Digital Twin for Supply Chain Master Planning In Zero-Defect Manufacturing

Julio C. Serrano[1], Josefa Mula[1], Raúl Poler[1],

[1] CIGIP, Centro de Investigación en Gestión e Ingeniería de la Producción
EPSA, Universitat Politècnica de Valencia, Ed. Georgina Blanes, C/ Alarcón 1,
03801 Alcoy, Spain
{jserrano, fmula, rpoler}@cigip.upv.es

Abstract. Recently, many novel paradigms, concepts and technologies, which lay the foundation for the new revolution in manufacturing environments, have emerged and make it faster to address critical decisions today in supply chain 4.0 (SC4.0), with flexibility, resilience, sustainability and quality criteria. The current power of computational resources enables intelligent optimisation algorithms to process manufacturing data in such a way, that simulating supply chain (SC) planning performance in real time is now possible, which allows relevant information to be acquired so that SC nodes are digitally interconnected. This paper proposes a conceptual framework based on a digital twin (DT) to model, optimise and prescribe a SC's master production schedule (MPS) in a zero-defect environment. The proposed production technologies focus on the scientific development and resolution of new models and optimisation algorithms for the MPS problem in SC4.0.

Keywords: Supply chain 4.0, master production schedule, digital twin, reinforcement learning, zero-defect manufacturing, conceptual framework

1 Introduction

The effect of technological advances on industrial companies is remarkable and guides their development towards a production paradigm in which flexibility, robustness, resilience, responsiveness and sustainability emerge as decisive SC management elements, for not only the future occupation of better market positions, but also for survival purposes [1].

The flow of materials, products and information in the traditional SC goes through stages that are largely discrete and isolated from one another [2], and this problem pushes it towards digital transformation. The operations strategy needs to ensure that the acquisition of new digital technologies is perfectly aligned with the SC decision area, which implies making productive decisions to properly manage resources and acquiring the right competences to meet market requirements.

Critical decisions in addressing a SC4.0 strategy are mainly related to SC atrributes: (1) digital; (2) smart; (3) visible; (4) interconnected; (5) labour-organised; and (6) sustainable. These attributes are particularly relevant for the planning area in SC4.0. At the tactical decision level, the procedures applied in the master production schedule

(MPS) process differ significantly depending on which decisions are made to reinforce these SC attributes.

In order to react rapidly to unforeseen situations, production systems should be developed as autonomous systems with the ability to accomplish their assignments without human supervision, and by choosing from a set of alternative actions and orchestrated events in real time as a reaction to changes in relevant internal and external data [3]. In this context, the digital twin (DT) [4] potential to simulate, optimise, predict and share data in real time is noteworthy from not only the planning point of view, but also as a means by which the "*do things right at the first time*" idea, emphasised by the zero-defect manufacturing (ZDM) philosophy, becomes feasible [5].

This paper aims to present an overview of the addressed problem and proposes an initial DT-based framework for autonomous MPS management in an SC4.0 context with a zero-defect characteristic to answer a threefold research question: 1) what general conceptual framework characteristics can respond to the problem by a holistic approach considering the SC structure and its hierarchies, intervening actors, processes, resources, data, information and flows?; 2) how does this framework push the SC towards the zero-defect goal?; and 3) which mechanisms can endow DT with the ability to autonomously manage SC MPS?

The rest of the paper is organised as follows. Section 2 presents the contribution of this study to applied artificial intelligence (AAI) systems. Section 3 offers an overview of the related literature. Section 4 describes the proposal. Finally, Section 5 discusses the proposal implications, provides the main paper contributions and conclusions, and points out the lines towards which further research can be conducted.

2 Contribution to applied artificial intelligence systems

The potential of artificial intelligence is remarkable at any decision level of operations planning and control (OPC) [6], and its application possibilities are numerous. For the MPS at the tactical level, its emphasis is placed on time and spatial disintegration of cumulative planning targets and forecasts, along with the provision and forecast of required resources. This procedure eventually becomes difficult and slows down as the number of considered resources, products and time periods increases [7]. Most of the classic modelling approaches present limitations as the MPS dimension grows, particularly if the MPS is posed as a multi-objective issue. These limitations can lead to unacceptable computational times for a decision support system (DSS) when this is expected to facilitate real-time decision making, especially if it is intended to provide it with a certain level of autonomy.

For this reason, the addressed MPS issue is determined by its degree of complexity, its non-linear stochastic problem condition and by the feasibility of its formulation as a Markov decision process (MDP) [8]. All this generates an appropriate context for applying reinforcement learning (RL) techniques, in which the decision maker or agent, based on a reward policy, continually observes and learns from its environment until efficient levels of reliability and computational times are achieved.

Here the main contribution to AAI systems comes from using a deep RL (DRL) method for modelling a DSS with an optimising-prescriptive role, and in such a way that when unexpected events occur in the MPS, the DSS can meet rescheduling needs in real time.

3 Literature review

Since the term SC4.0 [9] was coined halfway through the last decade, research on this topic abounds. This term has one main meaning, which usually refers to the SC emerging from the Industry 4.0 (I4.0) context [10], although some researchers also use it to refer to the digital SC [11]. In any case, the SC is a conceptual framework that has been approached from many different angles and has had more than 50,000 entries in Scopus in the past decade alone. In an attempt to identify each trend, Maryniak et al. [12] diagnose the dominant SC topic areas in the last three decades.

According to the Association for Supply Chain Management (APICS), the MPS is a line on the master schedule grid that reflects the anticipated build schedule of those items assigned to it, and it represents the items that a company plans to produce that are expressed as specific configurations, quantities, and dates. The MPS is determined by the SC planning environment according to: (i) its strategies (make to stock, make to order, engineer to order, configure to order, assemble to order, among others.); (ii) the number and type of involved stakeholders (suppliers, warehousers, manufacturers, distributors or retailers); (iii) structure (hierarchy with its tiers and relationships); and (iv) the nature of activities (production, distribution and/or procurement).

In the specific segment of the SC literature that focuses on the MPS, proposing new resolution and optimisation models has been a recurrent approach. Chern et al. [13] put forward a multi-objective MPS resolution model with a heuristic method based on a genetic algorithm. Grillo et al. [14] use the fuzzy set theory to model uncertainty and propose a metaheuristic particle swarm optimisation (PSO) technique as a solution method. A method to achieve an optimal MPS in an uncertain environment is proposed by Sutthibutr and Chiadamrong [15], based on a multi-objective linear fuzzy model with an α-cut analysis. Arani and Torabi [16] integrate physical/material tactical plans with financial ones to account for their reciprocal effects. Ghasemy et al. [17] propose a mixed integer nonlinear programming model with probabilistic constraints to determine centralised planning, viewed from the social sustainability perspective under uncertainty. Martin et al. [18] address the uncertain MPS with two robust optimisation approaches. The MPS problem for a centralised SC of replenishment, production and distribution is tackled by Peidro et al. [19] by presenting a fuzzy multi-objective linear programming approach.

According to Orozco-Romero et al. [20], the DT approach is a solution that enables both real-time digital monitoring and control and automatic decision making. Marmolejo-Saucedo et al. [4] review the scientific literature on DTs in SC management. The association of DTs with disruptive risk management and resilience in the SC is noteworthy. In this line, Barykin et al. [21] attribute the need to build DTs to the poor reliability and stability of SCs due to errors in their operation, and assert that DT can generate information on the impact of such errors, and can influence SC performance by observing different scenarios that simulate the location of errors and their duration, and to analyse recovery policies. Ivanov et al. [22] explain the SC DT concept and propose a framework for risk management. Ivanov and Das [23] identify the need to implement such a partnership to map supply networks and to ensure their visibility as a tool to recover from disruption by taking the disruptive effect of the COVID-19 pandemic as an example. Dolgui et al. [24] propose reconfigurability as a SC parameter that characterises the SC in an uncertain and changing environment by addressing the notion of a reconfigurable SC, or a X-network, with DT as a basis for its design. SCs' resilience to fluctuations of make-to-order environments in customised production cases is addressed by Park et al. [25], who propose a logistics CPS based on DT technology. More closely in line with the objectives of the present paper, Wang et al. [26] address the SC planning problem from a DT perspective by, detailing its benefits and potential compared to traditional approaches.

Regarding the use of AAI as a support for production planning in the SC domain, it is worth noting that most contributions focus on the operational decision level. Of those dealing with planning at the tactical decision level, most either focus on inventory replenishment and dynamic supplier selection problems, or pose planning problems, but by means of approaches prior to using deep reinforced learning (DRL) mechanisms with which to tackle large sets of states and actions by completing training in reasonable time lapses with, for example, artificial neural networks (ANN) or proximal policy optimisation (PPO). More in line with our research, Alves and Mateus [27] consider a DRL approach based on a second version of proximal policy optimisation (PPO2) to solve the problem of a four-step SC with two nodes per step and stochastic demands. For Peng et al. [28], the optimisation approach is similar, but the considered SC structure is simpler, based on a single factory and warehouse that does not contemplate supply steps. In a study restricted to the semiconductor sector SC, Lauer and Legner [29] describe a framework for measuring instability in the MPS based on machine learning.

Finally, the application of the ZDM philosophy in the SC domain has been, albeit sparsely, also addressed by researchers. Most have focused more on the quality management discipline than on OPC, and the zero-defect outcome comes indirectly from applying other strategies or philosophies. For Siddh et al. [30], the zero-defect outcome is the effect of integrating lean six sigma into the SC as their central idea states that if you can know how many defects the process has, you can also systematically figure out how to eliminate them. Pardamean and Wibisono [31] propose a framework to explain the impact of six sigma on SC performance based on increasing process capability in the value stream by seeking zero defects and reducing process variation. Poornachandrika and Venkatasudhakar [32] present a behavioural process and a system model for achieving zero defects with a case study conducted in an automotive company. Unlike the above authors, Thakur and Mangla [33] use the zero-defects concept in the SC as the effect of sustainable practices.

It can be concluded that the literature on the MPS problem in the SC is numerous, varied and adds value to this research in terms of: (i) the use of AAI systems to support production planning in the SC domain is limited and mostly focused on DRL-based methods; (ii) conceptual framework proposals based on RL-driven DT are limited; (iii) the zero-defects concept in the SC domain is not approached as a *per se* strategy, but appears as the effect of applying other strategies.

4 Proposal

The MPS plays a crucial role in SC4.0 and has been a sustained driver of research into new planning technologies, which has provided continuous scientific development, and generated new models with a wide range of approaches. However, the growing scale and complexity of the MPS has influenced the persistence of knowledge gaps, especially in today's dynamic environment where new technological developments occur at an ever-increasing speed.

The proposed conceptual framework (Fig. 1) is characterised by virtually replicating the MPS by merging physical and virtual processes and resources in a DT. Infrastructure, data and information are elements that belong to the manufacturer's sphere. The scope of this replication extends from the manufacturer sphere (the centre of the SC) to the other actors involved in it by means of cloud-computing tools.

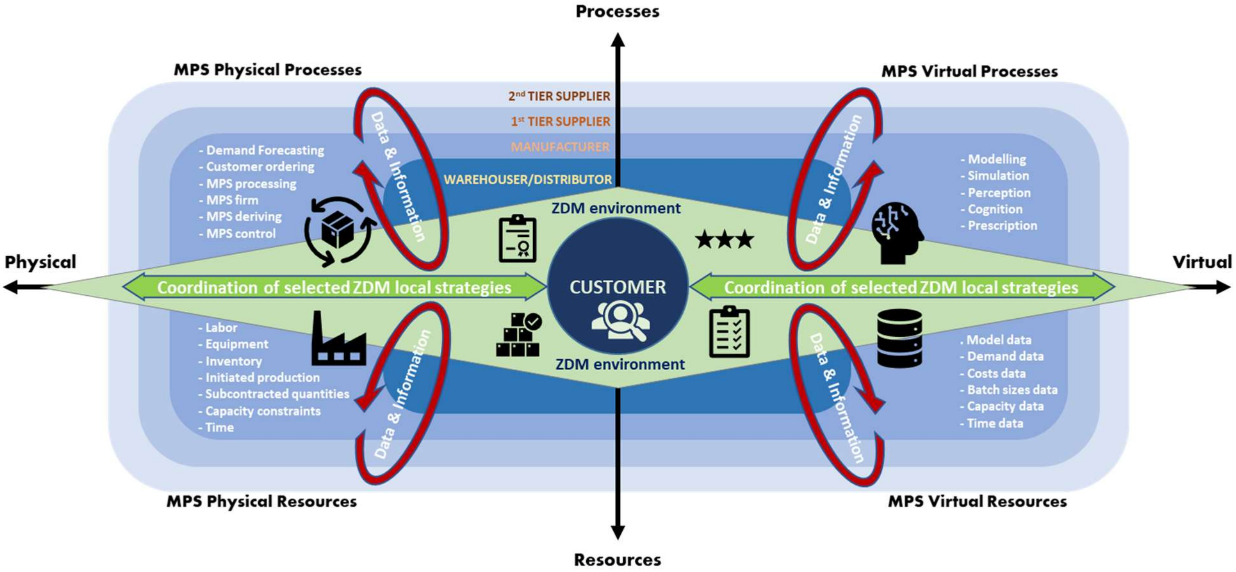

Fig. 1. Conceptual framework of DT-based and ZDM-oriented manufacturer's MPS

Within this framework, the SC is understood as a single domain for all the intervening actors, in which they use personalised blocks of data and information about MPS, but from a single common origin: the DT. This scheme not only facilitates the flow of data and information about production planning between actors, but also creates a coordination channel for individual zero-defect strategies in the SC that makes it possible to: (i) enable collaborative manufacturing with the DT as a means of sharing data and information about processes and resources; (ii) allow, for each involved stakeholder, the monitoring of those MPS process parameters that need to be shared in this collaborative manufacturing context, to improve early defect detection, or even prediction, as a way to empower prevention policies; (iii) enhance data storage, analysis and visualisation by unifying these performances through the DT; (iv) collaboratively launch rescheduling production across the entire SC in only one action that is generated and spread by the DT. In a nutshell; 1) collaborative manufacturing; 2) process monitoring; 3) data management enhancement; and 4) rescheduling ability. Four of the seven ZDM system [34] areas would be gathered and considered in this model to, therefore, favour a zero-defect goal within the SC.

The implementation of the DT for SC master planning according to the described framework requires several stages. The first is to develop the manufacturer's specific domain before extending it to other actors. The virtual process in this restricted DT space is described below as kernel of the model.

The process is based on the DRL method and is developed by two elements: the training environment and the DRL agent (Fig. 2).

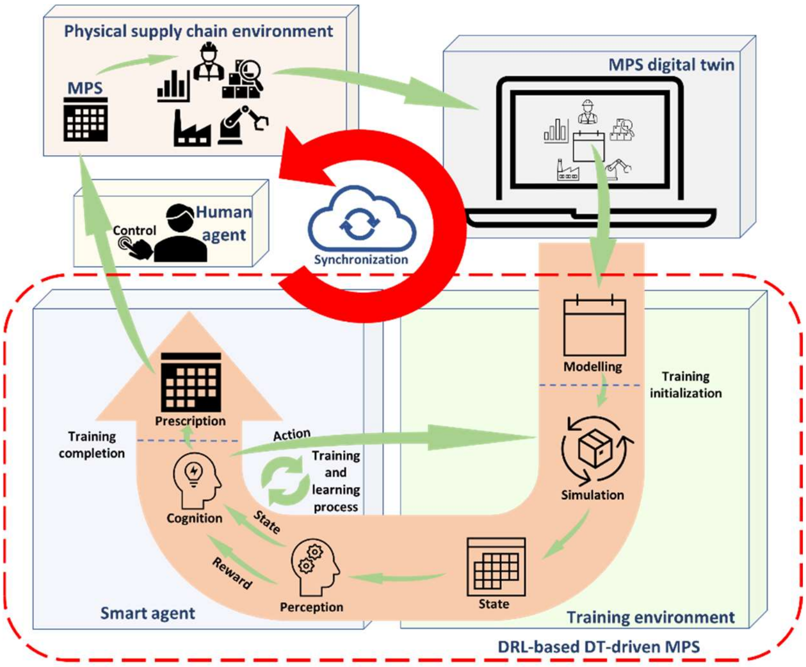

Fig. 2. Setup of DRL-based DT-driven MPS

Basically, the training environment is the MPS modelled in such a way that it is made up of: 1) an observation space; 2) an action space; 3) an initial state; and 4) the action function. The observation space specifies the variables of the MPS issue and delimits the boundaries between which they may vary. The action space determines what actions on the MPS issue can be decided, and to what extent. The initial state represents the state of the MPS in the first time period considered in the master planning, before the application of any action, and is defined by the value adopted by the MPS variables within the observation space in that period. Finally, the action function defines what varies from a state to the next, after applying an action belonging to the valid action space. The DRL agent must play its role in the arena shaped by the above-described environment. In essence, this is a DRL algorithm that collects information about the current MPS state in the training environment and acts on it by triggering an advance to a new state. For this step, the environment grants the agent a reward, whose value depends on a specific policy that assesses how much the new state improves the MPS. With this reward, and by observing the new MPS state, the agent is prepared to perform a new action, which will lead to a new state and a new reward, and so on cycle after cycle.

States and its rewards are stored so that, after enough cycles, the agent covers one part of the observation space that is large enough to start triggering the appropriate action for each MPS state which, from this one, more quickly leads towards either the optimal solution to the issue or a suboptimal one that is accepted as being valid. With it, the training phase finishes, and the agent is trained to continue taking actions in the MPS either semi-autonomously with a prescriber role or even, depending on its reliability level, autonomously as a decision maker.

The MPS issue from this perspective is characterised by an MDP represented by a tuple (S, A, R, δ) where: S is the system's state space, and each state is a vector that collects the real or normalised values of the parameters defining the MPS during each time period; A is the set of control actions; R is the set of possible rewards; δ is a discount factor that acts on future rewards based on an evolutionary policy.

In short, the proposed DT: 1) is conceived as a DSS implemented by the manufacturer, and shared with suppliers, warehousers, distributors and retailers; 2) receives the data and information about the processes and resources required to generate the MPS as input from all these actors; 3) processes the MPS problem autonomously and based on the DRL method; 4) provides, as output, a permanently optimised MPS in the event of any change in input; 5) allows the manufacturer to transmit, without delay, changes to lower planning levels, such as MRP or CRP; 6) derives a master supply schedule to suppliers at their different tiers for their own planning; 7) derives to warehousers, distributors and retailers the available products to promise per period; 8) delimits the data and information of each actor depending on its role. This research work addresses tasks 1 to 6.

5 Conclusions

This paper has proposed an initial DT-based conceptual framework to model, optimise and prescribe the MPS in an SC with SC4.0 attributes and a ZDM context. This framework has focused on optimisation algorithms to solve the MPS problem in the specific described environment, based on applying DT and DRL techniques.

The proposed DT-based model, designed to accommodate the set of actors in the SC, along with their physical and virtual processes and resources, has been described. The DRL-based DT-driven MPS setup has also been presented.

Both the described framework and its configuration are considered to be a first contribution of this research. Its design aims to improve SC performance by reinforcing its digitisation, intelligence, visibility, interconnectedness, organisation and sustainability attributes, which is the goal for any traditional supply chain that to transform into SC4.0 is pretended. DT technology is distinguished by the potential to simultaneously and positively influence all these aspects because: (i) digitisation is an intrinsic property of a DT; (ii) while the commonest purpose of a DT is to simulate, analyse, predict or optimise, the paradigm admits moving one step further towards the action of autonomously prescribing, an ability that lies in the intelligence attribute; (iii) a model in which the DT replicates a specific planning subject (e.g. the MPS) for its shared use across the entire SC has the capacity to take visibility, interconnectedness and organisation qualities to a higher level; (iv) a more effective ZDM strategy facilitated by the model design contributes to SC sustainability.

DRL-based modelling can help to solve the problem of correlating immediate planning actions with their long-term consequences, and to allow big data problems to be tackled. Unlike analytical or heuristic approaches, the DRL-based modelling approach provides an acceptable solution to that problem in a real environment, such as manufacturing, where feedback usually befalls delays in time. It has also been shown that DRL systems are effective tools for dealing with problems for which a numerical resolution is harder because of the large number of possible states.

This proposal has some limitations. The model does not foresee the inclusion of financial considerations. Moreover, the value of the resources involved in the MPS by the actors intervening in the SC means that it is advisable to restrict the DT's prescriptive action in a first stage, so that the final confirmation depends on the human operator. This recommendation would continue to be advisable until the system's reliability has been properly verified.

Regarding the research perspectives, this conceptual framework has to be considered an initial starting point and roadmap for modelling, applications and empirical validations in a real-world SC MPS case study. Additionally, studying if the modelling approach can be extended to other planning levels like MRP, CRP or scheduling is necessary, along with which assumptions and restrictions. This will require further research.

While the proposed conceptual framework accommodates all the actors in the SC, developing the model beyond the manufacturer and its suppliers at the two closest tiers is challenging, and opens up a supplementary research line. The same conclusion is reached for the task of incorporating additional supplier tiers into the previous two, plus logistics warehousers, wholesale distributors, retailers and, finally, customers.

Finally, the described conceptual framework, and the technical background behind the proposed DT, can be adapted to other novel alternative tactical planning frameworks, such as the adaptive sales and operations planning (AS&OP), which derive from the demand-driven adaptive enterprise (DDAE) model, by substituting the MPS subject for other different ones; e.g., replenishment of items in the buffers identified at the tactical level. It also would allow it being modelling as a non-linear and stochastic and/or fuzzy problem, and even being formulated as an MDP, to face uncertainty. This would be a promising future research line to open.

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