, thus involving time waste and loss of production. Differently, the *Synchro-push* approach is based on the *push* production control mechanism that is innovated by removing its main weakness, which is the unreliability of the lead-time (based on which the *push* traditionally works). In fact, through a continuous real time update of the inventories status, the *Synchro-push* approach overcomes this problem by simultaneously performing a cycle of two scheduling activities (i.e. periodically regenerated with a different time frame):

- the first scheduling is carried out for the launch of production orders;
- the second scheduling runs with a shorter time period, managing the transfer orders to the buffers of the components needed for production.

In this way, all the different production flows are managed centrally in an integrated and close-to-real-time decision, ensuring their synchronization, thus achieving altogether the continuous plant capacity planning and the reactivity and flexibility of the overall production management system. It is worth remarking that integrating logistics of the required components in the planning view is essential to lead to a close-to-real-time decision: indeed, feeding materials to different stations is "the end" of a processing chain, as physical activity, and is finally decided in a close to-real-time fashion under the *Synchro-push* approach.

Qualitatively, the advancements of the *Synchro-push* approach compared to the state of the art (and especially to a Kanban based lean manufacturing production model) are due to the possibility to manage continuous changes in the production mix, without any inefficiency, furthermore reducing the level of WIP to its practical minimum. It is clear that this is a relevant requirement brought by the need for high responsiveness.

Such innovative approach requires advancements in the current physical configurations and control logics of the production system. In particular, the traditional solution for the automation of logistic flows in logistic and manufacturing systems envisions low level components that are controlled by a first control level (i.e. a PLC), which centralizes all the control logic. Although the mechanics are already quite modular, an (almost) complete new re-design would be necessary in case of the extension or reshaping of a pre-existing plant (due to the re-wiring and writing of new PLC software programs). Moreover, the control components (e.g. for logistic conveyors) are not designed in a modular way, but according to the specific needs of the application case. This is not respecting one of the founding elements for re-configurability. Besides, from an operations management perspective, today's most spread control logic solution for production is based on the *Just in Time* (or *Lean manufacturing*) approach: this corresponds to the most advanced implementation of the *pull* approach to production control, which suffers with environments with high variability in the production mix.

To exploit the full potential of the *Synchro-push* approach, the factory should be built based on CPS, as they are offering a lot of potentials. Firstly, they enable to divide the physical components of a logistic and manufacturing system into elementary units. Each of these is an independent entity controlled by its own controller and linked to the system communication network by well proven communication technologies. In this way, the CPS concept is brought to the manufacturing company (and in particular SMEs) application level and the logistic and manufacturing modules are totally independent from each other, allowing an unprecedented composability for any physical system configuration required.

The advancement of the CPS-based modular factory to the state of the art is given by the possibility of composing plants by modules.

Qualitatively, the following advantages are claimed:

i) the software system can be easily customized (to the point of being automated) to any physical plant configuration;
ii) the activities of configuration and re-configuration of logistic and manufacturing plants are speeded up.

5. Conclusion

Manufacturing companies, especially SMEs, are subjected to two pressing market needs: ability to quickly implement product changes, and ability to produce very small lots of a large variety of products. This requires a modular production plant, which can be easily reconfigured, and a responsive production control system, that can manage small product lots and a variable production mix in an efficient way. Nowadays, the current approach to these issues is based on two alternatives:

i) to efficiently produce products in large lots and then keep them in the inventory for fast reaction to the customers' demand (with related inventory holding costs), or
ii) to make frequent set-ups of the plant following the customer requests, but working with a very low efficiency.

This paper aims at contributing to the solution to these issues by the *Synchro-push approach*: a new philosophy for production control that can potentially offer better performance compared to the JIT approach, that is so commonly used in industry today, by using the planning power of the push approach, without suffering its drawbacks. The new approach is made possible by the recent development of smart technologies that allow real-time monitoring and close-to-real-time decision making in production control and that support higher levels of plant modularity.

This is particularly interesting for SMEs which are notoriously chosen as suppliers of big companies for their flexibility in offering customised products with short life-cycle. However, SMEs do not have the possibility to invest big amounts of money in making their systems more flexible and responsive. The Synchro-push concept represents a production management approach and technique that can be implemented in a stepwise process, with enabling technologies that have lately become not-expensive and therefore meeting the interest of any company, in particular of the SMEs.

The paper presented the new concept and described it with respect to the state of the art of production control techniques and from an enabling technologies point of view. From an operations management perspective, the *Synchro-push* control might bring the following advantages:

- capacity planning of the production mix (that can change any moment) taking into account the workstations capacity and the routing of products through workstations;
- no need to update the content of intermediate buffers when the production mix changes (this occurs in contrast to what happens in Kanban-based production systems, where the production mix must remain stable, otherwise the content of buffers needs to be updated);
- reduction of WIP to its theoretical minimum in the conditions of highly changing production mix; indeed, differently, JIT control logic works well for repetitive productions (i.e. with quite stable production mixes), but requires the presence of a certain level of WIP; besides, JIT is becoming inefficient with the current market trend increasingly moving toward small lots in combination with high variability of production mixes.

Further research is needed on this topic in order to test and quantify the performance improvements with respect to traditional production control approaches. This could be done both with simulation and modelling and applying the concept, through collaborative projects, to real industrial pilot cases in selected industries in order to validate and demonstrate the advantages of such an approach by defining clear KPIs to compare traditional pull and push solutions and the synchro-push production management.

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