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Development of a multidimensional conceptual model for job shop smart manufacturing scheduling from the Industry 4.0 perspective

Julio C. Serrano-Ruiz, Josefa Mula*, Raúl Poler

Universitat Politècnica de València, Research Centre on Production Management and Engineering (CIGIP), C/ Alarcón 1, Alcoy, Alicante, Spain

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ABSTRACT

Based on a scientific literature review in the conceptual domain defined by smart manufacturing scheduling (SMS), this article identifies the benefits and limitations of the reviewed contributions, establishes and discusses a set of criteria with which to collect and structure its main synergistic attributes, and devises a conceptual framework that models SMS around three axes: a semantic ontology context, a hierarchical agent structure, and the deep reinforcement learning (DRL) method. The main purpose of such a modelling research is to establish a conceptual and structured relationship framework to improve the efficiency of the job shop scheduling process using the approach defined by SMS. The presented model orients the job shop scheduling process towards greater flexibility, through enhanced rescheduling capability, and towards autonomous operation, mainly supported by the use of machine learning technology. To the best of our knowledge, there are no other similar conceptual models in the literature that synergistically combine the potential of the specific set of Industry 4.0 principles and technologies that model SMS. This research can provide guidance for practitioners and researchers' efforts to move toward the digital transformation of job shops.

List of acronyms

AMSA	Autonomous master scheduling agent
A2C	Advantage actor-critic
DDPG	Deep deterministic policy gradients
DQN	Deep Q-network
DES	Discrete event simulation
DRL	Deep reinforcement learning
DT	Digital twin
E-DRSA	Event-driven rescheduling agent
FIPA	Foundation for Intelligent Physical Agents
ICT	Information and communication technologies
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of things
JSSP	Job shop scheduling problem
MDP	Markovian decision process
OPC-UA	Open protocol communication unified architecture
OSA	Ordinary scheduler agent
OSI	Open systems interconnection
PHM	Prognostic health management
PPC	Production planning and control
PPO	proximal policy optimisation
SAC	Soft actor-critic
SGD	Stochastic gradient descent
SME	Small and medium enterprise
SMS	Smart manufacturing scheduling
ZDM	zero-defect manufacturing

Introduction

The information and communication technologies (ICT) deployed by the Industry 4.0 paradigm enable the growing complexity of current industrial contexts to be addressed by evolving their production systems toward positions of greater competitiveness, resilience and sustainability [1–3]. Within this technological framework, smart manufacturing scheduling (SMS) promotes the optimisation of production processes in an interoperable interaction context through the synergic application of not only digital twin (DT) technology to enable automatic, autonomous and self-adaptive scheduling in real time, but also the zero-defect manufacturing (ZDM) management model to guide systems and processes towards a scenario without disturbances or disruptions [4]. Thus SMS indicates a way to address the digital and sustainable

* Corresponding author.
E-mail address: fmula@cigip.upv.es (J. Mula).

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transformation of the shop floor with Industry 4.0 principles [3], [5–7] by promoting automation and autonomy in the production processes [8] the ability of the systems that underpin processes to respond in real time to changes in the environment [9], and the configuration of processes, systems and the shop floor environment as a common space of high interoperability [10].

The basic features of these four principles suggest increased efficiency in shop floor processes: (i) automation enables the mechanical reaction of systems to expected changes in the environment based on established patterns to control the evolution of processes [4]; (ii) automation is complemented by autonomy, a capability that allows systems to adapt processes to both planned and unplanned changes in the environment [4]. It should be noted that automation and autonomy can be seen as different manifestations of the same capability because autonomy would represent a high level of automation, understood as a measurable continuum along which low levels denote, for automated systems, the existence of a greater dependence on human control or external systems to perform their function normally, while high levels represent their independence of such controls [8], [11]; (iii) real-time capability enables, in turn, automatic and autonomous systems to interact with the environment on the same time scale by performing their function normally without altering the programmed rate of progress of processes and, thus, avoiding their destabilisation, slowdown or interruption [12]; and (iv) interoperability enables systems to work together, even when using different languages, and/or interfaces, or when operating on different platforms [13]. Hence the individual application of all these four principles adds potential benefits to the efficiency of shop floor processes, and a synergistic effect can be expected from a joint implementation strategy.

The digital transformation strategy in production planning and control (PPC) systems with the processes that comprise their operational decision level becomes feasible by combining DT technology with its offline simulation, analysis and prediction capabilities, and with the ZDM model to mitigate and neutralise in advance any disturbances or disruptions that may alter processes [14]. This article provides a conceptual reference model for the application of the SMS strategy to the job shop scheduling process [4]. The main contribution of this proposal is to establish a structured relation framework for the job shop scheduling process based on the design principles of automation, autonomy, real-time action capability and interoperability in conjunction with DT technology and the ZDM management model to contribute to improve its efficiency and the performance of production dynamics on the whole.

The rest of the article is organised as follows. Section 2 reviews the state of the art on the SMS approach within the job shop frame with the support of the interoperability principle. Section 3 introduces the modelling methodology and, based on the information acquired in the previous section, proposes a conceptual model that relates and integrates the SMS features herein described. Section 4 presents the conclusions and future research lines.

Table 1
Main terms definition.

Term	Definition
Job shop	Machine environment in which each job has its own predetermined route to follow [15].
Scheduling	Decision-making process that deals with the allocation of resources to tasks over given time periods. Its goal is to optimise one objective or more [15].
SMS	Fostering ZDM objectives oriented towards zero-disturbance and zero-disruption to optimise production processes by implementing DTs to facilitate the modelling of automatic and autonomous scheduling systems [4].
Automation	Automatic control of the manufacture of a product through a number of successive stages; the application of automatic control to any branch of industry or science; by extension, the use of electronic or mechanical devices to replace human labour [16].
Autonomy	Ability that orients a system towards adaptive behaviour and decentralised decision-making management to restrict the size of problems and to facilitate their convenient solution in order to eliminate the need for other systems to intervene, or even the human operator[4].
Real-time action capability	A set of conditions, qualities and abilities that allows a device or system to correctly perform a function when interacting with a real-world physical process that shares the same temporal constraints [17].
Interoperability	The ability of two or more systems or components to exchange and use information [18]. The set of abilities and capabilities of a system to interact with other interfaced systems requesting services or products provided by the system with the help of enabling systems. This interaction is requested to fill, in harmony, a common mission reflecting the expectations of all the stakeholders in any situation and possibly for a limited time [19].
DT	Virtual representation (an identical sibling) of an entity in the real world. A DT contains both the attributes and behaviour of the entity that it models, which supports the creation of comprehensive, detailed digital descriptions (definitions and models) of the corresponding subject [20]. The replicated entities can be either physical objects or processes.
ZDM	Holistic approach for ensuring both process and product quality by reducing defects through corrective, preventive and predictive techniques using mainly data-driven technologies by guaranteeing that no defective products leave the production site and reach the customer, and aiming for higher manufacturing sustainability [21].

Literature review

The research is framed within the job shop scheduling process from the SMS perspective as a core concept and its six fundamental pillars: the design principles of automation, autonomy, real-time action capability and interoperability, together with the DT enabling technology and the ZDM management model. All these main concepts appear in Table 1.

Literature review methodology

The methodology used to perform this literature review is based jointly on the works of Thomé et al. [22], which focuses on operations management, and Serrano-Ruiz et al. [4], which centres on SMS. The literature review herein conducted differs from the work of Serrano-Ruiz et al. [4] mainly due to: (i) the time difference between the dates on which the two studies were produced; (ii) the integration of the interoperability concept into the SMS model; and (iii) the context defined by the job shop, which leaves aside other shop floor configurations.

The literature review was organised and carried out along four lines, which are shown in order of sequence in Fig. 1: (i) the adoption of the literature review carried out by Serrano-Ruiz et al. [4] both in methodology and results terms; (ii) a supplementary search in the Scopus and Web of Science databases using the same search methodology as in Serrano-Ruiz et al. [4] to identify new relevant contributions on SMS, which were published between the consultation dates of both studies, namely between 22 February and 18 November, 2021; (iii) filtering all previous results to identify and select only those matching the semantic field "job shop"; and (iv) adding to previous results those obtained in a parallel query of contributions by relating interoperability in the job shop context to one of the scheduling, DT and ZDM concepts or more. The intersection interoperability ∩ job shop ∩ Industry 4.0 has been considered not relevant for the present research because it is far removed from the SMS approach.

Firstly, the 68 papers specified in the SMS literature review were collected from Serrano-Ruiz et al. [4]. Subsequently, four Scopus and Web of Science queries were conducted using the terms "Industry 4.0", "scheduling", "digital twin" and "zero-defects" by defining SMS, in the search fields "title", "abstract" and "keywords" of documents written in English in 2021 of a typology journal article or conference proceedings,

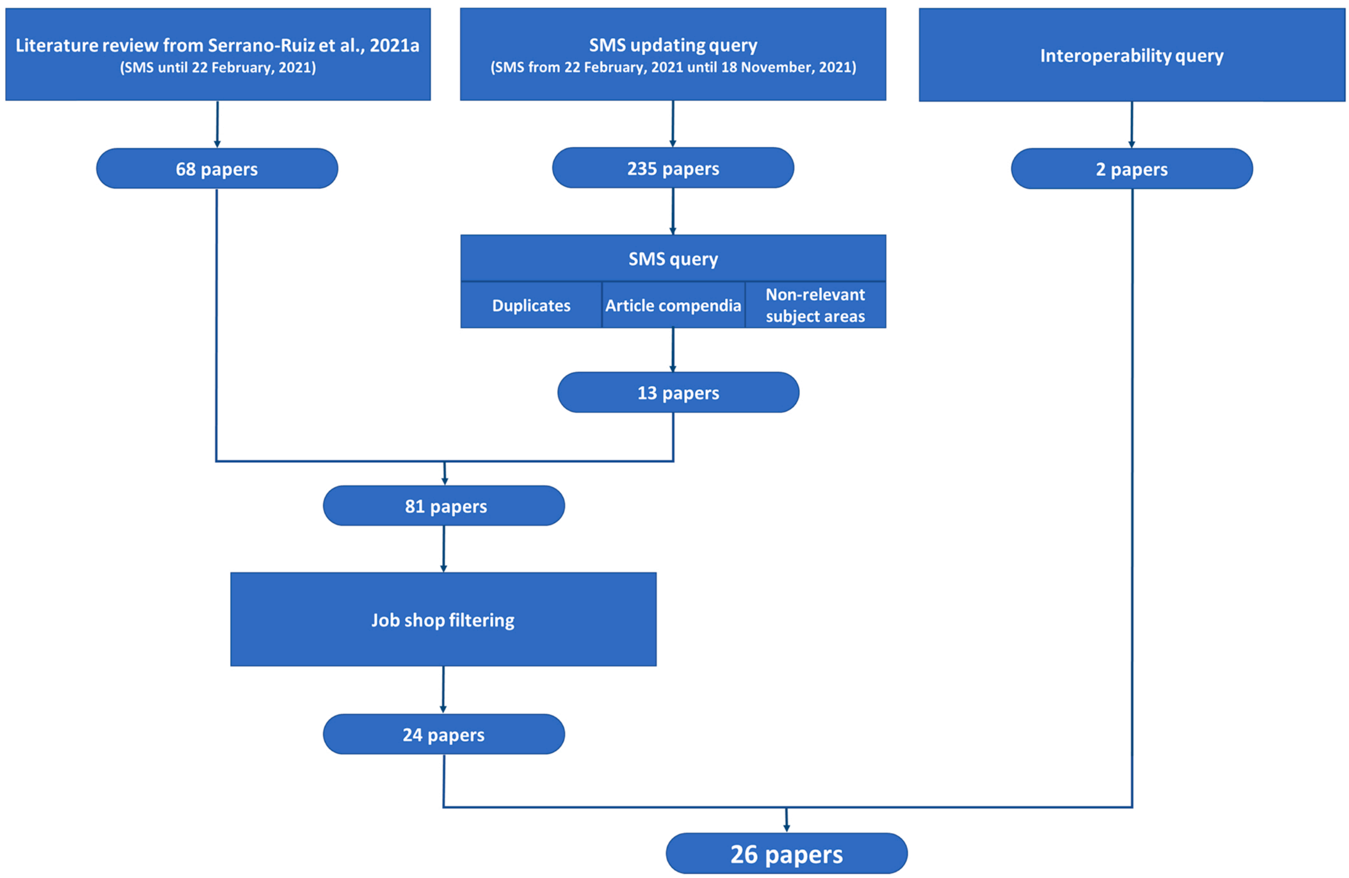

Fig. 1. Searches, collection, quality evaluation, analysis and synthesis methodology diagram (based on Serrano-Ruiz et al. [4]).

and in the subject areas "engineering", "computer science", "business, management and accounting", "decision sciences", and "multidisciplinary" for Scopus, or "management", "engineering manufacturing", "industrial engineering", "engineering multidisciplinary", "automation control systems", "computer science systems", "computer science theory methods", "computer science artificial intelligence", "computer science interdisciplinary applications", "computer science cybernetics", and "operation research management science" for Web of Science. As in Serrano-Ruiz et al. [4], the results were considered relevant where: (i) the association of the three main concepts occurs, called space 1 (scheduling ∩ DT ∩ ZDM); (ii) the scheduling process is assisted by DT technology, but not by the ZDM model, called space 2 (scheduling ∩ DT - space 1); and (iii) the scheduling process is associated with the ZDM model, called space 3 (scheduling ∩ ZDM - space 1). Using these criteria, 158 papers were pre-selected from Scopus and 77 from Web of Science. Then a first non-detailed reading discarded: (i) the papers already present in the 68 from Serrano-Ruiz et al. [4]; (ii) other existing duplicates; (iii) compendia of articles; (iv) those belonging to irrelevant subject areas to this research work; and (v) those whose subject matter was irrelevant to the SMS approach. Ten papers were selected from Scopus and three from Web of Science to be added to the 68 from Serrano-Ruiz et al. [4].

The next step was to refine the query by filtering these 81 papers to discard those that did not specifically apply to the job shop context using the terms "job shop", "job-shop" and "jobshop" as filters to, thus, form conceptual spaces 1', 2' and 3'; and finally select 24 papers (Table 2).

The last step consisted of a literature search in the Scopus and Web of Science databases that related interoperability in the job shop context to at least one of the scheduling, DT and ZDM concepts using the terms "interoperability", "job shop", "scheduling", "digital twin" and "zero-defects", in the search fields "title", "abstract" and "keywords" of the documents written in English since 2010 (excluded) of the journal article or conference proceedings typology. In all, two relevant papers were found in the manufacturing and supply chain spectrum (Table 3), both from the conceptual space called space 4 (interoperability ∩ job shop ∩ scheduling), because the intersection of interoperability and job shop with DT or ZDM did not yield any results.

Fig. 2 graphically represents the research framework of this research work with the consulted conceptual spaces to which the 26 selected papers belong.

Content and taxonomic analysis

Understanding the selected literature and its relation with SMS required a content analysis (Table 4), which consisted of the following:

1. The identification of the research approach.
2. The identification of the SMS features that are the subject of consideration throughout the paper.
3. The identification and description of the model or conceptual framework.
4. The identification of the modelling approach to the posed job scheduling problem.
5. The identification and description of the procedure for solving the job shop scheduling problem (JSSP).
6. The identification of the physical and virtual entities that constitute the DT.
7. The identification of the enabling technologies involved in DT modelling.
8. The identification of the adopted ZDM strategies regarding defects.

Table 2
Selected literature on the conceptual space defined by the SMS and job shop concepts.

	Author/s	Paper title	Conceptual space
1	Barni et al. [23]	Digital twin based optimization of a manufacturing execution system to handle high degrees of customer specifications.	2’
2	Borangiu et al. [24]	Smart manufacturing control with cloud-embedded digital twins.	1’
3	Debevec et al. [25]	Digital twin of unique type of production for innovative training of production specialists.	2’
4	Dobler et al. [26]	Supporting SMEs in the lake Constance region in the implementation of cyber-physical-systems: Framework and demonstrator.	2’
5	Fang et al. [27]	Digital-twin-based job shop scheduling toward smart manufacturing.	2’
6	Feng et al. [28]	Simulation optimization framework for online deployment and adjustment of reconfigurable machines in job shops.	2’
7	Hu et al. [29]	Petri-net-based dynamic scheduling of flexible manufacturing system via deep reinforcement learning with graph convolutional network.	2’
8	Liu et al. [30]	CNC machine tool fault diagnosis integrated rescheduling approach supported by digital twin-driven interaction and cooperation framework.	2’
9	Magnanini et al. [31]	Effect of work-force availability on manufacturing systems operations of job shops.	2’
10	Majdzik et al. [32]	(IMS2019) Integrated fault-tolerant control of assembly and automated guided vehicle-based transportation layers.	2’
11	Park et al. [33]	Digital twin application with horizontal coordination for reinforcement-learning-based production control in a re-entrant job shop.	2’
12	Psarommatis et al. [34]	A computational method for identifying the optimum buffer size in the era of zero defect manufacturing.	3’
13	Psarommatis et al. [35]	Identification of the critical reaction times for re-scheduling flexible job shops for different types of unexpected events.	3’
14	Psarommatis et al. [36]	Improved heuristics algorithms for re-scheduling flexible job shops in the era of zero defect manufacturing.	3’
15	Psarommatis et al. [37]	A two-layer criteria evaluation approach for re-scheduling efficiently semi-automated assembly lines with high number of rush orders.	3’
16	Psarommatis and Kiritsis [38]	A hybrid decision support system for automating decision making in the event of defects in the era of zero defect manufacturing.	3’
17	Serrano-Ruiz et al. [39]	Smart digital twin for ZDM-based job shop scheduling.	1’
18	Yan et al. [40]	Research on flexible job shop scheduling under finite transportation conditions for digital twin workshop.	2’
19	Yu et al. [41]	Job shop scheduling based on digital twin technology: A survey and an intelligent platform.	2’
20	Zhang et al. [42]	Digital twin-driven cyber-physical production system towards smart shop-floor.	2’
21	Zhang et al. [43]	Review of job shop scheduling research and its new perspectives under Industry 4.0.	2’
22	Zhang et al. [44]	Bi-level dynamic scheduling architecture based on service unit digital twin agents.	2’
23	Zhang et al. [45]	Digital twin enhanced dynamic job shop scheduling.	2’
24	Zupan et al. [46]	Local search with discrete event simulation for the job shop scheduling problem.	2’

Table 3
Selected literature on the conceptual space defined by interoperability ∩ job shop ∩ scheduling.

	Author/s	Paper title	Conceptual space
1	Bloomfield et al. [10]	Interoperability of manufacturing applications using the core manufacturing simulation data (CMSD) standard information model.	4
2	Chou et al. [47]	A bio-inspired mobile agent-based integrated system for flexible autonomic job shop scheduling.	4

9. The evaluation of the degree of automation of the adopted ZDM strategies.
10. The approach given to the interoperability principle in research.

First of all, it is worth noting that the objectives of none of the papers is to deepen knowledge and to improve the state of the art as regards a similar approach to that proposed herein for SMS. Hence it can be deduced that it is a novel approach. Nevertheless, almost all the papers, albeit partially, contribute to SMS by providing knowledge about the main SMS features in the job shop context, which allows a robust conceptual model to be built. In addition, several aspects can be drawn from the performed quantitative and qualitative analyses of content: (i) the majority research approach is experimental, used in 24 of the 26 papers, which implies that the presented approaches, frameworks or models have been empirically validated; (ii) the most widely addressed SMS features are automation (24 papers), real-time action capability (21 papers) and DT (21 papers); (iii) five of the papers (Table 4, papers 1, 14, 16, 23 and 26) do not introduce new frameworks or models, but provide studies, improvements or reviews of the state of the art on SMS-related topics; (iv) of the 21 articles defining new models or frameworks, in 15 (Table 4, papers 4, 5, 6, 7, 9, 10, 11, 15, 17, 19, 20, 21, 22, 24 and 25) the main object of modelling is the job shop scheduling process. In the other six (2, 3, 8, 12, 13, and 18), processes from the supply chain and manufacturing context are modelled, and implications for the scheduling process exist, but with a secondary role or with an indirect implication; (v) the most frequent modelling purpose is the rescheduling process of the job shop for certain events or situations (Table 4, papers 10, 15, 17, and 25), such as defect detection, receipt of urgent orders or machine breakdowns. The presented models and frameworks also address other purposes of interest for the SMS job shop model, such as automation, interoperability, flexibility, coordination with plant transport elements, integration with cloud platforms, and interaction with scheduling processes in logistics or inventory contexts; (vi) the most frequent JSSP modelling approach in the reviewed literature is heuristic (10 papers), but the difference with analytical (seven papers), simulation (six papers) and artificial intelligence (six papers) models is small; (vii) the majority of the reviewed papers that adopt the DT as an enabling technology establish the shop floor itself with its production assets as a physical entity, such as resources, orders and products, and/or its systems, such as control, tracking or maintenance. Only four of the papers take the scheduling process as the physical entity per se subject to

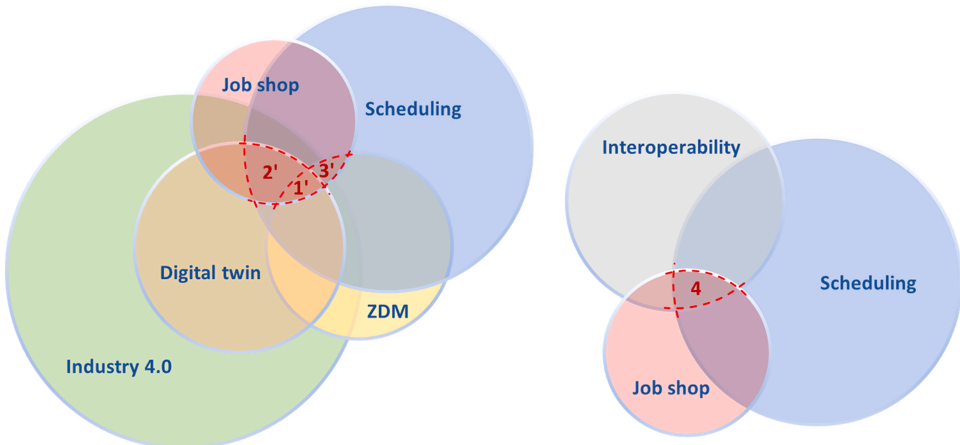

Fig. 2. Graphical representation of the research framework, sum of the conceptual spaces:(i) scheduling ∩ DT ∩ ZDM ∩ job shop, called space 1', (ii) ((scheduling ∩ DT) - space 1) ∩ job shop, called space 2', (iii) ((scheduling ∩ ZDM) - space 1) ∩ job shop, called space 3', and (iv) interoperability ∩ job shop ∩ scheduling, called space 4.
Based on Serrano-Ruiz et al. [4].

virtual replication, because most consider systems, or the combination of systems and processes, the physical entity; (viii) something similar applies with the virtual entity established for the DT as only two papers choose to limit virtualisation to the scheduling process; (ix) of the key technologies involved in modelling the DT, simulation stands out. More than half the papers (14 papers) consider simulation an inseparable part of the DT. Machine learning, sensorisation (both with six papers each) and cloud computing (five papers) are at some distance away from the next most involved technologies, big data, Internet of Things (IoT), and prognostic and health management (PHM) (with four papers each); data mining (two papers) and augmented reality (1 paper) are relegated to the bottom of this scale; (x) seven of the papers consider ZDM up to a point, but of them, none of the four possible strategies regarding defects stands out as the most frequent, which is also the case for the automation level of the ZDM strategy in shop floor processes; and (xi) up to 10 papers contemplate interoperability; here it is worth noting that all three strategies considered in the analysis appear in the selected papers, and the use of standardised protocols is the most numerous with seven papers, followed by employing the DT with four papers, and the design and use of ontologies with three papers. Fig. 3, Fig. 4 and Fig. 5 graphically summarise the information on these findings.

The reviewed literature contains some models or conceptual frameworks that deserve being paid more attention given the existence of a relevant degree of alignment with the SMS approach. For example, this is the case of the agent-based integrated system for flexible autonomic job shop scheduling by Chou et al. [47], with a hierarchical agent structure, in which a scheduling centre agency interacts with the agents corresponding to each manufacturing cell or shop floor machine; each agent is assigned different specialised functions and is given differentiated access to order or machine databases, and all this with both decentralised decision making and high interoperability. The latter is facilitated by the system's compliance with the FIPA (Foundation for Intelligent Physical Agents) standard from Institute of Electrical and Electronics Engineers (IEEE); the whole leads to greater automation, autonomy, real-time action capability and the ZDM objective, all of which are elements of the SMS approach. Zhang et al. [44] also envisage the virtual job shop as a hierarchical environment formed by agents. In this case however, it is configured at two levels with the presence of a central agent, where the upper level implements three agents for the scheduling of production, inventory and logistics, while the lower level virtually replicates each job, which is an example of integration of the supply and storage perspective into job scheduling. The perspective of Fang et al. [27] on the interaction of the elements forming part of the physical and virtual planes in the job shop and its dynamic interactive scheduling strategy is also noteworthy and, in this case, from the DT technology perspective and given the possibilities of its effective implementation. The research of Hu et al. [29] and Liu et al. [30] provide two different approaches, both based on the DT, that show how machine learning can drive the scheduling process towards greater efficiency or resilience, respectively, by either: fostering greater adaptability of the scheduling process to the stochastic manufacturing environment, an approach that is presented by Hu et al. [29], or integrating the fault diagnosis of shop floor resources into scheduling, as investigated by Liu et al. [30]. Both possibilities lead to more reliable and robust automation that is less prone to the effects of certain disturbing or disrupting events, which is also oriented towards SMS. Magnanini et al. [31] show the effect of work-force availability on the scheduling process by, thus, introducing a realistic point of view for those job shops that integrate operators by foreseeing the problems that derive from this circumstance, but also from a sustainable point of view by introducing human factor considerations into their model. The framework presented in the research by Psarommatis et al. [37] offers the potential usefulness for assessing rescheduling needs in ZDM contexts where urgent orders regularly occur. The model presented by Psarommatis and Kiritsis [38] further deepens the previous approach, and adds the integration of an online quality analysis of the manufacturing process with a hybrid scheduling model, and tends not to only react by generating production rescheduling when the occurrence of a quality event renders it necessary, but to also act by mitigating the effect of such events, which favours a more stable planning context, a ZDM context and, consequently, alignment with SMS. The research of Yan et al. [40] addresses the transport systems that configure the job shop as a space in which transport conditions are finite, by favouring the possibilities of scheduling automation through the intervention of a DT designed specifically to monitor and simulate the scheduling insertion strategies of both process and transport device jobs. It is also worth highlighting the dynamic improvement approach of the scheduling process assisted by the DT, which is based on the monitoring and simulation of the scheduling strategies of both process and transport device jobs. Finally, the work by Zhang et al. [45] is based on monitoring machines to detect and identify alterations in the physical magnitudes of the manufacturing process to help to anticipate risks to its continuity to be able to automatically generate rescheduling instances.

In light of all that stated so far about the selected literature, we find that although it offers a rich variety of approaches, they all have something in common: from the SMS perspective, all the contributions present partial approaches that, to a greater or lesser extent, leave aside some of the axes that define SMS as a strategy, such as its design

Table 4
Content analysis of the selected literature.

	Author/s	Research approach	SMS features	Model or conceptual framework introduction	Scheduling modelling approach	Scheduling solution approach	DT physical entity	DT virtual entity	DT Key enabling technology	ZDM strategy	ZDM automation level	Interop. approach
1	Barniet al.[23]	E	DT	–	H/S	Modified sorting algorithm	Planning, performing and supervising production jobs	The feasible schedule and shop floor 3D visualisation	SM	–	–	–
2	Bloomfieldet al.[10]	E	AT/RTIT/DT	A framework that enhances interoperability between manufacturing applications throughout multiple stages of life cycle, even planning	S	A commercial scheduler	The physical system	The manufacturing system of a new product being developed	SM	–	–	SP
3	Borangiuet al.[24]	E	AT/AURT/ ITDT/ZDM	A model for the smart control of large-scale manufacturing systems	A/AI	A timed smart decision-making procedure	Production assets (resources, products, orders) and the system (control, tracking, maintenance)	A view of past, current and future states and behaviors of shop floor resources, processes and outcomes	BD/DM/CCML/ IoTPHM	DE/PR	–	DT
4	Chouet al.[47]	E	AT/AURT/IT	A model of a bio-inspired mobile agent-based integrated system for flexible autonomic job shop scheduling	H	Genetic algorithm	–	–	–	–	–	SP
5	Debevecet al.[25]	E	AT/RTDT	A DT-based model called unique type of production	–	–	Schedule plan, machining parts, resources and energy	Schedule and resource data and simulation results	SM	–	–	–
6	Dobleret al.[26]	E	AT/AURT/DT	A framework to support small- and medium-sized enterprises (SMEs) in the Lake Constance region for the optimisation of manufacturing lines	C/H/S/S/AI	As-is simulation, artificial intelligence simulation, Giffler and Thompson algorithm, ant colony optimisation algorithm with and without filter	The current job shop situation	The virtual job shop situation at four layers for each machining type	SM/ML	–	–	–
7	Fanget al.[27]	E	AT/RTDT	A scheduling model with DT	A,H	Fast non-dominated sorting genetic algorithm	Scheduling resources and scheduling execution	Scheduling data and scheduling models	BD/S/CCSM/IoT	–	–	–
8	Fenget al.[28]	E	AT/RTDT	A simulation model of reconfigurable machines in the job shop	H/S	Tabu search algorithm	Job shop	Job shop monitoring, decision making and control	S	–	–	–
9	Huet al.[29]	E	AT/AURT/DT	A model to solve the dynamic scheduling problem of flexible manufacturing systems	AI	Algorithm 1: Discrete event simulation (DES) Algorithm 2: Deep Q-Network scheduling agent	The system, that involves shared resources, route flexibility and stochastic arrivals of raw products	The virtually replicated manufacturing system	SM/ML	–	–	–
10	Liuet al.[30]	E	AT/RTIT/ZDM	A computer numerical control machine tool fault diagnosis and	AI	A Monte Carlo tree search algorithm	Data aware machines and devices in the smart shop	Shop rescheduling, maintenance and knowledge	DM/S/S/SMML/ PHM	DE/PR		O

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Table 4 (*continued*)

	Author/s	Research approach	SMS features	Model or conceptual framework introduction	Scheduling modelling approach	Scheduling solution approach	DT physical entity	DT virtual entity	DT Key enabling technology	ZDM strategy	ZDM automation level	Interop. approach
				production rescheduling model								
11	Magnaniniet al.[31]	E	AT/DT	A general data model of operators and operators' tasks in a DT based on a parametric DES model	S	DES	The real job shop system	The virtual job shop system based on a data model, a parametric DES, a key performance indicators module and a user interface	S/SM	–	–	–
12	Majdziket al.[32]	E	AT/RTDT	A max-plus algebra-based DT model of the flexible assembly system	A	Algorithm 1: The model predictive control of automatic guided vehiclesAlgorithm 2: A fault-tolerant control	The flexible assembly system	A max-plusalgebra-baseddigital model of the flexible assembly system	S	–	–	–
13	Parket al.[33]	E	TA/ITDT	A production control model based on reinforcement learning for efficient control in a re-entrant job shop	AI	The duelling networks technique	The real production system	A virtual system for production control	IoT/SM/ML	–	–	SP/O/DT
14	Psarommatiset al. [34]	E	AT/ZDM	–	H	Tabu search algorithm	–	–	–	–	–	–
15	Psarommatiset al. [35]	E	AT/RTZDM	A model for rescheduling in the scenario of unexpected events in the ZDM context	A	Events management algorithm	A specific ZDM strategy in a manufacturing stage	Utility value	SM/PHM	DE/REPS/PV	S	–
16	Psarommatiset al. [36]	E	ZDM	–	H	Tabu search algorithm	–	–	–	–	–	–
17	Psarommatiset al. [37]	E	AT/RTZDM	A two-layer criteria evaluation model for rescheduling with rush orders	–	–	–	–	–	PV	M	–
18	Psarommatis and Kiritsis[38]	E	AT/AURT/ ITZDM	A model to automate the decision-making procedure in the event of defect detection	S	–	–	–	–	DE/REPV	A	O
19	Serrano-Ruizet al. [39]	C	AT/AURT/ DTZDM	An initial conceptual conceptual smart DT framework for scheduling job shop orders in a ZDM environment	AI	Deep reinforcement learning (DRL)	Physical job shop	A smart DT for monitoring, training and prescription	CC/SM/ML	DE/PR	S/A	–
20	Yanet al.[40]	E	AT/RTIT/DT	A flexible JSSP model under finite transportation conditions	A	Improved genetic algorithm	Physical shop floor	Virtual equipment	SM	–	–	SP
21	Yuet al.[41]	E	AT/AURT/DT	A model of an intelligent dispatching cloud	H	An integrated management scheduling algorithm	Physical shop floor	Virtual shop floor	BD/S/CCSM/IoT	–	–	–

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Table 4 (*continued*)

	Author/s	Research approach	SMS features	Model or conceptual framework introduction	Scheduling modelling approach	Scheduling solution approach	DT physical entity	DT virtual entity	DT Key enabling technology	ZDM strategy	ZDM automation level	Interop. approach
				platform to solve the JSSP		based on a genetic algorithm						
22	Zhanget al.[42]	E	AT/AURT/ITDT	A product manufacturing DT model to support job scheduling	H	Genetic, differential evolution or simulated annealing algorithms	Shop floor	Digital shop floor	BD/CC/SMHR/PHM	–	–	SP/DT
23	Zhanget al.[43]	C	AT/AURT/DT	–	–	–	–	–	–	–	–	–
24	Zhanget al.[44]	E	AT/AURT/ITDT	A bilevel distributed dynamic scheduling model based on a DT scheduling agent	H	A multi-agent negotiation algorithm	Physical manufacturing resources	Virtual manufacturing resources	BD/S/SM/MLIoT/PHM	–	–	SP/DT
25	Zhanget al.[45]	E	AT/RTIT/DT	A DT-enhanced dynamic scheduling model	A	Genetic algorithm	Physical shop floor elements	Production and logistics service units for virtual scheduling	SM/IoTPHM	–	–	SP
26	Zupanet al.[46]	E	DT	–	H	Multistart local search "Remove and Reinsert" algorithm	JSSP	Virtual JSSP	SM	–	–	–
S/N	This paper	C	AT/AURT/ITDT/ZDM	A multidimensional conceptual model for job shop smart manufacturing scheduling	S/AI	A DRL framework with simulation-based training of both production processes and disturbing events	JSSP	Virtual JSSP	BD/DM/SIoT/CC/SMML/PHM	DE/REPR/PV	A	SP/O/DT

Note: research approach: **C** (conceptual), **E** (empirical); SMS feature: **AT** (automation), **AU** (autonomy), **RT** (real-time action capability), **IT** (interoperability), **DT** (digital twin), **ZDM** (zero-defect manufacturing); modelling approach: **C** (conceptual), **A** (analytical), **H** (heuristics), **S** (simulation), **AI** (artificial intelligence); DT enabling technology: **BD** (big data), **DM** (data mining), **S** (sensorisation), **IoT** (Internet of things), **CC** (cloud computing), **SM** (simulation), **ML** (machine learning), **AR** (augmented reality), **PHM** (prognostic health management); ZDM strategy regarding defects: **DE** (detection), **RE** (repair), **PR** (prediction), **PV** (prevention); ZDM automation degree: **A** (automatic), **SA** (semiautomatic), **M** (manual); interoperability approach: **SP** (based on standardised protocols), **O** (with the design and use of ontologies), **DT** (based on the inherent interoperability characteristic of the DT).

principles, the enabling technology of the digital twin or the ZDM management model. The reason for this may be due to the fact that, in order to cover the entire technological spectrum underlying SMS, it is necessary to intervene in not only the PPC area, but also in other areas of the operations management field, such as quality management or maintenance management, and in other fields like ICT, which is a considerably difficult task on the whole. The research presented in this paper addresses this difficulty from a holistic perspective, which integrates the whole to outline how planning processes interact with the other areas involved in the operations management field to ensure the ZDM strategy, and how ICT can configure the DT to ensure the desired automation, real-time action capability and interoperability; and all this exclusively from the modelling domain defined by the PPC area. Additionally in other fields like the IoT [48], real-time scheduling has also been identified as a complex problem that requires new techniques like agent-based scheduling, which can employ reinforcement learning to offer more efficient results. The flow shop research by Sahin et al. [49] shows that multi-agent system-based environments, in which each agent is endowed with autonomy, form a more suitable structure for handling dynamic events simultaneously in real-time, and this enables the possibility of scheduling systems to operate online, a solution that is very much demanded by industry and clearly aligns with SMS.

SMS conceptual model

The methodology adopted to carry out SMS modelling is based on the proposal by Hernández et al. [50] for PPC processes. The five phases of the proposal adapted to the SMS modelling process are (Fig. 6): (i) visualisation, (ii) analysis, (iii) conceptualisation, (iv) modelling; and (v) proposal.

SMS Dimensions

In Serrano-Ruiz et al. [4], three trends in researchers' approaches to the SMS approach are identified: (i) approaches whose alignment with SMS lies in applying DT enabling technology and/or the ZDM management model, as core enabling tools; (ii) approaches whose alignment with SMS is highlighted by the additional application of some of the main enabling digital technologies of the Industry 4.0 paradigm, other than the DT technology or the ZDM model, as a supplementary support to them; and (iii) approaches whose alignment stems from providing scheduling systems with the inherent capabilities of SMS. Of these three trends, 13 axes of alignment with SMS were identified (Fig. 7) by showing the main implementation paths in each trend to point towards automatic and autonomous scheduling that is synchronised in real time with physical shop floor processes. Additionally, this state-of-the-art review identifies the research present in the literature that contributes to shape all the alignment axes and discusses the most immediate implications deriving from it.

From there, the next step is to determine the modelling domain by defining its dimensions, and to establish the interrelation framework of the SMS conceptual model. It is assumed that all three tendencies identified by Serrano-Ruiz et al. [4] can constitute a dimension of the SMS conceptual model because the possible set of their combinations integrates all the possible SMS approaches. However, the role played by each dimension differs. While the use of the DT and ZDM support in conjunction with some other Industry 4.0 enabling technology may be qualified as a push strategy, where the focus of the approach to SMS lies on the tools and means to drive production systems and processes towards it, the purpose of approaching SMS by equipping systems and processes with its inherent capabilities can be said to be a pull strategy, where the focus falls on the intended outcome, and the purpose is to pull systems towards that outcome.

In this proposal, the conceptual SMS model is constructed by starting from enabling tools, which would constitute input dimensions, to achieve the inherent capabilities of SMS which, in this case, would constitute output dimensions. Based on this approach, the conceptual construct of SMS in the job shop scheduling context could be graphically represented as a three-dimensional space (Fig. 8) in which: (i) the first dimension is marked, as main enabling tools, by DT technology and the ZDM model, which are referred to as SMS core tools; (ii) the second dimension is marked by the nine enabling technologies identified in the reviewed literature, i.e. big data, data mining, sensorisation, IoT, cloud computing, simulation, machine learning, augmented reality and PHM of production systems, herein referred to as SMS assisting technologies; and (iii) the third dimension is shaped by the principles of automation design, real-time action capability and interoperability but, additionally, the resilience of the scheduling process to potentially disruptive events is added. Together the four would configure the SMS capabilities.

The autonomy concept is not used in the construct because it is assimilated as a high automation level, understood as a continuum from its lowest level, where the dependence of the system under study for information acquisition and analysis, decision selection and action implementation on other systems, or on the human operator, is complete, up to its highest level, where, ideally, such dependence does not exist [8], [11].

In the represented conceptual construct, all the 72 possible combinations of the three dimensions constitute a vector of potential alignment with SMS that is defined by coordinates CT, AT and CAP where: (i) the alignment with SMS occurs by aiming to obtain a capability (CAP), selected from among the four considered, by applying the combination of one of the two SMS core tools (CT) and one of the nine SMS assisting technologies (AT); (ii) the larger the number of vectors considered in implementing a job shop scheduling process, the higher the degree of alignment with SMS; (iii) the alignment potential of the 72 vectors is heterogeneous insofar as while this potential is high in some vectors, it may be lower in others, to the extent that it is irrelevant; and (iv) existing knowledge on the 72 vectors and their potential for alignment with SMS are also uneven. In some cases this is because of either the evidence and immediacy of their synergic interrelation or the existence of literature that validates this interrelation. This is the case, e.g., of the vector (1,7,1), which identifies the actions that lead to greater automation of the job shop scheduling process through DT technology assisted by machine learning techniques, as seen, for example, in the proposal of Park et al. [33]; or the vector (2,9,4), which distinguishes the actions performed to improve the resilience of the job scheduling process to events of a disturbing and/or disruptive nature by the ZDM strategy and the assistance of techniques for the PHM of production systems, as in the work of Psarommatis et al. [35]. However, there are also certain vectors that are only slightly addressed or are ignored, such as (2,8,2), which points out actions that aim to promote improvements in the real-time action capability of the job scheduling process through the ZDM strategy using augmented reality techniques, an approach that is not mentioned in the literature. Such lack of knowledge about certain vectors may evidence either a research gap or simply the fact that the vector under study lacks value. This construct constitutes a structured conceptual space for SMS-related concepts and their interrelations, and establishes a qualitative basis on which to develop its conceptual model by identifying and relating each of its potential benefits.

SMS conceptual model

Its structure is based on the division of contexts that the DT technology proposes through the idealisation and segregation of the job shop scheduling process into two different environments: the physical and the virtual. The artifice involved in this idealisation basically aims to create an environment that replicates the scheduling process as closely as possible beyond the physical plane, where analysis, simulation and optimisation are enabled in isolation and can be carried out on sidelines without altering the normal course of production processes, except on those occasions when the intervention of systems in this virtual environment is actually required.

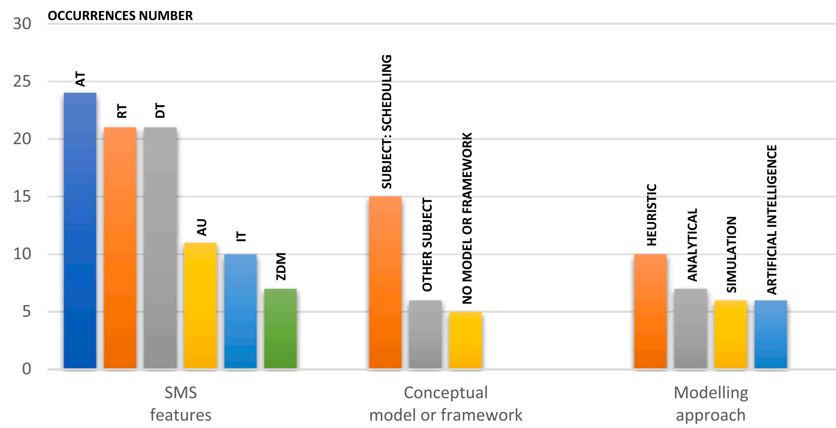

Fig. 3. Main characteristics of the selected papers in the literature on SMS.

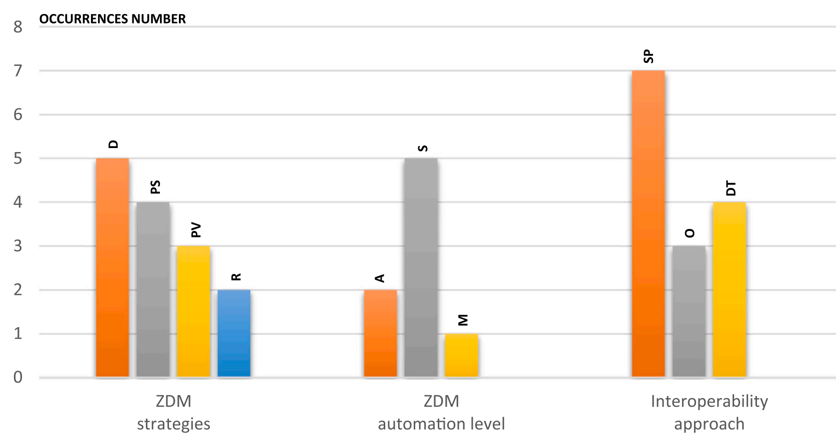

Fig. 4. The DT modelling approach used in the selected papers in the literature on SMS.

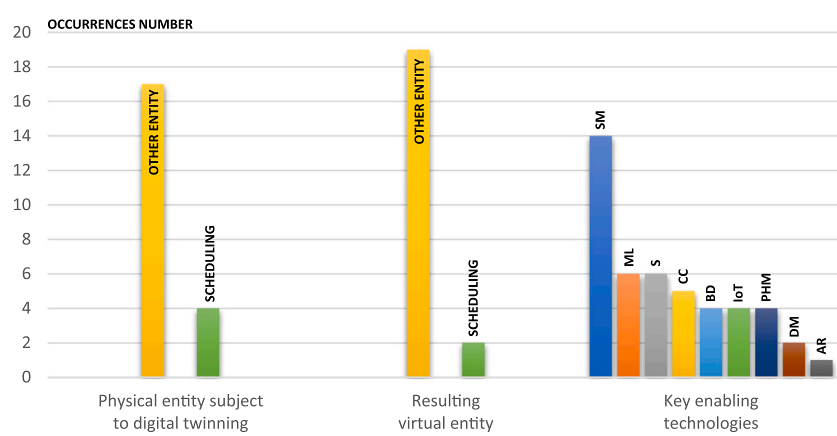

Fig. 5. ZDM and interoperability approaches of the selected papers in the literature on SMS.

The performance of the proposed model is aligned with that of the SMS conceptual construct (Fig. 8). The result of exploring the interrelations that are directly or indirectly manifested between enabling tools and capabilities, vector by vector among the 72 potentially possible ones (Fig. 9), points to a significant level of convergence with SMS.

Neither the physical SMS environment nor the entire virtual environment are not the focus of modelling. In line with this, the proposed model relegates physical systems and processes to the background, including the sensing and control layer, to consider that their research does not form part of the PPC field itself despite the characteristics of the physical SMS environment are critical for the model's feasibility. Here the approach that SMS outlines matches an automated, interoperable and data-driven physical job shop context with online quality processes. All those systems and elements needed to establish the necessary interconnection with the modelled virtual environment, which are represented in Fig. 10 by the seven layers of the standard open systems interconnection (OSI) model, are obviated for the same reason

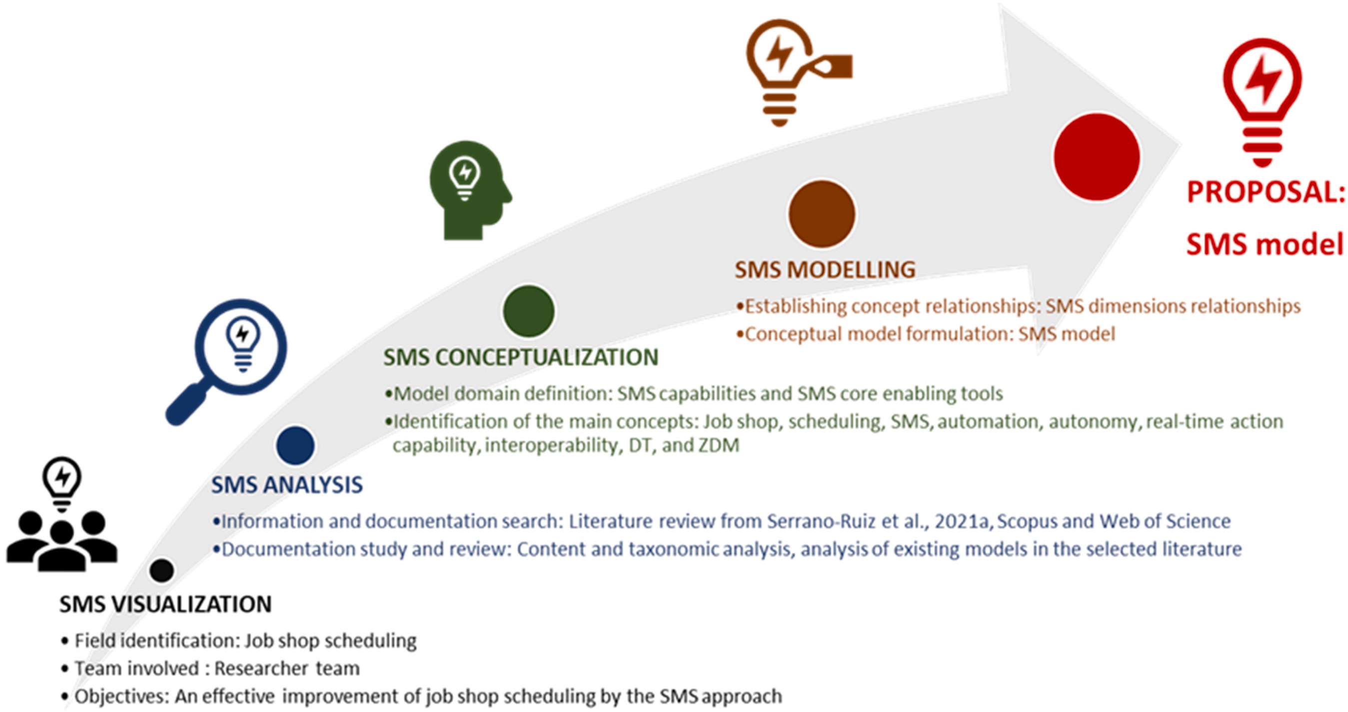

Fig. 6. SMS modelling process.
Based on Hernández et al. [50].

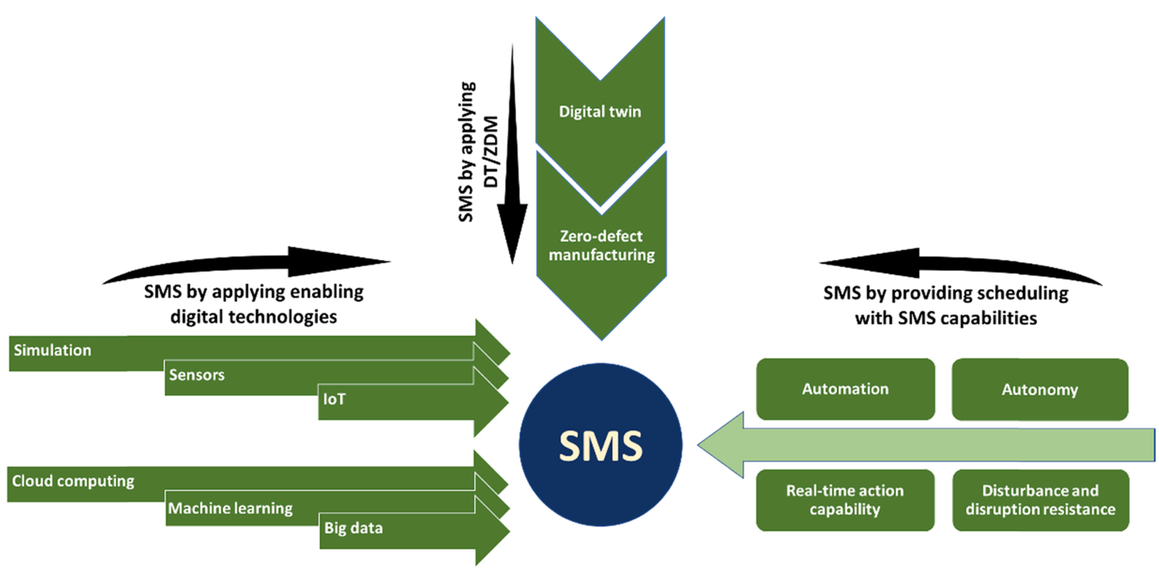

Fig. 7. SMS classification map.
Source: Serrano-Ruiz et al. [4].

regardless of them belonging to one environment or the other. Similarly, an element belonging to the job scheduling virtual environment, which is as important for the SMS approach as the cloud manufacturing platform is also skipped in the proposed model. Using a decision model to organise and manage the resources and services provided by the participants of a cloud manufacturing environment is crucially relevant for the system's effectiveness and efficiency [51]; indeed, a smart manufacturing approach effectively based on Industry 4.0 must start from the premise that organisations should share their manufacturing resources so that: when demand exceeds their capacity, the organisation overcomes this constraint by acquiring the right to use the capacity offered by other organisations; or when their capacity exceeds demand, the organisation can materially make this excess capacity available to other organisations [52]. Both assumptions are hardly possible outside a cloud-based manufacturing environment. The modelling of this environment type admits a remarkable diversity of approaches, ranging from the two-stage mechanism for production planning and revenue allocation by Suginouchi and Mizuyama [52], to the three resource-sharing strategies proposed by Cao et al. [53], and includes other models like those proposed by Carlucci et al. [51] based on the non-cooperation model in the minority game theory, or that of Liu et al. [54] based on the Gale-Shapley algorithm.

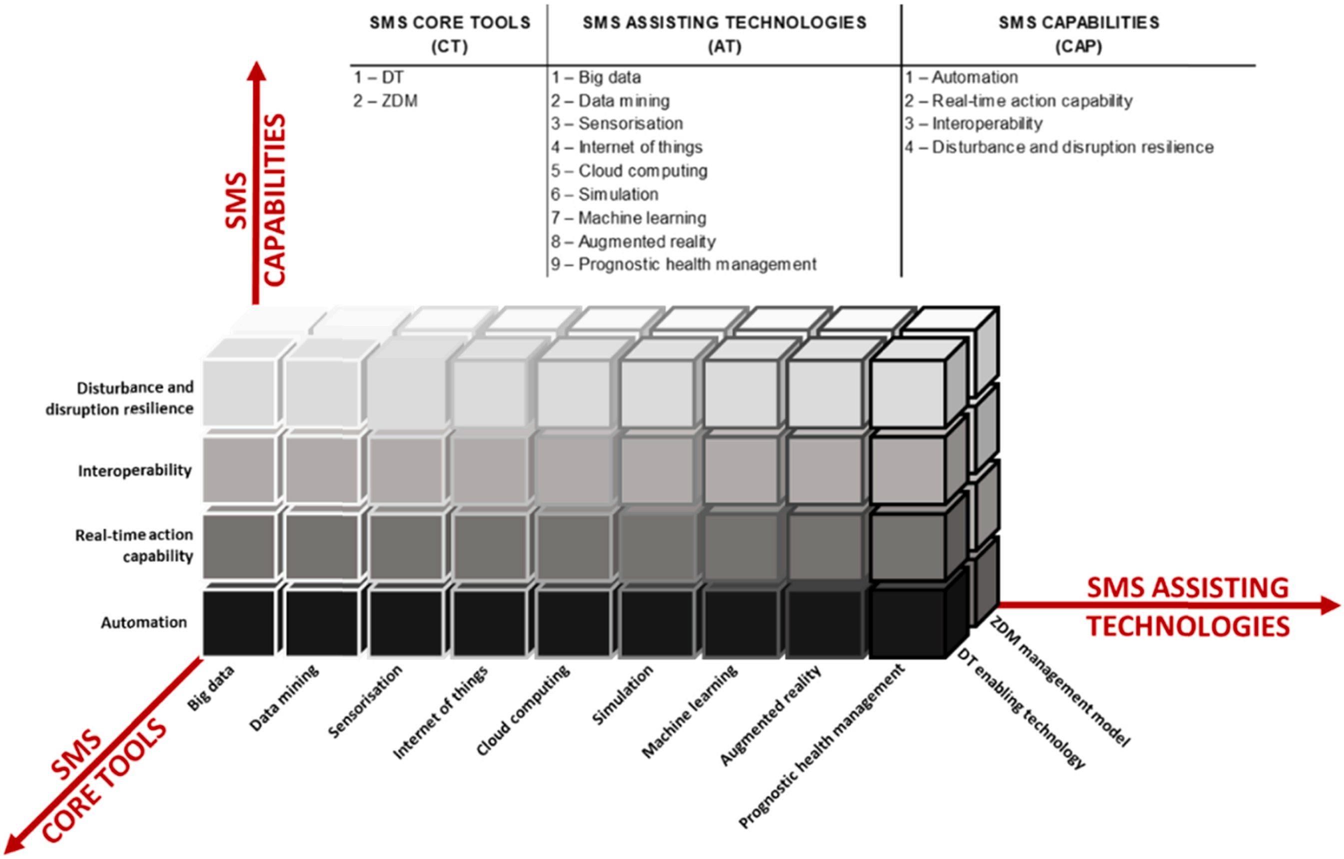

Fig. 8. SMS dimensions: core tools, assisting technologies and capabilities.

Therefore, modelling work is restricted to the part of the virtual environment where the whole logical process of the DT is carried out, which in Fig. 10 is delimited by the thick green line that includes the so-called ontology-based virtual SMS frame. At this point, it is worth highlighting the main peculiarities of its configuration: (i) the whole set rests semantically on the ontology by Serrano-Ruiz et al. [55]; (ii) it is characterised by a hierarchical agent structure, where an autonomous master scheduling agent (AMSA) controls the performance of other agents; (iii) the scheduling dynamically progresses without a closed order sheet or a predefined end period and, therefore, is subject to the flow of new orders; (iv) the scheduling progress is observed and conceptualised as a Markovian decision process (MDP); (v) the modelling approach is a hybrid DRL system, in which an ordinary scheduler agent (OSA), based on a deep Q-network (DQN), captures as a state a set of defining features of the JSSP to approximate its value function and policy by means of a neural network. Then this neural network is trained with an optimiser such as the stochastic gradient descent (SGD) algorithm, to obtain the optimal (or near-optimal) prioritisation of the jobs corresponding to the current state during the ordinary course of the scheduling process. The state preparation process for the neural network is based partly on the two-dimensional convolution transformation method proposed by Zang et al. [56]; (vi) the ordinary course of scheduling is altered by four categories of extraordinary events, which trigger rescheduling through the action of four different specialised agents called event-driven rescheduling agents (E-DRSAs), which act by modifying the JSSP to newly prioritise jobs, or reprioritisation, without modifying the weights and biases of the neural network, except in the most extreme cases where the magnitude of the evaluated change

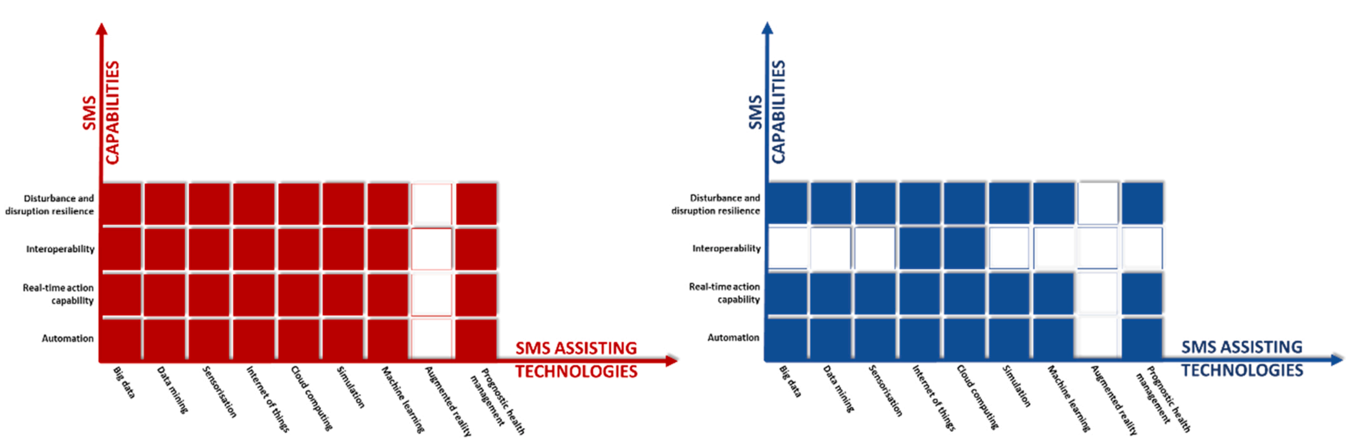

Fig. 9. DT (denoted in red) and ZDM (shown in blue) as core enabling tools: The interrelations considered in the model among the SMS dimensions.

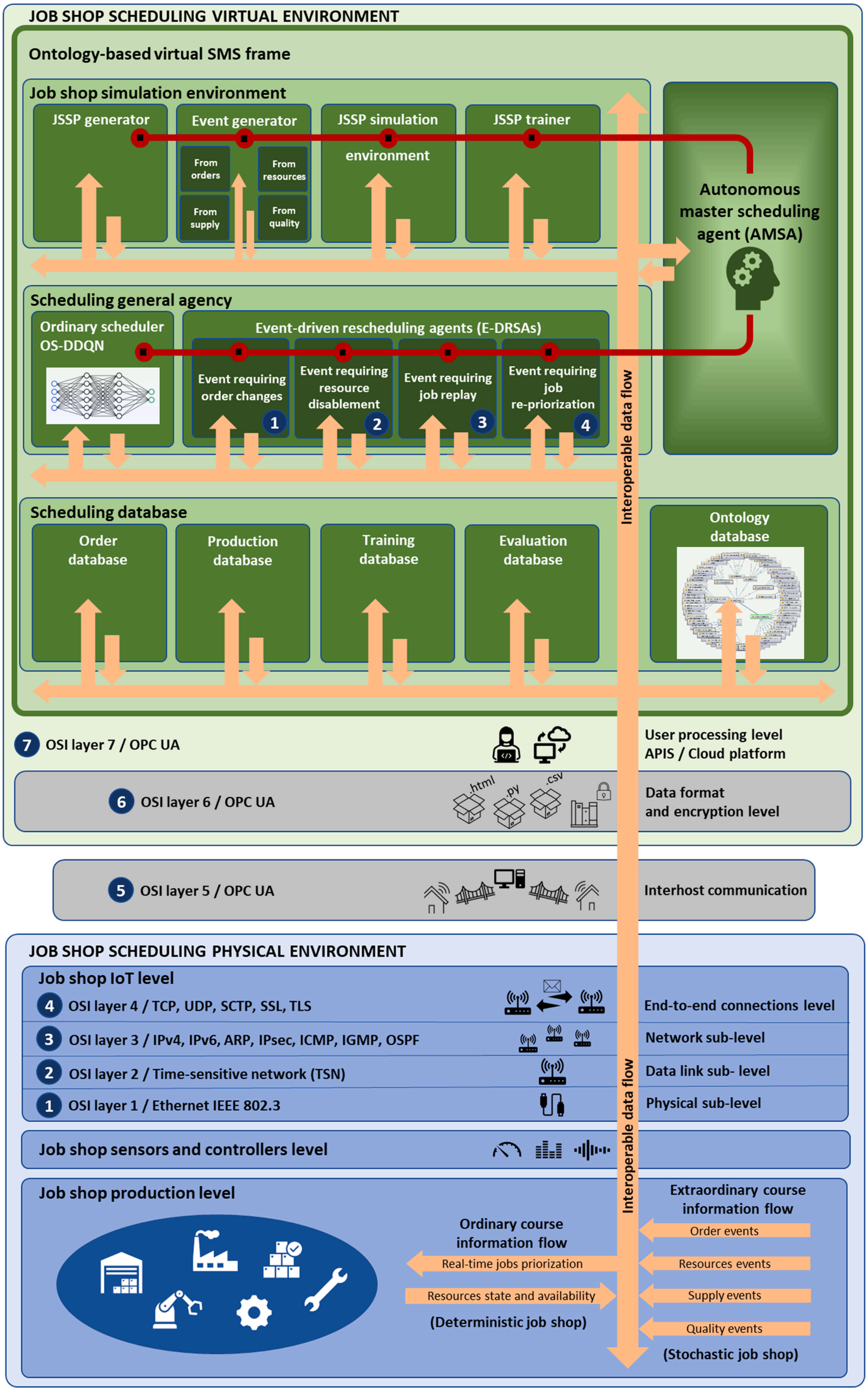

Fig. 10. General scheme of the SMS model and its topological framing within job shop scheduling.

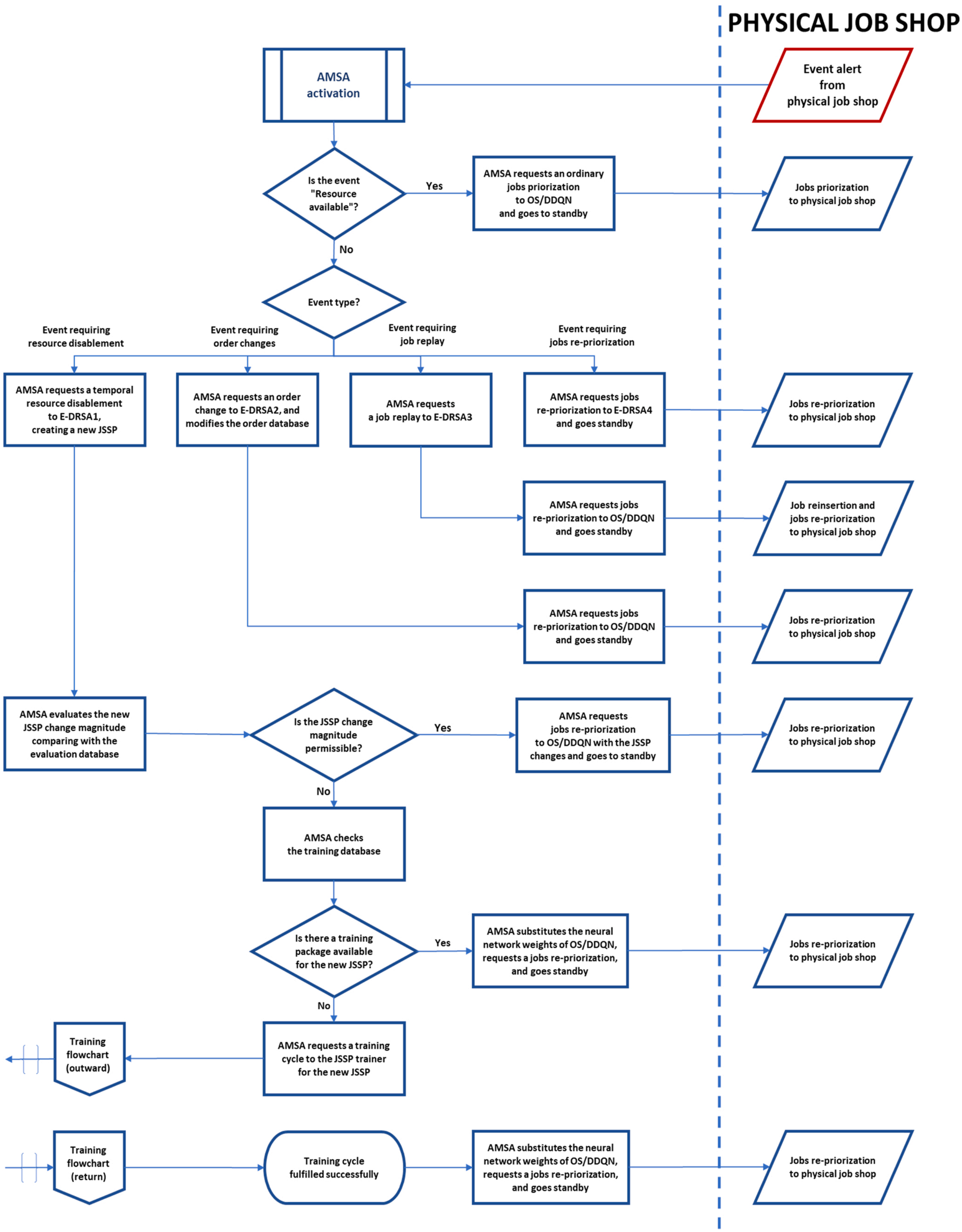

Fig. 11. The sMS flow chart in the operation mode.

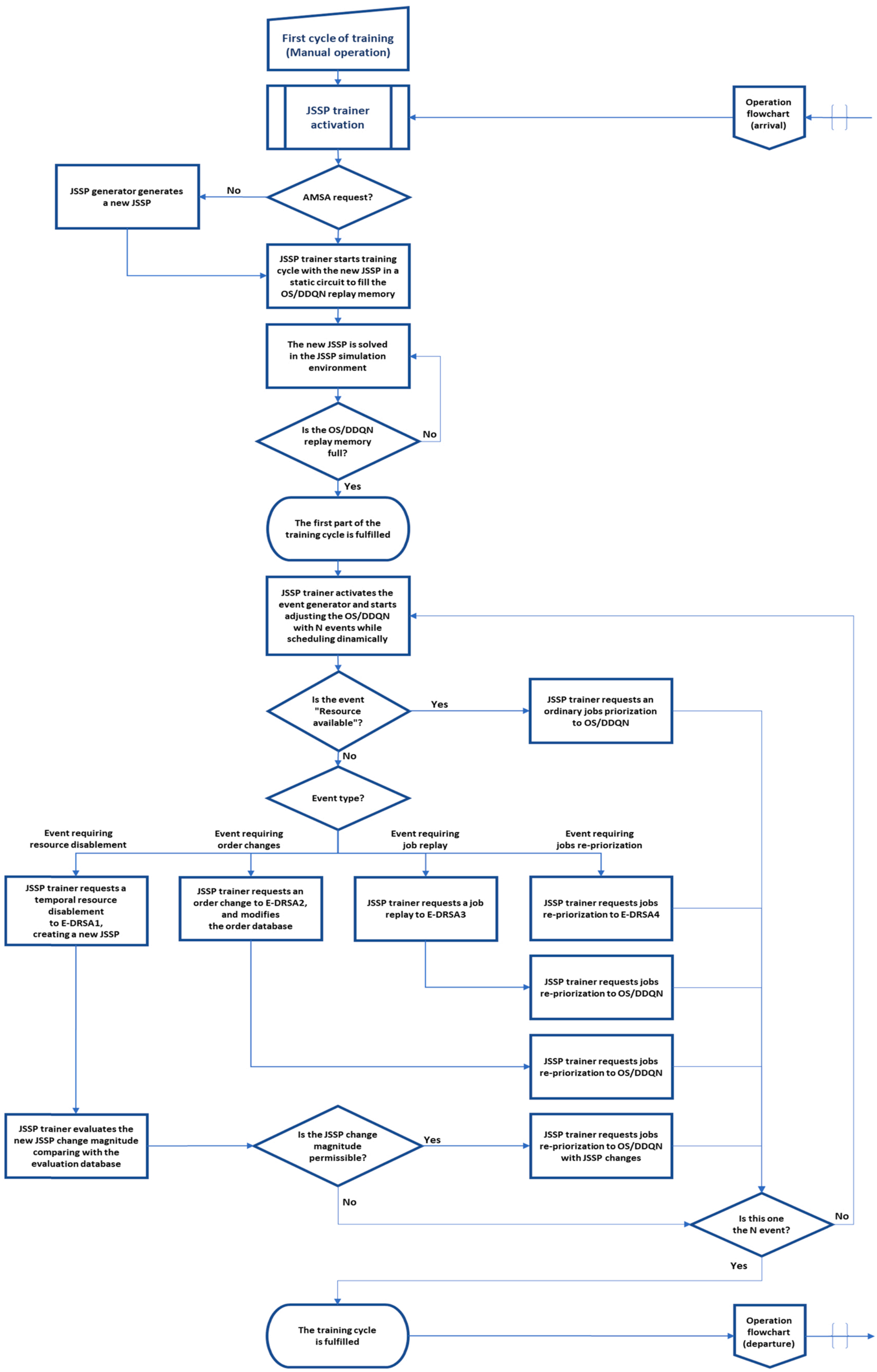

Fig. 12. The SMS flow chart in the training mode.

suggests the need to activate a new training cycle of the neural network (Fig. 11 and Fig. 12); and (vii) the training of the neural network in the virtual job shop simulation environment, developed using a DES system, is managed by a JSSP trainer. Training is performed in two phases: initially, the ordinary component of the problem is addressed based on the interaction with a static and deterministic job shop scheduling environment generated ad hoc. Next the result of the previous phase is supplemented with an extraordinary or stochastic component, which is generated by an event generator with a random pattern, but based on real production data. Here the mission is to simulate stochasticity to transfer it to the properties of the JSSP that characterise its states and, with this modification, to retrain the neural network within the margin that allows its stability during a variable number of episodes depending on each case that will, in turn, depend on the neaural networks' characteristics and parameters, replay memory size, the characteristics of the JSSP and the evaluated magnitude of randomness present in real production data. Thus, finally, the stochastic pattern is also imbued in the neural network parameterisation.

As stated before, four categories of events are considered in the model. They alter the ordinary course of job shop scheduling and trigger the need for rescheduling: (i) order-related events, such as the arrival of new or urgent orders, partial or total reprioritisation of orders, change of due dates, or cancellation of orders; (ii) resource-related events, such as the execution of preventive maintenance orders, machine breakdowns and their repair, the presence of faulty tools and their repair or replacement, failures of internal transport systems for parts, subassemblies or products, or failures of power, steam, lubricant or other essential supplies to operate resources; (iii) events related to material or parts supply failures; and (iv) quality-related events, such as the online detection of defective parts or products. The treatment of the effects of this considerable number of events in the scheduling process contemplated in the model is simplified here by reclassifying them into four other categories which, unlike the previous ones, do not focus on the origin, but on the action required to manage them: (i) partial and temporary disabling of resources; (ii) changes to the order sheet; (iii) repetition of jobs; and (iv) reprioritisation of jobs.

With all of the above, the modelled DT aims to provide the system with significant flexibility. According to Lindström et al. [14], it is possible to gain flexibility through enhanced rescheduling capacity that facilitates the adaptation of the scheduling process to the randomness imposed by real environments. In the proposal put forward, this capacity is supported mainly by both the machine learning techniques used in modelling and the structure of the specialised agents making up the DT.

The other core tool of SMS, ZDM, also plays a significant role in the model, which derives from: (i) the integration of online quality into physical plane processes for the real-time detection of faults and defects, and their repair whenever feasible [57]; (ii) the consideration and integration of extraordinary events for their treatment; (iii) the general reconfiguration of resources when any of them is disabled for the process due to an event; and (iv) the rescheduling capability [14].

On the SMS capabilities of automation, autonomy and real-time action capability, it is worth noting that they have various enabling elements in the model. However, the main exponents worth highlighting are: (i) the conception of the virtual environment with a marked data-driven characteristic; (ii) the promotion of the whole as a highly interoperable space, purposely designed to facilitate the synchronisation of the physical and virtual environments and to, therefore, mitigate or eliminate any potential problems arising from the use of different sampling frequencies [58]; (iii) the self-tuning capability, which orients the model towards semi-autonomous or near-autonomous operation; (iv) the modelling based on machine learning, specifically DRL; and (v) centralised decision making, which is made by the AMSA which, like a brain, organises the operation of the different elements making up the virtual SMS framework.

Furthermore, in relation to interoperability as an SMS capability, the criticality of connection and communication between the physical and virtual environments should be mentioned, as should how the model addresses this issue by basing this capability on the following four pillars: (i) the consideration of the open protocol communication unified architecture (OPC UA) for layers 5–7 of the OSI model [59]; (ii) the operation of the different elements making up the virtual SMS environment within a semantic ontology framework [60]; (iii) the implementation of DT technology, which enables an interoperability space in the job shop to establish real-time data synchronisation between its management processes and those of the physical plane [61]; and (iv) the interaction between the physical and cyber job shops with tools like distributed applications, or apps [61].

Resilience to disturbances and disruptions, as the last SMS capability, is one of researchers' most widely expressed concerns in the reviewed literature, such as Fang et al. [27], Liu et al. [30], Psarommatis et al. [37], or Zhang et al. [45]. For this reason, it is conferred special significance in the model. Orientating the model towards acquiring this resilience is mainly fostered by the proposed hybrid DRL method, which provides the system with enhanced rescheduling capacity that transforms the process into an automatic one and triggers it in real time, which orients job shop scheduling towards greater adaptability to the different scenarios created by the occurrence of a wide range of potentially disturbing or disruptive events. From this perspective, it is a reactive approach that differs from predictive approaches, like that of Yu et al. [41], insofar as instead of developing strategies in advance to compensate for disturbances when they occur, it favours the action of modifying and adapting decision making at the exact time when a disturbance occurs and, thus, comes closer to the solution proposed by Vijayan et al. [62], which is based on acquiring this resilience by simulating stochastic interruption scenarios within a DT frame to generate tailored scheduling.

Conclusions

This paper presents an aggregated conceptual SMS model in which the DT enabling technology and the ZDM management model converge in job shop scheduling to favour automation, autonomy, real-time action capability and resilience to potential disturbances and disruptions. The purpose of this model is to provide a reference base for both practitioners and academics to deepen their understanding of the involved conceptual terms and their interrelations within a structured conceptual framework. According to Serrano-Ruiz et al. [4], SMS can make a significant contribution to develop advanced production scheduling tools that provide a robust response to the digital transformation patterns implied by current production paradigms, such as Industry 4.0 or supply chain 4.0, which configures it as a planning strategy. Based on a scientific literature review that relates the concepts of job shop, scheduling, automation, autonomy, real-time action capability, interoperability, the DT, the ZDM and the SMS itself, this research identifies, collects and analyses the contributions that are most aligned, partially or totally, and directly or indirectly, with the SMS strategy. Subsequently, the SMS dimensions are established, which allow a distinction to be made among: (i) SMS core tools, in the case of DT technology and the ZDM model; (ii) SMS assisting technologies, which include big data, data mining, sensorisation, IoT, cloud computing, simulation, machine learning, augmented reality, and PHM of production systems; and (iii) SMS capabilities, a dimension that integrates automation, real-time action capacity, interoperability and resilience to disturbances and disruptions. These dimensions are established as the elements that enable the structuring of the potential interrelations between the concepts involved in this strategy based on the 72 vectors that express the set of their possible combinations. Given the basis of this construct and the selected literature review, the aggregate model is contextualised, formalised and presented by assessing its degree of alignment with SMS, reviewing and substantiating its sources of synergy with the strategy, and describing the elements and processes that make it up. To the best of our knowledge, this work has not been carried out before and therefore represents a novelty in the knowledge field of the PPC processes. Although the selected literature offers a rich variety of close approaches, they all address SMS from a partial perspective. The research herein presented intends to bridge this gap by offering a holistic approach to SMS which, while not claiming to encompass all the modelling domains of the areas and fields involved in SMS, aims to integrate them effectively from the univocal perspective of the modelling domain of the PPC area. At this point it should be noted that the modelling realm is limited to the domain defined by the logical processes generated by the DT and carried out in the virtual environment. However, they are also placed in the overall manufacturing context, which is subject to not only the PPC area, but also to quality management or maintenance management, and in an environment shaped by ICTs. The support of a semantic ontology framework, the hierarchical agent structure, the DRL-based modelling approach, and the inclusion in the model of the stochastic events of the job shop are the most remarkable configurational singularities of the model. Its main features could be summarised as flexibility, fostered by enhanced rescheduling capacity, and orientation towards autonomous operation, which is fundamentally supported by machine learning technology.

Regarding the main academic implications, this research bridges the research gap detected on the studied topic and it lays the conceptual foundation that will subsequently facilitate the theoretical and practical development of a job shop SMS. In terms of managerial implications, it is worth noting that this research can constitute a roadmap to guide practitioners' efforts towards the digital transformation of their job shops with a unique and smart approach that aims to maximise the synergies of a small and, therefore, manageable number of Industry 4.0 technologies.

Finally, the fundamental general lines are set out that, in the authors' opinion, should guide future SMS research: (i) firstly, the implementation of the conceptual model through mathematical and computational modelling to lead to the development of the necessary software; (ii) the empirical validation of the model both in the laboratory and through its implementation in a real case; and (iii) it also seems appropriate to extend this validation by experimentally verifying whether the model is generalisable or if, on the contrary, it involves some limitations as to its application to job shops of certain types or industrial sectors. These general lines of research will foreseeable be significantly conditioned by some major challenges that are worth mentioning here, as they may provide additional specific lines of research: (i) One comes from the environment surrounding the modelling domain; it should be specifically noted that the physical environment of the job shop is key for the feasibility of SMS because it must be characterised by automation, interoperability, data orientation, integration of online quality processes and immersion in an IoT context. (ii) Another remarkable defiance stems from the selection of the DES system that will support the virtual job shop simulation environment as well as the tools that make up the DRL framework [63], so that together they form not only an efficient, but also a compatible and interoperable environment. (iii) Also the difficulty in transferring information in the training process about the randomness of the productive environment that characterises the job shop to the neural network that model the DQN algorithm, so that this knowledge allows the algorithm to effectively discriminate the suitable selection of actions based on a right estimation of the value function while, simultaneously, the stability level of the DQN algorithm remains within an acceptable range, an issue already alluded to by some researchers such as Lang et al. [64]. (iv) And lastly, it should also be mentioned the capability of the value-based method represented by the DQN algorithm, compared to other methodologies such as policy-based or actor-critic (combination of the properties of the value-based and policy-based methods) such as the advantage actor-critic (A2C), soft actor-critic (SAC), deep deterministic policy gradients (DDPG) or proximal policy optimisation (PPO) methods which, although they do not yet have significant implementations in the field of JSSP, are beginning to provide good results in other types of problem, and point to possible improvements to the method presented here.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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