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ADAUTO FARIAS BUENO

# SHOP FLOOR CONTROL IN SMART FACTORIES' ERA: PATHS AND MATURITY MODEL

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# SHOP FLOOR CONTROL IN SMART FACTORIES' ERA: PATHS AND MATURITY MODEL

Doctoral Dissertation presented to the Post Graduate Program in Industrial Engineering at the Federal University of São Carlos, as part of the requirements for obtaining the Doctor degree in Industrial Engineering.

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# ABSTRACT

Scholars and practitioners have conceived Industry 4.0 as a comprehensive set of emerging technologies clustered in smart technological ecosystems into industrial companies. Since Smart Manufacturing is at the core of this concept, Production Planning and Control (PPC) plays a "*brain*" role in companies because it can lead them toward Smart Factories. This Doctoral Dissertation aims to investigate the relationships between Industry 4.0' technologies and the manufacturing industry from a Shop Floor Control/Production Planning and Control function perspective. Firstly, we delimit the relationships between Industry 4.0 and the organizational entity of PPC/SFC from an extensive Systematic Literature Review. Second, we proposed a standard framework to develop maturity models into Industry 4.0' era. Third, we proposed and designed a focus-area and prescriptive Smart Shop Floor Control Maturity Model ($S^2$FC MM) based on five research iterations from Design Science Research - DSR. Our $S^2$FC MM contains five focus areas comprised of 20 key factors covered by 98 capabilities (maturity matrix). $S^2$FC MM is a progression maturity model with five maturity levels entailing the Industry 4.0-concept. $S^2$FC MM was validated and implemented in a steel manufacturing company.


**Keywords:** Industry 4.0; Smart Production Planning and Control; Smart Manufacturing; Maturity Model, Maturity Paths, Artifacts.

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| | |
|---|---|
| Acatech | Deutsche Akademie der Technikwissenschaften |
| AI | Artificial Intelligence |
| AGV | Automatic Guided Vehicle |
| AJG | Academic Journal Guide |
| AM | Additive Manufacturing |
| APC | Autonomous Production Control |
| AR | Augmented Reality |
| AT | Ancillary Technologies |
| BITKOM | Bundesverband Informationswirtschaft, Telekommunikation und neue Medien |
| BDA | Big Data and Analytics |
| CAE | Computer-Aided Engineering |
| CAM | Computer-Aided Manufacturing |
| CC | Cloud Computing |
| CMg | Cloud Manufacturing |
| CNC | Computerized Numerical Control Machines |
| Co-bots | Collaborative Robots |
| CR | Closely Related |
| CPFR | Collaborative Replenishment Forecasting Planning |
| CPS | Cyber-Physical Systems |
| CPPS | Cyber-Physical Production Systems |
| DSM | Dependendy and Structure Matrix |
| DSR | Design Science Research |
| DSRM | Design Science Research Methodology |
| ERP | Enterprise Resource Planning |
| ETO | Engine-to-Order |
| FMS | Flexible Manufacturing Systems |
| FIS | Fuzzy Inference System |
| GPS | Global Positioning System |
| GSM | Global System for Mobile Communications |
| ICT | Information and Communication Technology |
| IDBA | Industrial Big Data and Analytics |
| IIoT | Industrial Internet of Things |
| IoT | Internet of Things |
| IS | Information Systems |
| JIT | Just-in-time |
| LR | Loosely Related |
| MES | Manufacturing Execution System |
| MIS | Management Information System |
| ML | Machine-Learning |
| MM | Maturity Model |
| MPS | Master Planning Scheduling |
| MR | Mixed Reality |
| MRP | Materials Requirement Planning |
| MTO | Make-to-Stock |
| M2M | Machine-to-Machine |
| NFT | Not Full Text |
| NR | Non-Related |

| | |
|---|---|
| NRQ | Not Quality Ranking |
| OM | Operations Management |
| ORR | Order Review and Release |
| OSCM | Operations and Supply Chain Management |
| PEID | Product-Embedded Intelligent Devices |
| PLC | Programmable Logic Controller |
| PoC | Proof of Concept |
| PRISMA | Preferred Reporting Items for Systematic Review and Meta-Analysis Statement |
| PR | Partially Related |
| PPC | Production Planning and Control |
| PwC | PricewaterhouseCoopers |
| QR-Code | Quick Response Code |
| RAMI | Reference Architectural Model for *Industrie 4.0* |
| RFID | Radio Frequency Identification |
| SC | Supply Chain |
| SCM | Supply Chain Management |
| SER | Search Engine Reason |
| SCADA | Supervisory Control and Data Acquisition |
| SFC | Shop Floor Control |
| $S^2$FC | Smart Shop Floor Control |
| SJR | Scimago Journal Ranking |
| SLR | Systematic Literature Review |
| S&OP | Sales and Operations Planning |
| TRC | Time-Range Criteria |
| URC | Union Rule Configuration |
| WSN | Wireless Sensor Network |
| VDMA | Verband Deutscher Maschinen- und Anlagenbau |
| VMI | Vendor Managed Inventory |
| VR | Virtual Reality |
| ZVEI | Zentralverband Elektrotechnik- und Elektronikindustrie |

## TABLE OF CONTENTS

# 1 INTRODUCTION

In this Ph.D. Dissertation chapter, the research design is presented. This chapter details the contextualization of the subject studied, the problem definition, and the theoretical lens used for problem investigation. The study's importance and motivation are also presented, and the research methodology chosen is described. Lastly, the Dissertation structure is presented, where we show each of the five-chapter content.

## 1.1 Contextualization

Industry 4.0 (I4.0) is an approach based on digitalization, automation, and integration drivers (ARBIX et al., 2017). It impacts business, management, and manufacturing processes. Furthermore, it integrates all actors in the enterprise's value-creation chain (KAGERMANN; HELBIG; HELLINGER, 2013). I4.0 is realized by Smart Manufacturing systems into Smart Factories (HAMADA, 2019; KUSIAK, 2018; ORELLANA; TORRES, 2019). Therefore, its core purpose is to support the value-creation through Smart Manufacturing Systems and new digital business propositions (KIEL et al., 2017).

However, how can manufacturing companies and their production managers support and leverage I4.0 benefits along with Production Planning and Control/Shop Floor Control? For this purpose, we propose a Smart Shop Floor Control Maturity Model in this Dissertation, aiming to investigate, propose a solution, and fill the theoretical-practical gap for this problem. For this, we design, validate, and implement our Maturity Model (MM) along with a steel manufacturing company. So, here is our starting point.

The smart Shop Floor Control-concept (SFC) is an advanced way for operations manufacturing execution, monitoring, and planning and control activities at the bottom of the PPC function (BUENO *et al.*, 2022; BUENO; GODINHO FILHO; FRANK, 2020; OLUYISOLA *et al.*, 2021; TAO; ZHANG, 2017; ZHUANG; LIU; XIONG, 2018). Thus, a smart SFC arises from: *(i).* the full implementation of smart technologies/ecosystems of I4.0 (ZHUANG; LIU; XIONG, 2018); (*ii).* mastering resources and smart capabilities provided by these technologies (BUENO; GODINHO FILHO; FRANK, 2020); (*iii).* people skills, and organizational issues like digital culture, data-driven decisions, change management for digitalization, fit of manufacturing legacy system to the smart concept, and digital value-creation (GHOBAKHLOO; IRANMANESH, 2021; SCHMITZ; HAGEMANN, 2020; SCHUH et al., 2017); *(iv)*. the convergence of cyber and physical spaces of Shop Floor Control (TAO; ZHANG, 2017; ZHUANG; LIU; XIONG, 2018).

For manufacturing companies harnessing I4.0 benefits, SFC function needs comprise: *(i).* digitalized operations and smart capabilities for manufacturing planning and control. In this scenario, SFC activities such as production scheduling, order release, and monitoring are carried out on the fly. Also, manufacturing digitalization allows the development of smart shop floor capabilities such as sensing, visibility, traceability, and real-time monitoring; *(ii).* automation. I4.0 also boosts automatized process opportunities; for example, physical assets automation opens new ways for manufacturing execution carried out and managed by a smart SFC function. So, automation concerns physical (operations) and managerial (informational/decisional) autonomy, enabling self-capabilities for shop floor tasks and operations management support; *(iii).* manufacturing integration. For this, digitalized infrastructure and networking are required to link business layers vertically and horizontally with supply chains and customers (end-to-end). Therefore, integrating systems, machines, and processes of shop floor control is another benefit of I4.0. Integration enables collaboration and sharing capabilities between different tasks on the shop floor, customization of products by customers from apps, interoperability of ICT systems, synchronization of planning and manufacturing execution tasks, and digital servitization (e.g., scheduling as-a-service). These capabilities leverage the shop floor's flexibility, agility, adaptability, and responsiveness (performance indicators). *(iv).* performance improvements. I4.0 improves the company's performance indicators by embedding smart features on tangible and intangible assets, improving the organizational profile of operations. Therefore, to leverage the I4.0 benefits, manufacturing companies should endeavor transformational efforts in manufacturing processes and operations management into Shop Floor Control function domain. People labor with digital and data-driven skills, training, projects, and I4.0 strategy are required for this.

Therefore, a smart Shop Floor Control function results from transformational, informational, and automational processes (MOONEY; GURBAXANI; KRAEMER, 1996) towards digitalization, integration, and automation aiming for value-creation (SCHMITZ; HAGEMANN, 2020).

So, into the Operations and Supply Chain Management field (OSCM), we observed that Maturity Models are useful tools for this purpose, i.e., MMs support managers and other practitioners toward fully implementing I4.0. MMs can provide the previous benefits for the Shop Floor Control function, such as performance improvements, new digital business processes, and digital value-creation (NAYERNIA; BAHEMIA; PAPAGIANNIDIS, 2021; PACCHINI et al., 2019).

Shop floor managers and professionals should use MMs as a starting point to enhance the manufacturing and supply chain companies' practices and performance (GÖKALP; MARTINEZ, 2021) from I4.0 technologies (e.g., minimizing the lead times of orders and maximizing the reliability of scheduling carry out). Besides that, MMs are artifacts that allow a company to benchmark internal/external performance and practices within a specified domain (e.g., Shop Floor Control) and establish improvement roadmaps (ASDECKER; FELCH, 2018). Manufacturing companies, shop floor managers and professionals benefit from MMs in four basic ways. First, MM provides "*what to measure*" in the Shop Floor Control, highlighting the modeling of attributes (descriptive perspective/model) (RÖGLINGER; PÖPPELBUSS; BECKER, 2012). Second, MMs provide a "*measurement tool*" to assess the maturity of practices/capabilities (evaluation tool) on the Shop Floor Control function (prescriptive perspective/model)(METTLER; BALLESTER, 2021). Third, MMs deliver a set of processes, key factors, practices, and capabilities to be implemented along with the maturity levels identified (maturity matrix and improvement roadmap). Fourth, MM supports managers to position an "*as-is status*" against a "*to-be status*" along with characteristic maturity levels within a domain (benchmarking model). Consistent MM deploying enables shop floor managers and professionals problem-solving regarding upgrading ordering systems, scheduling, manufacturing execution and monitoring capabilities based on I4.0 technologies. Therefore, we address MMs as a managerial artifact to improve manufacturing companies' performance by implementing key factors and capabilities oriented by a highly technology-oriented shop floor environment (BASKERVILLE et al., 2018; HEVNER; GREGOR, 2022).

Traditionally, MMs in I4.0 and OSCM are comprised by the technology and process dimensions. But, in OSCM, people perform key roles and responsibilities for digital transformation. Also, people carry out organizational processes, manufacturing execution operations, planning and control processes, and business processes aiming for value-creation. Therefore, our vision for a smart SFC MM is socio-technical-centric (conjoint approach from technology, people, and value-creation processes) (METTLER; BALLESTER, 2021; MITTAL et al., 2018). People conduct the I4.0 strategy. Thus, factors and capabilities related to I4.0

dimensions can be organized as a toolkit from MM, which helps companies and their managers to reach higher maturity levels in I4.0, supporting them to conquer associated benefits.

### 1.2 Research gap and objective

In recent years, research in the I4.0 subject has been exponential growth within the OSCM. However, fewer studies have been published encompassing the PPC's topics. For example, Castelo-Branco et al. (2019) measured the I4.0 adoption degree in manufacturing firms across European Union countries. The authors claim the need for research in some I4.0 adoption subjects, such as the industrial sector structure, the role of each country's economy, and the differences in business models or management styles. Caiado et al. (2021) developed a maturity model for OM, PPC, and Supply Chain dimensions from I4.0's perspective (OSCM 4.0 MM). This study proposes assessing I4.0's maturity in manufacturing companies using a fuzzy inferential system model and simulation. In addition, the OSCM 4.0 MM aimed to address the digitalization level of the supply chain, manufacturing and PPC, measuring I4.0's readiness and maturity based on 15 indicators. However, in Caiado et al.'s (2021) MM, only one dimension addressed the PPC function. Other important studies on this subject are Dalenogare et al. (2018), Frank, Dalenogare, and Ayala (2019), Orellana and Torres (2019), Asdecker and Felch (2018), Ramos et al. (2020).

Therefore, searches with similar proposals to Castelo-Branco et al. (2019) and Caiado et al. (2021) are still scarce in Latin America and Brazil. Furthermore, regarding PPC function and its activities, few studies address digitalization, integration, and automation phenomena effects with an in-depth investigation encompassing, for example, the I4.0 effects in Aggregate Planning, Detailed Planning, and Shop Floor Control activities.

One recent study encompassing the PPC topic within I4.0 is presented by Oluyisola et al. (2020). They developed a smart PPC model grounded on a use-case matrix and product–process framework investigating four companies. Additionally, Oluyisola et al. (2021) advanced in their research, presenting a smart PPC system that uses the Internet of Things (IoT), (big) data analytics tools, and machine learning (ML) running on the cloud to enable optimized performance to the PPC processes. Other studies, such as Dombrowski and Dix (2018), applied the Advanced Industrial Management Reference Framework to quantitatively analyze I4.0 technologies' effects on PPC activities and logistics objectives.

We verified by an extensive literature survey based on 120 articles along with PPC and I4.0 topics (2010-2021) that there is a research gap regarding Smart PPC/SFC function progress (e.g., models, methods, and paths). Also, we have not found tools to support Shop Floor Control managers and companies in mastering and improving smart capabilities from I4.0 technologies. Some of these findings are presented in Chapter 2 of this Dissertation. From this, we build a Research Agenda that lists some research topics in Smart PPC. Therefore, a **research gap** exists in modeling, designing, measuring, and developing a Smart SFC function into manufacturing companies based on I4.0 environments.

By investigating and delimiting this scope, we observe the PPC/SFC field lacks studies about managerial artifacts (models, frameworks, architectures, roadmaps, evaluation tools) based on I4.0 implementation. These tools can be applied to develop smart solutions in manufacturing companies and contribute to advances in this field's knowledge base and artifacts. In this sense, this Ph.D. Dissertation **aims** to cover this gap by *(i).* investigate Smart PPC capabilities provided by main I4.0 technologies, *(ii).* design and implement a Maturity Model for reaching smart capabilities along with the Shop Floor Control function and its activities, *(iii).* propose Shop Floor Control maturity capabilities within the I4.0-concept through a Maturity Model.

So, we investigate the research problem of how manufacturing companies and their production managers can support and leverage I4.0 benefits along with PPC/Shop Floor Control. With regard to the general objective, this Doctoral Dissertation **aims** to investigate the design and implementation of a focus-area Maturity Model for the Shop Floor Control function, outlining evaluation and capabilities to conduct the traditional Shop Floor Control activities toward the *highest maturity levels of I4.0-concept.*

## 1.3 Research motivations

The doctoral Dissertation's main motivation is to cover the research gaps above from designing and proposing a Maturity Model for supporting the Shop Floor Control function's maturity progress into I4.0. We address the Dissertation's originality from research and proposal of methodological advances for building novel Maturity Models. We also propose by the first time an innovative managerial Maturity Model to support the Shop Floor Control function progress in I4.0-concept.

We found six core motivators for this Ph.D, which are based on the premise that a smart Shop Floor Control supports: *(i).* the smart capabilities mastering; *(ii).* the performance improvements; *(iii).* off-profile performance gains *(iv).* integration of the Smart Factory layers; *(v).* the value-creation processes/chain; *(vi).* planning and control's emerging factors. e.g., sustainability. We observed in literature encompassing OSCM and I4.0 that MM can support companies to develop a smart PPC/SFC to harness the benefits of I4.0 adoption. Our evidence was surveyed from studies such as Oluyisola et al. (2020), Ding et al. (2019); Prathima, Sudha and Suresh (2020), Schuh et al. (2017); Grassi et al. (2020b, 2020c, 2020a); Parente et al. (2020); Soto et al. (2020); Oztemel and Gursev (2020); Terrazas, Ferry, and Ratchev (2019); Ji and Wang (2017); Fei and Tao (2017).

***(i).* the smart capabilities mastering:** one of the sources of manufacturing companies' competitive advantage is the customized smart capabilities mastered from industrial innovations and I4.0 technologies (BAG; GUPTA; KUMAR, 2021; JIANG et al., 2020). Our previous systematic review listed 18 smart capabilities that PPC/SFC should master from I4.0's technologies (BUENO; GODINHO FILHO; FRANK, 2020). Emerging technology purchasing and its unfocusing application is insufficient for sustainable manufacturing advantages, requiring a correct technological application, projects, competencies, and higher technological abilities and resources (capabilities). Smart capabilities and resources should be developed and sustained for manufacturing operations/processes, planning, and control activities. Besides that, organizational factors need to be fitted by developing digital skills, data-driven management, digital culture, SFC methods and systems changes. SFC must transform itself from new practices derived from I4.0, consolidating a solid bundle of smart capabilities aiming at value-creation (RODEN et al., 2017). Therefore, the smart capabilities or resources from I4.0 technologies are a core motivation for the SFC evolution towards a smart configuration, being the basement for the smart PPC's orchestrator role within the Smart Factories.

***(ii).* the performance improvements:** smart Shop Floor Control activities based on smart capabilities provide performance improvements to the Smart Factories (BUENO; GODINHO FILHO; FRANK, 2020). Several studies indicate manufacturing performance benefits from I4.0 initiatives (BÜCHI; CUGNO; CASTAGNOLI, 2020; BUER; STRANDHAGEN; CHAN, 2018; DUMAN; AKDEMIR, 2021; MOEUF *et al.*, 2018). The main performance indicators highlighted in the literature regards to smart SFC within I4.0-context are a decrease in cost (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017; RAUCH; DALLASEGA; MATT, 2018), lead time improvements (ACHILLAS; TZETZIS; RAIMONDO, 2017; LI et al., 2019), energy and resources optimization (BAG; GUPTA; KUMAR, 2021; ZHAO et al., 2019), inventories reduction (ANDERSSON; JONSSON, 2018), complexity minimization (DALLASEGA et al., 2019; KANG et al., 2018); and, also increase of flexibility (MEYER; (HANS) WORTMANN; SZIRBIK, 2011; MOURTZIS; VLACHOU, 2018), agility and responsiveness increase ((BABICEANU; SEKER, 2016; LIN et al., 2019), robustness and reliability increase (JIANG et al., 2018; MA; NASSEHI; SNIDER, 2019), profitability and productivity (HOLMSTRÖM *et al.*, 2016; LEE; LIANG, 2018), quality and customer satisfaction (HELO; HAO, 2017; SHAMSUZZOHA et al., 2016). Hence, a positive behavior of performance indicators is a motivator to reach an SFC's smart status (maturity stage).

***(iii).* off-profile performance gains:** a smart Shop Floor Control state provide off-profile performance gains to the Smart Factory. Off-profile performance gains are interesting complementary effects of I4.0's technological resources adoption. For this, different manufacturing process environments and their specificities are considered (DAS; NARASIMHAN, 2001; STRANDHAGEN et al., 2017) regards the fit of I4.0 technology and possible off-profile performance gains (DAS; NARASIMHAN, 2001) in "off-diagonal" position along with of the product-process matrix of Hayes and Wheelwright (1979). For example, from I4.0 technologies capabilities such as cloud manufacturing, manufacturing flexibility, a common performance indicator for the make-to-order environment, can also be increased for the make-to-stock environment by digital servitization (YU et al. 2018). For more exploration of this motivator and off-profile performance discussion, see Yu et al. (2018), Stranhagen et al. (2017), and Grundstein et al. (2017). Therefore, gains around off-profile performance indicators motivate a mature SFC in the I4.0-concept.

***(iv).* integration of the Smart Factory layers:** Cyber-Physical System (CPS) building enables the integration of the Smart Factory layers by seamless interaction between physical and cyber elements within an industrial company, from the bottom-up shop floor to the business top layers (TAO; ZHANG; NEE, 2019). This concept becomes feasible, reaching the utmost level of shop floor planning and control within the I4.0: the smart level. CPS, in our conception, is the image of the full realization of the I4.0-concept within the Smart Factory context. Thus, the SFC is the ground-zero for CPS development encompassing the different smart Production Planning and Control environments (e.g., make-to-order, make-to-stock, among others). CPS embeds physical assets with communication and computational power, allowing the physical manufacturing space to be monitored, coordinated, optimized, and controlled through cyberspace by real-time capabilities (TAO; ZHANG, 2017). For this, CPS requires **a digital thread** connecting all production assets (physical and managerial): 1. manufacturing (machines, AGVs, materials, products, devices), *(ii).* technologies/I4.0 ecosystems and devices (industrial IoT, industrial (big) data, cloud manufacturing, among others), 2. manufacturing execution systems (MES, APS), and decisional and business systems (ERP, CRM, DSS) (PALASCIANO et al., 2017; STICH; HERING; MEISSNER, 2015; TAO; ZHANG; NEE, 2019), *(iv).* people and organizational functions (GÖKALP; MARTINEZ, 2021; LONGO; NICOLETTI; PADOVANO, 2017; SONY; NAIK, 2020a).

A **digital thread** enables the CPS a bidirectional interaction flow between physical manufacturing assets and cyber components (ZHANG; ZHU, 2019). A digital thread works in a dual manner, i.e., manufacturing data and information feeding cyberspace, located the systems and decisional components (ZHANG; ZHANG; YAN, 2019). In turn, cyberspace responds to the physical environment with feedback, i.e., actions, coordination, planning, and control (TAO et al. 2019). So, the core technology of CPS on smart SFC consists of manufacturing system virtualization by digital thread establishment with IoT, ICT systems and digital interfaces, hardware and software, algorithms, and digital twins, among others. Therefore, a smart SFC function needs **CPS development**. It is based on the premise that CPS development requires from manufacturing companies the scrutinization, studies, projects, and actions towards focused I4.0 realization, integrating physical and cyber spaces along with Smart Factories in only **high-level Decision Support System,** the CPS (QU et al., 2019). The CPS's building is a catalyst for digital efforts to I4.0, linking SFC and remaining functions, systems, and layers within an only integrator system of Smart Factory (ANSARI; GLAWAR; NEMETH, 2019; ZHUANG; LIU; XIONG, 2018).

***(v).* the value-creation processes/chain:** a smart Shop Floor Control improves the manufacturing's value-creation chain. I4.0 implementation provides the manufacturing system opportunities for value-creation (VEILE et al., 2020; VEILE; SCHMIDT; VOIGT, 2022) by: *(i).* new and smart products offering (RAFF; WENTZEL; OBWEGESER, 2020), new business processes models development (SIMCHI-LEVI; WU, 2018b), customer-value prospection (e.g., mass customization and digital servitization) (GEBAUER et al., 2021), (re) design and deployment of the new digital organizational process (ALIEVA; VON HAARTMAN, 2020), and supplier' and key-partners involvement (e.g., by horizontal integration) (BITKOM; VDMA;

ZVEI, 2016). Thus, smart SFC supports the value-creation chain within Smart Factories by operationalizing, managing, and controlling the manufacturing in the back-end position. Several examples of value-creation deployment from smart SFC are related to literature topics, such as end-to-end digital print process value-creation for shop floor scheduling and control (ZENG; LI, 2013), shop floor autonomous control by CPS (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017), scheduling-as-a-service by CMg (HELO; HAO, 2017), additive manufacturing use for value proposition in mass customization business strategy (ACHILLAS et al., 2015; ACHILLAS; TZETZIS; RAIMONDO, 2017). Value-creation propositions from smart SFC require entrepreneurial mindset changes, platform-based cooperation by smart technologies, common standards based on I4.0's reference architectures, interoperability, and innovation strategy (PILLER, 2022). From a people and organizational perspective, value creation is grounded on digital skills employment from collaborative, cooperative, data-driven decisions (URBINATI et al., 2019). Managers should hold adaptive competencies (based on soft, digital, computational/programming, and technological skills) to drive the new processes and business models oriented to I4.0 (FARERI et al., 2020). Therefore, value-creation is both a strategic and business proposition motivator that depends on a smart SFC.

***(vi).* planning and control's emerging factors:** we also draw attention to some additional motivators based on emerging sustainability factors and distributed/decentralized SFC function. These factors affect the five motivators previously described (internal to Smart Factories) because sustainability and decentralization are related to customers' demand requirements adaption and the new digital business processes model. In I4.0, SFC needs greater flexibility and autonomy degrees to match new demand requirements and keep up with social behavior changes from digital technologies. For example, a decentralized SFC is better for planning and controlling higher automated environments embedded with self-capabilities (DE LAS MORENAS; GARCIA-HIGUERA; GARCIA-ANSOLA, 2017; TANG *et al.*, 2018). Besides that, a smart SFC is better flexible in addressing climate emission reductions in manufacturing or circular economy issues (BAG; GUPTA; KUMAR, 2021; DEV; SHANKAR; QAISER, 2020).

**Distributed SFC** idea is based on controlling the manufacturing from networking and embedding computational elements in manufacturing assets, where machines, resources, and systems hold some autonomy and computational processing capacity (BENDUL; BLUNCK, 2019). From this, manufacturing assets and operational technology (OT), information technology (IT), and IoT devices are embedded with a certain degree of autonomy and a couple of automated decisions in the operations field (BITKOM; VDMA; ZVEI, 2016). Only essential data and relevant information are sent to data analytics platforms, information systems, and enterprise business layers (FAROOQUI et al., 2020; VDI; VDE; ZWEI, 2016). Therefore, the outcome from the more distributed structure is reaching major flexibility and autonomy, but it is linked to the demand requirements viewpoint (external to Smart Factories). For more details about this discussion, see Grassi et al. (2020c), Bueno et al. (2020), Bendul and Blunck (2019), Ma et al. (2019), Raileanu et al. (2018), Adamson et al. (2017), Trentesaux (2009).

A smart SFC should also be driven by **production sustainability**, which concerns capabilities of energy optimization, sustainable goals for performance achievements, and sustainable value-creation propositions (KIEL et al., 2017). The concept of sustainability in smart SFC concerns the development of green and resource-saving practices and capabilities. For example, green optimization within production scheduling and smart grid adoption in MES systems for real-time energy optimization in a CNC. OSCM literature presents sustainability as an emerging indicator for shop floor control function (BAG; GUPTA; KUMAR, 2021). Therefore, the maturity elements like energy and resource-saving, green manufacturing, and green optimization coupled with production control can be core aspects of **digital business process development** focused on sustainability within the I40 context. For more details about this discussion, see our previous studies of Bag et al. (2021), Oluyisola et al. (2021), Cui et al. (2020), Sony and Naik (2020a), Kusiak et al. (2018), Kiel et al. (2017), Camarinha-Matos (2016).

### 1.4 Smart Shop Floor Control and Maturity Models: outlining and definitions

We observe that the current phase of manufacturing companies in the Fourth Industrial Revolution is the implementation of I4.0 resources and practices, aiming for associate performance benefits. Operations and Supply Chain Management's (OSCM) literature shows positive effects between smart Shop Floor Control activities/operations (I4.0-based) and performance indicators (BUENO; GODINHO FILHO; FRANK, 2020; OLUYISOLA *et al.*, 2021). Performance indicators such as agility and responsiveness, flexibility, cost, and quality are improved using resources and smart capabilities of I4.0 technologies on the shop floor (BUENO; GODINHO FILHO; FRANK, 2020; DUMAN; AKDEMIR, 2021). Bititci et al.

(2015) state that a higher maturity level in a domain is associated with higher performance. Moreover, shop floor managers and professionals use MMs as a compass that guides them from where to start, indicating what the parameters/attributes are (implementation key factors) and how to measure them, establishing what they are and how to reach the highest levels of I4.0 maturity (evolutionary pathways/roadmaps). Hence, MMs are valuable tools (artifacts) to leverage I4.0 on manufacturing companies' operations and performance (ALCÁCER et al., 2022; ASDECKER; FELCH, 2018; RAFAEL et al., 2020; SCHUH et al., 2017; WAGIRE et al., 2021).

Shop floor managers and professionals should use MM as a starting point to enhance the manufacturing and supply chain companies' practices and performance (GÖKALP; MARTINEZ, 2021) from I4.0 technologies (e.g., minimizing the lead times of orders and maximizing the reliability of scheduling carry out). Besides that, MM are artifacts that allow a company to benchmark internal/external performance and practices within a specified domain and establish improvement roadmaps (ASDECKER; FELCH, 2018). Manufacturing companies, shop floor managers and professionals benefit from MM in four basic ways.

We adopt Lacerda and von Wangenheim's (2018) definition of maturity as the extent (stage) to which an organizational function or company consistently implements resources and technologies, processes and practices, capabilities and indicators within a defined domain. The superior status of attributes (characteristics, capabilities, indicators, or patterns) in a domain or entity contributes to achieving established goals (e.g., shop floor control). As a result, MM is a practical problem-solving tool guided by evolutionary stages that define measurable progress transitions (CARALLI; KNIGHT; MONTGOMERY, 2012; RÖGLINGER; PÖPPELBUSS; BECKER, 2012).

Lastly, Shop Floor Control function smart status represents in our study the highest manufacturing system's ability or power to value-add by establishing operations, planning and control, practices, and capabilities based on I4.0. Our definition of capability is based on van Steenbergen et al. (VAN STEENBERGEN et al., 2013), who state that capability is the ability to achieve a certain goal using the available resources. Here, I4.0 comprises a comprehensive source of technologies, resources, and innovativeness approaches for Shop Floor Control operations, planning and control, and performance. For example, by harnessing the benefits of I4.0's resource implementation as sensors, shop floor managers aim digital data-collection and data-driven decisions. For this, a transformational process is required to guide the digitalization of machines, networking infrastructure for real-time machine monitoring, vertical and horizontal integration of systems such as ERP and MES, and decisional automation by expert systems and AI tools.

### 1.5 Methodology and research questions

From an SLR carried out (Chapter 2) and gaps observed, we intend to provide theoretical/practical advances for the knowledge base of the PPC/SFC field n I4.0 by proposing a Maturity Model focused on Shop Floor Control (Chapters 3 and 4). For this, we use a mixed-methods approach to conduct the research (CRESWELL; CLARK, 2018).

#### 1.5.1 Method release

Our research firstly investigates the main capabilities embedded in a smart PPC. Secondly, we search how to design and deploy a Maturity Model for the Shop Floor Control. For this, we employ mix-methods based on the Design Science Research methodology approach (see PEFFERS et al., 2007). Accordingly, we apply the following research mix-methods to operationalize the study: 1. Systematic Literature Review (SLR); 2. scoping review, 3. qualitative methods such as expert interviews, focus groups, meetings/workshops/field observation, 4. Fuzzy Expert/Inferential System modeling; 5. Case study.

**— Research questions (RQ) and methods addressed in Article 01 (Chapter 2)**

In Chapter 2, we explored the I4.0 topic within the PPC subject. Article 2 addressed the research gap of the absence of reviews showing the relationships between PPC and I4.0 technologies regarding smart capabilities. To deal with this, firstly, we performed a scoping review to build an analytical framework employed in the subsequent SLR (ARKSEY; O'MALLEY, 2005; COLQUHOUN et al., 2014). Scoping review was chosen in this Dissertation to address exploratory literature search within a thematic analysis of smart PPC (PETERS; MEIJBOOM; DE VRIES, 2018). Scoping review method was performed based on its traditional five stages (ARKSEY; O'MALLEY, 2005; COLQUHOUN et al., 2014): 1. identifying the research question(s); 2. identifying relevant studies; 3. selecting studies; 4. charting the data; and, 5. comparing, summarizing, and reporting results.

Secondly, we did a comprehensive literature search of PPC and I4.0 topics by the Systematic Literature Review method (LEVY; J. ELLIS, 2006; TRANFIELD; DENYER; SMART, 2003). For this, we based on Tranfield et al.'s guidelines (2003). Thus, SLR's article 2 is based on three research questions (RQs) highlighted below. These RQ address the relationships between the I4.0 technologies, smart capabilities of PPC, effects on performance, and the presence of moderator factors that influence smart PPC development. RQs are presented to follow:

**Q1.** *What are the smart capabilities necessary for PPC that can be provided by I4.0?*
**Q2.** *Does the integration of PPC with I4.0 determine performance implications?*
**Q3.** *What are the environmental factors which influence the development of smart capabilities for PPC?*

**— Research question (RQ) and methods addressed in Article 02 (Chapter 3)**

In Chapter 3, we propose a MM development framework that embeds the DSR iterative research approach. For this purpose, we define five steps for the framework's creation and research: 1. research procedures to ground the framework proposal; 2. the development of an initial framework proposal; 3. a refinement and validation of the framework proposal; 4. final version of the framework, 5. the framework as a Proof of Concept example. For this, general DSR research guidelines and existing frameworks were synthesized, such as Becker et al. (2009), among others. Literature surveys and a scoping review ground the framework. DSR guidelines and Sony and Kodali's (2013) criteria supported the framework's initial proposal design. Qualitative methods, such as expert meetings and an expert panel, were used for the framework refinement and validation. Finally, a Proof of Concept (PoC) example was used to demonstrate the framework's usability (ELLIOTT, 2021).

Most MM frameworks used in OSCM and I4.0 clarify "*what*" the MM should contain (e.g., maturity levels, dimensions, and assessment tools). However, they do not fully explain "*how*" precisely to operationalize the MM development steps (research, design, validation, and follow-up). It has led to design and scientific critiques concerning model reproducibility, reliability, and quality. Therefore, a critical methodological research gap remains concerning operationalizing MMs' development steps. These gaps are: *(i)*. the lack of *common procedures* among the various existing frameworks; and *(ii)*. the lack of *standardized* *design elements* for MM development. Article 3 aims to address this gap. Hence, this article aims to answer the following research question:

**Q4.** *How can one build, validate, and apply a DSR-based MM development framework for the OSCM and I4.0 domain?*

**— Research questions (RQ) and methods addressed in Article 03 (Chapter 4)**

We apply a transparent procedure from two building blocks to research and design a smart Shop Floor Maturity Model – $S^2$FC MM. The building blocks are grounded on our previous MM development framework, presented in Article 02: *(i).* procedures to research and design the model's elements ("*how to design*"), and *(ii).* elements' design of MM ("*what to design*").

$S^2$FC MM design followed five steps comprising iterative research processes (research iterations, RI #). $S^2$FC MM was built from mix-methods use (CRESWELL; CLARK, 2018; SAUNDERS; LEWIS; THORNHILL, 2019). For this, firstly, we use SLR and scoping review performed in Article 01 for research of model design. Second, we carry out qualitative methods such as focus groups, expert interviews, direct observation, workshops and meetings with practitioners to develop the model's category lists. Lastly, we use Fuzzy Expert System modeling and case study for the model evaluation tool building and implementation.

We do not find any maturity model that helps the manufacturing managers and professionals conduct the SFC towards a smart status within I4.0 environments. Therefore, Article 03 aims to answer the following research questions:

***Q5.*** *How to design a smart Shop Floor Control Maturity Model?*

***Q6.*** *How to measure and improve the smart Shop Floor Control maturity?*

## 1.6 Dissertation structure

This Dissertation is structured into five chapters (Figure 1.1). Therefore, we adopt an article Dissertation format.

In this Introduction, Chapter 1, we presented the research design elements of the Dissertation.

In Chapter 2, we performed an extensive Systematic Literature Review about a cross-thematic area of interest in our Doctoral Dissertation: PPC function and I4.0 technologies/concept. Our purpose was to survey the main smart capabilities that leverage the PPC function/activities.

In Chapter 3, we propose a novel framework comprising elements, procedures, and recommendations determining a standard baseline for developing I4.0 Maturity Models (MMs) in Operations and Supply Chain Management (OSCM).

Chapter 4 presents the Shoop Floor Control Maturity Model ($S^2FC$ MM).

Chapter 5 discusses the core findings establishing research advances and managerial contributions. Finally, limitations and future research directions are presented.

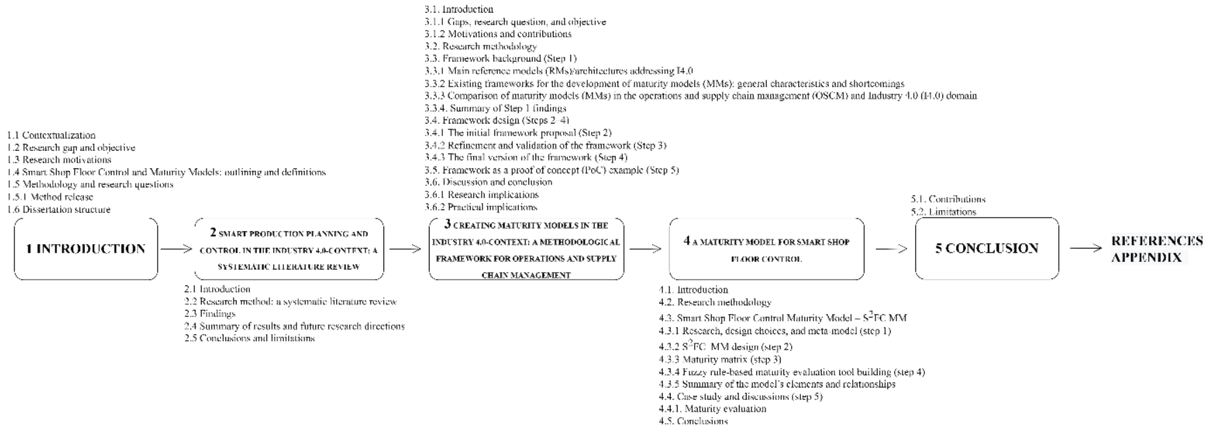



**Figure 1.1.** Dissertation structure

## 2 SMART PRODUCTION PLANNING AND CONTROL IN THE INDUSTRY 4.0-CONTEXT: A SYSTEMATIC LITERATURE REVIEW

**Abstract:** Scholars and practitioners have considered Industry 4.0 (I4.0) a comprehensive set of emerging technologies that establish a new industrial perspective based on the "*Internet of Things*". As smart manufacturing is at the core of the I4.0 concept, production planning and control (PPC) should play a key role in Industry 4.0 activities. Prior research has mainly focused on technological issues of I4.0, while little is known about how PPC is influenced by digital capabilities and how it operates in this new context. We conduct a systematic literature review to develop an analytical framework that explains how PPC in the I4.0 context is influenced by smart capabilities from five base technologies (Internet of Things, Cyber-Physical Systems, (big) Data and Analytics/Artificial Intelligence, and Additive Manufacturing), and how this is related to manufacturing system performance indicators, and environmental factors. The review includes studies from 2011 (when the I4.0 concept was coined) to October 2019. Our findings provide a complete list of 18 smart capabilities (e.g., real- time capabilities, adaptability and dynamicity, visibility and traceability, autonomy, smart scheduling, PPC-as-a- service); 13 performance indicators (e.g., manufacturing flexibility, agility, reliability); and environmental factor conditions (e.g., product, demand, and manufacturing process). We also propose a future agenda with ten research directions for PPC's study in the I4.0-context.

### 2.1 Introduction

Production Planning and Control (PPC) activities aim to define what, how much, and when to produce, buy, and deliver so that the company can match manufacturing performance with customer demands (BONNEY, 2000). Therefore, PPC is a value-adding process of manufacturing activity (WIENDAHL; VON CIEMINSKI; WIENDAHL, 2005). PPC needs to continually adapt to operational and strategic environments, complex customer requirements, and new supply chain opportunities (VOLLMANN et al., 2005; YIN; STECKE; LI, 2018). Thus, PPC needs to be dynamic, adaptive, and integrative (ADAMSON; WANG; MOORE, 2017; HELO; HAO, 2017; IVANOV et al., 2016; KONG et al., 2015).

The rapid industrial environmental changes impose an evolutionary and integrative perspective in operations management and, consequently, in the PPC Function (OLHAGER, 2013; OLHAGER; RUDBERG, 2002). Thus, the PPC Function considers, for example, material requirements planning (MRP), enterprise resource planning (ERP), just-in-time manufacturing, and collaborative planning, forecasting, and replenishment, among other activities (JACOBS et al., 2018; RONDEAU; LITTERAL, 2001). In recent years, the PPC function has been strongly supported by information and communication technology (ICT) (SHAMSUZZOHA et al., 2016). ICT supports planning and control for core aspects of production, e.g., forecast demands, sales and operations planning (S&OP), MRP, master production scheduling (MPS), and production scheduling (NAHMIAS; OLSEN, 2015). PPC Function can also include interface activities such as procurement, shipment, capacity analysis, input/output control, and ordering systems (CHAPMAN, 2006).

With the advent of the Internet of Things (IoT) and cyber-physical systems (CPS) in industrial contexts, digital capabilities have provided the opportunity for creating a new PPC context (ALTAF *et al.*, 2018; MOEUF *et al.*, 2018; THÜRER *et al.*, 2019). Emerging digital capabilities of the "*Fourth Industrial Revolution*" (i.e., I4.0) can create new opportunities for PPC. The German conceptualization of I4.0 focused on establishing and sustaining real-time optimized value networks (KAGERMANN; HELBIG; HELLINGER, 2013), setting out multiple actors, and covering autonomous manufacturing resource networks (BITKOM; VDMA; ZVEI, 2016). Many other extensions and broader perspectives have been proposed after this initial concept coined in Germany (FRANK; DALENOGARE; AYALA, 2019). However, we follow the traditional view of the German model, which has been consolidated worldwide as the dominant view of the Fourth Industrial Revolution. This view considers the manufacturing process as the core activity of I4.0 (DALENOGARE et al., 2018). In this sense, the PPC Function, which is a central part of the manufacturing system, may also face changes with the advent of I4.0 technologies(CATTANEO *et al.*, 2018; DOMBROWSKI; DIX, 2018; MOEUF *et al.*, 2018; VOLLMER *et al.*, 2017). Dombrowski and Dix (2018) stated that managerial functions, including the PPC, could be transformed by using digital technologies, being more integrated, and automated. Traditional activities of PPC can be affected by concepts such as the vertical integration of physical and digital production environments (WANG et al., 2016), which considers cyber-physical systems and digital (GILCHRIST, 2016; GRAESSLER; POEHLER, 2017; ZHONG et al., 2017c) and the integration of ERP, manufacturing execution systems, and machine-to-machine approaches for ordering systems (HOWALDT; KOPP; SCHULTZE, 2017).

Although I4.0 technologies are assumed to support PPC activities, the I4.0 literature has not investigated yet specific characteristics of this crucial function of the production systems. The literature on this topic is widespread, and it lacks a holistic view that clarifies the relationships between I4.0 and PPC function,
showing how I4.0 affects PPC activities through new smart capabilities. Therefore, this study's main objective is to investigate the relationship between PPC and I4.0 through a systematic literature review (SLR). We relate PPC with I4.0 in a conceptual framework representing the intersections and studies addressing several perspectives.

Chapter 02 is organized as follows: Section 2.2 presents the systematic literature review strategy, the connections between the primary constructs, and presents the conceptual framework that guides the current study. Section 2.3 presents and discusses the main findings from the literature review. A future research agenda is established in Section 2.4, while section 2.5 concludes the Chapter and presents the research limitations.

## 2.2 Research method: a systematic literature review

Our research method follows an SLR approach to ensure replicability by using transparent procedures and steps (TRANFIELD; DENYER; SMART, 2003) . Therefore, as shown in Figure 2.1, we followed the recommendations of Levy and Ellis (2006), Tranfield et al. (2003), and Webster and Watson (2002), which served as methodological and operational guides for the research.

### 2.2.1 Stage 1: Planning the review

After identifying the research gap (absence of reviews showing the relationships between PPC and I4.0), the first step was to determine the nature of I4.0 and its means of realization and what PPC is, and its scope and activities. Then, we developed constructs, keywords, and search strings. Thus, an analytical framework with three research questions was consolidated (see the next subsection, i.e., "*analytical framework*"). We used this framework to create a research protocol that sets the details for conducting Stage 2 (SLR processing).

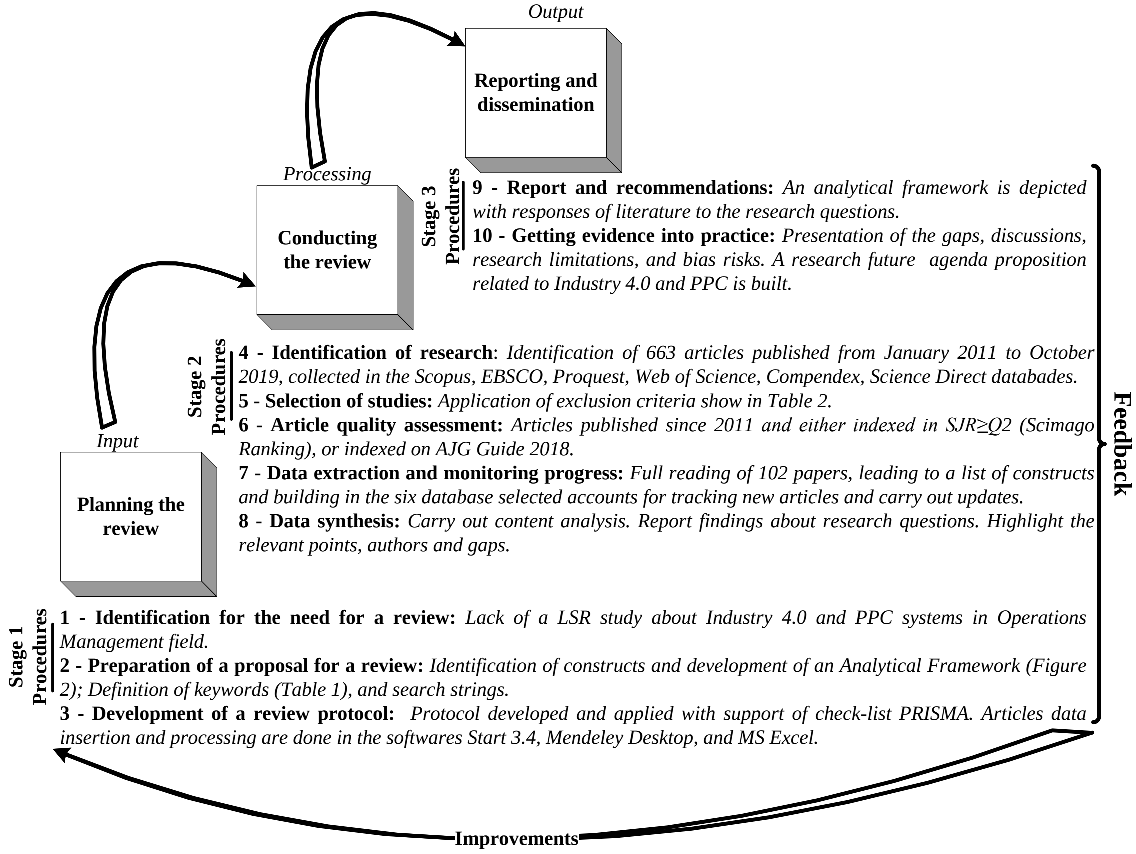



**Figure 2.1.** Systematic Literature Review (SLR) using mixed guidelines from Tranfield et al. (2003), and Levy and Ellis (2006)

### *2.2.1.1 Analytical framework*

In this study, a preliminary collection of references and exploration of the literature found no accessible SLR-type articles related to the functional relationships between I4.0 and PPC, approaches to smart capabilities and performance, or environmental factors moderating the relationship of PPC with performance.

The analytical framework of Figure 2.2 presents the different theoretical points of view regarding the relationships between I4.0, PPC, performance, and environmental factors. A similar framework was presented by Buer et al. (2018) to study the links between I4.0 and lean manufacturing, which we used as a reference. The purpose of our framework was to establish a relationship reference for a subsequent summary of the results for each PPC activity, as well as the respective smart capabilities and attributes provided by leading technologies in I4.0. Using this framework, we also aimed to investigate the changes toward smart PPC, i.e., structural changes necessary to introduce new smart capabilities for the PPC function in the I4.0 context. Based on this, a framework with three research questions is detailed below.

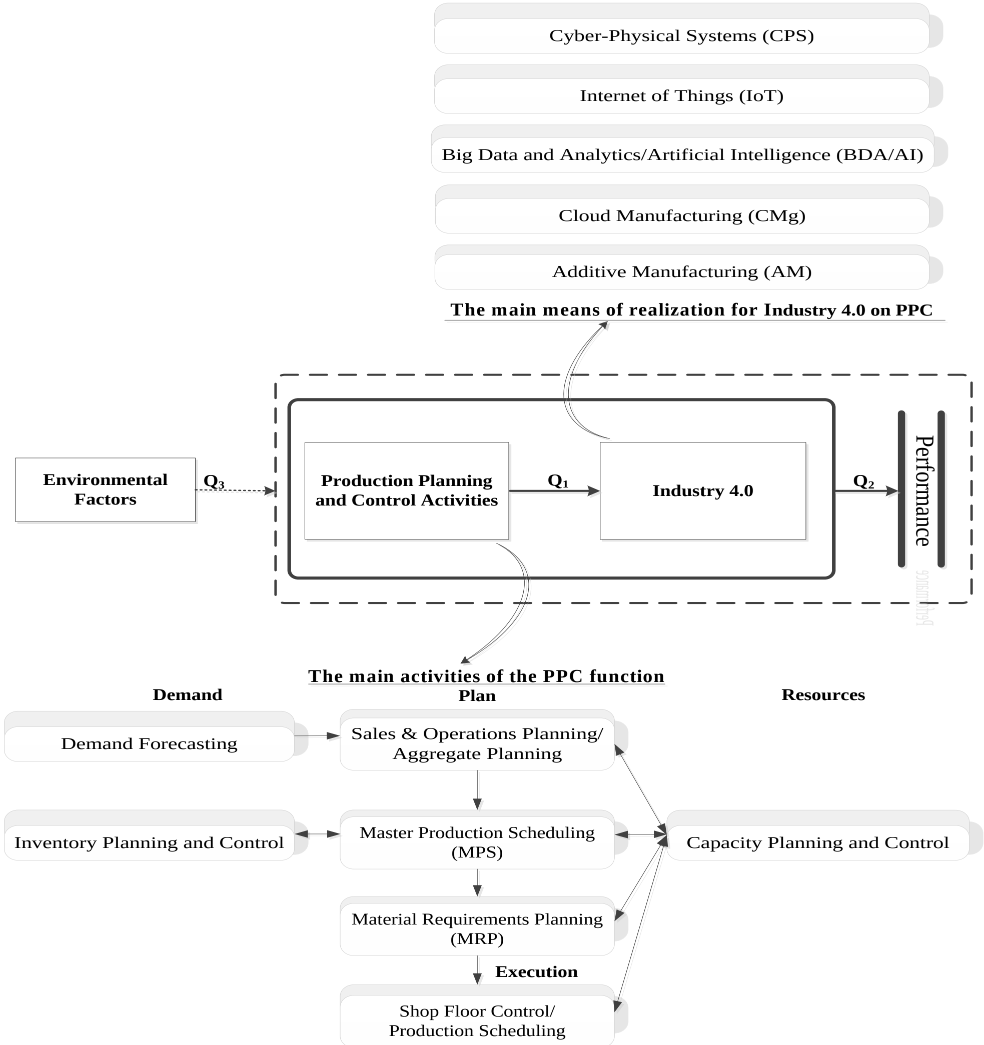



**Figure 2.2.** Analytical framework

The three research questions of the present study are as follows:

**Q1.** The PPC function and its activities are evolutionary, integrative, and capable of adapting activities, methods, tools, and structures to support the impacts of I4.0. *Therefore, what are the smart capabilities necessary for PPC that can be provided by I4.0?*

In this study, smart capabilities are defined as capabilities and resources that leverage the PPC function and its activities toward digitalization, integration, and automation (ARBIX et al., 2017) through the exploration of smart technologies, as well as the mechanisms of networking power, applied in smart manufacturing planning and control.

**Q2.** The integration between the PPC function and I4.0 can affect different manufacturing system performance dimensions. *Does the integration of PPC with I4.0 determine performance implications?*

**Q3**. Moderating factors are likely to influence the integration potential between the PPC function and I 4.0, as well as the performance resulting from this integration. *What are the environmental factors that influence the development of smart capabilities for PPC?*

Each of the constructs of Figure 2.2 is explained below, considering: the means of realization for I4.0, PPC function, performance implications, and environmental factors.

**PPC function:** The PPC Function is responsible for making decisions regarding planning, starting, controlling, monitoring, scheduling, and reprogramming of a production planning, and ensuring the delivery of the products of a manufacturing company (BONNEY, 2000). The framework depicted in Figure 2.3 lists the PPC function's main activities, as triggered by strategic manufacturing planning. This PPC structure is based on Vollmann et al. (2005), Chapman (2006), and Jacobs et al. (2018), and often comprises a hierarchical structure. The main activities of a generic PPC are also shown: demand forecasting (DFO), S&OP/aggregate planning, MRP, MPS, inventory and capacity planning and control (INV, CAP), production scheduling, and shop floor control (SFC) activities.

**The means of realization for I4.0:** The "*means of realization*" for I4.0 is the term used in this study to refer to any smart technology or mechanisms in the literature that constitutes a method for developing an I4.0 concept inside the PPC perspective. This term is based on Moeuf et al. (2018). The means of realization for I4.0 can be impactful and can boost and suitably sustain the development of a smart PPC function (DOMBROWSKI; DIX, 2018; MOEUF *et al.*, 2018). Accordingly, we surveyed 50 current references to delimit the scope and the means of realization for I4.0 from the PPC perspective.

The subject exploration revealed the scope of research involving manufacturing planning and control with I4.0. It could be divided into five essential means of realization that may occur alone or in clustering, namely the CPS, IoT, big data and analytics with artificial intelligence (BDA/AI), cloud manufacturing (CMg), and additive manufacturing (AM). This systematic review uses these key five technologies as potential vectors to realize I4.0 inside manufacturing planning and control.

**Performance implications:** Current OM literature has already noted the performance dimension implications regarding the relationships between PPC and I4.0 (DALENOGARE et al., 2018). For example, Moeuf et al. (2018) identified flexibility, cost reduction, quality improvement, reduced delivery time, and productivity improvement as linked to PPC practices for small and medium-sized enterprises (SMEs). Buer et al. (2018) identified cost, flexibility, productivity, quality, reduced inventory, and reliability as the manufacturing system performance dimensions affected by integrating lean manufacturing with I4.0. Both reviews found evidence justifying an analysis of the literature regarding the performance effects of integrating manufacturing and I4.0. This relationship will be approached from the strategic performance dimensions of operations linked to smart manufacturing planning capabilities and control (JACOBS et al., 2018).

**Moderating factors:** Our article considers a contingency theory (SOUSA; VOSS, 2008) as the theoretical basis for the third question (Q3) regarding manufacturing planning and control moderator factors. This viewpoint considers environmental variable effects on both the integration and operations performance of PPC and I4.0. In this way, the contingency theory supports investigating how organizations can adapt their PPC structures to fit into environments to develop superior performance (SOUSA; VOSS, 2008). Often, this adaptation also concerns production planning environments and methods; therefore, in this review, moderator factors are defined as identifiable environmental elements (BUER; STRANDHAGEN; CHAN, 2018). It can moderate the applicability of I4.0 in an organization's operations and can harness smart capabilities via planning and control. Our systematic review is based on environmental variables linked to product, demand, and manufacturing processes, as listed and explained by Jonsson and Mattsson (2003).

### 2.2.2 Stage 2: Conducting the review

Levy and Ellis (2006) argued that an SLR process should synthesize quality literature to provide a solid foundation for a field of research. Webster and Watson (2002) stated that the main contributions would likely be found in leading journals. Thus, we adopted the same logic applied in the literature review of Ghadge et al. (2012) and Kamalahmadi and Parast (2016), and also in the systematic review of Maestrini et al. (2017), i.e., using only journal articles in the study.

Our SLR focused on the analysis and scrutiny of a body of articles on the subject of I4.0 combined with PPC and considered only articles from the year 2011 onward. Then, for consideration of the quality of a publication, a mutually contingent condition was adopted, in which a journal had to be classified in either the Academic Journal Guide 2018 (AJG) or one of the two highest quartiles (Q1 or Q2) of the Scimago Journal Ranking (SJR). The time range was set from January 2011 to October 2019. Kagermann et al. (2013) established the beginning of the I4.0 era as the year 2011, as the I4.0-concept was presented for the first time at the Hannover Fair in Germany (HERMANN; PENTEK; OTTO, 2016).

Concerning the SLR's operational steps, the Scopus, Web of Science, Science Direct, ProQuest, EBSCO, and Compendex databases were surveyed using two strings formulated from the keywords in Table 2.1. The search returned 658 documents. In general, the criteria guiding the selection of databases were based on the insertion of the most significant number of possible sources that traditionally hosted journals publishing works of high impact on the research subject.

We extracted the keywords related to I4.0 from an exploratory survey of 50 recent scientific articles conducted in Stage 1 of this SLR. We also crosschecked the keywords with the recent systematic reviews of Liao et al. (LIAO et al., 2017), Buer et al. (2018), and Moeuf et al. (2018). The search terms comprised keywords presented in the first column of Table 2.1.

PPC is a more well-established domain in the OM literature than I4.0. Accordingly, the keywords presented in the second column of Table 2.1 for the PPC construct are assumed to be sufficient and comprehensive for the PPC domain. The first keyword in the second column, "*planning and control*" refers to a PPC function in a generalized manner. In contrast, the group of keywords below encompasses the specification of traditional activities of the PPC function, according to Chapman (2006), Vollmann et al. (2005), and Jacobs et al. (2018). Thus, we clustered the PPC activities in the demand dimension: "*demand forecasting*", "*inventory planning and control*"; in the resources dimension: "*capacity planning and control*"; and also, in the planning and execution dimension: "*S&OP*," "*aggregate planning*" "*materials requirement planning*" "*master production scheduling*" and "*production scheduling*" as shown in Table 2.1.

**Table 2.1**. The keywords used in the research

| I4.0 construct | | Production Planning and Control (PPC) construct |
|---|---|---|
| ‘industry 4.0’OR | | |
| ‘industrie 4.0’ OR | | |
| ‘the fourth industrial revolution’ OR | | |
| ‘the 4th industrial revolution’ OR | | ‘planning and control’OR |
| ‘smart manufacturing’ OR | | |
| ‘smart production’OR | | |
| ‘smart factory’ OR | | |
| ‘cyber-physical system’ OR | | |
| ‘cyber-physical production system’ OR | AND | |
| ‘internet of things’ OR | | |
| ‘industrial internet’ OR | | ‘demand forecasting’ OR |
| ‘big data and analytics’ OR | | ‘sales and operations planning’ OR |
| ‘artificial intelligence’ OR | | ‘aggregate planning’ OR |
| ‘digitalization’ OR | | ‘materials requirement planning’ OR |
| ‘digitization’ OR | | ‘master production scheduling’ OR |
| ‘additive manufacturing’OR | | ‘production scheduling’ OR |
| ‘cloud manufacturing’OR | | ‘inventory planning and control’ OR |
| ´digital factory’ | | ‘capacity planning and control’ |

The next procedure comprised applying the “Preferred Reporting Items for Systematic Review and Meta-Analysis” (PRISMA) (MOHER et al., 2009) approach to the following activities (see Figure 2.3): identification, screening, eligibility, and inclusion. These steps in PRISMA supported the operationalization of activities 4 to 8 in the SLR, as shown in Figure 2.1. We applied a preset to the databases’ search engines to guarantee accuracy in the return of the articles. We set up the search engines by inserting the two strings adopted in this process and recorded the files in a database. In the identification phase, we obtained a return of 658 documents. We added five documents obtained by cross-referencing and snowballing, and we excluded 300 duplicate documents, resulting in 363 remaining documents.

**Table 2.2**. Details of inclusion and exclusion criteria

| Criteria type | Criteria | Code | Criteria detail |
|---|---|---|---|
| Exclusion | Search engine reasons | SER | SER (1): The paper has a title and abstract in English, but does not have the full text<br>SER (2): The article does not come from an academic journal, that is, it originates from a book, a book section, or a conference proceeding |
| | No full text | NFT | The paper does not have available text to be assessed |
| | Time range | TRC | The article was not published within the defined time range: as of 2011 |
| | Not quality ranking | NRQ | The article does not have a Scimago Journal Ranking (SJR) at levels Q1 or Q2, and the article is not published in a journal that is indexed in the Academic Journal Guide 2018 |
| | Not peer-reviewed | NRP | The article is not peer-reviewed academically |
| | Non-related | NR | NR (1): The article does not relate the relationships of the PPC function or its activities to the main means of realization for I4.0 adopted in this review<br>NR (2): The paper is not an academic article |
| | Loosely related | LR | The article is Loosely related to PPC integration with I4.0, that is, the article does not express discussion or results regarding the constituent relationships of the research framework |
| Inclusion | Partially related | PR | PR (1): The article generically addresses the subject of I4.0, focusing on integration with one or a few elements of the PPC function and its activities<br>PR (2): Integration of PPC with I4.0 frames only one of several research objectives, or some extracts of the article |
| | Closely related | CR | The research focus of a paper clearly and strictly addresses the integration of PPC with I4.0 and its capabilities |

The first five exclusion criteria (SER, NFT, TRC, NRQ, NRP, NR) presented in Table 2.2 were applied to the 363 identified articles in the first screening process. As a result, we excluded 244 documents. From a reading of the abstracts, keywords, titles, and conclusions, the remaining exclusion criteria in Table 2.2 (NR and LR) were applied, resulting in the additional exclusion of 20 articles. Accordingly, we obtained a final set of 102 articles. These articles were eligible for full reading and possible inclusion in the systematic review. The details regarding the number of articles excluded due to each criterion in Table 2.2 are shown in Figure 2.3.

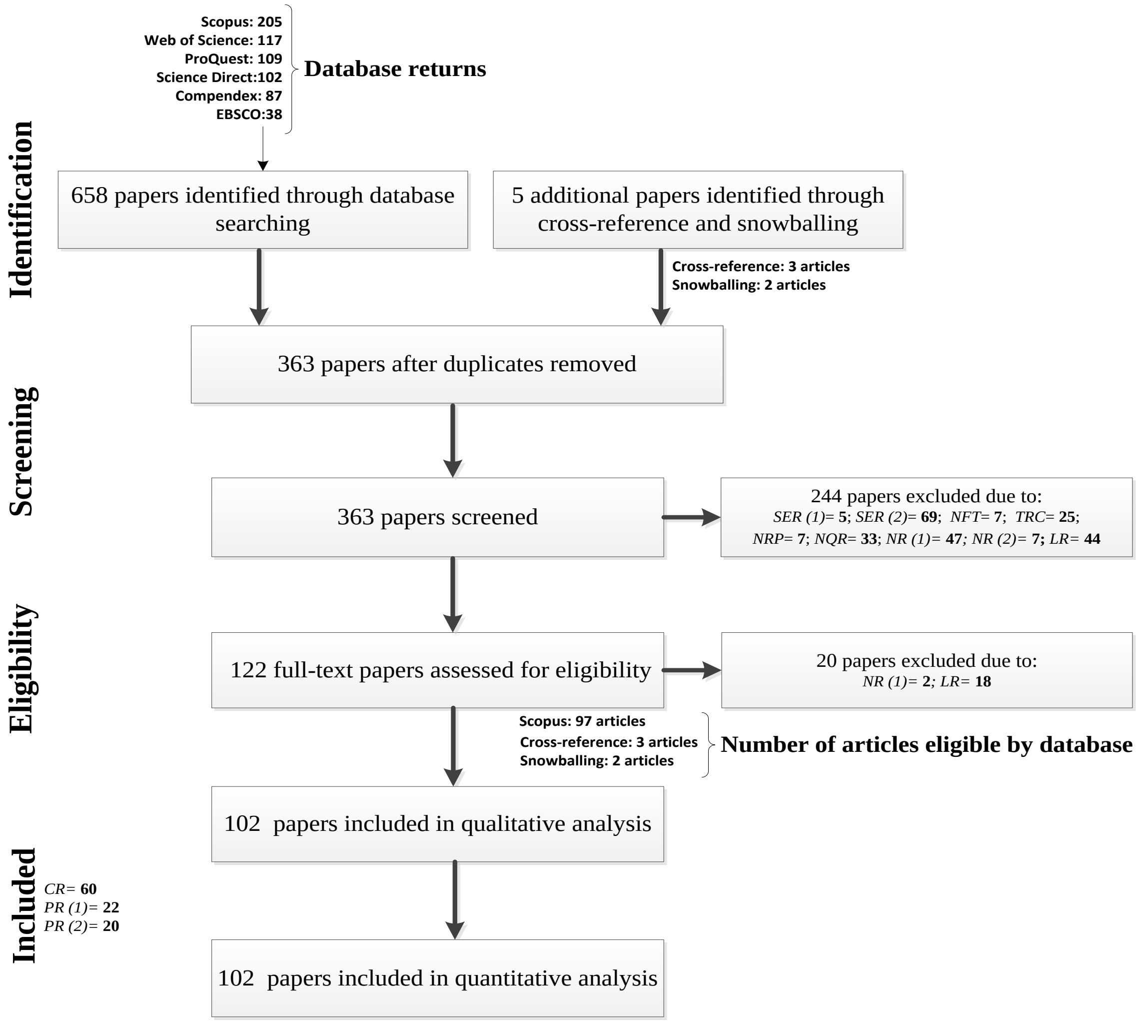



**Figure 2.3.** PRISMA flowchart of the systematic review

### 2.2.3 Stage 3: Reporting and dissemination

SLR's last stage considers the report and presentation of the theoretical and empirical findings regarding the three research questions. Besides, a "*content analysis*" showing an overview of the articles and the quantitative and qualitative analyses are presented in Section 2.3.

## 2.3 Findings

In this section, firstly, an overview of the field of research is presented. In the rest of the section, the results expressed in the literature about each relationship of the analytical framework presented in Figure 2.2 will be discussed.

### 2.3.1 An overview of the included articles

As shown in Figure 2.4, between the years 2011 and October 2019, there was a trend of accelerated growth in I4.0 related articles that considered PPC as a term. Fifty-four articles comprise empirical research, and 48 articles comprise conceptual types of research. Regarding the methods employed, 25 are experimental studies with modeling and simulation, 21 are conceptual research studies (e.g., bibliographical surveys, review studies, and theoretical discussions), 20 are industrial cases with modeling and simulation, 17 are studies involving only modeling and simulation, 17 are case studies, one is a survey, and another study is a Delphi survey.

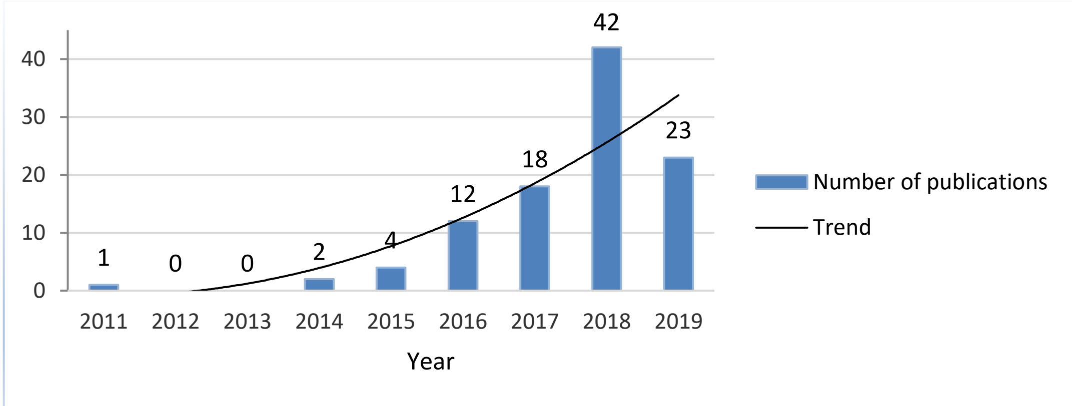



**Figure 2.4**. Distribution of articles per year

As for journals, the highest frequencies of articles are from the International Journal of Production Research (13 articles), International Journal of Computer Integrated Manufacturing (six articles), Journal of Intelligent Manufacturing (six articles), Computers and Industrial Engineering (six articles), Computers in Industry (five articles), Journal of Manufacturing Systems (five articles), and Production Planning and Control (four articles). Between one and two articles were extracted from the other journals. The 102 eligible articles (for both quantitative and qualitative analyses) were compared and can be found and extracted through the Scopus database. The Scopus database is one of the most significant databases for the subject searches addressed in this review.

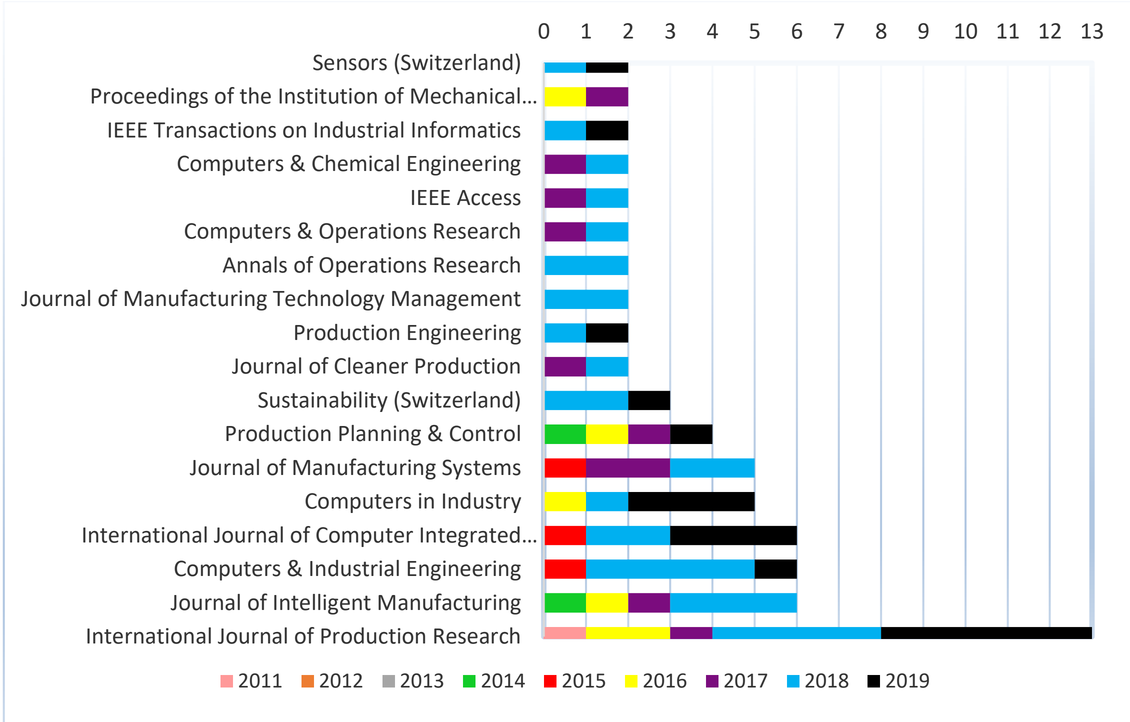
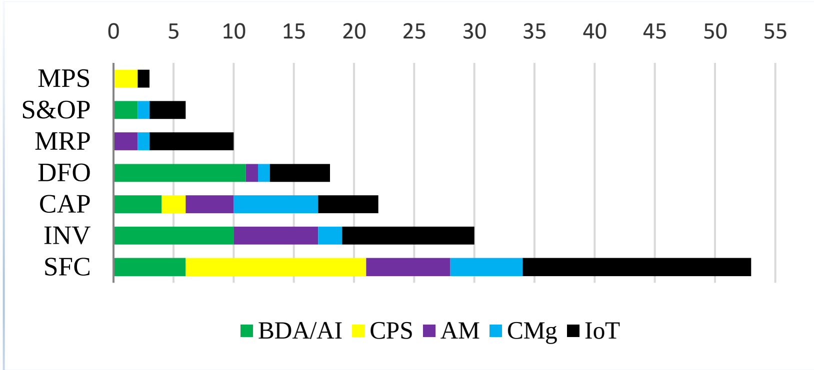



**Figure 2.5.** Distribution of articles per journal and year

The magnitude of harnessing the I4.0 technologies by each PPC activity considered in this SLR is represented in Figure 2.6. This association regards articles with codes of 1 to 87 (see codes in Figure 2.7). The I4.0 technologies most explored are IoT (51 articles) and BDA/AI (33 articles) by shop floor control and scheduling activities (53 articles), and also inventory planning and control (30 articles). Note that some articles related to PPC activities explore more than one technology. The red color numbers in columns and rows in Figure 2.6 show the higher frequencies of each I4.0 technology on each PPC activity within the articles.

The remaining articles, with codes 88 to 102 associated with the entire PPC function with I4.0 technologies. These papers explore with the highest frequency CPS (eight articles) and BDA/AI (six articles) (see Figure 2.8).

Universities and research centers studying the combination of PPC and I4.0 are spreading across all continents, emphasizing research conducted in Asia, especially in China (responsible for approximately ¼ of the articles analyzed in this review). The rest of the articles originated from research institutions in countries such as Germany, the United Kingdom, the USA, Finland, Italy, France, Norway, Sweden, India, Canada, and Greece. For researchers, the main departments/areas of origin are Industrial/Mechanical Engineering (37%), Business, Management, and Economics (17 %), Information Systems and Computer Science (11 %), Electric/Electronic, Robotics/Automation (5%), other areas (30% - statistics, mathematics, and other related fields).




| | CMg | CPS | AM | BDA/AI | IoT | Number of articles |
|---|---|---|---|---|---|---|
| MPS | 0 | 2 | 0 | 0 | 1 | 3 |
| S&OP | 1 | 0 | 0 | 2 | 3 | 6 |
| MRP | 1 | 0 | 2 | 0 | 7 | 10 |
| DFO | 1 | 0 | 1 | 11 | 5 | 18 |
| CAP | 7 | 2 | 4 | 4 | 5 | 22 |
| INV | 2 | 0 | 7 | 10 | 11 | 30 |
| SFC | 6 | 15 | 7 | 6 | 19 | 53 |
| **Number of articles** | 18 | 19 | 21 | 33 | 51 | |

**Figure 2.6.** Distribution of articles addressing PPC activities and I4.0 technologies

### 2.3.2 Key findings: analytical framework

Next, we discuss the results of the three research questions in the analytical framework section. The results were extracted using the content analysis technique from 102 articles.

*2.3.2.1 What are the smart capabilities for Production Planning and Control (PPC) provided by I4.0?*

***i.*** **Analyzing the Smart Capabilities Explored for Demand Forecasting, Capacity Planning and Control, and Inventory Planning and Control**

*Demand Forecasting:* According to Figure 2.9 and related articles/authors in Figure 2.7, the leading smart capabilities explored in the demand dimension and reported in the literature are based on the IoT, and concern real-time data collection and integration with aggregate planning and inventory management (MAN; NA; KIT, 2015; YERPUDE; SINGHAL, 2017; YU et al., 2018b). The forecasting processing and data analytics portion are strongly focused on BDA/AI tools for supporting smart capabilities concerning the predictability of resources, improving the accuracy and performance of forecasting, processing sets of big data and analytics using machine learning methods, automatic selection of demand predictors, real-time data collection, and monitoring and diagnosis with data analytics tools for the integration of demand forecasting with capacity and inventory management (ANDERSSON; JONSSON, 2018; CHOI; WALLACE; WANG, 2018; FU; CHIEN, 2019; GONZÁLEZ-VIDAL; JIMÉNEZ; GÓMEZ-SKARMETA, 2019; HAMISTER; MAGAZINE; POLAK, 2018; LEE; LIANG, 2018; LOLLI *et al.*, 2019; YIN; CHAO, 2018; YUE *et al.*, 2018). Other capabilities explored by forecasting include accurate fulfillment of seasonal demands for spare parts (MUIR; HADDUD, 2017) based on AM and real-time data collection, and processing for auctions with demand forecasting based on cloud services (KONG et al., 2015).

*Capacity Planning and Control*: The main smart capabilities for capacity planning and control are explored in the digital environments of the IoT and CMg with BDA/AI, and support integration of forecasting and inventory activities (for more details, see Figure 2.10, and related articles/authors in Figure 2.7). The core capabilities explored for capacity management are the digitalization of capacity resources with real-time data collection and monitoring through products with product-embedded intelligent devices (PEID) (MEYER; (HANS) WORTMANN; SZIRBIK, 2011), synchronization of a PPC plan module (MPS, MRP, capacity and production scheduling) (RAUCH; DALLASEGA; MATT, 2018; YU et al., 2018a), data-driven-predictive capacity planning (WAN et al., 2018), and traceability and/or processing of machine and real-time monitoring status products (LIAO; WANG, 2019). AI applications in CPS support the integration of control tasks (order releasing, sequencing, and capacity control) (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017) and predictive maintenance planning into PPC (ANSARI; GLAWAR; NEMETH, 2019). CMg and BDA/AI support capabilities such as scalability, reconfiguration, and flexibility in production capacity management (HELO; HAO, 2017; KONG et al., 2015; YUAN et al., 2017), production resource monitoring with information and material flow optimization, integration and synchronization of capacity with other systems and operations, and predictive and robust capacity management (AHMADOV; HELO, 2018; KATCHASUWANMANEE; BATEMAN; CHENG, 2016; LEE; LIANG, 2018; LIN; CHONG, 2017; NING; YOU, 2018; SUBRAMANIYAN *et al.*, 2018; YU *et al.*, 2018a). AM has been explored to optimize and manage a distributed, flexible, and available capacity of 3D-printers (ACHILLAS; TZETZIS; RAIMONDO, 2017; LI; KUCUKKOC; ZHANG, 2017; LIU *et al.*, 2014; MUIR; HADDUD, 2017).

*Inventory Planning and Control:* In this dimension of PPC activity, the smart capabilities provided by I4.0 technologies are actively explored, as highlighted by the IoT and AM (for more details, see Figure 2.10, and related articles/authors in Figure 2.7). The main capabilities observed in the literature are real-time monitoring and control with PEID (MEYER; (HANS) WORTMANN; SZIRBIK, 2011), integration between forecasting, customer service, and aggregate planning (HWANG; KIM; RHO, 2016; MATHABA et al., 2017; RAMAKRISHNAN; GAUR; SINGH, 2016), smart inventory system concepts (sensor data, analytics, CPS integration, and green attributes) (ZHENG; WU, 2017), automatic inventory management, continuous monitoring and optimization (TEJESH; NEERAJA, 2018), IoT-driven e-Kanban, and smart vendor managed inventory systems (THÜRER *et al.*, 2019; YERPUDE; SINGHAL, 2017).

The smart capabilities reported in the literature in AM environments include flexibility of choice between decentralized and centralized safety inventories, mass customization/direct digital manufacturing for low-volume production, and improvements in the real-time traceability and decentralized control of parts, kits, and available spare parts stocks (ACHILLAS et al., 2015; ACHILLAS; TZETZIS; RAIMONDO, 2017; GHADGE et al., 2018; HOLMSTRÖM et al., 2016; JIANG; KLEER; PILLER, 2017; KUNOVJANEK; REINER, 2020; LI; KUCUKKOC; ZHANG, 2017; LIU et al., 2014).

Concerning CMg with BDA/AI, the smart capabilities concern the integration of inventory systems with enterprise and execution manufacturing systems, PPC activities and tasks, optimization, automated storage and retrieval systems, and real-time traceability based on AI methods (ANDERSSON; JONSSON, 2018; BEVILACQUA; CIARAPICA; ANTOMARIONI, 2019; CHOI; WALLACE; WANG, 2018; HAMISTER; MAGAZINE; POLAK, 2018; HELO; HAO, 2017; KONG et al., 2015; LEE; LIANG, 2018; LOLLI et al., 2019; SIMCHI-LEVI; WU, 2018a; YANG; ZHANG; CHEN, 2016).

***ii.*** **Analyzing the Smart Capabilities Explored for Sales and Operations Planning (S&OP)/Aggregate Planning, Master Production Scheduling (MPS), and Material Requirements Planning (MRP)**

*S&OP/Aggregate Planning:* For these activities, the smart capabilities exploration concerns real-time data collection (IoT) for information sharing and collaboration, aggregate planning based on CMg, and applying BDA/AI and analytics technologies for enterprise and control systems integration (FANG et al., 2016; SHAMSUZZOHA et al., 2016)(for more details see Figure 2.10, and related articles/authors in Figure 2.7).

Aggregate planning is found in searched articles exploring IoT digital capabilities for multi-level data sharing, traceable data flows, and integration with demand forecasting, inventory control, and manufacturing execution system (MES)/ERP systems (YU et al., 2018b). In a CMg environment, the S&OP employs real-time integration to feed PPC operational tasks and adaptive real-time pricing integrated with sales data, adequate level capacity data, production scheduling, and S&OP desegregation (KONG et al., 2015). The smart capabilities explored for BDA/AI include real-time optimization prices combined with big data processing, information cost and inventory level monitoring integrated for S&OP processes (SIMCHI-LEVI; WU, 2018a), and spare parts demand planning integrated with S&OP (ANDERSSON; JONSSON, 2018).

*MPS:* Only three articles were identified for MPS based on IoT and CPS (RAUCH; DALLASEGA; MATT, 2018; ROSSIT; TOHMÉ; FRUTOS, 2019c, 2019a). IoT supports demand-driven and real-time capabilities for the PPC function, providing synchronization of the IoT with the capacity, scheduling, MPS, and MRP (RAUCH; DALLASEGA; MATT, 2018). The CPS support capabilities concerning real-time production scheduling, enterprise, and control systems, with distributed and collaborative decision-making through MES, MPS/ERP, and CPS integration (ROSSIT; TOHMÉ; FRUTOS, 2019b). More details can be found in Figure 2.10 and from the related articles/authors shown in Figure 2.7.

*MRP*: MRP is mostly based on the IoT (for more details, see Figure 2.10, and related articles/authors in Figure 2.7). The core capabilities provided by the IoT to MRP are: the integration of building information models, ERP/MRP systems with resources and data systems, and MRP element digitalization following context-awareness resources (RAUCH; DALLASEGA; MATT, 2018; TEZEL; AZIZ, 2017), real-time resources status monitoring, responsive shop floor material management (WANG; ONG; NEE, 2018; XU; CHEN, 2018), automatic data collection from material controls integrated with ordering systems (LIN et al., 2018), data-driven simulations to predict material flows and shop floor operations behavior (GOODALL; SHARPE; WEST, 2019), and real-time sensing and positioning using a data-driven optimization of materials, and intelligent automated guided vehicles (HUANG et al., 2019).

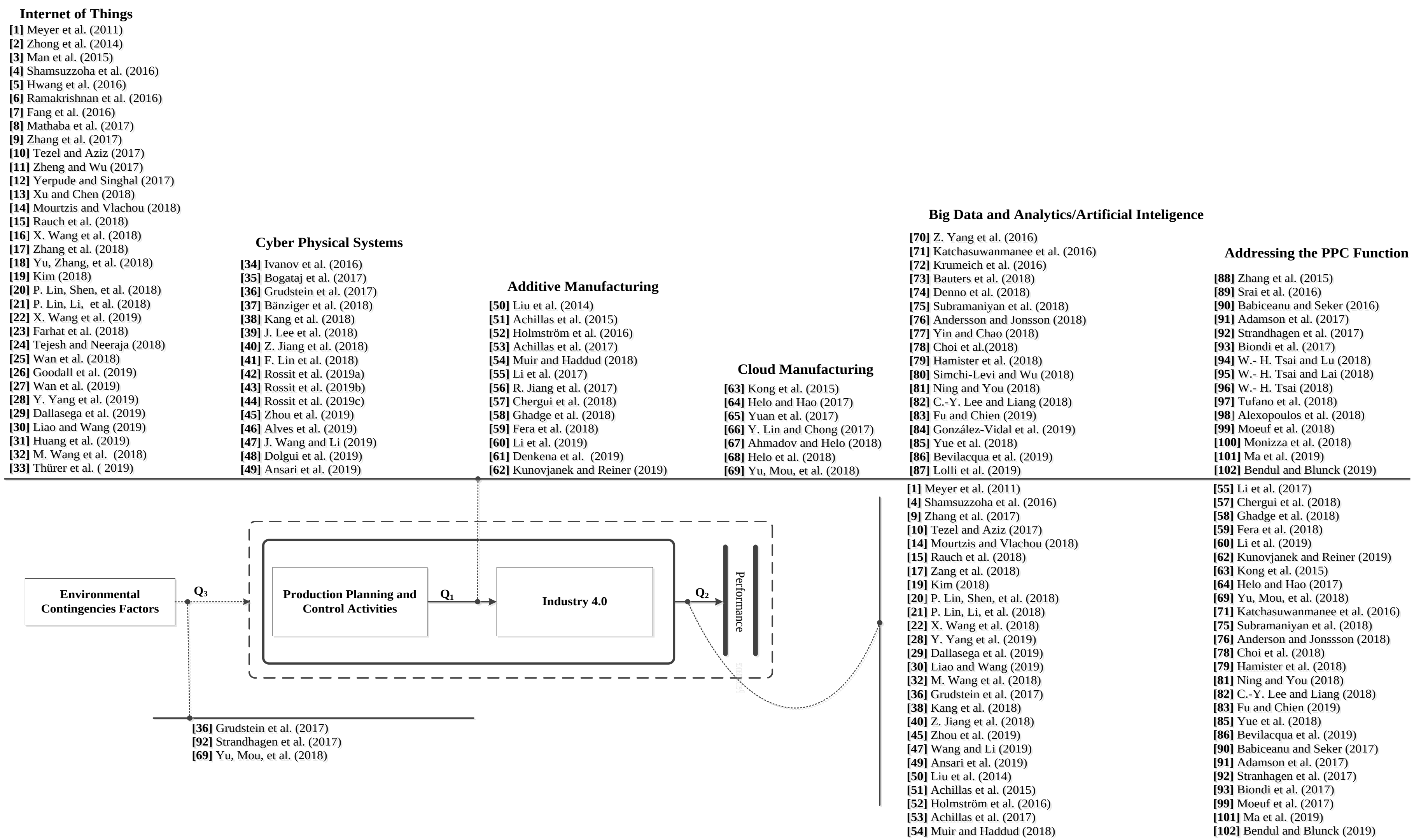



**Figure 2.7.** Results from analytical framework– authors, time range, and related I4.0 technologies

In a CPS environment, the IoT supports capabilities related to extending MRP with real-time calculations, early reports, traceability, and food chain visibility (BOGATAJ; BOGATAJ; HUDOKLIN, 2017), in addition to MRP automatic optimization, prediction, and re-scheduling based on the digital twin model (LIN et al., 2019). AM technology provides smart capabilities, including direct digital manufacturing with minimization of the handling and processing of materials, and minimization of the MRP complexity with a reduction of logistics flow is smart (ACHILLAS et al., 2015; ACHILLAS; TZETZIS; RAIMONDO, 2017; KUNOVJANEK; REINER, 2020). In CMg, the research has explored servitization's capability, which frames ERP/MRP systems as serviced by cloud platforms.

### *iii.* Analyzing the Smart Capabilities Explored for Production Scheduling/Shop Floor Control

*Production Scheduling/Shop Floor Control:* The production scheduling and shop floor control activities are explored in greater detail with respect to I4.0 in all technologies considered for this study (the details can be seen in Figure 2.9, and the related articles/authors in Figure 2.7). The leading smart capabilities explored for the IoT are related to digitalization and networking integration in the context of manufacturing execution, rather than planning and control systems. These smart capabilities at the level of manufacturing execution, scheduling, and control include real-time shop floor monitoring, resource traceability, data collection, data mining (LIAO; WANG, 2019; MEYER; (HANS) WORTMANN; SZIRBIK, 2011; THÜRER et al., 2019; ZHONG et al., 2014), and real-time information sharing for collaborative production scheduling (SHAMSUZZOHA et al., 2016). The concept of smart scheduling is based on the integration of digital capabilities for real-time, data-driven, collaborative, green energy aware, and automatic data collection, and can be used for, e.g., 3D-printer scheduling (FARHAT *et al.*, 2018; GOODALL; SHARPE; WEST, 2019; KIM, 2018; LIAO; WANG, 2019; LIN *et al.*, 2019; THÜRER *et al.*, 2019; WANG *et al.*, 2020b; WANG; ONG; NEE, 2018; ZHANG; WANG; LIU, 2017). The remaining capabilities concerning the IoT concentrate on adaptive and distributed shop floor control, integrated scheduling of enterprise and control systems (MOURTZIS; VLACHOU, 2018; WAN et al., 2018), synchronization task scheduling, operations (vertical/horizontal synchronization) for real-time visibility of the shop floor on a mobile display (GOODALL; SHARPE; WEST, 2019; LIN et al., 2018, 2019; RAUCH; DALLASEGA; MATT, 2018), data-driven simulations to predict material flows and shop floor operations behavior (WAN et al., 2018), flexible and reconfigurable production scheduling

(WAN et al., 2019), responsiveness (DALLASEGA et al., 2019) and real-time optimization (KIM, 2018; LIN et al., 2019; WANG et al., 2020b; ZHANG et al., 2018).

The main smart capabilities provided by CPS for production scheduling and control are related to smart scheduling and automation. Smart scheduling in the context of CPS is based on the smart capabilities of scalability, modularity, autonomous and decentralized data collection, data-driven operations, adaptiveness, flexibility, and collaboration, for scheduling and shop floor control systems (ALVES *et al.*, 2019; DOLGUI *et al.*, 2019; IVANOV *et al.*, 2016; JIANG *et al.*, 2018; KANG *et al.*, 2018; LIN; WONG; GE, 2018; ROSSIT; TOHMÉ; FRUTOS, 2019d, 2019b, 2019c; WANG; LI, 2019). Other capabilities concern cooperative cyber-physical production systems integrated with the IoT-MES/APS. Shop floor control predominates the smart capabilities regarding automation, such as autonomous production control and task integration based on CPS/AI (BOGATAJ; BOGATAJ; HUDOKLIN, 2017; GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017), predictive maintenance integrated to production scheduling and based on CPS/AI (ANSARI; GLAWAR; NEMETH, 2019), intelligent planning and control algorithms for optimized and automatic human-robot task allocation (BÄNZIGER; KUNZ; WEGENER, 2020), manufacturing cells with autonomy (intelligent perception, optimization/simulation, awareness, prediction, and control), and self-optimization (self-thinking, self-decision-making, self-execution, and self-improvement) (ZHOU et al., 2020).

Concerning AM, the main capabilities explored are direct digital manufacturing, real-time traceability of parts and machines, decentralized control of individual parts and kits, scalability, synchronization operations, planning and control, dynamic order acceptance for on-demand production, optimum allocations of 3D-printers, mass customization control, 3-D printer production, inventory integration, and product model (ACHILLAS; TZETZIS; RAIMONDO, 2017; DENKENA; DITTRICH; JACOB, 2019; HOLMSTRÖM et al., 2016; LI et al., 2019), optimization of 3D-printer scheduling (CHERGUI; HADJ-HAMOU; VIGNAT, 2018; FERA et al., 2018; LI et al., 2019), integration of detailed adaptive process planning, and AM production planning and scheduling (DENKENA; DITTRICH; JACOB, 2019).

In a CMg environment, the main capabilities explored are servitization, production scheduling-as-a-service for manufacturing-as-a-service (HELO; HAO, 2017; HELO; PHUONG; HAO, 2019), digitalization of production scheduling via real-time auction and performance analytics (KONG et al., 2015), optimization production scheduling, flexibility, and reconfigurable lines based on cloud services (AHMADOV; HELO, 2018; LIN; CHONG, 2017; YUAN et al., 2017).

The core smart capabilities based on BDA/AI are real-time MES and object traceability for adaptive and optimized production scheduling (KATCHASUWANMANEE; BATEMAN; CHENG, 2016), smart scheduling based on big data-driven collection, analysis, and optimization, energy-smart/green optimization (KRUMEICH; WERTH; LOOS, 2016; LEE; LIANG, 2018), predictability/event-driven scheduling (BAUTERS *et al.*, 2018; LEE; LIANG, 2018; SUBRAMANIYAN *et al.*, 2018), and automated data analytics/embedded self-learning/AI (DENNO; DICKERSON; HARDING, 2018).

### *iv.* Analyzing the Articles Addressing the Entire PPC function, Without Focusing on any Specific Activity

The SLR articles (codes 88 to 102) highlighted in Figure 2.8 discuss PPC as a function of management (see articles in Figure 2.7); they do not address any PPC activity, but rather approach the PPC function in a holistic manner, facilitating the exploration of smart capabilities using I4.0.

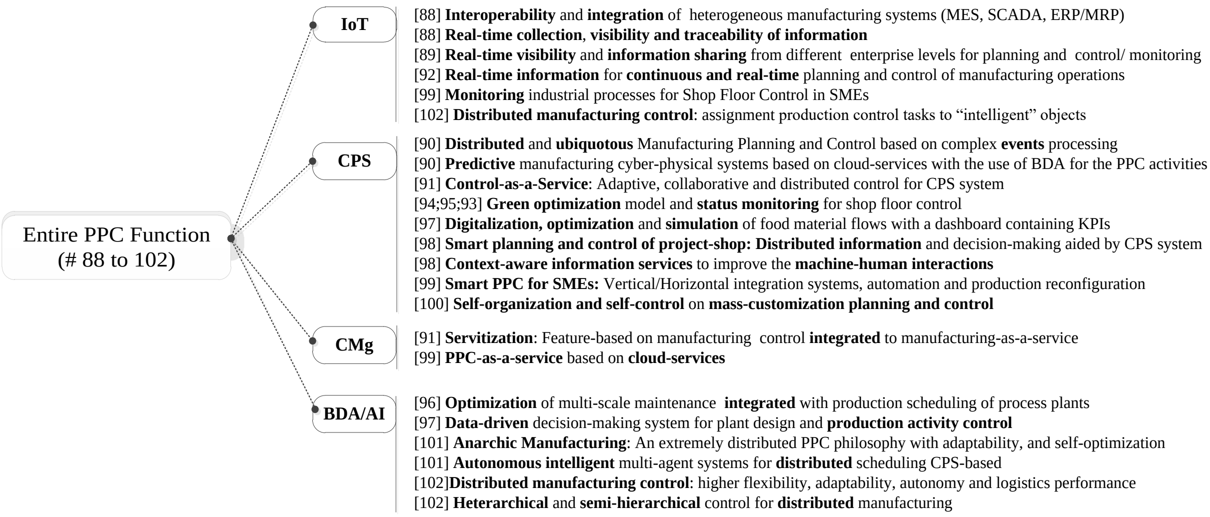


**Figure 2.8.** Smart capabilities regarding PPC function

In this way, the core smart capabilities explored for the PPC function in articles 88 to 102 are mostly based on IoT technologies concerning the interoperability and integration of heterogeneous manufacturing execution and planning systems (e.g., for MES/ supervisory control and data acquisition, and MRP/ERP) (ZHANG et al., 2015), digitalization, the real-time collection, visibility, traceability, and sharing of information from enterprise-level planning and control and operations monitoring (MOEUF *et al.*, 2018; SRAI *et al.*, 2016; STRANDHAGEN *et al.*, 2017; ZHANG *et al.*, 2015), and distributed manufacturing control (BENDUL; BLUNCK, 2019). Concerning the CPS environment, the literature approximates the PPC function from an I4.0 perspective as a cyber-physical production system (CPPS). Therefore, the smart capabilities reported in articles searched for this item address distributed and ubiquitous PPC control systems endowed with complex events processing and a predictive manufacturing CPS integrated with BDA and cloud services (BABICEANU; SEKER, 2016), servitization (control-as-a-service), adaptive, collaborative, and distributed control for the CPPS (ADAMSON; WANG; MOORE, 2017), green optimization models and status monitoring for shop floor control (TSAI, 2018; TSAI; LAI, 2018; TSAI; LU, 2018), digitalization, optimization, and simulation using key performance indicator dashboards (TUFANO et al., 2018), smart planning and control for projects/shops with distributed information, context-aware information services, decision-making supported by a CPPS for improving machine-human interactions (ALEXOPOULOS et al., 2018), smart PPC for SMEs, vertical/horizontal integration systems, automation with production reconfiguration, and self-organization and self-control, based on a CPPS constructed for mass customization planning and control (PASETTI MONIZZA; BENDETTI; MATT, 2018).

In a CMg environment, the articles exploring the PPC function strongly address servitization, such as in the context of PPC-as-a-service based on cloud computing and cloud services (ADAMSON; WANG; MOORE, 2017; BABICEANU; SEKER, 2016; MOEUF *et al.*, 2018), in addition to feature-based manufacturing control for manufacturing-as-a-service (ADAMSON; WANG; MOORE, 2017).

Finally, the BDA/AI technologies provide new organizational philosophies for the PPC function, including anarchic manufacturing, i.e., an extremely distributed PPC system with adaptability and self-optimization (autonomous and intelligent multi-agent systems) (MA; NASSEHI; SNIDER, 2019), distributed manufacturing control, trade-offs regarding hierarchical, semi-hierarchical, and hierarchical manufacturing control systems (BENDUL; BLUNCK, 2019), optimization multi-scale maintenance integrated with plant process scheduling (BIONDI; SAND; HARJUNKOSKI, 2017), and data-driven decision-making for production control (TUFANO et al., 2018).

#### *2.3.2.2 Does the integration of PPC with I4.0 determine manufacturing system performance implications?*

Table 2.3 presents the articles addressing each performance dimension in a clustered manner. We identified 52 studies linking manufacturing systems performance to the various indicators;

however, both flexibility and cost were the more prominent performance indicators obtained from the exploration of smart capabilities provided by I4.0.

Table 2.3 provides some indicators, as demonstrated in the 30 empirical types of research analyzed. Cost reduction, reliability, and lead time improvements are the indicators demonstrated from the 13 empirical/ field types of research (see Figure 2.10). Despite these findings, the reduced number of studies empirically demonstrating impacts on performance indicators from the exploration of I4.0 is insufficient for any generalization, as these studies show sparingly different indicators (see Table 2.3).

Many of the studies shown in Table 2.3 discuss performance indicators as *potentials of performance* (see Figure 2.10). Thus, we observed that most of the research analysis encompassing performance is based on theoretical studies, or empirical studies that do not demonstrate the performance indicator acting in real cases. Thus, our analysis concerning performance described below is based on the theoretical viewpoints provided by the analyzed 52 articles. In the Table 2.4 we built a comprehensive explanation regards 13 performance indicators found in the SLR: operational manufacturing flexibility, manufacturing agility and responsiveness, manufacturing complexity, manufacturing quality, manufacturing customer satisfaction, sustainable manufacturing, manufacturing robustness, manufacturing costs, manufacturing lead time, manufacturing productivity, manufacturing reliability, manufacturing profitability, supply chain inventories.

We observed from the articles that both manufacturing operations and PPC can be made more flexible by harnessing the benefits provided by I4.0. However, we addressing in this article the manufacturing system concept, which the operational and agile manufacturing environment (MEYER; (HANS) WORTMANN; SZIRBIK, 2011). Achillas et al. (2015) addresses the interconnections between mass customization, manufacturing flexibility, and responsiveness for production on-demand. Kong et al. (2015) discusses the influence of flexibility on adaptive PPC for an auction process. Shamsuzzoha et al. (2016) addresses collaborative and flexible production planning for product development through virtual enterprises.

Agility, reliability, and robustness are likely to be improved in a smart manufacturing context by the exploration of smart capabilities. In general, the studies report improvements in reliability with respect to the traceability and visibility of information, resources, and products, and real-time capabilities. The reliability of plans and operations increases customer satisfaction (HELO; HAO, 2017; JIANG et al., 2018; KIM, 2018; LIN et al., 2018; MOEUF et al., 2018; TEZEL; AZIZ, 2017).

In addition, the improvement of specific objectives in production scheduling is verified through the reduction of the total setup times, total tardiness, and makespan, and increases in the throughput time, due date reliability, work-in-process, and utilization (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017; HELO; HAO, 2017; KIM, 2018; LIN et al., 2019). Mourtzis and Vlachou (2018) and Bendul and Blunck (2019) argue that the digitalization of manufacturing planning and control results in a manufacturing quicker response, improved flexibility, and an increase of productivity by approximately 30%.

Lastly, quality, profitability, and productivity of manufacturing are performance indicators less reported in the research, but positively related to I4.0 adoption (BENDUL; BLUNCK, 2019; HOLMSTRÖM et al., 2016; JIANG et al., 2018; KATCHASUWANMANEE; BATEMAN; CHENG, 2016; KIM, 2018; MOEUF et al., 2018; MUIR; HADDUD, 2017; NING; YOU, 2018; YANG et al., 2019; ZHOU et al., 2020). Performance indicators as energy saving and resources constitute an emerging green indicator that is coupled to I4.0 effects (ACHILLAS et al., 2015; BENDUL; BLUNCK, 2019; HELO; HAO, 2017; KATCHASUWANMANEE; BATEMAN; CHENG, 2016; WANG et al., 2020b; ZHANG; WANG; LIU, 2017). Moreover, the complexity minimization in networking manufacturing concerns of products, planning processes, operations, shop floor control, production scheduling, and management systems is another emerging indicator coupled to the structural aspects of smart manufacturing in smart factories (ACHILLAS et al., 2015; BENDUL; BLUNCK, 2019; DALLASEGA et al., 2019; KANG et al., 2018; RAUCH; DALLASEGA; MATT, 2018; WANG; ONG; NEE, 2018; ZHANG; WANG; LIU, 2017).

#### *2.3.2.3 What are the environmental factors which influence the development of smart capabilities by PPC?*

We found only three papers addressing environmental contingency factors as moderators for integrating PPC and I4.0 and the corresponding effects on manufacturing performance (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017; STRANDHAGEN et al., 2017; YU et al., 2018a). These three articles show that some PPC smart capabilities are influenced by the following environmental factors: product, demand, and manufacturing process.

Regarding the product, PPC-as-a-service is an example of a PPC smart capability moderated for product requirements. These requirements are related to product design modularization and communality integrated to order release, inventory, and sourcing decisions based on cloud manufacturing (CMg). The product environmental variables found on moderate the PPC regarding scalable product variety and greater flexibility based on holding generic stocks before the customer order (YU et al., 2018a). Thus, product variables seem to positively influence the suitability of the PPC-as-a-service for integrated MTO and MTS environments.

PPC-as-a-service is also moderated for demand. The demand forecasting and inventory accuracy are especially important for manufacturing systems with high demand uncertainty, e.g., single-piece production for customized products, therefore, it influences the tech- nology adoption (CMg) and its smart capabilities. These smart capabilities enable the PPC to manage to resources sharing pool to meet single-piece demand (by using the idle manufacturing in the customization stage for smoothing demand fluctuations). The demand environmental variables found on (YU et al., 2018a) are, for example, reliable P/D ratio for customized production, procurement ordering of semi-finished items, and forecast for distributed independent demand for customized items on assembly, data inventory-demand accuracy, replenishment stock, and customer order synchronization for better release-order and sourcing decisions. Thus, customized demand seems to influence the suitability of the PPC-as-a-service for integrated MTO and MTS environments positively.

Regarding process manufacturing factors, shop floor control's autonomy is moderated by environmental variables related to complex manufacturing processes. Thus, the following environmental variables moderates the SFC autonomy for a complex manufacturing environment, according to Grundstein et al. (2017): a broad mix of products and operations in complex job shop manufacturing (batch processes with unrelated parallel machines), the throughput time of the order, and the setup times. Customer-oriented complex job shop manufacturing variables seem to positively moderate the suitability of the autonomous production control (SFC autonomy), mainly for complex manufacturing environments (ETO, MTO). Besides, Strandhagen et al. (2017) show by four case studies, which companies with a low degree of repeatability in production, low material flow complexity, and a high degree of engineering-to-order are less suitable for transition to I4.0 in terms of logistical production flows.

**Table 2.3.** Articles addressing the influence of the smart PPC on manufacturing systems performance

| Articles | Performance indicators | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Legend:<br>C= conceptual research<br>E= empirical/field research<br>✓[d]= demonstrated indicator | Cost | Flexibility | Productivity | Agility | Reliability | Quality | Energy and Resources | Profitability | Lead Time | Robustness | Inventories | Complexity | Customer Satisfaction |
| [C]Meyer et al. (2011) | | ✓ | | ✓ | | | | | | ✓ | | | |
| [E]Liu et al. (2014) [Case Study] | ✓ | | | | | | | | ✓ | | ✓ | | |
| [E]Kong et al. (2015) [Case Study] | ✓ | ✓ | | ✓ | | | | | ✓ | | | | ✓ |
| [E]Achillas et al. (2015) [Case Study] | ✓[d] | ✓ | | | | ✓ | ✓ | | ✓[d] | | | ✓ | ✓ |
| [E]Shamsuzzoha et al. (2016) [Case Study] | ✓ | ✓ | | | | | | | ✓ | | | | ✓ |
| [E]Katchasuwanmanee et al. (2016) [Experimental Research/Simulation] | | | ✓ | | | | ✓ | | | | | | |
| [C]Holmström et al. (2016) | | | ✓ | | | | | | | | | | |
| [C]Babiceanu and Seker (2016) | ✓ | ✓ | ✓ | ✓ | | | | | | | | | |
| [E]Strandhagen et al. (2017) [Case Study] | | ✓ | | ✓ | | | | | | | ✓ | | |
| [E]Helo and Hao (2017) [Case Study] | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | |
| [C]Tezel and Aziz (2017) | | | ✓ | | ✓ | | | | | | | | |
| [C]Adamson et al. (2017) | | ✓ | | | | | | | | | | | |
| [E]Biondi et al. (2017) [Experimental Research/Simulation] | ✓ | | | | ✓ | | | | | | | | |
| [E]Grudstein et al. (2017) [Case Study/Simulation] | ✓[d] | | ✓[d] | | ✓[d] | | | | | ✓ | | | |
| [E]Achillas et al. (2017) [Case Study] | ✓[d] | ✓ | | | | | | | ✓[d] | | | | |
| [E]Muir and Haddud (2017) [Survey] | | | | | ✓ | | | | ✓[d] | | ✓[d] | | |
| [C] Z.Jiang et al. (2018) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | | |
| [E] P. Lin, Shen, et al. (2018) [Case Study] | | | | | | | | | ✓ | | ✓ | | |
| [C;E]Li et al. (2017;2019) [Experimental research/Simulation] | ✓ | ✓ | | | | | | | | | | | |
| [E]Mourtzis and Vlachou (2018) [Case Study] | | ✓ | ✓ | | | | | | ✓ | | | | |
| [C]Subramaniyan et al. (2018) | | | ✓ | | | | | | | | | | |
| [E]Yu, Mou, et al. (2018) [Case Study/Simulation] | | ✓ | | ✓ | | | | | ✓ | | ✓ | | |
| [E] P. Lin, Li, et al. (2018) [Case Study/Simulation] | | | ✓ | ✓ | ✓[d] | | | | ✓ | | | | |
| [C]Fera et al. (2018) | ✓ | | | | | | | | | | | | |
| [E]Zhang et al. (2018) [Experimental research/Simulation] | ✓ | | | | | | ✓ | | | | | | |
| [C]Chergui et al. (2018) | | | | | ✓ | | | | | | | | |

| Articles | Performance indicators | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Legend:<br>C= conceptual research<br>E= empirical/field research<br>✓d= demonstrated indicator | Cost | Flexibility | Productivity | Agility | Reliability | Quality | Energy and Resources | Profitability | Lead Time | Robustness | Inventories | Complexity | Customer Satisfaction |
| [E]Ghadge et al. (2018) Experimental Research/Simulation | | ✓ | | ✓ | | | | | | | | | |
| [E]Hamister et al. (2018 Case Study | ✓d | | | | | | | | | | ✓d | | |
| [E]Kim (2018) Experimental Research/Simulation | | ✓ | | | ✓ | | | | | | | | |
| [E]Ning and You (2018) Experimental Research/Simulation | | | | | | | | ✓d | | | | | |
| [C]Moeuf et al. (2018) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | | | ✓ |
| [E]Yue et al. (2018) Case Study/ Simulation | | | | ✓ | ✓ | | | | | | | | |
| [E]Zhang et al. (2017) Case Study/Simulation | | ✓ | | | | | ✓ | | | | | ✓ | |
| [E]Rauch et al. (2018) Case Study | ✓d | | | | ✓ | | | | | | | ✓ | |
| [E]Andersson and Jonsson (2018) Case Study | | | | | ✓d | | | | | | | | |
| [C]Choi et al. (2018) | ✓ | | | | | | | ✓ | | | ✓ | | |
| [E]C.-Y.·Lee and Liang (2018) Case Study | ✓d | | | | ✓ | | | ✓d | | | | | |
| [C]Bendul and Blunck (2019) | | ✓ | ✓ | ✓ | | | ✓ | | | ✓ | | ✓ | |
| [C]Y. Yang et al. (2019) | ✓ | | | | | ✓ | | | | | ✓ | | |
| [C]Dallasega et al. (2019) | ✓ | | | ✓ | | | | ✓ | | | ✓ | ✓ | |
| [C]Ma et al. (2019) | | ✓ | | | ✓ | | | | | ✓ | | | |
| [C]Kang et al. (2018) | | ✓ | ✓ | | | | | | ✓ | | | ✓ | |
| [C]Zhou et al. (2019) | ✓ | ✓ | | ✓ | | ✓ | | | | | | | |
| [E]Fu and Chien (2019) Case Study/Simulation | ✓ | ✓ | | | ✓d | | | | | | ✓ | | |
| [E]Liao and Wang (2019) Experimental Research/Simulation | ✓ | | | | | | ✓ | | | | | | ✓ |
| [E]X.Wang et al. (2019) Case Study/Simulation | | | ✓ | | | ✓ | | | | ✓ | | | |
| [E]Bevilacqua et al. (2019) | ✓ | | | ✓ | ✓ | | | | | | ✓ | | |
| [C]Ansari et al. (2019) | | | | | ✓ | | | | | ✓ | | | |
| [C]Kunovjanek and Reiner (2019) | | | | | | | | | | | ✓ | | |
| [C]J. Wang and Li (2019) | | | ✓ | | | ✓ | ✓ | | | | | | |
| [E]M.Wang et al. (2020) Case Study | ✓d | | ✓d | | | | | | | | | | |

**Table 2.4.** Smart PPC influence on manufacturing systems performance: description

| **Performance Indicators: Descriptions and Definitions*** (see the source of example in the Literature column) | **Literature** |
|---|---|
| **Indicator:** Manufacturing flexibility (machines and resources, manufacturing systems, shop floor)<br>**Definition:** Adaptation to operational manufacturing change requirements<br>**Description:** Smart PPC provides flexibility for adaptive manufacturing can be made and manage in real-time. *For example, data collection by IoT devices on shop floor allows real-time (re)-scheduling, orders progress monitoring, resources traceability and visibility that enable operational flexibility in environment manufacturing | Bendul and Blunck (2019)<br>Helo and Hao (2017)<br>Zhang et al. (2017)* |
| **Indicator:** Manufacturing agility and responsiveness (machines and resources, manufacturing systems, shop floor)<br>**Definition**: Quick response to manufacturing change requirement<br>**Description:** Smart PPC provides responsiveness for manufacturing to react quickly to changes. *For example, real-time data collection allows an automatic task pool assignment in an IoT-enabled APS system that reacts to a responsive manner to changing for small batch production | Wan et al. (2019)<br>Dallasega et al. (2019)<br>P. Lin, Li, et al. (2018)* |
| **Indicator:** Manufacturing complexity (manufacturing systems, shop floor/layout, assembly, products)<br>**Definition**: Simplified operations manufacturing, products, and installation<br>**Description:** Smart PPC provides the minimization of manufacturing complexity. *For example, IT-support allows real-time modelling, scheduling and monitoring in ETO environment that enable minimize the high degree of complexity in the planning and coordination between manufacturing shop and the installation of products and components | Rauch et al. (2018)*<br>Achilas et al. (2015)<br>Kang et al. (2019) |
| **Indicator:** Manufacturing quality (manufacturing systems, products, machines, and resources)<br>**Definition:** Manufacturing accuracy and "*make do right*" for products, management, and assemblies<br>**Description:** Smart PPC provides accuracy, efficiency, and adaptability for manufacturing quality improvements. *For example, the use of CPPS affects the manufacturing quality and efficiency concerning scheduling activity positively | Yang et al. (2019)<br>Zhou et al. (2019)<br>Z. Jiang et al. (2018)* |
| **Indicator:** Manufacturing customer satisfaction (internal and external customers)<br>**Definition:** Customer satisfaction integrated into manufacturing<br>**Description**: Smart PPC provides ways to the manufacturing maximizing customer satisfaction. *For example, IoT and modeling and simulation for integrated production-delivery scheduling, which considers low carbon emission and accurate delivery time (customer satisfaction criteria) | Liao and Wang (2019)*<br>Huang et al. (2019)<br>Chergui et al. (2018) |
| **Indicator:** Sustainable manufacturing (manufacturing systems, energy management, assembly, products, machines, and resources)<br>**Definition:** Manufacturing focused on saving resources and green operations<br>**Description:** Smart PPC provides ways to save energy, resources and develop sustainable operations. *For example, using Big Data techniques and modeling and simulation based on saving energy for a green production process scheduling | Liao and Wang (2019)<br>Zhang et al. (2018)<br>Katchasuwanmanee et al. (2016)* |
| **Indicator:** Manufacturing robustness (machines and resources, manufacturing systems, shop floor)<br>**Definition:** Manufacturing stability and reaction to unexpected changes<br>**Description:** Smart PPC provides robustness and stability for manufacturing to react against unforeseen changes or disruptions. *For example, the use of RFID/PEID and modeling and simulation for the shop floor monitoring to react to disturbances, e.g., material shortage | Ma et al. (2019)<br>Ansari et al. (2019)<br>Meyer et al. (2011)* |
| **Indicator:** Manufacturing costs and lead times (machines and resources, manufacturing systems, shop floor, operations logistic flow)<br>**Definition:** Lead times and costs of manufacturing operations | Liu et al. (2014)<br>Achilas et al. (2015)*<br>Li et al. (2017) |

| **Performance Indicators: Descriptions and Definitions*** (see the source of example in the Literature column) | **Literature** |
|---|---|
| **Description:** Smart PPC provides ways to improve costs (operations manufacturing, machines, resources) and lead times (cycle time, setup time, wait time, working time) manufacturing reduction. *For example, AM for customized small production volumes provides both cost and lead time reduction in the MTO environment | |
| **Indicator:** Manufacturing productivity and profitability (machines and resources, manufacturing operations, manufacturing systems)<br>**Definition:** Productivity of manufacturing operations and profitability of the entire manufacturing system<br>**Description:** Smart PPC affords an increase in productivity and profitability in manufacturing. *For example, CMg, ERP/TI tools, and optimization were used to increase the productivity and profitability in an IoT-based shop-floor material management system | Helo and Hao (2017)<br>Lee and Liang (2018)<br>Wang et al. (2018)* |
| **Indicator:** Manufacturing reliability (machines and resources, operations manufacturing, manufacturing systems)<br>**Definition:** Reliability in the manufacturing operations and systems performance<br>**Description:** Smart PPC affords more reliability for the performance of manufacturing. *For example, using the CPPS concept for autonomous production control (sequencing, order release, and capacity control integration) to meet due dates | Grudstein et al. (2017)*<br>Andersson and Jonsson (2018)<br>Fu and Chien (2019) |
| **Indicator**: Manufacturing and supply chain inventories (manufacturing system, supply chain, operations logistic flow)<br>**Definition:** Number of products, parts, resources, and materials streaming in the manufacturing chain<br>**Description:** A smart PPC provides a reduction of inventories in the manufacturing and supply chain. *For example, the use of AM positively affects the overall inventory performance in the supply chain (less stock, less spare parts obsolescence, delivery time improvement) | Liu et al. (2014)<br>Muir and Haddud (2017)*<br>Kunovjanek and Reiner (2019) |


**Figure 2.9.** A “big picture” for smart planning and control: smart capabilities, I4.0 technologies, and articles (by code)

## 2.4 Summary of results and future research directions

In this section, we summarize the results obtained through our systematic review (Figure 2.10), which can be used to address research in the literature, thereby constructing a future research agenda for a subject. Our research gaps are based on the 102 articles presented in Figure 2.7 and detailed in Figure 2.9. Future research and projects can focus on investigating these gaps and advancing the theories and practices supported by this emergent research field. In short, the main gaps were clustered. The first cluster concerned long-term gaps regarding tactical and strategic planning activities (PPC engine and front-end) in smart manufacturing PPC systems. The second cluster concerned PPC organizational issues and structural changes in the context of a new smart PPC. Besides, the drivers toward smart PPC can further cluster smart capabilities based on digitalization/real-time capabilities, automation/autonomy capabilities, and integration systems capabilities, along with their respective variants.

Briefly, our results have shown that IoT provides many attributes that can be used in PPC activities, through the exploration of new capabilities. According to Figure 2.6, production scheduling/shop floor control is the activity that most incorporates the new capabilities provided by I4.0, such as smart scheduling, real-time capabilities, distributed dynamic scheduling, CPS enablement, adaptive production scheduling, shop floor control synchronization, integration systems, and green production scheduling optimization.

In contrast, according to Figure 2.9, in the context of S&OP/aggregate planning, MPS, and MRP, the new capabilities provided by I4.0 are poorly explored. The central smart capabilities (explored jointly for engine and front-end PPC activities) include integration systems, digitalization/real-time capabilities, automation, traceability, context-aware objects, adaptiveness, servitization (ERP/MRP-as-a-service), data-driven optimization and simulation, synchronization processes and systems, MRP complexity minimizations, and distributed and collaborative aggregate planning for decision-making.

The results expressed in Figure 2.9 also demonstrate that the Shop Floor Control activities are those that have explored smart capabilities the most through the attributes provided by I

I4.0, evidencing greater applicability and exploration for PPC activities linked in a short-range, and concentrated in shop floor planning and control and its interface activities (demand forecasting, inventory, and capacity management). For demand forecasting, we observed a concentration of studies regarding the exploration of BDA/AI tools for improving accuracy in forecasting and for integration with enterprise and control systems, data collection, and analytics methods.

Concerning the structure and organization of the traditional PPC, more distributed configurations are imposed on manufacturing by AM, CMg, and CPS. There is a trend of PPC design and manufacturing control taking on a central role, owing to the reduced need for redesigns for engine activities, greater autonomy, intelligence for shop floor control activities, and greater precision in the implementation of PPC system design (BENDUL; BLUNCK, 2019; LIU et al., 2014; MA; NASSEHI; SNIDER, 2019). Studies regarding this topic were scarce in our review, leading to the research gaps 7 and 8.

New capabilities have emerged to support manufacturing planning and control in this scenario of smart manufacturing, such as anarchic manufacturing (MA; NASSEHI; SNIDER, 2019), manufacturing-as-a-service (HELO; HAO, 2017), AI tools for smart manufacturing (NING; YOU, 2018), and CMg scalability/modularity´ for PPC (YU et al., 2018b). The latent capabilities (such as awareness-context PPC, adaptability, predictability, scalability, and integration systems and tasks provided by the attributes and new capabilities of I4.0) mainly favor the flexibility and agility/responsiveness indicators. Adopting smart capabilities can help facilitate the emergence of new manufacturing performance indicators, such as resource-saving and green optimization scheduling (energy saving/smart energy grid/sustainability). These performance indicators appear to be already emerging for smart manufacturing.

Concerning the indicator performance, flexibility is the most impacted in the integration between PPC and I4.0. Although operational flexibility is the most significant promise for I4.0, its implementation is the hardest and a less achieved by enterprises (DALENOGARE et al., 2018; FRANK; DALENOGARE; AYALA, 2019). Our premise is that industries need a profound change in both structure and PPC systems. There are lacking studies addressing this gap of research according to our findings.

Flexibility is a core performance advantage promised by I4.0 (Table 2.3). However, this finding is not empirically demonstrated in articles. In contrast, cost minimization and the improvement of lead times are demonstrated but are not generalizable. Performance indicators such as quality and productivity are less addressed in the 52 studies analyzed, and still constitute potential research gaps.

Concerning environmental factors, three studies indicated that manufacturing process, product, and market factors could affect PPC integration with I4.0, and could also affect performance. However, there remain too few contingencies' studies to support conclusions regarding this research question.

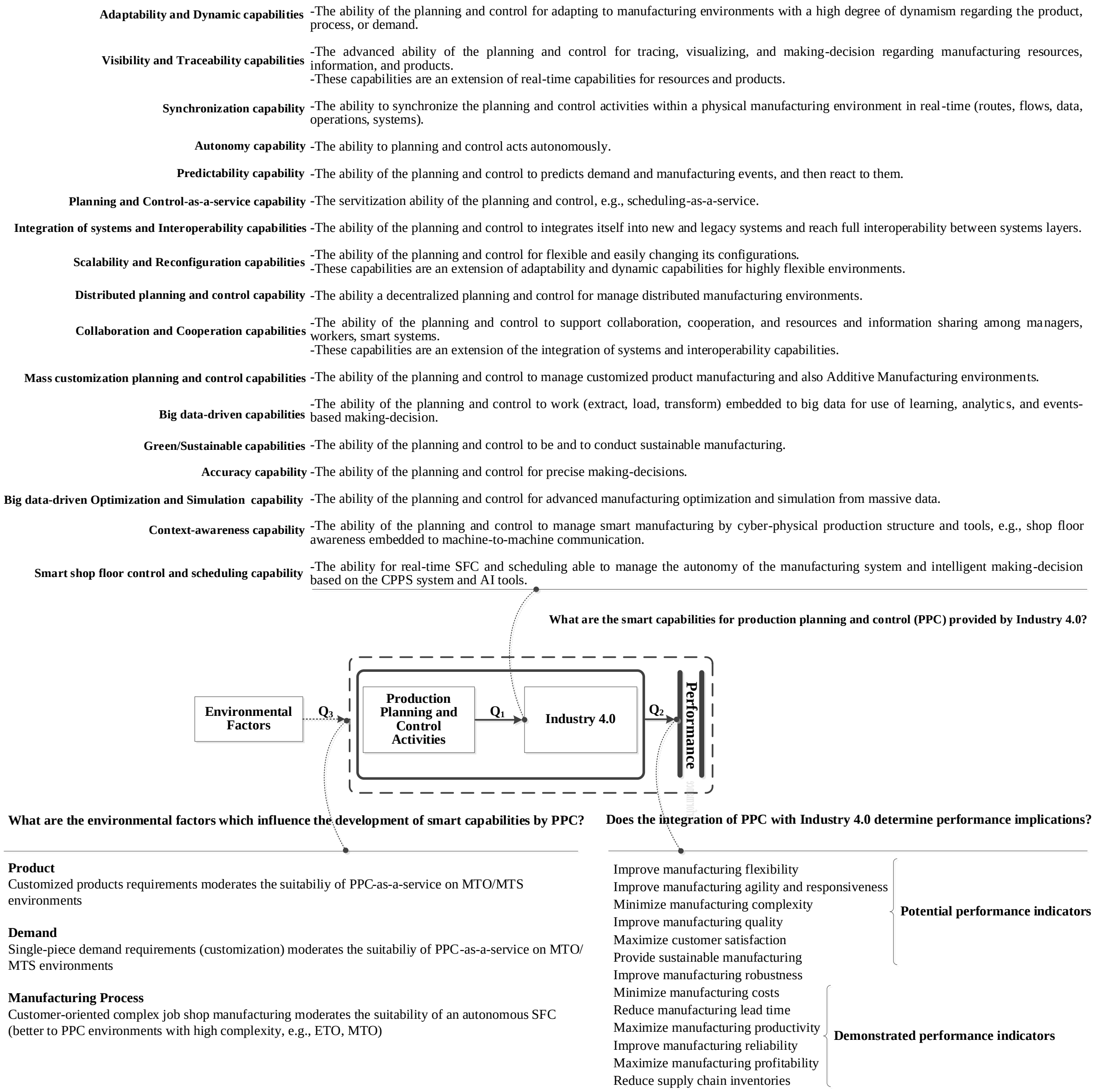



**Figure 2.10.** Summary of smart capabilities provided by I4.0 to PPC

The 18 smart capabilities explored for all PPC activities, the 13 performance indicators, and the three environmental factors were synthesized, and are presented as a summary of results in Figure 2.10 (i.e., the answers to research questions 1, 2, and 3).

Our SLR found some gaps concerning smart capabilities for PPC. From these gaps, we propose a future research agenda with ten research topics (RT). The first gap concerns the absence or a low number of studies investigating smart capabilities exploration by front-end and engine PPC activities (tactical planning). BDA has been explored significantly for demand forecasting, but CPS, AM, and CMg have been poorly explored (RT 1). Also, according to the gaps in the PPC planning activities, S&OP studies have not explored CPS, AM, and BDA/AI's smart capabilities. The MRP studies have not explored CPS and BDA/AI, and only one research study explored CMg. MPS is the PPC activity less impacted by the smart capabilities exploration provided by I4.0 and appears only in three studies (one exploring IoT, and two for CPS) (RT 2).

Literature indicates the need for integration as a recurrent capability for PPC planning activities. We also observed a lack of studies regarding the effects and role of scalability/modularity for planning and control capacity and inventory planning and production scheduling through the exploration of CMg. This subject is addressed just in very few studies (RT 3) (HELO AND HAO, 2017; KONG et al., 2015; WAN et al., 2019; ZHANG et al., 2018). The reduction of complexity in planning (design, manufacturing, and inventory control) from AM's adoption was another observed gap (RT 4).

We observed end-to-end integration with BDA and CPS for demand management, and data feeding for S&OP/aggregate planning and other planning activities. These also constitute challenging research subjects once studies with such goals are scarce (RT 5). It is interesting to notice that gaps 1, 2 and 5 can be addressed together once we did not observe studies exploring AI, machine learning, data mining, or (big) data tools and methods with applicants for the integration of demand forecasting, S&OP, aggregate planning, MRP, or MPS with real-time capabilities (RT 1, 2, and 5).

Similarly, few empirical studies (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017; MOURTZIS; VLACHOU, 2018) approach the effects of more distributed manufacturing (by adopting CPS, AM, CMg) causes on the traditional structures for planning, control, and operations performance. The exploration and implementation of the new management capabilities offered by I4.0 (IoT, CPS, AM, CMg, BDA/AI) can change organizational aspects, such as the PPC responsibilities, PPC objects, and PPC process. Moreover, cultural factors and maturity levels in an industry, sector, or country can be vectors for transitions to smart factories. Research is absent regarding this aspect. Therefore, we propose research topics 6, 7, and 8.

Our review also shows that the research concerning the applicability and fit of the integration of PPC/I4.0 in different environments is limited. (GRUNDSTEIN; FREITAG; SCHOLZ-REITER, 2017; MUIR; HADDUD, 2017; YU et al., 2018a). From this, arise research topic 9. Moreover, no studies were found regarding decision support systems for smart PPC systems, frameworks, or architectures in the context of moving toward PPC digitalization (RT 10). The ten proposed research topics are detailed as follows:

(RT 1) Research regarding how I4.0 can support PPC activities for medium/long-term planning (strategic and tactical levels), such as smart S&OP/aggregate planning, MRP/ERP, and MPS;

(RT 2) Studies encompassing S&OP, MRP/ERP, and MPS/APS integration systems, frameworks, and models, based on BDA/AI, CPPS, and CMg ecosystems;

(RT 3) Research focusing on smart PPC as-a-service, and addressing capabilities such as scalability, collaboration, cooperation, modularity, and the trade-offs from adopting pay-as-you-go services based on CMg;

(RT 4) Research on the impact of AM on the reduction of overall smart PPC complexity;

(RT 5) Empirical research regarding end-to-end integration based on BDA/AI and CPPS, as applied to demand management and other PPC activities like smart shop floor scheduling and control;

(RT 6) Theoretical and empirical studies regarding the adoption level of I4.0, maturity levels, and their influence on managers' awareness and their willingness to pay for the adoption of smart capabilities;

(RT 7) Studies on the effects of distributed manufacturing over the traditional PPC hierarchical structure discuss how new features of distributed manufacturing can affect the PPC configuration as to logistical objectives, degrees of autonomy, complexity, and effects on operations performance, like flexibility implementation;

(RT 8) Studies on how PPC design and autonomous manufacturing planning and control can be conceived periodicals with less expectation of re-planning or periodic planning at the tactical level (compression of front-end and engine PPC activities, owing to the more autonomous control on the shop floor and accurate PPC design afforded by I4.0);

(RT 9) Approaches to grounded theory through in-depth organizational investigation, e.g., use of theoretical lenses such as contingency theories with dynamic capabilities to jointly investigate the roles of moderating environmental factors with intangible asset factors on the applicability or development of smart PPC (endowed with smart capabilities) in different manufacturing environments;

(RT 10) Development of intelligent decision support systems, frameworks, architectures, and models to advance and consolidate smart manufacturing planning and control.

## 2.5 Conclusions and limitations

The 102 articles analyzed in this SLR indicated that IoT is the technology that predominantly supports most PPC activities in exploring smart capabilities. IoT can be highly integrated with other means of realization for I4.0, such as CMg, CPS, BDA/AI, and AM. The researchers for this new study area, PPC and I4.0, are concentrate in Asian and European Universities, mainly from Industrial/Production and Mechanical Engineering departments. Furthermore, these researchers are focusing on investigating key capabilities offered by IoT, CPS, Big Data/AI for shop floor control, scheduling, inventory control, and capacity planning.

Important attributes were expressed in the analyzed studies. The three drivers of smart capability exploration for PPC are the digitalization that supports, for example, real-time capabilities, synchronization of manufacturing stages, visibility and traceability, servitization/PPC-as-service, collaboration/cooperation, big-data-driven PPC, context-aware PPC, accuracy, smart PPC, mass customization/direct digital manufacturing planning and control, and green/sustainable PPC. The second driver observed was the integration of systems and operational tasks for clustering smart capabilities for advantages in predictability, interoperability, servitization/PPC-as-service, distributed PPC, scalability/reconfiguration, cyber-physical production systems, and ubiquitous manufacturing. The third driver is automation for supporting adaptiveness, dynamic, responsiveness and robustness in PPC, automatic scalability, reconfiguration, distributed and ubiquitous PPC, big-data-driven optimization and simulation, data-driven PPC, AI, and data analytics tools for intelligent PPC.

Concerning the exploration of new smart capabilities for PPC, the activities with interfaces on the shop floor (scheduling, capacity, and inventory) can be integrated into the IoT, CPS, and CMg. Demand forecasting can explore the capabilities provided by BDA/AI tools. It is interesting to notice that studies regarding S&OP/aggregate planning based on the smart capabilities provided by I4.0 are scarce.

Concerning performance measures, the digitalization of manufacturing planning and control positively impacts manufacturing flexibility. There is also a trend that the PPC smart capabilities be focused on green/sustainability performance indicators. Our study also shows that three environmental factors (product, demand, and manufacturing process) influence the development of smart capabilities by PPC.

The limitations of our literature review are as follows. First, there is no consensus regarding the means of realization of I4.0. Second, the systematic review processes are naturally subject to the researchers' biases in extracting and analyzing the results. Third, in our review, we dedicate the analysis exclusively to journals and adopt an objective quality criterion (AJG/SJR index) that excludes searches of non-indexed sources, conference proceedings, book chapters, and non-English language articles; all of these could contain relevant results. Finally, the number of studies addressing the propositions for moderating effects is insufficient for generalizing strong conclusions regarding this research question.

## 3 CREATING MATURITY MODELS IN THE INDUSTRY 4.0 CONTEXT: A METHODOLOGICAL FRAMEWORK FOR OPERATIONS AND SUPPLY CHAIN MANAGEMENT

**Abstract:** This article proposes a novel framework comprising elements, procedures, and recommendations determining a standard baseline for developing Industry 4.0 maturity models (MMs) in the field of operations and supply chain management (OSCM). Since many new MMs are emerging in this field and comparing and using these tools is a challenge both for scholars and practitioners, our goal is to create a solid and repeatable foundation for MM development. To do so, we employ a five-step design science research multimethod technique resulting in a MM development framework based on nine elements of development (problem-solving definition, MM comparison, meta-model definition, the decision to use a new architecture or to use an existing one, mapping of Industry 4.0 within OSCM-domain characteristics, MM design, assessment tool building, and follow-up) and seven iterative research aspects (element, method, planning of data and analysis, model's element design, testing and validation, changes, and outputs). The framework is then organized into a workflow for operationalizing MM development. The proposed framework is based on the shortcomings of existing ones, the contributions of previous architectures, and existing MMs. Finally, we show a proof of concept, in which we demonstrate that designers could focus on the operationalization of their models (hands-on) by increasing the design redundancy and agility, design learning and transparency, and traceability and standardization of the development steps, thus also minimizing development efforts, time, and re-working.
**Keywords:** Maturity model design; Operations and supply chain management (OSCM); Design science research; Smart supply chain.

### 3.1. Introduction

Customer demand, product specifications, manufacturing process, and technology are dynamic features of a socio-technical changeable environment (SONY; NAIK, 2020b). To respond to these changes in social, technological, and productive dynamics, manufacturing companies must continually adapt their operational, tactical, and strategic decisional requirements (OLHAGER, 2013). An adaptive manufacturing company can respond with greater agility, responsiveness, and flexibility to complex customer requirements (e.g. customized products) within smart factories' competitive environments (BUENO; GODINHO FILHO; FRANK, 2020).

To guide manufacturing companies toward the smart factories concept, managers must handle managerial artifacts that support them regarding advances in knowledge bases, roadmaps, and evaluation tools for digital practices and capabilities. These tools are standard components of managerial Maturity Models (MMs). MMs are powerful tools to exploit Industry 4.0's (I4.0) smart technologies within the operations and supply chain management (OSCM) field (CAIADO et al., 2021). MMs can provide OSCM managers with ways to advance toward I4.0's implementation and improvements (maturity), boosting the smart status of companies to achieve and leverage the gains associated with digitalization and smart technology adoption (GÖKALP; MARTINEZ, 2021). Recently, several MMs have been developed in the OSCM and I4.0 domain, including the OSCM4.0 MM (CAIADO et al., 2021), the digital transformation capability MM (GÖKALP; MARTINEZ, 2021), the digital product fitting MM (GUSTAFSSON; JONSSON; HOLMSTRÖM, 2019), and the delivery process MM 4.0 (ASDECKER; FELCH, 2018).

Therefore, MM are innovative artifacts that drive manufacturing and supply chain companies in value-creation through I4.0 technologies, resources/capabilities, and practices. With the introduction of I4.0, the development of MMs in the OSCM field has increased (CAIADO et al., 2021). This scenario seems to be leveraged by the need for artifacts that support practitioners in I4.0 technology implementation in manufacturing and supply chain companies (VAN GEEST; TEKINERDOGAN; CATAL, 2021). In this context, Becker et al. (2009) stated that MMs are useful tools to assess the "*as-is status*," defining measures, improvement actions, and evolution paths for reaching a particular maturity level ("*to-be status*").

In this context, Lacerda and von Wangenheim (2018) defined maturity as the extent (stage) to which an organizational function or company consistently implements resources and technologies, processes and practices, and capabilities and indicators within a defined domain (scope/entity). The superior status of attributes (characteristics, capabilities, indicators, or patterns) in a domain or entity contributes to achieving established goals (e.g., smart manufacturing). As a result, a MM is a practical problem-solving tool guided by evolutionary stages that define measurable progress transitions (CARALLI; KNIGHT; MONTGOMERY, 2012; RÖGLINGER; PÖPPELBUSS; BECKER, 2012).

From this, MMs emerge in OSCM as a tool (artifact) to model, measure, and improve the mastering of I4.0 capabilities for the processes and operations of manufacturing and supply chain companies. For this purpose, a development framework is an essential tool that works as a mechanism during MM building. First, it is useful for designers as a guideline, i.e., in addressing the "*what*" and "*how*" questions in developing MMs within a domain. Second, it provides traceable steps for the design, evaluation, and follow-up of MMs. Third, it supports designers in real problem-solving with scientific, focused design research procedures within a domain.

Managers and practitioners should use MMs as a starting point to enhance manufacturing and supply chain companies' practices and performance (e.g., quality and productivity) (GÖKALP; MARTINEZ, 2021). Further, MMs are artifacts that allow a company to benchmark internal/external performance and practices within a specified domain (e.g., OSCM) and establish improvement roadmaps (ASDECKER; FELCH, 2018). Managers and practitioners benefit from MMs in four primary ways. First, MMs provide "*what to measure*" (modeling tool of attributes). Second, MMs provide an "assessment tool" to measure the maturity of practices/capabilities (evaluation tool). Third, MMs deliver a set of practices/capabilities to be implemented, along with the maturity levels identified (maturity matrix and improvement roadmap). Fourth, MMs support managers in shifting from a "*to-be status*" to an "*as-is status*" position, showing also characteristic maturity levels within a domain (predictive tool). In summary, a development framework provides a bundle of "*design practices*" for MM building that MM designers can apply. Consistent MM deployment enables OSCM managers and practitioners to problem-solve, upgrade operations/supply chain practices, and improve their companies' performance via a highly technology-oriented environment such as I4.0.

MMs should help managers and practitioners overcome progressive stages toward implementing the I4.0 concept in their companies. For example, MMs support companies in transitioning from lower maturity in I4.0 (e.g., analogic operations) towards growing levels based on progressive digitalization, integration, and operations automation (BUENO et al., 2022; SCHUH et al., 2017). Hence, MMs support OSCM functions and digital business processes in achieving full-smart status in relation to the I4.0 concept, leading to value-creation. However, the development of OSCM's MMs is complex and challenging due to the mutual conciliation of transparent and rigorous design and research tasks (METTLER; BALLESTER, 2021).

Furthermore, MMs are frequently criticized for oversimplifying the practices modeled (VAN HILLEGERSBERG, 2019). The main issues regarding MMs are their quality/usability, poor design research, a lack of theoretical foundation and/or empirical evaluation, and a lack of validated assessment tools and selection criteria for existing models; these problems make it difficult for practitioners to use MMs (RÖGLINGER; PÖPPELBUSS; BECKER, 2012; VAN LOOY; POELS; SNOECK, 2017). To overcome these issues, we propose a novel framework that addresses MM building in the OSCM domain.

### 3.1.1 Background literature review

The operations and supply chain management (OSCM) field has lacked a standardized MM development framework. In contrast, in OSCM, the most widely used MM development frameworks are based on the information systems (IS) field; they are top-down oriented and vary in scope (components) and purpose. For example, de Bruin et al. (2005) presented a framework based on six general guidelines to build a MM (scope, design, population, test, deploy, and maintain). Another seminal framework, developed by Becker et al. (2009), also provides guidelines for MM development; these authors recommended iterative design guidelines based on design science research (DSR). Other examples of important frameworks dealing with MM development have been developed by Mettler (2010), Pöppelbuß and Röglinger (2011), and van Looy et al. (2017).

Mostly, MM frameworks used in OSCM and I4.0 clarify "*what*" the MM should contain (e.g., maturity levels, dimensions, and assessment tools). However, they do not fully explain "*how*" precisely to operationalize the MM development steps (research, design, validation, and follow-up). This has led to design and scientific critiques concerning model reproducibility, reliability, and quality.

Although these frameworks are valuable and widely accepted by designers, serving as the theoretical foundation for most MMs in the OSCM domain, the MMs designed from them suffer criticisms and shortcomings (VAN HILLEGERSBERG, 2019).

This seems to be linked to a methodological issue for development related to the difficulty of operationalizing model-building steps from different existing frameworks and design viewpoints. Therefore, a critical methodological research gap remains concerning how to operationalize MMs' development steps. These gaps are: *(i).* the lack of *common procedures* among the various existing frameworks; and *(ii).* the lack of *standardized design elements* for MM development. Our research aims to address this gap.

In this vein, this article presents a second-tier MM development framework, going down one level from the mainstream framework guidelines, by offering an operational and agile framework focused on the procedures, elements, and recommendations to build a synthetic MM design. A second-tier framework is a proposal containing specific elements to design and operational procedures for MMs development. We show the proposed framework as a proof of concept (PoC) example, demonstrating its use and utility for design purposes.

Our research aims to contribute with a standardized methodological framework to develop MMs in the OSCM and I4.0 domain. Our framework emerges from established literature based on recent MMs, architectures, and existing development frameworks. Furthermore, our framework aims to present a granular setting, as a second-tier framework, unlike existing frameworks; in other words, it deepens understanding of the operationalization tasks of the building steps and standardizes the elements of existing frameworks. Operationalization tasks for MMs development steps/guidelines concern setting procedures and elements to create a MM, i.e., the research, design, testing, measurement tool, validation/evaluation, design changes, implementation, and follow-up. Operationalization tasks/actions should constitute a workflow specifying both the transparent and agile procedures of MM development (i.e., answering "*how to design*") and also present "*what the main design elements are*," which are required for a practical and scientifically reliable MM (i.e., answering "*what to design*").

The second motivation is to propose a common MM development framework based on the DSR approach. DSR has grown in popularity recently as a natural and adherence methodological approach to developing managerial artifacts such as MMs in OSCM (GOECKS et al., 2021; METTLER; BALLESTER, 2021). The DSR approach provides procedures that naturally fit MMs' design, based on iterative research cycles (BECKER; KNACKSTEDT; PÖPPELBUSS, 2009). DSR iterations enable tests, redundancy, related changes, and continuous design learning, providing a robust methodological approach to designing artifacts (HEVNER; GREGOR, 2022). The DSR approach can assist MM designers in improving the reliability and validity of research, as well as the designed model's agility (METTLER; BALLESTER, 2021). The OSCM literature lacks a unified framework proposal that provides cyclic DSR procedures to operationalize MM development processes. We are motivated to address this issue by proposing a MM development framework centered on standard procedures/actions for design by specifying the core elements for a MM in the OSCM and I4.0 domain, i.e., pathways to operationalize an agile design/building.

The DSR methodology provides procedures that naturally fit MMs' design (BECKER; KNACKSTEDT; PÖPPELBUSS, 2009). The DSR approach can assist MM designers in improving the reliability and validity of research conjointly with the agility of designed models. The OSCM literature lacks a unified framework proposal that includes cyclic DSR procedures to operationalize MM development procedures.

Finally, our MM development framework provides pathways for building managerial artifacts (MMs). MMs guide managers and practitioners in value-creation, operations, and performance improvements within manufacturing and supply chain companies. It is possible to leverage I4.0 initiatives for novel digital business propositions through MMs. For example, Bechtsis et al.'s (2019) MM supports food supply chains' progress toward high levels of traceability and prevents potential risks from blockchain technology use.

The remainder of the article is structured as follows. The research methodology is presented in Section 3.2. Section 3.3 presents the findings and the theoretical underpinnings of the proposed framework. Section 3.4 describes the proposed MM development framework and its components. Section 3.5 presents a PoC example case. Finally, Section 3.6 discusses the main findings and their implications.

### 3.2. Research methodology

DSR supports creating and evaluating managerial artifacts by studying complex socio-technical systems to solve organizational-managerial problems and digital innovation in the I4.0 era (HEVNER; GREGOR, 2022).

Aligned to this, we propose a MM development framework that embeds the DSR iterative research approach. For this purpose, we define five steps for the framework's creation and research (Figure 3.1): (1). research procedures to ground the framework proposal; (2) the development of an initial framework proposal; (3). a refinement and validation of the framework proposal; (4). the framework's final version; and (5). the framework as a PoC example. For this purpose, we followed the DSR research cycles of Hevner et al. (2010). In the relevance cycle, we define the gaps, motivations, research questions, and framework development objectives (see Section 3.1). The rigor cycle comprises the research procedures and analysis to ground the framework's proposal (see Step 1 of Figure 3.1). The design cycle includes Steps 2–5 in Figure 3.1.

Our study adopts a multimethod approach (CRESWELL; POTH, 2018) (see Figure 3.1). From this, we aim to achieve a deeper understanding of the research topic by combining methods and data triangulation (JOSLIN; MÜLLER, 2016), obtaining more insights and perspectives for the research and design of the tasks in our framework. Multimethod research improves qualitative research reliability and validity (SAUNDERS; LEWIS; THORNHILL, 2019). The triangulation strategy of our study is based on Bechara and Van de Ven (2011, p. 349], which "… *assumes that the bias inherent in any particular theory, method, or data source will be eliminated, or at least minimized, by relying on the convergent information from different methods*." Accordingly, literature surveys and a scoping review (Step 1) were used to ground the framework. DSR guidelines and Sony and Kodali's (2013) criteria supported the design of the framework's initial proposal (Step 2). Qualitative methods, such as expert meetings and an expert panel, were used for the framework refinement and validation (Steps 3 and 4). Finally, a PoC example was used (Step 5) to demonstrate the framework's usability (ELLIOTT, 2021). These five steps are explained in detail below.

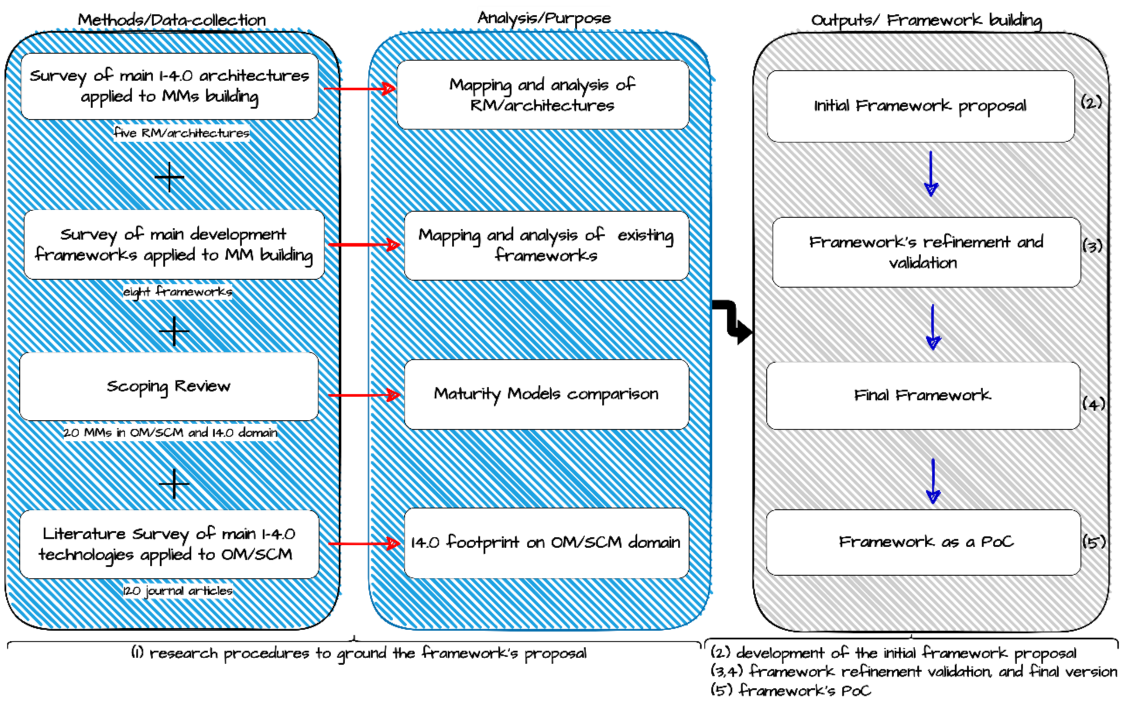



**Figure 3.1. Procedures for the framework's conception**

***Step 1: Research procedures to ground the framework's proposal.*** First, we looked for the main reference models (RMs) and architectures of I4.0 that are used to ground MMs within the OSCM domain (see Table 3.1). From this, we intended to determine which RMs and architectures can be followed, expanded, or partially used to design novel MMs (HEVNER; GREGOR, 2022). Thus, we chose five prominent RMs/architectures within the OSCM and I4.0 domain from a brief survey of studies (see Table 3.1). After this, we analyzed the "*purpose of use*" and "*shortcomings*" of these RMs/architectures concerning MM requirements within the OSCM and I4.0 domain.

Second, we mapped the guidelines most commonly used by MM designers to develop MMs. We selected eight widely adopted development frameworks (see Table 3.2). We examined these frameworks in light of the following criteria: (1). iterative DSR procedures; (2). the focus on what elements to develop in MMs; (3). the focus on how to operationalize MMs; (4). the category of frameworks (conceptual, design, and implementation); and (5), the frameworks' shortcomings (ANAND; KODALI, 2010).

Third, a scoping review was conducted to search, screen, analyze, and ground our MM development framework following current practices and core characteristics required for the MM design in the OSCM and I4.0. The scoping review was carried out following five traditional stages (ARKSEY; O'MALLEY, 2005): (1). determining the research question(s); (2). locating relevant studies; (3) selecting studies;

(4). charting the data; and (5). comparing, summarizing, and reporting the results. We searched the Google Scholar, Web of Science, and Scopus databases for the keywords "OSCM" and "maturity model" and "Industry 4.0" (and their variations). A total of 20 representative MMs that had been published in leading OSCM journals in the previous ten years (i.e., since the emergence of I4.0 in the literature) were screened and selected.

We used Caiado et al.'s (2021) criteria to evaluate these 20 MMs. This analysis aimed to assess the following key elements of the MM's structure (Table 3.1): (1). the MM's basic information (MM name, authors, year, and document type/source); (2). the OSCM domain/subdomain of application; (3). the MM's category list elements [*(i).* dimensions, views, perspectives, focus area; *(ii).* processes, practices, factors, capabilities; *(iii).* maturity levels, steps, phases, stages); and (4). the MM's research design (if the model is empirically tested/validated, and if the methodology is DSR-based). Furthermore, to conduct a complete analysis of MM, we used four additional criteria (Table 3.4): (5). I4.0 technologies adopted in the MM; (6). the purpose of use (descriptive, prescriptive, comparative); (7). RMs/architectures and MM guidelines adopted; and (8). the maturity evaluation tool.

Fourth, we examined 120 articles (2011–2021) extracted from our previous systematic literature review database (BUENO; GODINHO FILHO; FRANK, 2020). We then mapped the leading I4.0 technologies and capabilities for the OSCM domain's maturity progress (Table 3.5).

***Step 2: Development of an initial framework proposal.*** We proposed a framework to develop a DSR-based MM from iterative research procedures (BECKER; KNACKSTEDT; PÖPPELBUSS, 2009; HEVNER et al., 2004). This framework (see Figure 3.1 in Section 3.4.3.2) depicts the procedures to be carried out in each research iteration, as well as the main elements and recommendations for putting these iterative MM-building procedures into action.

***Steps 3 and 4: Framework proposal refinement, validation, and final version.*** Experts' meetings and a panel were utilized to refine our framework proposal and reach a validated final version. In the refinement step, meetings were conducted with five academic experts experienced in MM design in the OSCM domain; they also have expert knowledge of I4.0. In the validation step, the same five experts were invited to a panel aiming to reach a final version of the framework. Table 3.6 shows the expert meeting and panel information.

***Step 5: PoC example of the framework.*** We use the validated framework version to demonstrate its practicability through a PoC. In Table 3.7, we present an example of element building applied to our framework.

### 3.3. Framework background (Step 1)

This section is divided according to the procedures of Step 1 shown in Figure 3.1, presenting the knowledge base required to build new MM development frameworks and solve the problem addressed in relation to the: *(i).* main RMs/architectures; *(ii).* existing MM development frameworks; and *(iii).* latest MMs in the OSCM and I4.0 domain. Our purpose in this research step is to build a background for the conception of a novel and common development framework to build MMs in the OSCM and I4.0 domain.

#### 3.3.1 Main reference models (RMs)/architectures addressing I4.0

We analyzed the RM/architectures regarding their "*purpose of use*" and "*shortcomings*" (see Table 3.1).

***Purpose of use.*** In Table 3.1, we survey and analyze five exemplary RMs/architectures in I4.0. Reutilizing one of these RMs/architectures for MM building purposes (problem space) should boost the development process by harnessing the knowledge base (solution space) and associated design elements (HEVNER; GREGOR, 2022). Also, RMs help MM designers (academics and practitioners) in the preliminary scope definition of the model. The RM/architectural components shown in Table 3.1 serve as a "*starting point*" for MM designers to clarify the most relevant elements for their MM. Therefore, RMs/architectures are sources of exaptation and exploitation for a MM's design as innovation artifacts (HEVNER; GREGOR, 2022), saving time and design efforts by their reuse in MM development.

***Shortcomings.*** First, we observed the lack of integrated RMs and architectures covering the OSCM and I4.0 topics simultaneously. The RMs/architectures based on I4.0 presented in Table 3.1 show their nascent, little disseminated use in MM development in the OSCM domain. They have only recently started to be adopted for the design of some recent MMs. Second, we observed that some of the RMs and architectures in Table 3.1, such as RAMI (VD/VDE; ZVEI, 2015), are well-known and widely used in I4.0 applications (YLI-OJANPERÄ et al., 2019). However, they are still not widely used in MM development to ground the exaptation and exploitation strategies for novel MMs (HEVNER; GREGOR, 2022). Third, the five RM/architectures examined are primarily focused on the technological aspects of I4.0, limiting their reuse in the OSCM domain because of soft factors' shortcomings, such as people's digital skills, organizational culture changes, and smart processes/practices. These factors are critical to triggering and sustaining continuous digital improvements and changes toward smart manufacturing systems (BIBBY; DEHE, 2018; SANTOS; MARTINHO, 2019; SCHUH et al., 2017; SCHUMACHER; EROL; SIHN, 2016; SJÖDIN et al., 2018; WAGIRE et al., 2021).

**Table 3.1.** Main RM/architectures into OSCM and I4.0 domain

| Name | Description and Purpose | Architectural components |
|---|---|---|
| **RAMI 4.0- Reference Architecture Model Industrie 4.0**<br>***Source:* VDI/VDE and ZVEI** (2015) | RAMI 4.0 is both a reference model and an SOA oriented-architecture and standard requirements for applications of digitalization and connectivity solutions, automation, and integration to projects adhering to Industry 4.0, allowing a cyber-physical production ecosystem of the entire production chain.<br>Weber et al. (2017) state RAMI 4.0 as an "*…architecture model combines life cycle information and the value stream with hierarchical layers of the information pyramid of manufacturing. The elements of the hierarchical layers' origin from the equipment hierarchy model of the ISA 95 standard."* | *Layers:* Asset, Integration, Communication, Information, Functional, Business<br>*Hierarchy Levels:* Product, Field Device, Control Device, Station, Work Centers, Enterprise, Connected World<br>*Life-Cycle and Value Stream:* Development + Maintenance/usage + Production (Test), Maintenance/usage (Instance) |
| **IIRA- Industrial Internet Reference Architecture**<br>***Source:* Industrial Internet Consortium** (2017) | IIRA is a practice-based service-oriented architecture (SOA) to realize dynamic composition and automated interoperability for smart applications in wide-range industries.<br>Industrial Internet Consortium (2017) defines IIRA as an artifact which "…*system architects can use this IIRA systematically as an architectural template to define their unique IIoT system requirements and design concrete architectures to address them*." | *Viewpoints*: Implementation, Functional, Usage, Business<br>*Functional domains*: Control, Operations, Information, Application, Business<br>*Life-Cycle*: Conceptualization, Requirement, Prototyping/Design, Development, Build, Test/Validation, Operation, Evolution, Disposal<br>*Industrial Sectors*: Manufacturing, Health, Transportation, Energy, etc.<br>*Processes*: Safety; Security, Trust and Privacy; Resilience; Integrability, Interoperability and Composability; Connectivity; Data Management; Advanced Data Processing; Intelligent and Resilient Control; Dynamic Composition and Automated Interoperability |
| **SITAM- Stuttgart IT - Architecture for Manufacturing**<br>***Source:* Kasner et al.** (2017) | The Stuttgart IT Architecture for Manufacturing (SITAM) is an agile, learning, and human-centric reference architecture spanning the entire product life-cycle.<br>Weber et al. (2017)describe SITAM as *"...a multi-layered model comprising all processes, IT systems, physical devices and other data sources. On top of a hierarchical integration layer aligned with the product life cycle, the SITAM allows for multiple parallel middleware components to provide value-added services. This ideally equips it to: Human-to-Human, Human-to- Machine."* | *Layers*: Product life-cycle, Value-adding middleware, role-based applications<br>*Technologies:* Integration, Analytics, Mobile, Service Composition and Access, Cross-topics (Data Quality, Governance, Security and Privacy)<br>*Life-cycle:* Processes, Resources, IT-systems, Web<br>*Processes:* Engineering, Production Planning, Manufacturing, Usage and Support |
| **CPS 5C architecture- Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems** | 5C architecture is a step-by-step guide for developing and deploying a Cyber-Physical System for manufacturing applications, driving managers and industry manufacturing about how to construct a CPS from the initial data acquisition to analytics, to the final value creation. | *Processes:* Smart Connection, Data-to-information conversion, Cyber, Cognition, Configuration<br>*Layer:* Physical, OT, IT, Automation & Virtualization, Decisional |

| Name | Description and Purpose | Architectural components |
|---|---|---|
| ***Source:*** **Lee et al.** (2015) | Lee et al. (2015) present the CPS 5C architecture as able to "… *provides a viable and practical guideline for manufacturing industry to implement CPS for better product quality and system reliability with more intelligent and resilient manufacturing equipment*." | *Practices:* Condition Based Monitoring (CBM), Prognostics and Health Management, Cyber-Physical Systems, Decision Support System, Resilient Control System<br>*Capabilities:* Condition monitoring, Self-aware, Self-compare, Prioritize and Optimize, Actions to Avoid<br>*Technologies*: Sensors, Components, Machines, Fleet of machines, Managerial Decision, Top management decision<br>*Life-cycle:* Processes, Manufacturing virtualization, smart capabilities |
| **Smart Warehouse Reference Architecture**<br>***Source:*** **van Geest et al.** (2021) | The Smart Warehouse Reference Architecture is based on a rigorous design process and a detailed description of scientific methodology. The architecture links the needs of manufacturing stocks warehousing in Industry 4.0 technologies application-context, exploring business process modeling into smart factories.<br>van Geest et al. (2021) states Smart Warehouse Reference Architecture as *"…a domain model for representing the family of various warehouses. The domain model has been presented as a feature diagram that covers a comprehensive set of common and variant features of warehouses. With the domain model, we can characterize abroad range of warehouses and support the architecture design of smart warehouses. In parallel with the domain model, we have also provided the business process model that can be instantiated for various smart warehouses. For designing the reference architecture, we have adopted architecture viewpoints as defined in the software architecture design community. The reference architecture can be used to describe existing warehouses or prescribe and support the architecture design of new smart warehouses."* | *Processes:* Smart Warehouse, Receiving, Storing, Tracking and Tracing, Planning, Picking, Shipping, Downstream Stakeholders, Upstream Stakeholders, Warehouse Management System, Warehouse Communication Network<br>*Viewpoints Architecture:* Diagram context, Decomposition, Uses, Deployment<br>*Technologies:* Barcode, RFID, Augmented Reality, AGV, IoT, Scanners, Warehouse management system (WMS), Warehouse communication, Other related technologies and concepts (PEID, machine vision, smart robot arm, bin picking, physical internet, digital twin, machine learning) |

***Note**:* Other RM/architectures highlighted in the I4.0 domain are: SME- Smart Manufacturing Ecosystem (LU; MORRIS; FRECHETTE, 2016); Smart Manufacturing Standardization Reference Model (LI et al., 2018); I3RM - Industrial Internet Integrated Reference Model and ZDMP- Zero Defect Manufacturing Platform, and IVRA-Industrial Value Chain Reference Architecture (YLI-OJANPERÄ et al., 2019); IMSA- Intelligent Manufacturing System Architecture (FEDERAL MINISTRY OF ECONOMIC AFFAIRS AND ENERGY, 2018).

### 3.3.2 Existing frameworks for the development of maturity models (MMs): general characteristics and shortcomings

MMs in the OSCM and I4.0 domain are complex artifacts that comprise innovativeness in technology, people, organizational culture, and value-creation processes. Therefore, development frameworks are valuable tools that support designers in MM building tasks. However, what framework should one use among the existing ones? Table 3.2 lists the frameworks addressed to aid in the development of MMs. We apply a set of criteria to analyze these frameworks: the framework's category (conceptual, design, implementation); iterative DSR procedures; focusing on "*what are*" the elements to be developed in the MM; focusing on "*how to design*" the MM; and the framework's shortcomings.

We show, in Table 3.2, eight development frameworks adopted by recent MMs in the OSCM domain; among them, only three explicitly present guidelines based on iterative DSR procedures. Table 3.2 also shows each framework's category for the MM subject: five were classified as MM design frameworks; two as conceptual frameworks regarding MM development; and one as a MM implementation/use framework. Therefore, from Table 3, we analyze the guidelines and structure of these frameworks to propose a common MM development framework based on DSR.

All eight frameworks analyzed are clear about "*what are the elements to be developed*" in a MM. For example, Wendler et al. (2012) and Maier et al. (2012) addressed MMs' design elements from a general and conceptual perspective, but they did not fully show "*how to operationalize MMs building*" in a detailed manner. This is the main shortcoming of the eight frameworks analyzed (see Table 3.2). For example, it is common that there are design loops between the test, populate, and design steps, which in turn affect the building tasks' workflow, time, and efforts regarding the model's conception, where the iterative research process helps systematize these procedures. We know that a MM's design decisions are intrinsic to each MM proposal; however, a set of standardized elements and recommendations for development can help designers link the main existing frameworks' guidelines with focused procedures for agile building. Therefore, according to Table 3.2, none of the eight frameworks analyzed explicitly presents "*how to operationalize MM building*" in a standardized and granular way based on DSR. These findings support our framework proposal in Step 2 (Section 3.1), proposing seven detailed procedures for MM development to fill this gap.

### 3.3.3 Comparison of maturity models (MMs) in the operations and supply chain management (OSCM) and Industry 4.0 (I4.0) domain

We analyzed 20 MMs in the OSCM domain from the following criteria (Table 3.3): (1). the MM's basic information (MM name, authors, year, document type/source); (2). the OSCM application domain/subdomain; (3). the MM's category list elements [*(i).* dimensions, views, perspectives, focus area; *(ii).* processes, practices, factors, capabilities; *(iii).* maturity levels, steps, phases, stages)]; and (4). the MM's research design (if the model is empirically tested/validated, and if its methodological approach is DSR-based, i.e., design-oriented). Furthermore, we applied four additional criteria for an in-depth analysis of each MM (Table 3.4): (5). I4.0 technologies adopted in the MM; (6). purpose (descriptive, prescriptive, comparative); (7). architectures and MM guidelines adopted; and (8). evaluation tool presentation. Finally, four leading I4.0 technologies are described in Table 5. They represent the top smart technologies from I4.0 in recent MMs within the OSCM field.

**Table 3.2.** Frameworks used on MMs development into OSCM and I4.0 domain

| Framework, Type, Applying | Guidelines/principles | Focus on: Iterative procedures DSR-based | What to develop in the MM? | How to operationalize the MM's development? |
|---|---|---|---|---|
| **1.** de Bruin et al. (2005)<br>**Type:** Design Framework<br>**Applied by:** Gökalp and Martinez (2021) | Six linear guidelines: 1. Scope, 2. Design, 3. Populate, 4. Test, 5. Deploy, 6. Maintain | ○ | ● | ⊙ |
| **2.** Becker et al. (2009)<br>**Type:** Design Framework<br>**Applied by:** Caiado et al. (2021) | Eight iterative guidelines: 1. Problem definition, 2. Comparison of existing maturity models 3. Determination of the design strategy, 4. Iterative maturity model development, 5. Conception of transfer and evaluation, 6. Implementation of transfer media, 7. Evaluation, 8. Scientific Documentation | ● | ● | ⊙ |
| **3.** Mettler (2010)<br>**Type:** Design Framework<br>**Applied by:** Gökalp and Martinez (2021) | Five linear guidelines: 1. Identify need or new opportunity; 2. Define scope, 3. Design model, 4. Evaluate design, 5. Reflect evolution | ⊙ | ● | ○ |
| **4.** Pöppelbuß and Röglinger (2011)<br>**Type:** Conceptual Framework<br>**Applied by:** Comuzzi and Patel (2016) | Nine general principles: 1. Basic information, 2. Definition of central constructs related to maturity and maturation, 3. Definition of central constructs related to the application domain, 4. Target group-oriented documentation, 5. Intersubjectively verifiable criteria for each maturity level and level of granularity, 6. Target group-oriented assessment methodology, 7. Improvement measures for each maturity level and level of granularity, 8. Decision calculus for selecting improvement measures, 9. Target group-oriented decision methodology | ⊙ | ● | ○ |
| **5.** Wendler (2012)<br>**Type:** Conceptual Framework<br>**Applied by:** Vezzetti et al. (2014) | Three iterative general guidelines: 1. Maturity model development, 2. Maturity model application, 3. Maturity model validation | ● | ⊙ | ⊙ |
| **6.** Maier et al. (2012)<br>**Type:** Design Framework<br>**Applied by:** de Carolis et al. (2017) | Four iterative and general guidelines: Planning, Development, Evaluation, Maintenance | ⊙ | ⊙ | ⊙ |
| **7.** van Steenbergen et al. (2013)<br>**Type:** Design Framework<br>**Applied by:** Jansen (2020) | Six iterative guidelines: 1. Problem identification and motivation, 2. Define the objectives for a solution, 3. Design and development, 4. Demonstration, Evaluation, 6. Communication | ● | ● | ⊙ |
| **8.** van Looy et al. (2017)<br>**Type:** Implementation Framework<br>**Applied by:** Froger et al. (2019) | Three linear guidelines for existent MMs evaluation (user perspective): 1. Preparatory phase, 2. Intermediate phase, 3. Advanced phase | ○ | ● | ○ |

*Legend:* ○ not or only fragmentary addressed; ⊙ partially addressed; ● addressed

**Table 3.3.** Analyze of main Maturity Models in OSCM and I4.0 domain (part I)

| **#Maturity Model Name** | **Literature:**<br>**1.** Author/Year<br>**2.** Source<br>**3.** Document Type | **Domain (D)/Subdomain (S)** | **Categories List Elements** | | | **Research Design:**<br>**1.** Empirically Tested?<br>**2.** Methods (Design + Assessment Tool)<br>**3.** Model Validation<br>**4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | |
| **1.** Industrie 4.0 Maturity Index | **1.** Schuh et al. (2017)<br>**2.** Acatech (association)<br>**3.** Report | **(D)** Industry 4.0/Operations Management<br>**(S)** Connectors and technology/ network components manufacturing industry | Culture<br>Organizational Structure<br>Resources<br>Information systems | 8 principles<br>27 capabilities<br>5 functional areas:<br>**1.** Production<br>**2.** Development<br>**3.** Logistics<br>**4.** Services<br>**5.** Marketing and Sales | **1.** Computerisation<br>**2.** Connectivity<br>**3.** Visibility<br>**4.** Transparency<br>**5.** Predictivity Capacity<br>**6.** Adaptability | **1.** Yes<br>**2.** Case Study + Experts' Interview + Workshop<br>**3.** Harting AG & Co (Dutch manufacturing industry of connectors). KG's Espelkamp (Germany industry of technology and network components)<br>**4.** No |
| **2.** Industry 4.0 Maturity Model for Machine Tool companies | **1.** Rafael et al. (2020)<br>**2.** Technological Forecasting and Social Change (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Manufacturing<br>**(S)** Machine Tool Industry: SMEs | Strategy and Organization<br>Smart Factory<br>Smart Operations<br>Smart Products<br>Data-driven Services<br>Employees | 24 subdimensions | **0.** Outsider<br>**1.** Beginner<br>**2.** Intermediate<br>**3.** Experienced<br>**4.** Expert<br>**5.** Top Performers | **1.** Yes<br>**2.** Literature review + Case Study + Eight consensus decision-making sessions + Five sections concept-sorting + Three Interviews/Experts Panel<br>**3.** European SME Machine Tool company<br>**4.** Yes |
| **3.** OSCM 4.0 Maturity Model | **1.** Caiado et al. (2021)<br>**2.** International Journal of Production Economics (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Supply Chain Management<br>**(D)** Industry 4.0/ Operations Management<br>**(S)** Aeronautical Industry | Customer<br>Logistics<br>Supplier<br>Integration<br>Production<br>Planning and Control- PPC | 15 indicators of maturity | **0.** Nonexistent<br>**1.** Conceptual<br>**2.** Managed<br>**3.** Advanced<br>**4.** Self-optimized | **1.** Yes<br>**2.** Scoping Review + six Experts Interviews + six Focus Group + Case Study<br>**3.** Brazilian aeronautical manufacturing company |

| #Maturity Model Name | Literature:<br>**1.** Author/Year<br>**2.** Source<br>**3.** Document Type | Domain (D)/Subdomain (S) | Categories List Elements | | | Research Design:<br>**1.** Empirically Tested?<br>**2.** Methods (Design + Assessment Tool)<br>**3.** Model Validation<br>**4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | |
| | | | Maintenance | | | **4.** Yes |
| **4.** M2DDM- A Maturity Model for Data-Driven Manufacturing | **1.** Weber et al. (2017)<br>**2.** Procedia CIRP (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Manufacturing<br>**(S)** Enterprise and Manufacturing Control | Data Storage and Compute<br>Service-Oriented Architecture<br>Information Integration<br>Digital Twin<br>Advanced Analytics<br>Real-time Capabilities | — | **0.** Non-existent IT Integration<br>**1.** Data and System Integration<br>**2.** Integration of Cross-Life-Cycle Data<br>**3.** Service-Orientation<br>**4.** Digital Twin<br>**5.** Self-Optimizing Factory | **1.** No<br>**2.** Literature Review<br>**3.** Not specified<br>**4.** No |
| **5.** HISMM-Hospital Information System Maturity Model | **1.** Carvalho et al. (2019)<br>**2.** Journal of Business Research (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Health-Care<br>**(S)** Digital Hospital | Data analysis<br>Strategy<br>People<br>Eletronic Medical record<br>Information Security<br>Systems and IT-infrastructure | 226 maturity items | **I**<br>**II**<br>**III**<br>**IV**<br>**V**<br>**VI** | **1.** Yes<br>**2.** SLR + Survey with 46 experts + five Experts Interviews<br>**3.** Five Portuguese hospitals (of different types)<br>**4.** Yes |
| **6.** Smart Factory Maturity Model | **1.** Sjödin et al. (2018)<br>**2.** Research-Technology Management (RTM) (journal)<br>**3.** Feature Article | **(D)** Industry 4.0/Manufacturing<br>**(S)** Automotive Industry | People<br>Process<br>Technology | Principles:<br><br>**1.** Cultivate People<br>**2.** Introduce Agile Processes<br>**3.** Configure Modular Technology | **1.** Connected technologies<br>**2.** Structured data gathering and sharing<br>**3.** Real-time process analytics and optimization | **1.** Yes<br>**2.** Six workshops + 31 in-depth interviews with managers + five case studies in trucks and cars plants + 10 site visits to trucks plants |

| **#Maturity Model Name** | **Literature:**<br>**1.** Author/Year<br>**2.** Source<br>**3.** Document Type | **Domain (D)/Subdomain (S)** | **Categories List Elements** | | | **Research Design:**<br>**1.** Empirically Tested?<br>**2.** Methods (Design + Assessment Tool)<br>**3.** Model Validation<br>**4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | |
| | | | | Indicators:<br>**1.** Increased process efficiency<br>**2.** Lower operational cost<br>**3.** Increased product quality<br>**4.** Increased safety and sustainability | **4.** Smart, predictable manufacturing | **3.** Two Swedish automotive plants- car and truck<br>**4.** No |
| **7.** Industry 4.0 Implementation Readiness Model | **1.** Pacchini et al. (2019)<br>**2.** Computers in Industry (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Manufacturing<br>**(S)** Auto-parts manufacturing industry | Big data<br>Internet of Things<br>Cloud Computing<br>Augmented Reality<br>Cyber-Physical Systems<br>Autonomous Robots<br>Additive Manufacturing<br>Artificial Intelligence | **1.** Ranges of $0 \leq DR < 10$<br>**2.** Ranges of $10 \leq DR < 25$<br>**3.** Ranges of $25 \leq DR < 50$<br>**4.** Ranges of $50 \leq DR < 75$<br>**5.** Ranges of $75 \leq DR < 90$<br>**6.** Ranges of $75 \leq DR < 90$ | **1.** Embryonic Initial<br>**2.** Initial<br>**3.** Primary<br>**4.** Intermediate<br>**5.** Advanced<br>**6.** Ready | **1.** Yes<br>**2.** Literature review + ABC classification + four experts' interview + Case Study<br>**3.** Brazilian auto-parts manufacturing industry<br>**4.** No |
| **8.** A Maturity Model of Product Fitting | **1.** Gustafsson et al. (2019)<br>**2.** Supply Chain Management: An International Journal (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Retail Operations Management<br>**(D)** Industry 4.0/Supply Chain<br>**(S)** Business footwear digitalization/customization | Technology<br>Supply Chain | **1.** In-shop operations efficiency<br>**2.** Benefit sales<br>**3.** Value-driven product development | **A.** Systemic use of digital model<br>**B.** Efficient parametrization<br>**C.** Digital model-derived parameters | **1.** Yes<br>**2.** Literature Review + 13 interviews/case survey+ three case study<br>**3.** Three Web retail companies<br>**4.** Yes |

| #Maturity Model Name | Literature: **1.** Author/Year **2.** Source **3.** Document Type | Domain (D)/Subdomain (S) | Categories List Elements | | | Research Design: **1.** Empirically Tested? **2.** Methods (Design + Assessment Tool) **3.** Model Validation **4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | |
| | | | | **4.** Efficient product flow<br>**5.** Efficient and responsive long-tail assortment management<br>**6.** Relationship-based sales<br>**7.** Appropriate assortment and replenishment | | |
| **9.** Industry 4.0 Implementation Maturity Model | **1.** Wagire et al. (2021)<br>**2.** Production Planning and Control (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Manufacturing<br>**(S)** Auto-parts manufacturing industry | People and culture<br>Industry 4.0 awareness<br>Organisational strategy<br>Value chain and processes<br>Smart manufacturing technology<br>Product and services-oriented technology<br>Industry 4.0 base technology | **1.** 1.00≤Mscore <2.00<br>**2.** 2.00≤Mscore <3.00<br>**3.** 3.00≤Mscore <4.00<br>**4.** 4.00≤Mscore ≤5.00<br><br>38 maturity measurement items | **1.** Outsider<br>**2.** Digital Novice<br>**3.** Experienced<br>**4.** Expert | **1.** Yes<br>**2.** Literature Review + 15 experts interviews + case study + AHP fuzzy model<br>**3.** Indian auto-parts manufacturing industry<br>**4.** Yes |
| **10.** Smart PPC-Technology Readiness Assessment | **1.** Saad et al. (2021)<br>**2.** Journal of Manufacturing Technology | **(D)** Industry 4.0/Production Planning and Control<br>**(S)** Sanitary ware industry | Real-time data management system | **1.** 0<R≤0.5<br>**2.** 0.5<R≤1.5<br>**3.** 1.5<R≤2.5<br>**4.** 2.5<R≤3.5<br>**5.** 3.5<R≤4 | **1.** Outsider<br>**2.** Beginner<br>**3.** Learner<br>**4.** Experienced<br>**5.** Leader | **1.** Yes<br>**2.** Literature Review + two meeting and three workshops + survey with |

| #Maturity Model Name | Literature: **1.** Author/Year **2.** Source **3.** Document Type | Domain (D)/Subdomain (S) | Categories List Elements | | | Research Design: **1.** Empirically Tested? **2.** Methods (Design + Assessment Tool) **3.** Model Validation **4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | |
| | Management (journal)<br>**3.** Research Article | | Dynamic production<br>Planning<br>Autonomous Execution Control | - 9 maturity driving factors<br>- 18 maturity technological factors | | SMEs (n=50) + AHP model + case study<br>**3.** Sanitary ware industry<br>4. No |
| **11.** Industry 4.0 Readiness and Maturity Model | **1.** Schumacher et al. (SCHUMACHER; EROL; SIHN, 2016)<br>**2.** Procedia CIRP (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Manufacturing<br>**(S)** Aerospace components industry | Products<br>Customers<br>Operations<br>Technology<br>Strategy<br>Leadership<br>Governance<br>Culture<br>People | 62 maturity items | **1.** No Implemented<br>**2...**<br>**3...**<br>**4...**<br>**5.** Fully implemented | **1.** Yes<br>**2.** Literature Review + experts interview + survey with professionals (n=23) + two case study<br>**3.** Austrian aerospace components industry<br>**4.** Yes |
| **12.** Defense Supply Network Industry 4.0 Maturity Model | **1.** Bibby and Dehe (2018)<br>**2.** Production Planning and Control (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Supply Chain<br>**(D)** Industry 4.0/Operations Management<br>**(S)** Defense Supply Network | Factory of Future<br>People and Culture<br>Strategy | **1.** Additive Manufacturing/3D Printing<br>**2.** Cloud<br>**3.** MES<br>**4.** IoT and CPS<br>**5.** Big Data<br>**6.** Sensors<br>**7.** e-Value chain<br>**8.** Autonomous Robots<br>**9.** Innovation Openness<br>**10.** Continuous Improvement Capabilities | **1.** Minimal<br>**2.** Development<br>**3.** Defined<br>**4.** Excellence | **1.** Yes<br>**2.** Literature review + workshops + 14 experts interview within focal firm + case study<br>**3.** 12 suppliers of a British defense industry<br>**4.** No |

| #Maturity Model Name | Literature: 1. Author/Year 2. Source 3. Document Type | Domain (D)/Subdomain (S) | Categories List Elements: I. Views/Dimensions or Perspectives or Focus Areas | Categories List Elements: II. Processes or Practices or Factors or Capabilities | Categories List Elements: III. Maturity Levels or Steps or Phases or Stages (in ascending order) | Research Design: 1. Empirically Tested? 2. Methods (Design + Assessment Tool) 3. Model Validation 4. It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | | **11.** Technological Investment<br>**12.** Agility Vision<br>**13.** Manufacturing Strategy | | |
| **13.** BDMM- Big Data Maturity Model | **1.** Comuzzi and Patel (2016)<br>**2.** Industrial Management and Data Systems (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Business/<br>**(D)** Industry 4.0/ Service Operations Management<br>**(S)** Digital content delivery service<br>**(S)** Financial consulting service<br>**(S)** Direct marketing service | Strategic Alignment<br>Data<br>Organization<br>Governance<br>Information Technology | **1.** Strategy<br>**2.** Processes<br>**3.** Analytics<br>**4.** Management<br>**5.** People<br>**6.** Culture<br>**7.** Governance<br>**8.** Information Management<br>**9.** TI infrastructure | **I**<br>**II**<br>**III**<br>**IV**<br>**V** | **1.** Yes<br>**2.** Literature review + nine experts' interview + three case study<br>**3.** Three digital services companies in big data and analytics<br>**4.** Yes |
| **14.** DPMM 4.0- Delivery Process in Supply Chains Maturity Model | **1.** Asdecker and Felch (2018)<br>**2.** Journal of Modelling in Management (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Supply Chain<br>**(D)** Industry 4.0/Outbound Logistics<br>**(S)** Delivery process and outbound logistics in electric equipment manufacturing supply industry | Order processing<br>Warehousing<br>Shipping | 15 SCOR processes/elements divided along with three groups: Order processing, Shipping, Warehousing | **1.** Basic digitization<br>**2.** Cross-department digitization<br>**3.** Horizontal and vertical digitization<br>**4.** Full digitization<br>**5.** Optimized full digitization | **1.** Yes<br>**2.** Literature Review + experts survey part I (n=43) + experts survey part II (n=37) + Case Study<br>**3.** Two German/USA electric equipment industries (of a company)<br>**4.** Yes |
| **15.** Digital Projects Requirements of Industry 4.0 in Manufacturing | **1.** Ramos et al. (2020)<br>**2.** International Journal of Computer Integrated | **(D)** Industry 4.0/ Information Systems/<br>**(D)** Industry 4.0/ Supply Chain<br>**(D)** Industry 4.0/Manufacturing Control<br>**(S)** Automotive Industry | Autonomy<br>Infrastructure<br>Integration<br>External maintenance<br>Processing | 15 maturity measurement processes | **Stage 01 -** Process Evaluation<br>**Stage 02 -** Project Definition<br>**Stage 03 -** Local System | **1.** Yes<br>**2.** PROMETHEE/AHP methodology + Expert's judgment + four projects within two industrial cases |

| #Maturity Model Name | Literature: 1. Author/Year 2. Source 3. Document Type | Domain (D)/Subdomain (S) | Categories List Elements: I. Views/Dimensions or Perspectives or Focus Areas | II. Processes or Practices or Factors or Capabilities | III. Maturity Levels or Steps or Phases or Stages (in ascending order) | Research Design: 1. Empirically Tested? 2. Methods (Design + Assessment Tool) 3. Model Validation 4. It is DRS-based? |
|---|---|---|---|---|---|---|
| | Manufacturing (journal)<br>**3.** Research Article | | Replacement<br>Support<br>Trainings<br>Usability | | **Stage 04 -** Legacy System<br>**Stage 05 -** Choose better solution<br>**Stage 06 -** Decision-Making | **3.** Four digital transformation projects in the automotive manufacturing industry in Brazil and Colombia<br>**4.** No |
| **16.** Industry 4.0 Maturity Model | **1.** Santos and Martinho (2019)<br>**2.** Journal of Manufacturing Technology Management (journal)<br>**3.** Research Article | **(D)** Industry 4.0/Manufacturing<br>**(D)** Industry 4.0/Operations Management<br>**(S)** Automotive Industry | Organizational strategy<br>Structure and culture<br>Workforce<br>Smart factories<br>Smart processes<br>Smart products and services | 41 maturity variables | **Level 0 -** low or none degree of implementation<br>**Level 1 -** pilot actions being planned or being developed<br>**Level 2 -** implementation of actions initiated, with some benefits being observed<br>**Level 3 -** partial implementation of actions, that enhance the competitiveness of the company<br>**Level 4 -** advanced implementation of actions, with clear economic returns<br>**Level 5 -** reference in applying the concepts and | **1.** Yes<br>**2.** Literature Review + Scoping Review + seven interviews with manufacturing professionals + Case Study<br>**3.** Two Brazilian automotive companies<br>**4.** No |

| #Maturity Model Name | Literature: **1.** Author/Year **2.** Source **3.** Document Type | Domain (D)/Subdomain (S) | Categories List Elements | | | Research Design: **1.** Empirically Tested? **2.** Methods (Design + Assessment Tool) **3.** Model Validation **4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | |
| | | | | | implementing the technologies of Industry 4.0 | |
| **17.** Maturity Model for Design Automation | **1.** Willner et al. (2016) **2.** Computers in Industry (journal) **3.** Research Article | **(D)** Industry 4.0/ Product Design **(S)** ETO Manufacturing Industries | Strategy Processes Systems People | 38 maturity practices | **Level 1 -** Ultimate Freedom **Level 2 -** Product Standardization **Level 3 -** Automation of Tendering **Level 4 -** Automation of Order Execution **Level 5 -** Full Automation | **1.** Yes **2.** Literature Review + Scoping Review + Focus group workshops + 13 interviews with product automation design professionals within ETO manufacturing companies + Four case study **3.** Two focus groups from workshops in four ETO manufacturers (special testing chamber, turbomachine, asphalt mixing plant, high-rise elevator) **4.** Yes |
| **18.** Digital Transformation Capability Maturity Model | **1.** Gökalp and Martinez (2021) **2.** Computers in Industry (journal) **3.** Research Article | **(D)** Digital transformation/Manufacturing Organization **(D)** Digital transformation/Operations Management **(S)** Organizational Processes in Chemical and Machine Industries | Strategic governance Information and technology Digital process transformation Workforce management | 26 maturity processes | **Level 0 -** Incomplete **Level 1 -** Performed **Level 2 -** Managed **Level 3 -** Established **Level 4 -** Predictable **Level 5 -** Innovating | **1.** Yes **2.** Literature Review + Interviews with three managers in machine company + three digital transformation professionals in a chemical company + Two Case Studies |

| #Maturity Model Name | Literature: **1.** Author/Year **2.** Source **3.** Document Type | Domain (D)/Subdomain (S) | Categories List Elements: **I.** Views/Dimensions or Perspectives or Focus Areas | **II.** Processes or Practices or Factors or Capabilities | **III.** Maturity Levels or Steps or Phases or Stages (in ascending order) | Research Design: **1.** Empirically Tested? **2.** Methods (Design + Assessment Tool) **3.** Model Validation **4.** It is DRS-based? |
|---|---|---|---|---|---|---|
| | | | | | | **3.** Two manufacturing companies: 1. machine; 2. chemical<br>**4.** Yes |
| **19.** IoT Maturity Model | **1.** Kim et al. (2021)<br>**2.** Journal of Industrial Information Integration (journal)<br>**3.** Research Article | **(D)** IoT/ Organizational Digital transformation<br>**(D)** IoT/ Manufacturing<br>**(D)** IoT/ Information Systems<br>**(S)** Organizational Digital transformation in cosmetics Manufacturing Industry | Data Quality Planning<br>Data Quality Control<br>Data Quality Assurance<br>Data Quality Improvement<br>Data-related Support<br>Data Provision | 95 maturity attributes | **Level 1 -** Basic<br>**Level 2 -** Managed<br>**Level 3 -** Established<br>**Level 4 -** Predictable<br>**Level 5 -** Innovating | **1.** Yes<br>**2.** ISO 8000-61/62/63; ISO/IEC 33000 series reference models + survey with 12 experts + case study<br>**3.** Cosmetic manufacturing company<br>**4.** Yes |
| **20.** Logistics 4.0 Maturity Model | **1.** Modica et al. (2021)<br>**2.** Production Planning and Control (journal)<br>**3.** Research Article | **(D)** Industry 4.0/ Logistics<br>**(D)** Industry 4.0/ Supply Chain<br>**(S)** Freight transportation services | Level of Autonomy<br>Decision Scope<br>Frequency of Acquisition<br>Level of automation<br>Network Span<br>Decision Level<br>Decision Scope<br>Application | Principles:<br>**1.** Automation,<br>**2.** Integration,<br>**3.** Intelligence<br>Process Layers:<br>**1.** Physical Thing<br>**2.** Data Acquisition<br>**3.** Connectivity<br>**4.** Analytics<br>**5.** Digital services<br><br>22 maturity processes | **Level 1**<br>**Level 2**<br>**Level 3**<br>**Level 4**<br>**Level 5** | **1.** No<br>**2.** SLR<br>**3.** Not specified<br>**4.** No |

**Table 3.4.** Analyze of main Maturity Models in OSCM and I4.0 domain (part II)

| **#Maturity Model Name**<br><br>**Model type:**<br>**(D)** Descriptive<br>**(P)** Prescriptive<br>**(C)** Comparative/ Benchmarking | **Industry 4.0 technologies adopted in MM analyzed** | **1.** Reference Model adopted<br>**2.** MMs framework/guidelines adopted in the design<br>**3.** Evaluation Tool |
|---|---|---|
| **1.** Industrie 4.0 Maturity Index: **(D)**<br>Schuh et al. (2017) | Solutions are contingent to the digital solution sought: IoT+ Big Data and Data Analytics + AI + ML+ AR + ICTs + Cloud + CPS + RFID + AUTO-ID + OPC-UA + microservices + SCRUM + AM | **1.** Production and Management Framework<br>**2.** Not specified<br>**3.** Not presented in the MM document |
| **2.** Industry 4.0 Maturity Model for Machine Tool companies: **(D, P)**<br>Rafael et al. (2020) | IoT + CPS + IoS | **1.** IMPULS MM from Lichtblau et al. (2015), ISO 2015/2018, and Literature Review<br>**2.** Becker et al. (2009)<br>**3.** Yes |
| **3.** OSCM 4.0 Maturity Model: **(D, P)**<br>Caiado et al. (2021) | CPS + IoT + Big Data + Data Analytics + Cloud + Cybersecurity + Blockchain + AM + AR/VR + Advanced Robotics | **1.** Literature Review<br>**2.** Becker et al. (2009)**,** and de Bruin et al. (2005)<br>**3.** Yes |
| **4.** M2DDM- Maturity Model for Data-Driven Manufacturing: **(D)**<br>Weber et al. (2017) | TI Systems + Big Data/Advanced Analytics + IoT/sensors + CPS/Digital Twin + Middleware/SOA + Cloud/Edge Computing | **1.** IIRA, SITAM, RAMI, Literature Review<br>**2.** Becker et al. (2009)**,** and de Bruin et al. (2005)<br>**3.** No |
| **5.** HISMM- Hospital Information System Maturity Model: **(D)**<br>Carvalho et al. (2019) | TI + Data Analytics + Cloud/Web Services + Auto-ID + Cybersecurity | **1.** Carvalho et al. (2016)<br>**2.** Hevner et al. (2004), and Mettler (2010)<br>**3.** No |
| **6.** Smart Factory Maturity Model: **(D)**<br>Sjödin et al. (2018) | IoT + AI + Big Data and Data Analytics | **1.** Parida's (2015) framework, and Literature Review<br>**2.** Not specified<br>**3.** Yes |
| **7.** Industry 4.0 Implementation Readiness Model: **(D)**<br>Pachinni et al. (2019) | IoT + Big Data + Cloud Computing + Autonomous Robots + CPS + Additive Manufacturing + Augmented Reality | **1.** SAE J4000/4001 standard (SAE 2001); IEC 15504-5 standard (ISO 2004), and Lucato et al.'s (2019) framework<br>**2.** Not specified<br>**3.** Yes |
| **8.** A Maturity Model of Product Fitting: **(D, P)**<br>Gustafsson et al. (2019) | Scanner Technology + Digital/Mobile Devices + 3D cameras + Modeling and Simulation Algorithms + Data Analytics + Web-Services Platform | **1.** Pagh and Cooper's (1998) framework, and Plomp and Batenburg's (2010) framework, and Literature Review<br>**2.** Holmström et al. (2009)<br>**3.** Yes (qualitative/by attributes) |

| #Maturity Model Name<br><br>**Model type:**<br>**(D)** Descriptive<br>**(P)** Prescriptive<br>**(C)** Comparative/ Benchmarking | **Industry 4.0 technologies adopted in MM analyzed** | **1.** Reference Model adopted<br>**2.** MMs framework/guidelines adopted in the design<br>**3.** Evaluation Tool |
|---|---|---|
| **9.** Industry 4.0 Implementation Maturity Model: **(D)**<br>Wagire et al. (2021) | IoT/IoS + Big Data + Cloud Computing + Autonomous Robots/Co-bots + AM + Augmented Reality/Wearables + Blockchain+ Simulation Tools + Mobile Devices + Smart Products + AI + Cybersecurity + M2M/H2M + TI Tools | **1.** Literature Review<br>**2.** Hevner et al. (2004), and Becker et al. (2009)<br>**3.** Yes |
| **10.** Smart PPC- Technology Readiness Assessment: **(D, P)**<br>Saad et al. (2021) | Sensors/Actuators + RFID/RTLS + Data Mining + Cloud Computing/VPN + Blockchain+Web-Services + ICTs Systems + M2M + IoP + ML/AI + Simulation + Design Automation + AR/VR + Digital Twin | **1.** Smart SME Technology Readiness Assessment Framework (SSTRA), and Literature Review<br>**2.** Hevner et al. (2004), and Becker et al. (2009)<br>**3.** Yes |
| **11.** Industry 4.0 Readiness and Maturity Model: **(D)**<br>Schumacher et al. (SCHUMACHER; EROL; SIHN, 2016) | IoT + CPS + CMg | **1.** Kagermann et al. (2013), and Literature Review<br>**2.** Becker et al. (2009)<br>**3.** Yes |
| **12.** Defense Supply Network Industry 4.0 Maturity Model: **(D, P)**<br>Bibby and Dehe (2018) | Additive Manufacturing/3DP + cloud + IoT/CPS + Big Data + Sensors + MES + e-Value Chain + Autonomous Robots | **1.** Literature Review<br>**2.** IMPULS Model from Lichtblau et al. (2015), and PwC<br>**3.** Yes |
| **13.** BDMM- Big Data Maturity Model: **(D, P)**<br>Comuzzi and Patel (2016) | Big Data/Apache Hadoop Framework + Data Analytics/Data Mining/Modeling and Simulation/Data + Visualization tools | **1.** Literature review<br>**2.** de Bruin et al. (2005), Pöppelbuß and Röglinger (2011), Becker et al. (2009)<br>**3.** Yes |
| **14.** DPMM 4.0- Delivery Process in Supply Chains Maturity Model: **(D, P)**<br>Asdecker and Felch (2018) | AI algorithms/Machine Learning + SOA/Cloud platform/web services + cybersecurity + simulation + IT-systems + digital twin/CPS + data analytics + IoT/RFID | **1.** SCOR Framework, and Literature Review<br>**2.** de Bruin et al. (2005)<br>**3.** Yes |
| **15.** Digital Projects Requirements of Industry 4.0 in Manufacturing: **(D)**<br>Ramos et al. (2020) | RFID + Mobile Phone + ICTs/Software + CPS | **1.** Kondratenko's (2018) framework, and Literature Review<br>**2.** Not specified<br>**3.** Yes |
| **16.** Industry 4.0 Maturity Model: **(D)**<br>Santos and Martinho (2019) | CPS + IoT + Cloud Computing + Big Data + Data Analytics + Service-Oriented Architecture/SOA + Autonomous and Smart Systems + AM/3D printing + Mobile Devices and Applications | **1.** Literature Review<br>**2.** de Bruin et al. (2005)<br>**3.** Yes |

| #Maturity Model Name<br><br>**Model type:**<br>**(D)** Descriptive<br>**(P)** Prescriptive<br>**(C)** Comparative/ Benchmarking | **Industry 4.0 technologies adopted in MM analyzed** | **1.** Reference Model adopted<br>**2.** MMs framework/guidelines adopted in the design<br>**3.** Evaluation Tool |
|---|---|---|
| **17.** Maturity Model for Design Automation: **(D)**<br>Willner et al. (2016) | CAD/CAM Systems + Design automation/knowledge-based engineering (KBE) process/technology + IT systems + Automated Data-Collection and Analytics + Integration of Systems + Optimization | **1.** Design automation/knowledge-based engineering (KBE), and Literature Review, and CMMI (2010)<br>**2.** Becker et al. (2009), de Bruin et al. (2005), and Neff et al. (2014)<br>**3.** Yes |
| **18.** Digital Transformation Capability Maturity Model: **(D, P)**<br>Gökalp and Martinez (2021) | Standardized Enterprise Architecture (EA)/Software+ Data and Business Process Layers + IoT Devices Infrastructure + Data Management + Data Analytics + Applications based on agile software development principles + IT Security Management | **1.** SPICE/ISO IEC 3300 series, and Literature Review<br>**2.** De Bruin et al. (2005), and Mettler (2010)<br>**3.** Yes |
| **19.** IoT Maturity Model: **(D, P)**<br>Kim et al. (2021) | IoT ecosystem + Data Management ecosystem + network | **1.** ISO 8000-61/62/63, ISO/IEC 33000 series, IoT DQM-PRM<br>**2.** Peffers et al. (2007), and Wieringa (2014)<br>**3.** Yes |
| **20.** Logistics 4.0 Maturity Model: **(D)**<br>Modica et al. (2021) | IoT and CPS ecosystems + Data Acquisition + Connectivity network + Data Analytics + Digital Services/Application | **1.** Literature Review<br>**2.** Not specified<br>**3.** No |

**Table 3.5.** Main I4.0's technologies used into MM on OSCM domain

| Technology | Definition | OM/SCM Applications/ Capabilities | Literature |
|---|---|---|---|
| **CPS** | A CPS is a technological ecosystem through which physical objects, digital resources, smart capabilities, manufacturing/supply chain assets, and enterprise systems are closely intertwined in a digital thread. CPS is the full realization of a smart manufacturing/supply chain | • Cloud-based cyber-physical system for **adaptive** shop floor scheduling<br>• **Integrating** holons, agents, and function blocks within cyber-shop floor control<br>• Digital Twin-based Cyber-Physical Production System for **autonomous** manufacturing in smart shop floor | Zhong et al. (2017c)<br>Mourtzis and Vlachou (2018)<br>Ding et al. (2019) |
| **IoT** | IoT is the set of digital technologies embedded within resources, devices, and assets to provide computational power, awareness, connectiveness, and cybersecurity to the manufacturing and supply chain environment. IoT performs a critical infrastructure for digital manufacturing and supply chains | • **Real-time** manufacturing information integration service for production planning and control system: aggregate, detailed, and shop floor levels<br>• **Context-aware** information services based on IoT for improving machine-to-human interaction and decision-making in a project-shop-based manufacturing planning and control environment<br>• **IoT vertical integration** strategies for a smart production planning and control | Zhang et al. (2015)<br>Alexopolous et al. (2018)<br>Ghobakhloo (2018) |
| **BDA and AI** | BDA/AI is a platform that is used for data ingestion, processing, warehousing, and analysis of manufacturing system big data for decision system supporting and improving business-value proposition. BDA and AI platform is a data processing engine platform and analytics tools system that feeds its IoT and legacy systems data sources for leverage data value within manufacturing planning and control and enterprise layers | • Shop floor scheduling and re-scheduling based on **big data analytics** of machines fault prediction<br>• A **data-driven MES-based algorithm** using large sets of data for **forecasting** of machines' active periods and throughput bottlenecks in the future production runs<br>• **Event-based data pipeline** architecture for data-collection of legacy and IoT systems on the shop floor | Ji and Wang (2017)<br>Subramaniyan et al. (2018)<br>Farooqui et al. (2020) |
| **CMg** | Cloud Manufacturing or cloud is a platform consisting of cloud services, web services, and integration tools for manufacturing planning and control virtualization. It comprises a set of cloud-based services and computing technologies applied to carry out the manufacturing and its planning and control activities as-a-service. The CMg platforms sustain manufacturing value-creation processes based on virtualization, digital servitization, customization, and vertical and horizontal integration solutions | • **Optimal scheduling** of **reconfigurabl**e assembly line for cloud manufacturing<br>• Data mining based **multi-level aggregate service planning** for cloud manufacturing<br>• Cloud ecosystem implementation for better control over **digital manufacturing** and **integration of systems** supporting and **manufacturing as-a-service** cloud-based | Yuan et al. (2017)<br>Yu et al. (2018a)<br>Helo et al. (2021) |
| **ICTs and Ancillary Technologies** | Ancillary technologies are a particular set of digital/smart technologies like digital twin, CPS combined with traditional ICTs and legacy systems technologies (e.g., PLC/SCADA systems), on supporting running the manufacturing and supply chain to transition | • **Digital Twin Shop-Floor Control** by **the integration** of physical shop-floor, virtual shop-floor, shop-floor service system, and shop-floor digital twin data | Tao and Zhang (2017)<br>Bueno et al. (2022)<br>Ciano et al. (2021) |

| Technology | Definition | OM/SCM Applications/ Capabilities | Literature |
|---|---|---|---|
| | towards the I-4.0 concept. ICTs and some IS particular technologies do not need to constitute a complex ecosystem for providing their smart capabilities, coupling themselves to the existing digital ecosystem, improving its functionalities. This ecosystem also comprises the fit manufacturing legacy systems and ICTs, digitalization, and automation processes such as MES embedded with IoT capabilities | • **Cloud** dual system scheduler with **distributed MES** (SS-dMES)<br>• Machines integrated with **MES/ERP** allow **real-time information** record and sharing that empower Kanban | |

### 3.3.4. Summary of Step 1 findings

In Section 3.3, we have analyzed five architectures of I4.0 (Section 3.3.1), eight MM development frameworks (Section 3.3.2), and 20 MMs in the OSCM and I4.0 domain (Section 3.3.3). These results were subsequently used as a design research background for our framework proposal. The main findings were as follows.

#### *3.3.4.1 Architectures/reference models (RMs) used in maturity models (MMs)*

We observe that the purpose of using reference architectures is to serve as templates (RM/architecture) for MMs design. The main shortcomings are the poor use of organizational and people factors inherent to managerial MM requirements in the OSCM domain (e.g., digital skills, culture, and business processes). The architectural elements are over-centered on technological factors; however, they offer the designer the possibility of harnessing RM/architecture components for new MMs and/or obtaining preliminary evidence of "*what to develop/design*" in these models, mainly in the I4.0 technological dimension.

Therefore, the analysis findings for these architectures served to ground the elements and recommendations for the framework. Also, these architectures can be checked regarding the exaptation and exploitation/advancement of solutions based on MMs (HEVNER; GREGOR, 2022). These architectures must be searched before starting the MM design, helping the designer think/refine the problem-solving by fitting design elements to artifact ideation (see Figure 3.3 in Section 3.4.3.2).

#### *3.3.4.2 Frameworks for maturity models (MMs) development*

We observed that mainstream MMs' development frameworks (Table 3.3) show the designers two aspects; the first is related to the procedures ("*how to develop the model*"), and the second is related to building elements ("*what to design*"). From these findings, we obtain evidence to define a standard workflow for MM development in OSCM within our framework proposal.

Therefore, the analysis of existing frameworks oriented us to generate the two components of our framework (two building blocks). The first component is a set of seven iterative procedures showing the designers "*how to operationalize*" the MM's development (see Figure 3.3 in Section 3.4.3.2). Also, the existing frameworks' analysis findings helped us establish, compile, and standardize the main logical elements that must be contained in a MM development framework. Therefore, the second component is a set of nine elements and recommendations showing designers "*what to design*" in their MM (see Figure 3.3 in Section 3.4.3.2).

*3.3.4.3 Maturity model (MM) comparison*

We applied several analysis criteria for the MM comparison. Subsequently, we mapped the main category elements, the development/design approach, and the leading I4.0 technologies for maturity progress in the OSCM domain, among other findings (see Tables 3.3 and 3.4). The findings from these MMs supported us with the mapping and standardization of the recent practices concerning maturity modeling based on artifacts, which we embedded in our framework proposal. From this, we consolidated the background of the two building blocks of the framework proposal.

## 3.4. Framework design (Steps 2–4)

This section is divided according to Steps 2–4 shown in Figure 3.1, representing the design cycle of our framework. In these steps, our objective is to build an agile and high-quality artifact for the MM development process based on reliable design and research. Our framework is aimed at MM development and research in the OSCM field. Therefore, the framework aims to provide standardization and agility for MM building. It provides seven research iteration procedures based on DSR (see Figure 3.3 in Section 3.4.3.2). Nine elements can be performed from iterative procedures applying incremental improvements in response to the changes needed for better design (learning-based), thus creating a more streamlined, standardized development process for MMs. The main elements and associated recommendations for development are shown in Figure 3.2 (see Section 3.4.3.1).

### 3.4.1 The initial framework proposal (Step 2)

We followed Soni and Kodali's (2013) guidelines for our framework design. Accordingly, we consolidated the framework's understanding and proposal by positioning and demonstrating it regarding the: *(i).* shortcomings of existing frameworks; *(ii).* novelty of the framework; *(iii).* source of the framework; *(iv).* framework validation; *(v).* method of validation; and *(vi).* elements (or constructs) of the framework.

***(i). Shortcomings of existing frameworks.*** Following Soni and Kodali's (2013) guidelines for framework building, we surveyed the main shortcomings of MMs' development frameworks, along with the OSCM domain. This mapping is based on analyses and findings from Sections 3.3.2 and 3.3.3. In summary, the main shortcomings are:

- lack of a common/standardized, integrated framework containing the established MM development guidelines based on DSR orientation, along with the OSCM and I4.0 domain;
- lack of a framework with a clear list of procedures and recommendations for MM designers based on cyclic research procedures and design processes (requirements → design → test → improvement/change → design learning → better design);
- design operationalization guidelines to support an agile MM development (focusing on showing to the designer "*what to design*" and "*how to design*"); and
- a set of key I4.0 technologies and capabilities for the maturity progress in the OSCM domain.

***(ii). The novelty of the framework.*** The novelty of the framework lies in covering the main shortcomings presented. In our proposal, a MM is built based on the following rule: each element of the model represents a process of intertwined research and design iteration(s), i.e., each MM element is conceived as an iterative process comprised of the seven procedures illustrated in Figure 3.3 (see Section 3.4.3.2).

Therefore, the novelty of our approach is to offer a MM development framework based on iterative procedures, with tests and validation for each of the model elements. These iterative research and design procedures can help MM designers overcome the criticism concerning the poor validity and reliability of MM artifacts and trace their workflow to improve the agility of future versions of these MMs. In summary, the novelty of the framework lies in:

- presenting core elements and associated design recommendations for MM design workflows (Figure 3.2, Section 3.4.3.1);
- presenting research iteration procedures to be operationalized in each element designed during MM development (Figure 3.3, in Section 3.4.3.2); and

- standardizing several design guidelines in a common and updated development framework.

***(iii). Source of the framework.*** The framework is classified as practitioner-based (MM designers). This framework type is developed to guide the real procedures in the field, i.e., deploying the MM's design.

***(iv and v). Framework validation and method.*** See Section 3.4.2.

***(vi). Elements of the framework.*** See Section 3.4.3.

### 3.4.2 Refinement and validation of the framework (Step 3)

During Step 3, our framework was presented to experts, whereby the procedures and standard elements proposed were scrutinized, improved, and validated. We used meetings with experts and a panel of academics experienced in MM development to verify the practicability of our framework (see Table 3.6). First, sequential meetings with five experts helped us refine the framework proposal until theoretical saturation (SAUNDERS; LEWIS; THORNHILL, 2019) was reached. In addition, an expert panel was performed during three rounds, comprising the same five experts, helped us validate the framework. Validation was reached when the expert group proposed no additional data and improvements for the framework, i.e., data and theoretical saturation (SAUNDERS et al., 2018). Thus, the framework elements and design were deemed valid and useful to build MMs, obtaining the final set of components shown in Figures 3.2 and 3.3.

**Table 3.6.** Experts' profiles and information

| ID | Position | OSCM experience (years) | MM experience (years) | Number of Meetings |
|---|---|---|---|---|
| I#1 | Operations Management/Industry 4.0 | >20/ | >10 | 5 |
| I#2 | Operations and Supply Chain Management | >20 | >5 | 3 |
| I#3 | Information Management Systems/Operations Management | >20 | >10 | 5 |
| I#4 | Operations Management/Industry 4.0 | >15 | >5 | 2 |
| I#5 | Operations Management/Logistics | >15 | >5 | 5 |

Duration of panel: approximately 40 minutes; Average duration of a interviews: approximately 1 hour.

### 3.4.3 The final version of the framework (Step 4)

Our framework is constituted based on two core components (building blocks):

- *Nine design elements with various associated actions/recommendations.* These help designers with the issue of "*what to design*" in a MM (Figure 3.2, Section 3.4.3.1). These procedures, elements, and research/design iterations, within a formalized framework, can help MM designers with the agility of the development of their models in the OSCM and I4.0 domain.
- *Seven iterative research procedures.* Each research iteration corresponds to the design of one element within the MM development. These seven procedures help designers with the issue of "*how to design*" a MM (Figure 3.3, Section 3.4.3.2).

#### *3.4.3.1 Nine elements for maturity model (MM) building (what to design in a MM)*

A flowchart of elements and recommendations about "*what to design*" in a MM are presented in this subsection and summarized in Figure 3.3 (see Section 3.4.3.2). Nine core elements constitute this building block of our framework. They are linked to three major phases during MM building: (1). MM requirements; (2). MM design; and (3). MM use/follow-up.

The nine elements discussed below are operationalized though our iterative design research procedures shown in Figure 3.2. These elements and recommendations support designers' decisions and actions during the model building.

In the first development phase (see Figure 3.3, Section 3.4.3.2), MM requirements concern elements related to the model's scope (DE BRUIN et al., 2005) and the research design for its conception.

*Element 1: Problem-solving.* This element is focused on development actions and recommendations concerning the understanding of how the artifact's behavior/use can solve an OSCM problem (problem space definition), the relevance, and the scientific process of artifact conception (solution space) (HEVNER; GREGOR, 2022).
*Recommendations:* define gaps or problem-solving that justify the model development; present motivations for the artifact building (knowledge base and design contributions); establish/generate a theory of problem explanation, if necessary [e.g. general systems theory (GST), resource-based view (RBV), socio-technical systems theory (STS), practice-based view (PBV), contingency theory (CT), dynamics capabilities (DC) theory, unified theory of acceptance and use of technology (UTAUT), or a novel theory for artifact design]; define the scope of the MM [outline the domain/entity, management

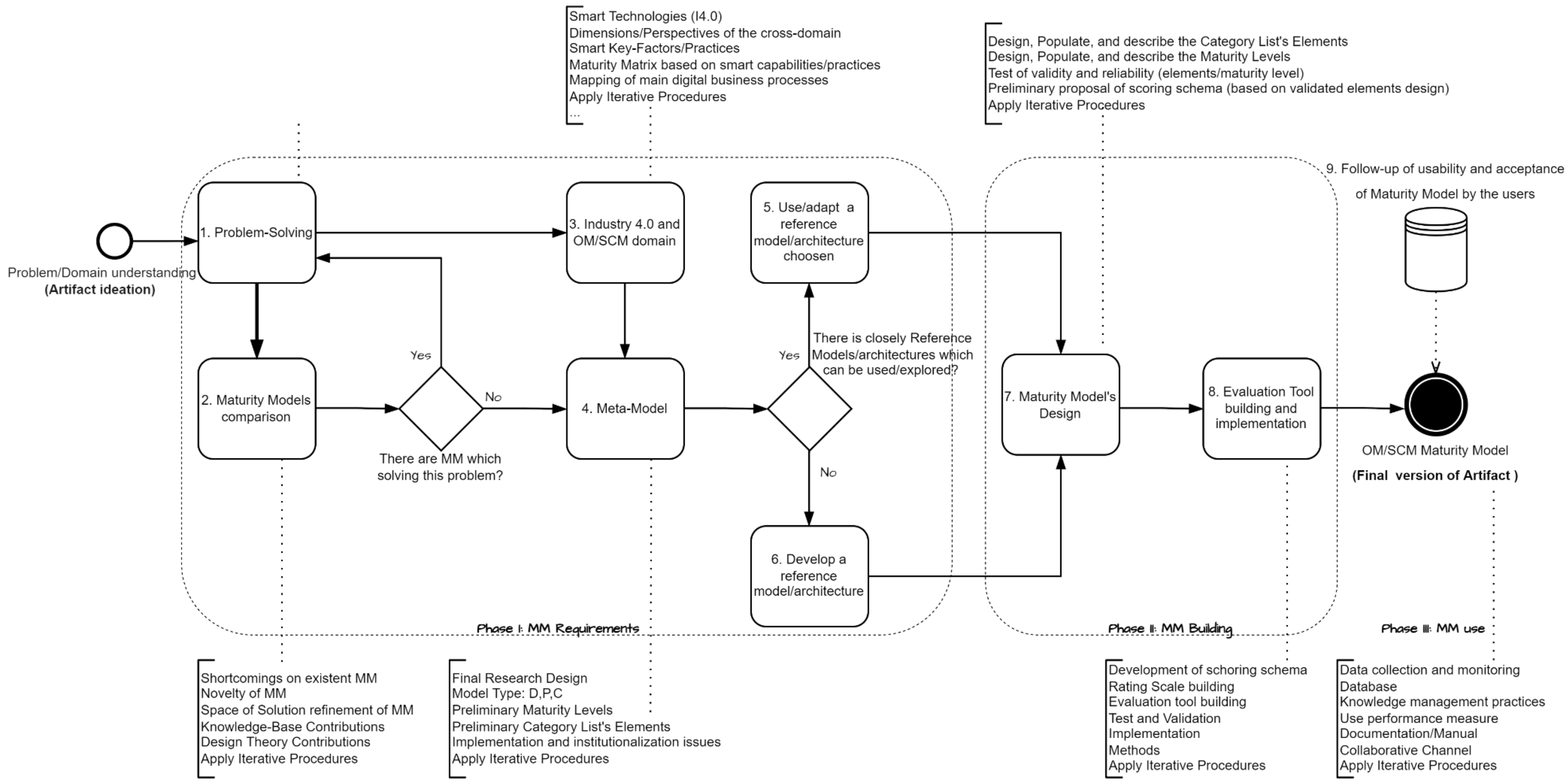



**Figure 3.2.** Elements of framework (“*what to design*”)

orientation/technology orientation/both, stakeholder participation (academia/practitioners/consultants/all of them), etc.]. During this element development process, the MM designers must think about and define the model scope, problem space, and solution space by using DSR-based artifact development (BECKER; KNACKSTEDT; PÖPPELBUSS, 2009; HEVNER; GREGOR, 2022; METTLER; BALLESTER, 2021).

*Element 2: MM comparison.* By carrying out this element, the MM's designer is able to map the core characteristics of recent approaches to MMs and what underpins their development pathways (both theoretical underpinning and design orientation) (BECKER; KNACKSTEDT; PÖPPELBUSS, 2009; METTLER; BALLESTER, 2021). For example, in Section 3.3, we compared 20 MMs in the OSCM and I4.0 domain based on eight criteria, observing that MMs in this domain are predominantly descriptive. Features found in this element act as a reference for designers' decisions regarding development pathways and MM contributions' positioning. *Recommendations:* applying the eight criteria presented in Section 3.3 is important to check the shortcomings of existing MMs in a domain from a determined research and design perspective, allowing a clear positioning and visualization of the novelty of a model. Element 2 helps designers better think about the solution space (as a new artifact) from evidence based on previous artifacts (MMs) and to survey the main shortcomings and mainstream design practices. This helps the designers map the existing models' contributions to the knowledge base. For example, in Tables 3.4 and 3.5, we observe a critical aspect among 20 MMs in the OSCM and I4.0 domain, i.e., the importance of "*people*" and "*organizational culture*" factors (occurring in 12 MMs). Intangible assets, such as people, culture, and organizational factors, are directly linked to digital transformation power and the harnessing of smart capabilities provided by I4.0 technologies because OSCM organizations are *"... the result of both human interaction and conscious design*" (SKYTTNER, 2005). Therefore, by handling Element 2, MM designers can capture key characteristics of existing MMs, harnessing them for to their model design (solution space).

*Element 3: Mapping of I4.0 and OSCM domain characteristics.* This element concerns the determination of synergic I4.0 technologies, capabilities, and influence on maturity levels. The "*I4.0 footprint*" is applied to the first, second, and remaining layers of elements' categories in implementing Element 3. This is essential to define the MM's scope formalization within the OSCM domain.

*Recommendations:* according to Table 3.5, IoT, CPS, cloud, big data and analytics/AI, ICTs, and ancillary technologies (e.g., additive manufacturing, smart robots and co-bots, virtual reality/augmented reality, blockchain, digital twin, etc.) are the core technologies that can be explored and harnessed by MMs in the OSCM and I4.0 domain (BUENO et al., 2022). For example, in Table 3.5, we mapped the I4.0 technologies of 20 MMs analyzed and found a pattern for the systemic working of smart technologies in recent MMs: IoT is mostly linked to digital and sensing infrastructure for operations' data collection (data sensing and transmission); data management technologies (e.g. machine learning) are mostly linked to the processing and value extraction (non-conformance patterns detection, maintenance events prediction, parameter monitoring, supporting decision-making) of data collected by IoT assets embedded in operations infrastructure; the raw data from IoT devices and information processed by data management tools can be stored on the cloud, and this also provides digital services, collaboration platforms, and hosting systems/tools, software, and databases; these technologies, in a systemic, integrated workflow, provide CPS capabilities to a company, connecting the physical (3-D printers, smart robots, machines, etc.) and digital environment of the operations (ICTs, modeling and simulation/data analytics tools, etc.). As I4.0 is a novel topic, its synergy and coupling to the OSCM domain need to be rigorously scrutinized to assign to the design tasks the right capabilities/practices for the right category elements within well-calibrated maturity levels.

<u>*Elements 4, 5, and 6: Meta-model definition and architecture adaption/development.*</u> A meta-model defines what the core components are that need to be designed in a MM, as well as their relationships (WENDLER, 2012). It comprises the final scope definition, drawing the components' relationships, and the final MM requirements specifications (full understanding of the problem and solution space, comparison and mapping of recent MM contributions, survey of dominant technologies and capabilities regarding maturity, maturity level configuration, model type, etc.). Finally, it is necessary to consider whether the meta-model helps MM designers to verify whether existing RMs (e.g., SCOR) or architectures (e.g., RAMI) underpin the MM or whether designers need to develop the MM's theoretical background.

Therefore, aligned to Noran (2011), the fifth and sixth tasks to be performed by designers in our framework are to check existing RMs/architectures that can be used for MM development. Several functions are performed by a RM/architecture (NORAN, 2011): *(i).* the primary goal is to speed up the modeling process by providing templates, thereby avoiding the need to start from scratch each time; *(ii).* as a response to the task/problem-solving in question, a RM may provide a suitable enough "*architecture*" of design; *(iii).* RMs can be used to enforce some consistency among existing models; and *(iv).* RMs can also aid in modeling knowledge acquisition by providing a "*learn-by-example*" approach and use case.

*Recommendations:* often, a meta-model comprises the following aspects: pre-defined maturity levels that represent the maturity progress in the domain; the domain is deployed from a list of categories (dimensions or views or perspectives or focus areas, which are deployed from processes or key factors or practices/actions or capabilities or indicators); practices or capabilities to perform maturity progress need to be implemented and institutionalized through medium-/long-term management efforts. Other associated issues include: research design and development strategy definition (e.g., grounded theory and DSR, or SLR and DSR); defining the model's purpose/scope (descriptive, prescriptive, comparative); and choosing the most adherent development framework for the MM desired.

For decisions regarding MM type choice, important issues need to be considered by designers. MMs can be built in the OSCM and I4.0 domain that cover three core purposes/types (PÖPPELBUSS; RÖGLINGER, 2011):

1. *Descriptive:* focuses on attributes modeling for the description of current practices or capabilities related to the maturity levels of a domain ("*as-is status*"), where the MM is applied as a diagnostic tool. These models cannot provide a measurement tool. For instance, Carvalho et al. (2019) presented a descriptive model for healthcare organizations based on maturity-influencing factors such as data analysis, strategy, people, electronic medic records, information security, systems, and IT infrastructure.

2. *Prescriptive:* besides the descriptive purpose, this offers a tested and validated maturity measurement tool, which is associated with a roadmap for improvements ("*to-be status*") (RÖGLINGER; PÖPPELBUSS; BECKER, 2012). For example, Caiado et al. (2021) presented a MM for OSCM 4.0 that describes and measures maturity on three dimensions [production planning and control (PPC)], OM with SCM, and OM], encompassing five perspectives deployed over 15 maturity indicators. This model is prescriptive because the user can measure the maturity and advances on the "*as-is status*" by triggering an action plan.

3. *Comparative*: focuses on modeling for the description, prescription, and benchmarking of similar practices and capabilities in different companies/industries. According to de Bruin et al. (2005), comparative MM *"... enables benchmarking across industries or regions. A model of this nature would be able to compare similar practices across organizations in order to benchmark maturity within disparate industries. A comparative model would recognize that similar levels of maturity across industries may not translate to similar levels of business value.*" For example, Göpalk and Martinez (2021) developed a digital transformation MM, which compared the organizational processes capabilities for digital transformation from two organizations, along with chemical and machine manufacturing domains.

In the second development phase, MM building (see Figure 3.3, Section 3.4.3.2), the elements related to design, assessment tool, tests, validation, and implementation are conceived.

*Element 7: MM design actions/tasks.* This concerns the conception/formalization of all MM elements, e.g., the conception of the category list elements, assigning the maturity levels, and populating the remaining elements previously defined in the meta-model. In this element, the elements category is refined, tested, and inserted as attributes/constructs for a scoring schema in an assessment tool. A measurement tool is highly recommended to evaluate the maturity of the domain; however, a MM can be merely descriptive of the domain without a numerical evaluation tool (NORMANN ANDERSEN et al., 2020). A detailed description of the category list elements and maturity levels is mandatory (descriptive model feature).

*Recommendations:* MM design actions comprise carrying out the iterative research process shown in Figure 3.2 for: all the category list elements' layers (typically one to three); maturity levels (typically three to nine); scoring schema and assessment tool; and maturity roadmap; and implementation of the MM in real cases in the OSCM domain. In summary, Element 7 recommends: designing, populating, and describing the category list elements; designing, populating, and describing the maturity levels; testing the validity and reliability of the model/assessment tool (elements/maturity level/scoring schema); a preliminary proposal for the scoring schema (based on validated elements design); applying a development framework; and applying a design/research protocol (e.g. (SALAH; PAIGE; CAIRNS, 2014)).

*Element 8: Assessment tool building, validation, and implementation.* Mettler (2010) stated that a MM is simultaneously a model and a method. Often, a measurement scale is embedded in maturity evaluation tools, which measures the global maturity of attributes or constructs from a scoring schema. Often, a scoring schema comprises a rating scale based on psychometric scales (e.g., Likert, Guttman, binary). Recently, MMs have used fuzzified rating scales (e.g. (CAIADO et al., 2021; CORRÊA et al., 2014)). Another emerging rating scale approach is based on multicriteria methods, such as AHP and PROMETHEE (RAMOS et al., 2020; WAGIRE et al., 2021).

*Recommendations:* the elements modeled in a MM are constructs or attributes to be measured using a scoring schema that captures the maturity level variation in the domain (degree of adoption, mastering, progress). Therefore, an assessment tool comprises the constructs to be measured, the correspondent maturity indexes or rating scale, rules, and associated maturity levels. Testing and validation of the assessment tool aim to ensure its reliability and validity in measuring the maturity from a representative case in the domain evaluated. After being tested and validated, an assessment tool is implemented as a maturity assessment method. For this purpose, survey research and case studies are common methods by which researchers/practitioners measure the maturity level. The output of assessment tool implementation is a global maturity score and its meanings, which deserves an investigation of the "*whys*" and possible recommendations through an improvement actions roadmap.

In the third phase, MM use, the elements related to the follow-up, updating, selection criteria, and database for knowledge management of the MM built are considered. This phase is neglected in most development frameworks analyzed but constitutes an essential period of the artifact lifecycle, mainly from the user's application perspective. For example, manuals/instructions, understandability, ease of use, usefulness, and practicality constitute key indicators for this follow-up phase.

*Element 9: Follow-up of usability and acceptance of the MM by the users.* MMs in the OSCM domain can be considered "alive" artifacts that must adapt to and follow up regarding environmental changes in companies with complex production systems, characterized by technology, people, organizational culture and transformational processes, and value-creation. This follow-up must measure the acceptance and the MM's performance. Data collection and monitoring of practitioners'/users' experience, knowledge management practices, and a database are important initiatives in a MM's follow-up phase. These practices ground new versions of MMs (improvements).

*Recommendations:* a periodical evaluation of the MM's usability and acceptance by the OSCM community; direct linking with users/practitioners based on a collaborative channel for future updated MM versions; performance measurement and criteria of the MM's usability evaluation (user perspective) [for this, the rating and choosing criteria of van Looy (2013; 2017) can be applied]; clear and easy-to-use documentation/manuals for the MM; establishing a database for the MM reporting use cases, PoC, problems, users' suggestions for improvement, updates, the profile of adopting users, practitioners' perceptions, and performance evaluation metrics; and adopting knowledge management practices to improve the MM design, usability, practicality, and learning.

### *3.4.3.2 Seven iterative procedures for the development of a maturity model's (MM's) elements (how to design a MM)*

Iterative research cycles are one of the pillars of DSR guidelines for artifacts design according to the specialized literature on this subject, such as Hevner et al. (2004), Peffers et al. (2007), Becker et al. (2009), and Baskerville et al. (2018), as well as in recent applied research, such as Caiado et al. Therefore, our framework offers an iterative research cycle approach that supports designers regarding how to operationalize MM building (elements conception). In our proposal, a complete research iteration (cycle) comprises seven procedures (Figure 3.3), as described below.

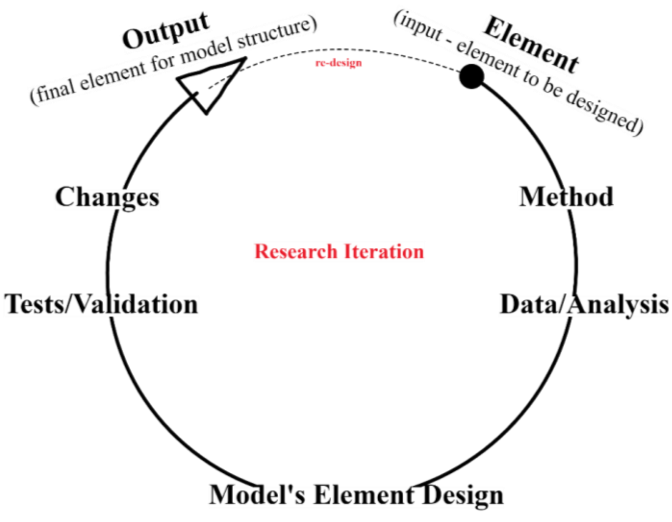



**Figure 3.3.** Iterative research procedures in the framework ("*how to design*" a maturity model)

*Procedure 1: Define an element and carry out an iterative design/research cycle.* A cycle comprises the procedures to develop each MM element within a specific phase during MM building. For example, during meta-model conception (element), designers should use the seven procedures proposed to search, analyze, design, and validate it. Core elements used to develop a MM are presented in Figure 3.2. Each element is an input to an iterative research cycle, and the output is a validated element to put in the MM.

*Procedure 2: Define methods used in the research iterations*. Methods can vary according to the element designed in each development phase. Our framework comprises three development phases: MM requirements; MM design; and MM use/follow-up. During the phase of MM requirements' definition, methods such as SLR/literature survey, scoping review, and qualitative methods are most common (see Table 3.4). They can be used to define and size the model's elements (e.g., five or nine levels; main smart technologies; with or without zero level). Qualitative methods, grounded theory, and case studies are most used during the MM design phase. The most common methods for the measurement tool building are survey research, item sorting methods (e.g., Q-sort), multicriteria modeling (AHP, PROMETHEE), and case studies.

Finally, there is incipient research in OSCM regarding the main methods and tasks of MM use/follow-up phase. For this purpose, we recommend that designers and practitioners in OSCM verify and/or adapt the 14 decision criteria (assessment criteria, improvements criteria, non-design criteria) and trade-offs presented by van Looy et al. (2013; 2017). Grounded theory and DSR are the main methodological approaches employed.

*Procedure 3: Establish adherent data-collection and -analysis procedures (knowledge base).* A well-structured research and design process must be transparent and reproducible in data collection. In Phase 1 of MM development (Figure 3.3), secondary data (journal articles, reports, with papers) are often the main sources used in data collection (see Table 3.4). In the grounded-theory approach, data collection based on primary data obtained via qualitative methods is used from the start of the design (RAMOS et al., 2020). In the DSR approach, a secondary data source is commonly used in the initial literature search and problem-solving searching processes (e.g., existing MM comparison). In Phase 2, the primary data source is commonly explored; the main methods used are qualitative methods (e.g., focus groups, Delphi surveys, expert interviews, workshops/meetings with practitioners). These methods use data collection based on interviews, questionnaires, forms, and field/direct observation. In Phase 3, the common methods employed are questionnaires and modeling tools (e.g., for survey research and multicriteria modeling and elicitation), in-depth interviews (case study), documents, and direct/field observation. Finally, a transparent protocol for design research is recommended during MM development. This helps designers establish, document, monitor, and reproduce their research strategy and actions. For this purpose, the MM evaluation template proposed by Salah et al. (2014) can be adapted as a protocol. Content analysis is the main technique applied to literature and qualitative data. Also, statistical and multicriteria analyses are used during this procedure. Establishing a knowledge base that grounds the MM design is the aim of this procedure (HEVNER et al., 2004); therefore, applicable methodology and problem/artifact foundations need to be very clear to the designer at the end of Procedure 3.

*Procedure 4: Design of model elements.* All the iterative research elements in Figure 3.2 represent the design/conception of each MM element. Hence, the design procedure formalizes the model's specific elements. For example, populating/creating the maturity matrix of a model is the formalization of the maturity matrix design. MM design is based on previous research procedures, such as element definition, methods chosen, data collection and analysis, and designer creativity and knowledge. Therefore, the elements design tasks help designers to formalize the MM's design research.

*Procedure 5: Tests/validation.* MMs are artifacts that must be designed for problem-solving. Therefore, the artifact needs to be tested and validated regarding its design purpose. We propose using the test of a MM based on research iterations (within specific elements' conception). Our approach avoids wasting time and resources when the validation fails at the end of linear and sequential MM development. The use of linear development processes is common for many MMs, where an overall test and validation are made at the end of the design or during the MM's practical evaluation. Possible indications for the refinement and re-design of the model from tests/validation procedures are costly given the time, resources, and efforts needed until the MM's development stage. Based on Becker et al. (2009), our framework proposes testing procedures within each element's design task (using a cyclic/research iteration approach), i.e., based on each of the designed elements via tests within the performed cycle (to each element). Our approach accelerates model development (agility), minimizes errors, and saves time and resources by creating a learning base for MM design. Therefore, this approach minimizes large-scale re-working, thus minimizing re-design efforts.

*Procedure 6: Make changes based on the research iteration's purpose, testing, and learning.* Tests and validation procedures often bring new contributions to MM design, which implies changes regarding the refinement of the model's elements. Besides test-based changes, changes in the attributes of the elements of a MM synthesize all of the design learning from the previous procedures.

*Procedure 7: Verify the output.* The output of an iterative research cycle is a validated MM element. After this, the element is added to the MM's structure, and so on, until all desired elements for the model are completed. When test outcomes trigger changes, a novel round for the current research iteration is needed to re-design the new element requirements (dotted line in Figure 3.3).

The iterative research cycles approach aligns the seven procedures before artifact validation, saving efforts via a focused development element. Errors, usability, methodology/method, and adherence to the proposal to solve the problem can be corrected in specific steps during MM development (research iteration). Research cycles provide agile development and ensure reliability in the model research (design research) and the building of artifacts (design science).

### 3.5. Framework as a proof of concept (PoC) example (Step 5)

According to Elliot (2021), a PoC demonstration serves as a prototype theory or model, conceptualized as abstract artifacts. We employ a PoC for the framework demonstration as a research technique (KENDIG, 2016). For this reason, in this section, we present our framework by applying it as an example of MM building, namely the smart shop floor control MM ($S^2$FC MM). The $S^2$FC MM is a MM developed as part of a Ph.D. Dissertation to assist manufacturing and supply chain companies in their I4.0 maturity progress. The $S^2$FC MM entails completing six research iterations based on our framework's procedures and processes (Figures 3.2 and 3.3). To build this model, we followed the three phases shown in Figure 3.2 and applied the seven procedures in Figure 3.3 according to each phase.

***Phase 1: MM requirements.*** The first task was an in-depth investigation of the problem of maturity progress for the shop floor control and planning function in the I4.0 era. Subsequently, 20 MMs were compared, followed by five I4.0 technologies that were considered critical for shop floor control maturity progress. A meta-model was defined to ground and guide the design efforts. The meta-model embeds five maturity levels and a category list of third levels that contain five focus areas, 20 key factors, and a maturity matrix with associated action/indicators. Finally, a smart shop floor control architecture was conceived as a reference to model constructs and categories. The seven research iterations procedures in Figure 3.3 were applied to each of the elements built in this phase. To show the building of an element from the framework proposed, we present in Table 3.7 the meta-model building for the S²FC MM example.

**Table 3.7.** Meta-model's research iteration: S²FC MM

| Procedures | Operationalization Tasks |
|---|---|
| **— Input (Element to be designed)** | **Meta-model (scope of the model):** Model requirements, Research Design, and preliminary elements |
| **— Method** | **1.** Systematic Literature Review and snowballing forward and backward<br>**2.** Scoping Review |
| **— Data/Analysis** | **1.** Time frame: until July 2020<br>**2.** Database: *i).* previous SLR (102 articles) (Bueno et al. (BUENO; GODINHO FILHO; FRANK, 2020)), *ii)* 18 additional articles searched by snowballing forward and backward (2021 year); *iii)* 20 maturity models analyzed from Scoping Review<br>**3.** Analysis: Content Analysis |
| **— Model element** | **1.** Preliminary Category Elements and their relationships<br>**2.** Preliminary Maturity Levels<br>**3.** Final Research Design<br>**4.** Choose of Development Framework to follow and model type<br>**5.** Implementation and institutionalization issues |
| **—Tests/Validation** | Four Meetings with experts and one Focus Group with SFC MM's research team |
| **— Changes** | — |
| **— Outputs (Element validated)** | S²FC MM meta-model contains:<br>**1.** Identification of key elements for the design:<br>- relationships between the main elements<br>- five maturity levels,<br>- five key technologies of I4.0<br>- reference architecture<br>- five focus-areas<br>- 20 key-factors<br>- maturity matrix: smart indicators/capabilities (n=110)<br>**2.** Research Method definition: Design Science Research methodology<br>**3.** Model Type: Prescriptive (P)<br>**4.** Development of Framework<br>**6.** Implementation and institutionalization issues: centered on PPC managers' roles and responsibilities |

***Phase 2: MM design***. In this phase, we used the design research background of the previous phase to populate, organize, and formalize the S²FC MM presented in the first proposal. Therefore, the S²FC MM contains five maturity levels: computerized; digitalized; integrated; autonomous; and smart. The S²FC MM contains six focus areas for maturity progress linked to 18 key factors to be measured. Actions/indicators of maturity are linked to these factors. After this, a fuzzified measure scale containing items, scores, and rules was developed. Iterative refinement cycles were performed for the S²FC MM proposal and evaluation tool. Salah et al.'s (2014) guidelines were adapted as a protocol for the research and design of the model.

***Phase 3: MM use/follow-up.*** In this phase, Van Looy et al.'s (2017) criteria for MM evaluation were used for periodical evaluation regarding the usability and acceptance of the model. Also, a model database and a list of improvements should constitute mechanisms for upgrading the new versions.

### 3.6. Discussion and conclusion

This article's aims were twofold. The first aim was to create a framework that addresses the "*what*" and "*how*" in developing MMs based on DSR research iterations. The article provides the OSCM community with a standard MM development framework based on comprehensive multimethod research. Our framework guides the development process toward a well-designed, reliable, and reproducible artifact. Second, through this framework, we aim to contribute to other MM researchers and practitioners in OSCM to ground their models in the I4.0 domain.

#### 3.6.1 Research implications

By performing an in-depth analysis of the components of existing development frameworks, we contribute to research on OM/SCM by proposing, building, validating, and applying a novel and common framework that synthesizes existing ones and adds details to the operationalization of MM building. We explore a variety of factors that influence MM development (architectures, current frameworks, and a list of recent MMs) to demonstrate the strengths and drawbacks of existing frameworks (shortcomings and main guidelines adopted). Using this mapping, we present the response to the first half of our research question (*Q1*), providing a DSR-based MM development framework as an artifact. For this, we use a set of criteria to design, validate, and use this framework (responding to the second half of *Q1*).

Our findings highlight challenges in MM development techniques that designers and academics should consider while designing or investigating MMs. Our concept treats the construction of each MM element as an iterative research process, as recommended by DSR studies. This procedure is carried out using seven procedures from a cycle that includes, for example, design, tests/validation, and learning about the model element design. Furthermore, we combine three main phases for MM development, each one having specific elements that need to be built. Our framework also provides development recommendations to guide designers in creating their MMs.

### 3.6.2 Practical implications

MM construction tools should assist designers in developing their models in an agile manner, with minimum errors (due to test redundancy) and traceable and transparent steps. Our framework adds a second tier of procedures and details to current frameworks, upgrading them (for example, by adding the user viewpoint approach) and standardizing widely used recommendations into a single artifact. The results also confirm that managerial artifacts building needs quick follow-up in research and design, encompassing environmental changes based on technology, people, organizational culture, and value-creation processes, along with the OSCM domain. Aligned to this, we assigned the I4.0 footprint to the framework, intending to clarify the current smart technologies impacting the OSCM domain. We further emphasize that the DSR method enables creating artifacts based on MM in technologically new surroundings.

In conclusion, our article brings a comprehensive understanding of normative development frameworks, which support MM development in the OSCM field, thereby supplementing current MM-building literature. As a result, we provide evidence concerning "*what to design*" and "*how to design*" in the context of MM artifacts based on the DSR approach.

# 4 A MATURITY MODEL FOR SMART SHOP FLOOR CONTROL

**Abstract:** Maturity Models are artifacts that support managers in conducting and measuring the smart capabilities progression within manufacturing companies towards to highest levels of Industry 4.0. Smart Shop Floor Control aims to harness smart capabilities from Industry 4.0 technologies for maximizing manufacturing value-creation and performance. However, there is a lack of Maturity Models to support the Smart Shop Floor Control progression. Therefore, our study addresses how to design, test, and implement a Smart Shoop Floor Control Maturity Model ($S^2$FC MM) in manufacturing companies. For this, we used the Design Science Research approach comprising a reproducible and rigorous design process based on mix-methods: literature survey, qualitative methods, fuzzy inference system modeling, and a case study into a multinational steel manufacturing company. Findings show that $S^2$FC MM provides a useful diagnostic tool based on focus-area, key factors, and capabilities. Furthermore, $S^2$FC MM supports the progression of the Shop Floor Control function by describing and measuring the maturity (as-is), prescribing an action roadmap (to-be) undertaken to reach the highest maturity levels.

**Keywords**: Industry 4.0, Smart Factory, fuzzy rule-based tool, DSR, Smart Manufacturing, Maturity Model

## 4.1. Introduction

Industry 4.0 (I4.0) has profoundly impacted the manufacturing business and research world in recent years (DUMAN; AKDEMIR, 2021; REINHARD; JESPER; STEFAN, 2016). Over a short period, companies have conceptualized and performed I4.0 initiatives that have significantly affected the manufacturing industry's performance and operations (CIANO et al., 2021; HERNÁNDEZ et al., 2020; REHSE; DADASHNIA; FETTKE, 2018). Manufacturing companies are structurally trying to improve their competitive position through smart/digital practices mastering, and capabilities development based on I4.0 technologies.

So, Shop Floor Control function is highly impacted by I4.0's changes because it performs both, transformational activities and new digital business processes. Aligned to this, companies endeavoring I4.0 from the Shop Floor Control function need managerial tools to support managers' efforts towards operational, organizational, value-creation, and performance improvements (PRATHIMA; SUDHA; SURESH, 2020; TAO; ZHANG, 2017). Thus, how should managers conduct these performance gains on the Shop Floor Control function? One of the pathways to reach this purpose is to follow progress improvement strategies based on Maturity Models applications (MM).

MM has the purpose of description, measurement, and improvements into a domain (METTLER; BALLESTER, 2021). Therefore, managers and professionals applying MM can model and measure the I4.0 implementation levels e taking action toward improvements in performance, new digital business propositions, and digital value-creation (NAYERNIA; BAHEMIA; PAPAGIANNIDIS, 2021; PACCHINI et al., 2019). Therefore, in our vision, in I4.0's journey, a MM may constitute a practical tool that supports maturity capabilities for companies to reach a smart status on Shop Floor Control.

Within this context, the present research aims to design, test and apply a Maturity Model for Shop Floor Control Function in companies dealing with I4.0 environments. So, our study presents a focus-area, prescriptive, and fuzzy rule-based Smart Shop Floor Control Maturity Model proposal ($S^2$FC MM) based on the Design Science Research Methodology approach.

Our study presents a Shop Floor Control Maturity Model that enables manufacturing companies to assess their progress towards the highest I4.0 levels (smart status), and achieve performance, people, and value-creation benefits. Prior MM and applied studies have strongly focused on technological issues of I4.0 maturity within the OSCM. However, little attention has been given to planning and control issues linked to the Smart Shop Floor Control's Function. In addition, MM in OSCM/PPC literature often presents some significant shortcomings, which we address in our proposed MM:

***(i).* from a design and solving-problem perspective**, most of the existing Maturity Models in the OSCM/PPC fields into I4.0 subject do not address focused and granular SFC's category elements oriented to a socio-technical approach encompassing technology, people, and value-creation process. Even though the subject area of Shop Floor Control and I4.0 is rapidly maturing, many manufacturing enterprises are still endeavouring to transition and mastering of innovation practices and smart capabilities within Smart Factories. There is little knowledge concerning the effective implementation of key factors and capabilities to sustain the smart SFC's evolutional paths. Therefore, well-designed MM are critical tools to support shop floor managers and professionals in the I4.0 journey.

***(ii).* from a practical perspective**, we observe a lack of a realistic, useful, and rigorously designed Maturity Model containing focus areas, implementation key factors, and actions/capabilities to improve manufacturing companies' shop floor status based on I4.0 environments. In this sense, Design Science Research methodology has been emerging in Maturity Models in OSCM/PPC field (ASDECKER; FELCH, 2018; CAIADO et al., 2021; COMUZZI; PATEL, 2016; GUSTAFSSON; JONSSON; HOLMSTRÖM, 2019; WILLNER; GOSLING; SCHÖNSLEBEN, 2016) as an adherent approach that bonds the rigor, problem-solving, and design-validation aspects. We intend to solve this methodological gap for SFC MM using an innovative procedure based on transparent and cyclic design research iterations (BASKERVILLE et al., 2018; HEVNER; CHATTERJEE, 2010).

***(iii).* from a methodological perspective**, it lacks to extend the innovative assessment tools by applying in MM, aiming to capture imprecision and uncertainty from maturity process data-collection. So, MM lacks in OSCM/PPC field constitute innovative assessment tools to measure the maturity level within I4.0 environments considering imprecision and uncertainty inherent to the data-collection process. Measure instruments in MM are based on natural language quantifiers that involve uncertainty from incomplete, inconsistent, or even missing data. In this sense, to overcome the challenge of designing a realistic MM to deal with imprecision and uncertainty, the main requirement is to implement Zadeh's (1965) classical fuzzy theory. So, we propose an innovative fuzzified approach for the MM's evaluation tool, focusing on providing a fuzzified evaluation tool and structured roadmap to support manufacturing companies and practitioners on digital/smart transformation requisites towards high maturity levels in the Shop Floor Control Function. Fuzzy Expert Systems have been applied in maturity models' measure instruments in the last years (CAIADO et al., 2021; CORRÊA et al., 2014; SOARES et al., 2021), aiming to improve the accuracy and precision of maturity evaluation.

Our article is structured as follows. Section 4.2 describes the research methodology. Section 4.3 describes $S^2$FC MM: elements, assessment tool, and relationships. Section 4.4 shows $S^2$FC MM implementation in a steel manufacturing company. Section 4. 5 presents the article's conclusions.

## 4.2. Research methodology

To research and design the smart Shop Floor Maturity Model ($S^2$FC MM), we apply a transparent procedure based on two building blocks presented in Chapter 3: *(i).* procedures to research and design the model's elements ("*how to design*"), and *(ii).* elements' design of MM ("*what to design*"). These procedures and elements are shown in Figure 4.1 and detailed in the Appendix A. They were synthesized from the main existing DSR frameworks (MAIER; MOULTRIE; CLARKSON, 2012; METTLER, 2010; RÖGLINGER; PÖPPELBUSS; BECKER, 2012; ROSEMANN; DE BRUIN, 2005), architectures and reference models in the subject, and MM literature addressing I4.0. Therefore, we build the $S^2$FC MM from DSR's methodology use.

The design of the $S^2$FC MM followed five steps comprised of iterative research and building processes (research iterations, RI #). Our research address mix-methods for the $S^2$FC MM building (CRESWELL; CLARK, 2018; SAUNDERS; LEWIS; THORNHILL, 2019), employing literature survey methods in step 1 (SLR and scoping review), qualitative methods in steps 2, 3, and 4 (focus groups, expert interviews, direct observation, workshops and meeting with practitioners), expert system modeling in step 4, and case study in step 5. See the protocols to conduct the qualitative methods in Tables C1, C2, and C3 in Appendix C. In Figure 4.1, it is possible to check each of the five steps performed regarding *(i).* research methods used in each step (left); *(ii).* model component/element designed and tested in each step (center in yellow); *(iii).* the outputs of each step (right).

**Step 1 – meta-model creation:** this step addressed the research background for $S^2$FC MM, meta-model creating, and methodology approach. For this, we used the methods listed in Figure 4.1. For the research background of $S^2$FC MM, we use *(i).* our previous SLR (BUENO; GODINHO FILHO; FRANK, 2020) encompassing 102 articles (2010-2019), and *(ii).* a snowballing forward and backward procedure, gathering 18 additional articles (2020-2021). We adapt Jansen et al.'s (2020) meta-model to define the core components that must be designed in $S^2$FC MM. Then, for meta-model components (preliminary category list), we surveyed 20 existing Maturity Models into OSCM and I4.0 field; we also used eight MM development frameworks, and five I4.0 adoption architectures. The meta-model design is shown in section 4.3.1. For details of tasks and procedures performed during Step 1, see Table A1 in Appendix A.

**Step 2 – category list design and testing:** in this step, we used qualitative methods (see Figure 4.1 and Table A2 in Appendix A) to refine and test the initial category list developed. For design and testing tasks during step 2, we adopted a triangulation strategy from data sources and methods such as focus groups and expert interviews (see Tables B1 and B2, in Appendix B). Therefore, we realize a cycle of design, refinement, testing, and validation for category list elements, according to Caiado et al. (2021) and DSR guidelines (BECKER; KNACKSTEDT; PÖPPELBUSS, 2009). From this, we aim to ensure the validity and reliability of model elements and measurement items (BECHARA; VAN DE VEN, 2011; CRESWELL; POTH, 2018; LEWIS, 1998). Step 2's outputs are described in section 4.3.2.

**Step 3 – maturity matrix development:** in this step, were used the outputs of steps 1 and 2 to survey a list of smart capabilities that cover each maturity key factor. Besides, aiming for refinement, testing, and validation of the maturity matrix, we performed one focus group, direct observation and workshops in a manufacturing company. Step 3's outputs are described in section 4.3.3. For details of tasks and procedures performed during Step 3, see Table A3 in Appendix A.

**Step 4 – fuzzy rule-based maturity evaluation tool building:** in this step, we used the key factors designed and tested in previous iterations and fuzzy expert systems modeling to build the measurement scale for $S^2$FC MM's evaluation tool. Therefore, we employ the fuzzy set theory approach (ZADEH, 1965) to model a Fuzzy Expert System, which was embedded into the evaluation tool (see Figures 4.4 and 4.5). The Fuzzy Expert System was designed and validated based on the participation of shop floor managers/practitioners. Lastly, we test the evaluation tool from a pilot test encompassing three manufacturing companies: a biorefinery, a food industry, and a seeds processing industry. We use an online self-assessment questionnaire based on SurveyMonkey for respondents' data collection (inputs for the fuzzy inference system of Figure 4.5). This questionnaire was based on key factors list. We operationalized the evaluation tool on MATLAB software. Step 4's outputs are described in section 4.3.4. For details of tasks and procedures performed during Step 4, see Table A4 in Appendix A.

**Step 5 – implementation and usability of the model proposal (the final version of the model):** in this step, we apply $S^2$FC MM to evaluate the Shop Floor Control function's maturity in a real case (see Figure 4.1 and Table A5 in Appendix A). For this, we selected a large Brazilian steel manufacturing company that conducts I4.0 projects on shop floor control function, i.e., a representative case, according to Yin's (2018) guidelines for case studies. The outputs of step 5 are presented in section 4.4. These outputs assure a final version of S²FC MM. It is reached from the model's successful implementation, overall validation, and usability/practicability as a MM artifact.

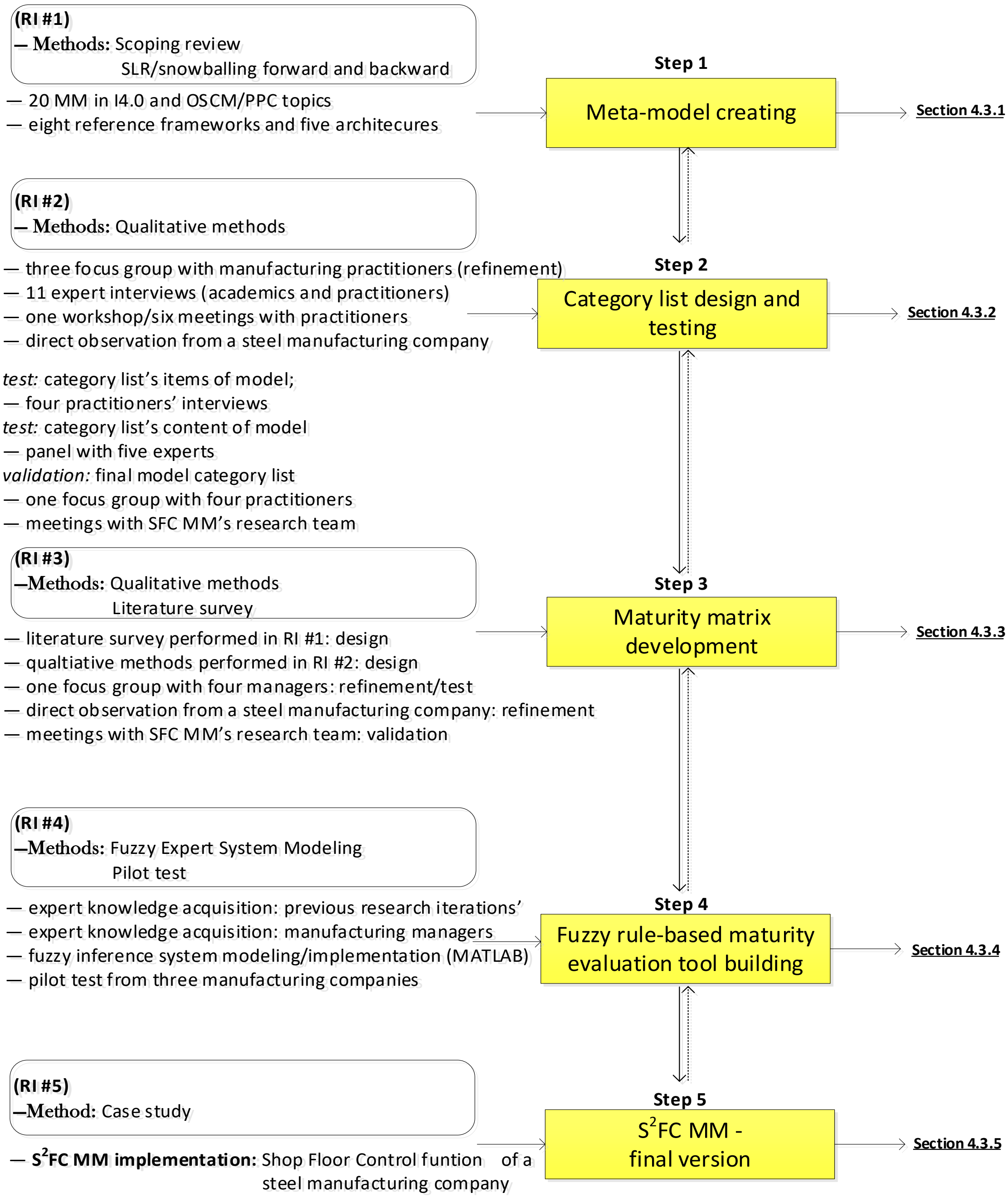



**Figure 4.1**. S²FC MM development

### 4.3. Smart Shop Floor Control Maturity Model – S²FC MM

We adopt Lacerda and von Wangenheim's (2018) definition of maturity as the extent (stage) to which an organizational function or company consistently implements resources and technologies, processes and practices, capabilities and indicators within a defined domain. A domain or entity's superior status of attributes (characteristics, capabilities, indicators, or patterns) contributes to achieving established goals (e.g., a smart Shop Floor Control). As a result, MM is a practical problem-solving tool guided by evolutionary stages that define measurable progress transitions (CARALLI; KNIGHT; MONTGOMERY, 2012; RÖGLINGER; PÖPPELBUSS; BECKER, 2012).

The smart Shop Floor Control concept is an advanced way for manufacturing execution, monitoring, planning and control of activities at the bottom of the PPC function (BUENO et al., 2022; BUENO; GODINHO FILHO; FRANK, 2020; OLUYISOLA et al., 2021; TAO; ZHANG, 2017; ZHUANG; LIU; XIONG, 2018). Therefore, a smart SFC comprises: *(i).* the full implementation of smart technologies/ecosystems of I4.0 (ZHUANG; LIU; XIONG, 2018), (*ii).* mastering resources and smart capabilities provided by these technologies, (*iii).* people skills, and organizational issues linked to digital culture, data-driven decisions, change management for digitalization, fit of manufacturing legacy system to the smart concept, and digital value-creation (GHOBAKHLOO; IRANMANESH, 2021; SCHMITZ; HAGEMANN, 2020; SCHUH et al., 2017), *(iv)*. the convergence of cyber and physical spaces of Shop Floor Control (TAO; ZHANG, 2017; ZHUANG; LIU; XIONG, 2018).

Therefore, the Shop Floor Control function smart status represents in our study the highest manufacturing system's ability or power to value-add by establishing operations, planning and control, practices, and capabilities based on I4.0. Our definition of capability is based on van Steenbergen et al. (2013), who state that capability is the ability to achieve a certain goal using the available resources.

I4.0 comprises a comprehensive source of technologies, resources, and innovativeness approaches for Shop Floor Control operations, planning and control, and performance. Our $S^2FC$ MM offers manufacturing managers, practitioners, and companies the progress supporting for SFC function towards I4.0. For example, by harnessing the benefits of I4.0's resource implementation as sensors, shop floor managers reach digital data-collection and data-driven decisions. However, to develop sensing infrastructure and related capabilities, a transformational process is required to guide the digitalization of machines, networking infrastructure, real-time machine monitoring, and vertical and horizontal integration of systems (e.g., ERP and MES). Therefore, we propose an $S^2FC$ MM to model, measure, and support the development of the shop floor's actions, focus-areas, key factors, and capabilities.

To follow, we present the output (element) for each research step/iteration of the $S^2FC$ MM design.

### 4.3.1 Research, design choices, and meta-model (step 1)

In this step, we realize the research tasks and design choices that orient the $S^2FC$ MM's building. The tasks performed were: the research for the problem-solving, comparison of existing maturity models, mapping of I4.0 technologies in the Shop Floor Control domain, meta-model definition conjointly to design a preliminary list of maturity model items, and the methodology choices (DSR approach). Outputs of research step 1 were:

*(i). the motivators, gaps and objectives, and research background:* they were described in section 4.1, Introduction;

*(ii). meta-model (Figure 4.2):* it is a framework that acts as a guide for identifying the core components that will orient the MM design. Our meta-model components comprise a preliminary categories list based on focus-areas containing key implementation factors that should contain a set of smart capabilities.

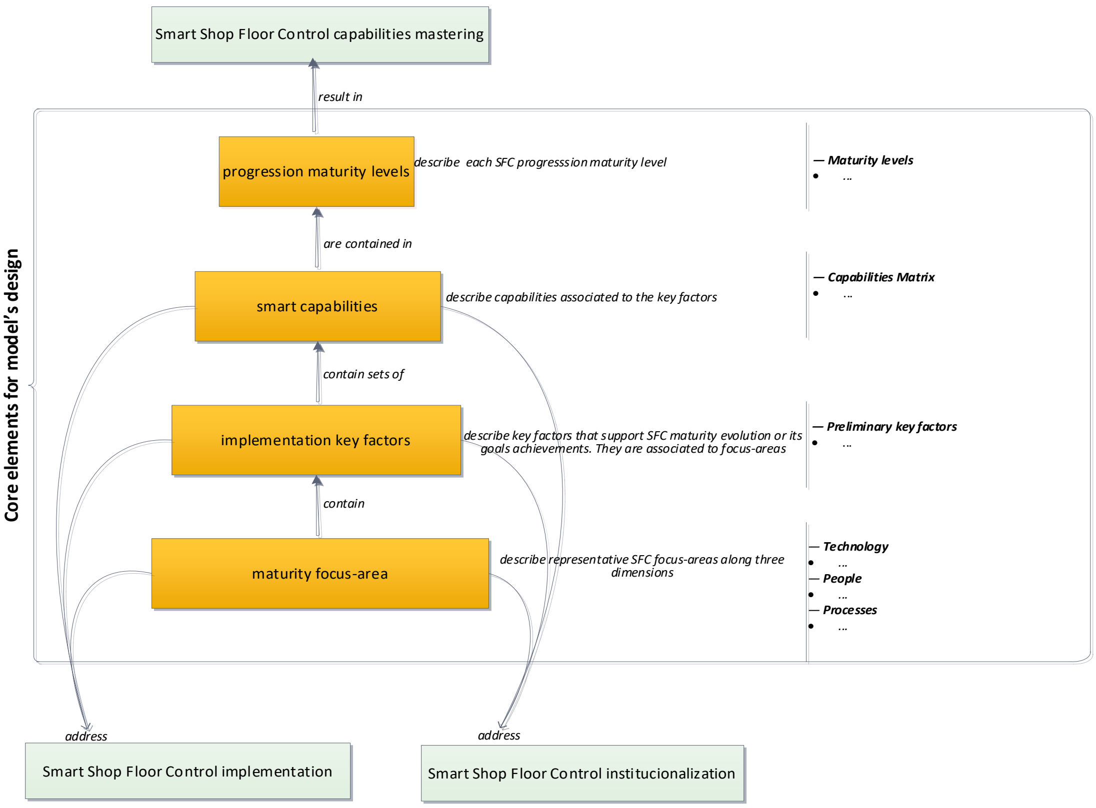



**Figure 4.2.** A meta-model for $S^2FC$ MM

### 4.3.2 $S^2$FC MM design (step 2)

$S^2$FC MM is a granular, focus-area, and prescriptive model. $S^2$FC MM aims to support planning and control managers, manufacturing practitioners, and companies to deploy smart features in the Shop Floor Control function. For this purpose, the $S^2$FC MM was designed per the following elements: five focus-areas, twenty key factors, five maturity levels, a capability matrix containing 98 capabilities, and a fuzzy rule-based maturity evaluation tool.

$S^2$FC MM is shown in Figure 4.3, and its elements/components are described in the following.

***(i). focused-areas:*** the five focus areas of $S^2$FC MM are shown in Figure 4.3 (for a detailed description, see Table D1, Appendix D). A focus area is a well-defined partition of a domain, i.e., the union of all focus-areas represents the complete functional domain (VAN STEENBERGEN et al., 2013). Our maturity model proposal is based on focus-areas that address key maturity factors and capabilities. A set of focus-areas works as a compass for shop floor managers' actions. Five focus-areas were designed from step 2 methods (see Figure 4.3): 1. Sensing and Networking (SN), 2. Data and Analytics (DA), 3. Skills and Culture (SC), 4. Systems and Strategy (SS) and, 5. Digital Value-Creation (VC). Each focus-area constitutes a specific maturity characteristic set. Our approach enables maturity model users to prioritize an area, focusing efforts and improvements according to the company's reality.

From step 2 findings, we group the focus-areas into three main dimensions: technology, people, and value-creation processes.

– *technology:* two focus areas are oriented by technology implementation and smart infrastructure: Sensing and Networking (SN) and Data and Analytics (DA). SN comprises key factors and capabilities related to smart infrastructure and digital resources on the shop floor. At the same time, DA includes a platform to support shop floor data management and data-value extraction (data transmission/extraction, processing, analytics, optimization).

– *people:* Skills and Culture (SC) area covers the people dimension for SFC function into I4.0. It deals, for example, with skills development for jobs and operations in I4.0 environments; it also deals with a cultural transformation by people toward a digital and data-driven Shop Floor Control's function.

– *processes*: Systems and Strategy (SS) and Digital Value-Creation (VC) areas address the organizational transformation (tangible and intangible assets) and digital operations/processes to support SFC's activities at the value-creation. Thus, SS comprises organizational development towards smart environments based on adjusting manufacturing systems, assets, methods, and I4.0 strategy deployment. VC area is centered on smart Shop Floor Control activities, e.g., smart production scheduling. It also supports value-creation proposals by new digital business and process propositions.

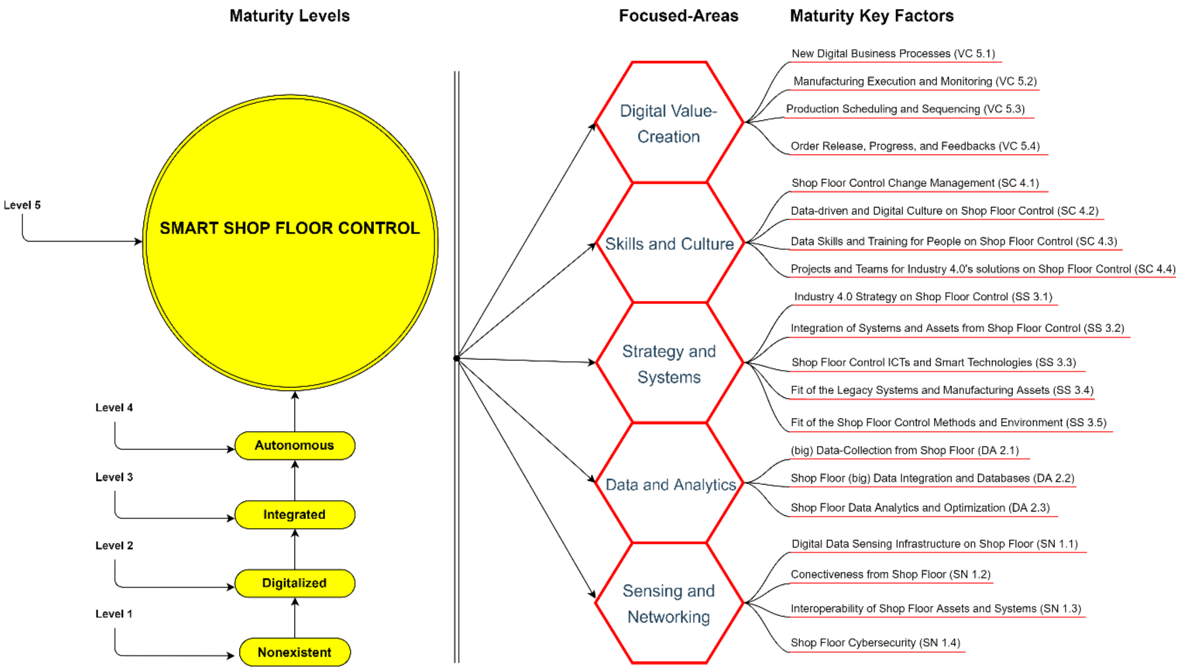



**Figure 4.3.** $S^2$FC Maturity Model

***(ii). maturity key factors:*** twenty maturity key factors are distributed along with five focus-areas of $S^2$FC MM (Figure 4.3). These factors are detailed in Tables D2 to D6 (Appendix D). A maturity key factor is an indicator assessed regarding the implementation degree into a focus-area. Therefore, key factors constitute maturity measure items of the evaluation tool. Based on research iterations and design tasks, each focus area was assigned to a mutually exclusive and collectively exhaustive (MECE) number of factors, resulting in a final set of twenty validated factors.

***(iii). maturity levels:*** they represent the progressive stages of the Shop Floor Control function towards the I4.0-concept. Maturity levels also represent the implementation magnitude of key factors (varying from 0-100 in our proposal), and the model's capabilities. It is possible to develop and address maturity improvement actions from maturity level evaluation (improvements roadmap).

Figure 4.3 shows the maturity levels of S²FC MM: Level I – Nonexistent, Level II Digitalization, Level III – Integration, Level IV – Automation, Level V – Smart. A life-cycle or progression perspective orients our model with the final maturity stage well-defined, i.e., the smart level (CARALLI; KNIGHT; MONTGOMERY, 2012; WENDLER, 2012). S²FC MM's maturity levels were inspired by the I4.0 Maturity Index by Schuh et al. (2017) conjointly with insights from our previous study about smart PPC (BUENO; GODINHO FILHO; FRANK, 2020). To follow, we describe the five S²FC MM's maturity levels:

**Level I – Nonexistent:** this level comprises ad hoc initiatives of I4.0, is characterized by analogic systems and devices, low computerization and unstructured digitalization, lack of comprehensive I4.0 planning and strategy, lack of people and company's understanding of basic notions of I4.0 and digital transformation. In summary, at this level, the Shop Floor Control function has a very low implementation of all key factors and, therefore, a very low presence of smart characteristics/capabilities of I4.0. Companies at this level must pivot towards I4.0 by adopting manufacturing computerization and digitalization base requirements. This level comprises outputs rated between 0 and 20 on the maturity measure scale.

**Level II – Digitalization**: this level comprises the base requirements for digital transformation encompassing manufacturing technologies, processes (operational and managerial), culture and people in the Shop Floor Control function. This level requires a digital infrastructure development that supports manufacturing operations and its management (manufacturing execution, production scheduling, order management, digital business processes). Digitalization level is featured by digital data-collection and transmission, real-time sensing, networking and connectiveness of manufacturing physical assets, implementation of digital systems (ICT, automation), I4.0 strategy and projects deployment, I4.0 base-technologies deployment (e.g., IoT, cloud, data management and analytics), people's training to work on digital environments, change management program implementation, new digital business processes mapping/development.

In summary, at this level, the Shop Floor Control function implements digitalization-related key factors; however, it has not fully developed the characteristics/capabilities of I4.0 linked to the integration level. Level II comprises outputs rated between 20 and 40 on the maturity measure scale.

**Level III – Integration**: this level comprises in-depth integration from the shop floor with all of the manufacturing assets and layers from the SFC function of a company, such as smart devices and operational technologies (OT), machines, processes, systems, people, managerial activities/tasks, factories, supply chains, customers, and business units. Integration level leads to requirements development that make possible Cyber-Physical Systems (CPS) conception. Integration level is characterized by interoperability issues, synchronization of shop floor function activities/tasks, vertical integration, horizontal integration, end-to-end integration, data management and analytics planning, projects and migration/fit strategies, employees' education for I4.0, visibility and traceability of manufacturing flow and related processes (e.g., operational, informational, decisional/managerial).

In summary, at this level, the Shop Floor Control function implements integration-related key factors; however, it has not fully mastered the characteristics/capabilities of I4.0 linked to the automation level. Level III comprises outputs rated between 40 and 60 on the maturity measure scale.

**Level IV– Automation**: this level comprises automation of operational processes (e.g., manufacturing execution) and managerial/decisional processes (e.g., automatic re-scheduling based on events). Automation level is featured by highly automated manufacturing systems (e.g., automated production lines, autonomous robots, PLC and SCADA systems, automated inspection systems), automation of managerial and decisional tasks (e.g., automatic order release, RPA to trigger an order completion message to a customer, autonomous decision-making and self-capabilities on the shop floor, autonomous decision-making based on real-time optimization; production self-scheduling, collaboration and cooperation of machines, M2M communication, simulation).

In summary, at this level, the Shop Floor Control function implements automation-related key factors; however, it has not fully mastered the characteristics/capabilities of I4.0 linked to the smart level. Level III comprises outputs rated between 60 and 80 on the maturity measure scale.

**Level V – Smart**: in our model, the smart level represents the highest Shop Floor Control function's ability or power to value-add from I4.0 technologies. It happens through the establishment of smart operations, smart shop floor planning and control (e.g., smart production scheduling, smart manufacturing, smart ordering system/management) based on the full implementation of key maturity factors and related capabilities. At this level, all five focus-area are fully mature with associated key factors implemented. Smart level is featured by sensing and transmission infrastructure mature, digital value-creation, traceable performance improvements and KPIs. Also, in this level, Shop Floor Control tasks run into a CPS system based on mature digital and data-driven skills by the employees, a strong digital culture, cybersecurity, intensive data management and analytics use, full smart capabilities and technologies implementation (e.g., smart grid, additive manufacturing, wearables devices, cloud solutions/platform, digital twin), success on I4.0 strategy, a roadmap of learned lessons smart operators, smart manufacturing, smart production scheduling, smart ordering systems.

In summary, at the smart maturity level, the smart capabilities enabled by I4.0 converge to better people labor (man-machine reconciliation), intelligence and knowledge replace routines. Smart features enable a transformational power to leverage value-creation based on innovation for operational and managerial SFC tasks, resulting in new digital business processes. Level III comprises outputs rated between 80 and 100 on the maturity measure scale.

### 4.3.3 Maturity matrix (step 3)

The output item (maturity matrix) for step 3 is partially depicted in Figure 4.4 and can be fully accessed in the "Database Maturity Matrix" file (https://bityli.com/NrlaCiS). Ninety-eight capabilities are distributed along with twenty maturity key factors linked to $S^2$FC MM focus-areas. A maturity matrix provides capabilities to be assessed and developed on each key factor. These capabilities constitute roadmap items for SFC function improvements and maturity progression. They should be checked and implemented (if not implemented) by the managers into the SFC function aiming to level progression. They comprise the base (items) for a company maturity roadmap. For example, imagine that a manufacturing manager in a food company's participating in the model's pilot test aims to increase the maturity level of the Shop Floor Control function. For this company, in the test pilot, we inferred a fuzzy rule-based maturity output of 38.80 for the Sensing and Networking area, i.e., according to our fuzzy Expert System, this output is rated in Level II - Digitalization. Therefore, to progress across this level, this manufacturing manager should analyze, by the maturity matrix, which of the eight capabilities associated with SN were not fully implemented, developing them.

| 1. Sensing & Networking (SN) | | | |
|---|---|---|---|
| 1.1 Digital data sensing infrastructure on shop floor | 1.2 Conectiveness from shop floor | 1.3 Shop Floor cybersecurity | 1.4 Interoperability of shop floor assets & systems |
| Capabilities/actions for maturity progress | | | |
| | | | |
| 1. Manufacturing **assets digitalization** | 3. **Industrial internet network** | 6. **Digital security** (confidentiality, integ | 7. **High/advanced interoperability** across the shop floor (of "things", digital |
| 2. (real-time) **Digital data sensing** from Shop Floor | 4. Reliable and stable **connectivity** from shop floor (e.g., Wifi/ubiquitous low latency r | | 8. **Standizarded data exchange/transmission/communication protocols** |
| | 5. (real-time) **Digital data transmission** from shop floor | | |

**Figure 4.4.** Maturity matrix for S²FC MM (an example of SN focus-area)

### 4.3.4 Fuzzy rule-based maturity evaluation tool building (step 4)

Fuzzy logic is an emerging approach in the OSCM field to address the imprecision of human judgment over uncertainty and inherent ambiguity in maturity models (ELIBAL; ÖZCEYLAN, 2022). No model in the shop floor planning and control domain embeds a fuzzified maturity evaluation tool for I4.0 environments. To overcome this gap, our S²FC MM embeds an evaluation tool that uses a Fuzzy Expert System (ZADEH, 1965). Thus, we design, test (pilot study for model calibration), validate, and implement a maturity tool self-assessment (based on step 4 findings). Therefore, S²FC MM's evaluation tool provides a (highly) realistic maturity diagnosis based on the fuzzy sets theory (ZADEH, 1965). To build the evaluation tool, we follow Corrêa et al.'s (2014) five procedures (see Figure 4.5): 1. define variables and fuzzy sets (Table 4.1), 2. create maturity levels and link them to its variables (Table 4.1), 3. define rules base (for nine fuzzy inference system - FIS, according to Figure 4.6), 4. input/output parameters (Table 4.1), 5. show maturity assessment results by the Fuzzy Expert System (section 4.4.4).

**Table 4.1.** Variables, inputs/outputs, and parameters of the maturity model

| **Linguistic variable** | **Type** | **Universe of Discourse** | **Value** | **Triangular fuzzy members** |
|---|---|---|---|---|
| KF 1.1 to KF 5.4 (key factors) | Input | [0-100] | Very Low<br>Low<br>Medium<br>High<br>Very High | (0, 0, 25)<br>(0, 25, 50)<br>(25, 50, 75)<br>(50, 75, 100)<br>(75, 100, 100) |
| – SN, DA, SS, SC, VC (focused-areas) | Input/Output | [0-100] | Very Low<br>Low<br>Medium<br>High<br>Very High | (0, 0, 25)<br>(0, 25, 50)<br>(25, 50, 75)<br>(50, 75, 100)<br>(75, 100, 100) |
| – Operational Technology, People, System and Value-creation (dimensions) | Input/Output | [0-100] | Very Low<br>Low<br>Medium<br>High<br>Very High | (0, 0, 25)<br>(0, 25, 50)<br>(25, 50, 75)<br>(50, 75, 100)<br>(75, 100, 100) |

| | | | | |
|---|---|---|---|---|
| Global maturity evaluation (Shop Floor Control function) | Output | [0-100] | Nonexistent<br>Digitalization<br>Integration<br>Automation<br>Smart | (0, 0, 25)<br>(0, 25, 50)<br>(25, 50, 75)<br>(50, 75, 100)<br>(75, 100, 100) |

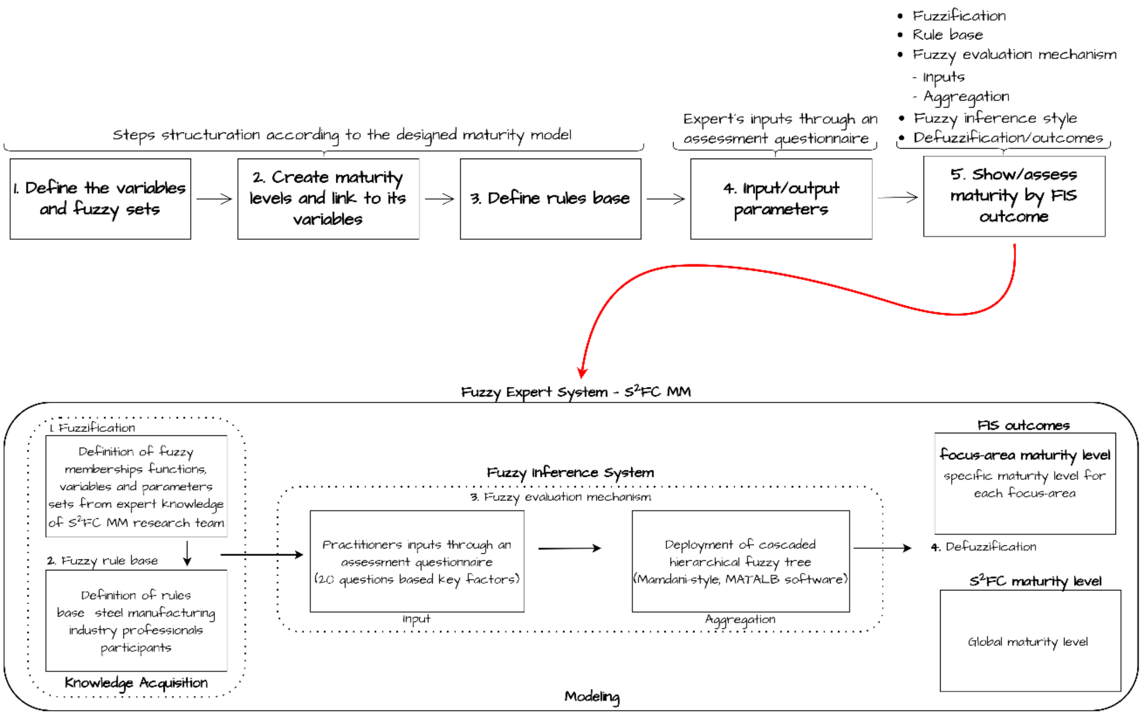



**Figure 4.5.** Fuzzy Expert System modeling [(based on Corrêa et al. (2014)]

Firstly, in procedure 1, we define linguistic variables and their fuzzy sets. We consider that five linguistic variables well represent the key factors (inputs), focus-areas (input/output), dimensions (input/output), and maturity levels (output), according to Table 4.1. The five maturity levels designed were linked to a respective fuzzy membership value to be measured by our Fuzzy Expert System (procedure 2).

In procedure 3, the rules base was developed and programmed into a fuzzy system. Fuzzy Expert Systems are grounded on expert knowledge acquisition (CAIADO et al., 2021; HAJIPOUR; KAZEMI; MOUSAVI, 2013). For this, we followed the knowledge engineering guidelines of Klir and Yuan (1996). We designed the evaluation tool based on expert knowledge acquired in procedure 4 (fourth research iteration), comprising the participation of experienced managers of a Brazilian steel company. The managers have experienced I4.0 technologies (>5 years) within SFC activities (>15 years) in the last five years. These professionals help us to develop and calibrate the FIS rules. Thus, we elicit nine FIS systems (Figure 4.6).

In procedure 5, we design nine fuzzy inference systems (FIS) represented in Figure 4.6. We implement this inference mechanism from a cascaded hierarchical fuzzy tree. This approach is based on Mamdani-style fuzzy inference (MAMDANI; ASSILIAN, 1975). In this approach, the low-level fuzzy systems' outputs are the inputs to the high-level fuzzy systems (GAVIÃO; BRITO; LIMA, 2015; VERGARA; GAVIÃO; LIMA, 2016). Thus, the FIS tree modeling presented in Figure 6 uses: *(i).* the standard Min-Max Mamdani operators; *(ii).* a triangular membership function based on five values for twenty key factors (two factors are not fuzzy; SN 1.1. and VC 5.1), five focus-areas, three dimensions, and five maturity levels (outputs) from a universe of discourse varying between 0-100, and *(iii).* centroid defuzzification (HAJIPOUR; KAZEMI; MOUSAVI, 2013); *(iv).* fuzzy logic-based toolbox on Matlab software was used to implement the FIS tree model (//www.mathworks.com).

We test S$^2$FC MM's evaluation tool from a pilot test based on the participation of practitioners from three manufacturing companies: a biorefinery, a food industry, and a seeds processing industry. Last, we implement it by measuring the maturity of an SFC function in a steel manufacturing company (case study).

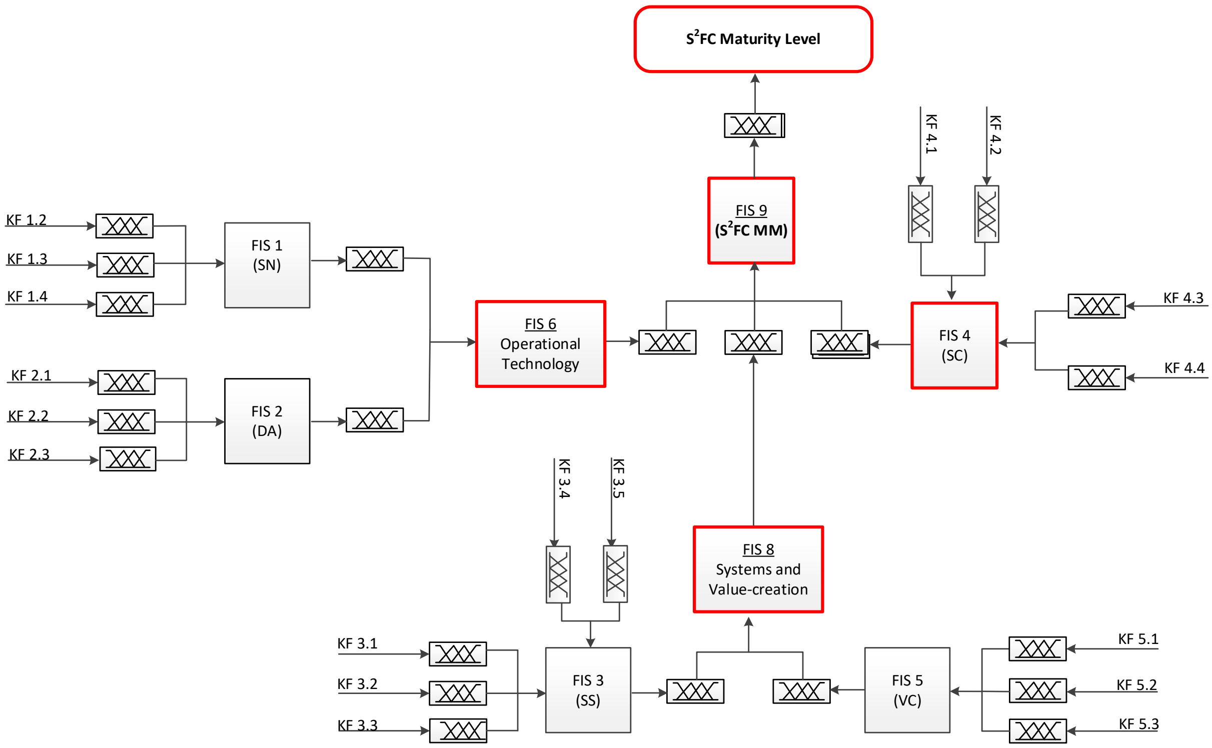



**Figure 4.6.** Cascaded hierarchical fuzzy tree [(based on Caiado et al. (2021)]

### 4.3.5 Summary of the model's elements and relationships

Figure 4.7 shows the model's elements and how they relate to them., where I4.0 orients the Shop Floor Control function domain, providing it with smart technologies and capabilities. Five focus-area are assessed from twenty implementation key factors. The key factors are evaluated by shop floor managers/practitioners from a questionnaire, scoring 0 to 100, where 0 represents a very low implementation and 100 a very high implementation (https://pt.surveymonkey.com/r/S86LWJ8). From this, a Fuzzy Expert System provides the maturity level evaluation for each focus-area and a global maturity level for the domain. Once the maturity level for a focus-area is assessed, the practitioners need to check the key factors and associated capabilities that have not been fully implemented at the current level. For this, managers should access the maturity matrix, map the capabilities lacking, and develop them from a customized progression roadmap. Therefore, the roadmap comprises the capabilities required for maturity progress, and the company team should ensure deployment actions, resources, people and responsibilities for this purpose.

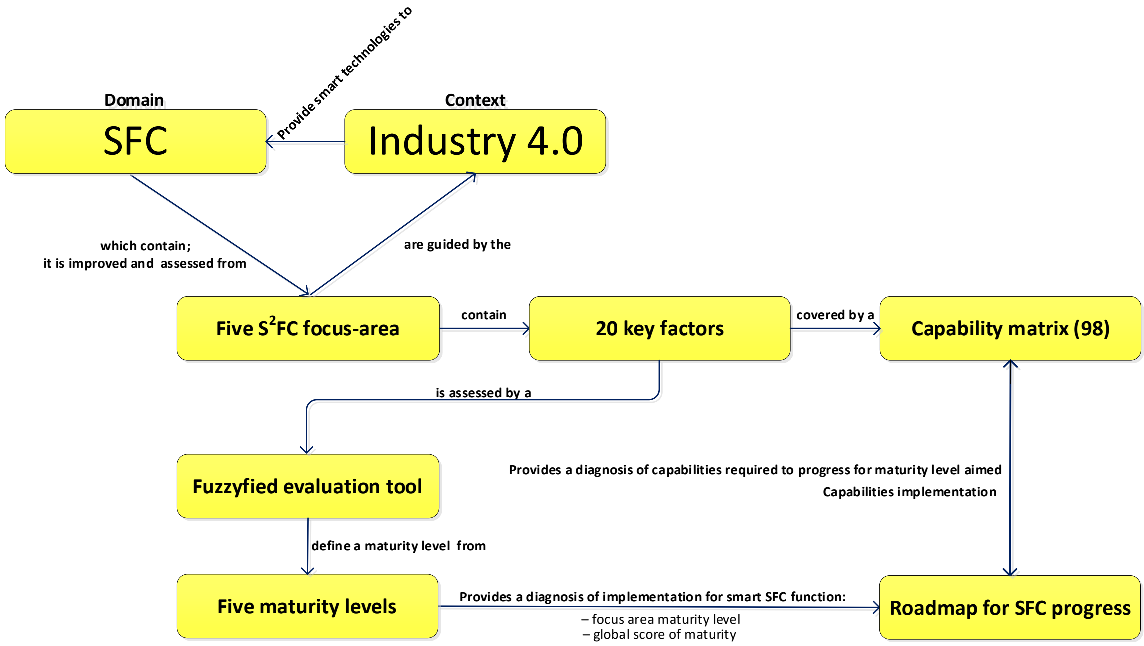



**Figure 4.7.** S$^2$FC MM: the relationships between the model's elements ("*how to read the model*")

### 4.4. Case study and discussions (step 5)

We use S$^2$FC MM for a self-assessment with managers in a Brazilian steel manufacturing company. The company has 312 employees, manufactures steel-based products such as tubes, sheets, and beams (W, H, I, U), and offers steel machining services (e.g., slitter). The case study used a self-assessment questionnaire concerning the implementation degree of twenty key factors (0 – not implemented to 100 – fully implemented). For this, we performed managers' interviews to evaluate the global maturity profile of the Shop Floor Control function in the steel company and also to analyze maturity capabilities development (improvements roadmap). Interviews lasted approximately 40 minutes. Thus, a plant manager, a senior ICT manager, a manufacturing manager, and an industrial engineer were interviewed. Each interview lasted between 25 to 40 minutes. The Shop Floor Control environment assessed has make-to-order characteristics. The company has been carrying out I4.0 projects that affect the Shop Floor Control function in the last five years; therefore, it is a representative case study for SFC function maturity research and the artifact's implementation.

### 4.4.1. Maturity evaluation

$S^2FC$ MM's questionnaire comprised the inputs to build a Fuzzy Expert System. After processing the inputs into the fuzzy system, we find: *(i).* maturity for each focus-area (Table 4.2 and Figure 4.8); *(ii).* maturity dimensions; *(iii).* global maturity for the Shop Floor Control function at the evaluated company.

**Table 4.2.** Maturity evaluation findings based on Fuzzy Expert System modeling

| Focus-area/ Key Factor | Score assigned (inputs) | Maturity output | Maximum membership | Maximum membership fuzzy set | Maturity rank (focus-area) |
|---|---|---|---|---|---|
| SN 1.1<br>SN 1.2<br>SN 1.3<br>SN 1.4 | 57.5<br>55<br>45<br>65.75 | 59.17 | 0.63 | Medium (M) | **Level III** – Integration |
| DA 2.1<br>DA 2.2<br>DA 2.3 | 46.25<br>41.25<br>56.23 | 49.3 | 0.97 | Medium (M) | **Level III** – Integration |
| SS 3.1<br>SS 3.2<br>SS 3.3<br>SS 3.4 | 33.75<br>37.5<br>48.75<br>37.5 | 33.34 | 0.67 | Low (L) | **Level II** – Digitalization |
| SC 4.1<br>SC 4.2<br>SC 4.3<br>SC 4.4 | 35<br>42.5<br>48.75<br>58.75 | 42.84 | 0.71 | Medium (M) | **Level III** – Integration |
| VC 5.1<br>VC 5.2<br>VC 5.3<br>VC 5.4 | 37.5<br>41.25<br>65<br>55 | 43.93 | 0.76 | Medium (M) | **Level III** – Integration |
| Global maturity – steel manufacturing company: **Level II** – **Digitalization** | | | | | |

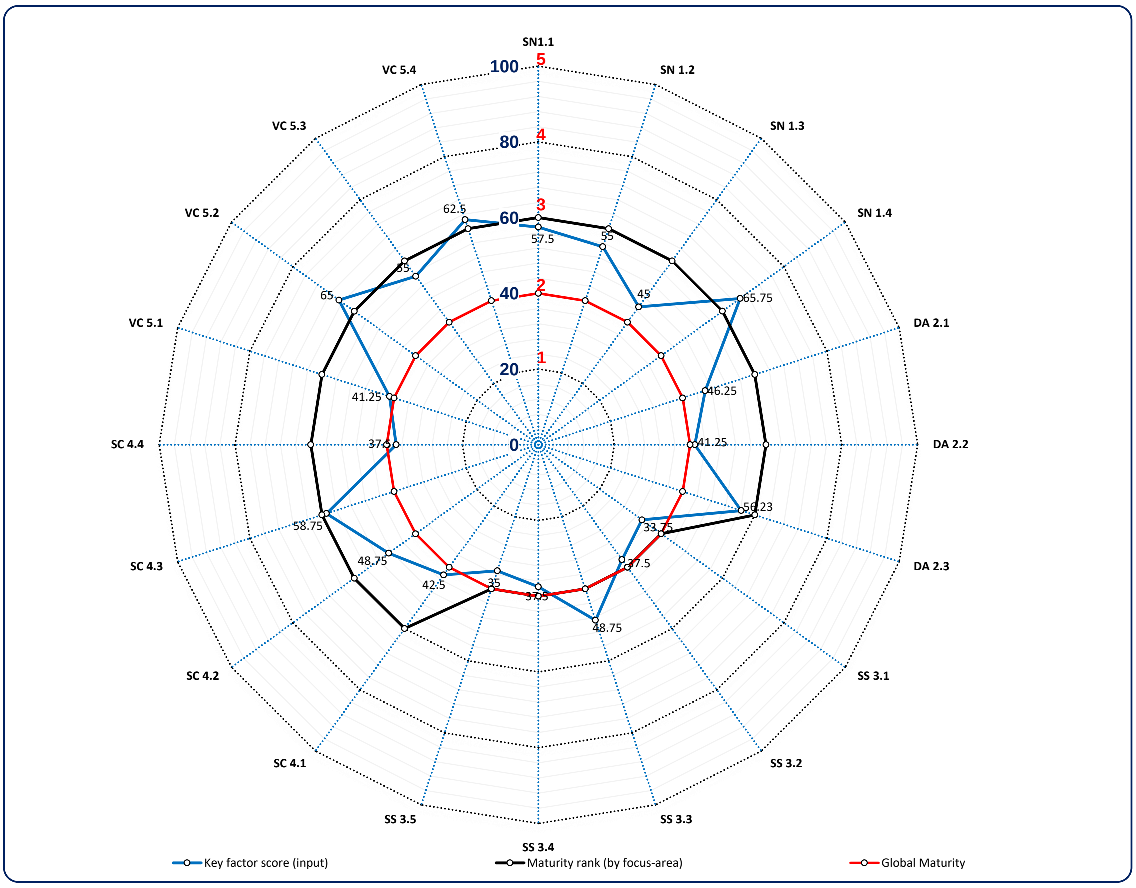



**Figure 4.8.** Maturity evaluation of steel manufacturing company

***(i)*. focus-area maturity:** according to Table 4.2 and Figure 4.8, five focus-area were classified in the Integration maturity level (level III): Sensing and Networking (SN), Data and Analytics (DA), Skills and Culture (SC), and Digital Value-Creation (VC). However, the System and Strategy focus-area (SS) was ranked with Level II – Digitalization. Therefore, this focus-area needs to develop its key factors and associated capabilities to enable the SFC function globally to progress to Level III.

The five maturity levels are framed by maturity intervals (outputs) measured by Fuzzy Expert System for each focus-area. For example, in Table 4.2, the fuzzy system outputs (average of four respondents in interviews) for SN is 59.17, with maximal membership (0.63) into the Medium (M) fuzzy set, implying a Level II of maturity (Integration). It means that SN has a relative development in all of the key factors towards the Integration maturity level; however, the Integration stage is not still fully developed. From this result, practitioners using $S^2$FC MM should verify applicable capabilities to overcome the current maturity level in the maturity matrix, establishing a customized roadmap according to maturity requirements in a specific focus-area. For example, the key factor SS3.1 presents low maturity in the steel company's evaluation; therefore, the managers linked to the Shop Floor Control function need to check what are the capabilities in the maturity matrix that requires actions regards to full-development such as "Guarantee of available financial and human resources for Industry 4.0 programs".

Our focus-area maturity model enables the users to prioritize those areas more feasible for progression according to their reality. For example, SC's focus-area requires less investment than SN; therefore, the steel company can focus efforts on this area, aiming to develop it until it reaches the smart level (Level V). Thus, during this time, the company can acquire capital to address areas that require high investment, such as SN and SS. Our $S^2$FC MM enables managers to have high flexibility in maturity development.

In focus-area evaluation, Strategy and System (SS) was rated with the worst maturity among the five areas of the SFC function. We observe that SS focus-area rating is influenced by the key factors linked to strategy and fit, which were assigned by managers with low maturity scores (inputs) and low fuzzified maturity scores (outputs). In the investigation of causes of this low maturity, managers related during interviews that the company does not have a formalized I4.0 strategy and does not have a defined planning of legacy systems fit for the entire plant. Ghobakhloo (2018) argues that companies endeavoring disruptive projects such as I4.0 needs a clear and deployed strategy. Aligned with this, we observe from interviews and direct observation on the steel shop floor that managers present a low understanding of the fit of legacy systems and methods/environment. Legacy systems and fitting procedures are closely coupled to strategy plan deployment and digital transformation actions (ORELLANA; TORRES, 2019). They enable to fit existing assets and organizational and production methods, upgrading them, if feasible, to new smart environments.

***(ii)*. dimensions maturity:** we evaluate three blocks of focus-areas according to structural characteristics named dimensions (see Table 4.1). First, SN and DA were grouped into operational technology dimensions supporting SFC control activities, i.e., sensing and networking infrastructure and data management (FIS6 in Figure 4.6). This dimension was ranked in Level III – Integration. Second, SS and VC were clustered in a systems and value-creation dimension that perform front-end smart SFC control activities (e.g., production scheduling, smart manufacturing). This dimension was also ranked in Level III – Integration. Lastly, SC represents the people and culture's dimension that englobes all key factors and capabilities strongly dependent on humans to perform both digital transformation and SFC function activities. This dimension was ranked in Level II – Digitalization, representing the dimension of worst maturity in the steel manufacturing company. It is an exciting result because recent OSCM literature has highlighted the importance of the people dimension for I4.0 maturity into manufacturing companies (BIBBY; DEHE, 2018; NAYERNIA; BAHEMIA; PAPAGIANNIDIS, 2021; WAGIRE et al., 2021).

***(iii).* global maturity:** the global maturity evaluated for the Shop Floor Control function of the steel company was Digitalization (Level II). This company's SFC function needs to focus on fully developing the key factors and capabilities related to digitalization along with five focus-areas. Although four focus-areas were ranked in Integration maturity level, some key factors/capabilities were not entirely developed in previous levels, such as SN1.1, SN1.2, and SN 1.3. It is a pattern for most focus-areas (see Figure 4.8). Despite four focus-areas are being rated as Level III – Integration, our rules base design for Fuzzy Expert System was oriented by the "*worst case*" of maturity. We design the rules base with dominance for the lowest level of maturity (worst maturity level), i.e., if System and Strategy is classified as Digitalization, this stage needs to be overcome, and then the SFC function will globally to progress to the third stage of maturity.

## 4.5. Conclusions

Our study proposed an MM approach strongly oriented to the design process through Design Science Research. We map a gap that none of the existing MM within the OSCM domain fully evaluated the maturity of Shop Floor Control into I4.0. Our $S^2$FC MM advances on measurement tool designing a fuzzy rule base system to assess maturity. Additionally, our model offers a capability maturity matrix to drive managers and companies toward maturity progress (improvement roadmap). $S^2$FC MM comprised five focus-areas, three dimensions, 20 key factors, 98 capabilities, five maturity levels, and an evaluation tool based on Fuzzy Expert System. Elements were originally built from a rigorous process along with iterative research and design processes (intensive use of DSR methodology). DSR research and design process is widely documented in the "Supplementary Material" and Appendix.

We observe that the current phase of manufacturing companies in the Fourth Industrial Revolution is the implementation of smart/digital resources and practices, aiming for associated performance benefits. Operations and Supply Chain Management (OSCM) literature show positive effects between smart Shop Floor Control activities/operations (I4.0-based) and performance indicators (BUENO; GODINHO FILHO; FRANK, 2020; OLUYISOLA et al., 2021). Performance indicators such as agility and responsiveness, flexibility, cost, and quality are improved using resources and smart capabilities of I4.0 technologies on the shop floor (BUENO; GODINHO FILHO; FRANK, 2020; DUMAN; AKDEMIR, 2021). Bititci et al. (2015) state that a higher maturity level in a domain is associated with higher performance. Moreover, shop floor managers and professionals can use maturity models to guide them on where to start improvements (ALCÁCER et al., 2022; ASDECKER; FELCH, 2018; RAFAEL et al., 2020; SCHUH et al., 2017; WAGIRE et al., 2021).

Shop floor managers and professionals should use $S^2$FC MM as a starting point to enhance the manufacturing and supply chain companies' practices and performance (GÖKALP; MARTINEZ, 2021) from I4.0 technologies (e.g., minimizing the lead times of orders and maximizing the reliability of scheduling carry out). Besides that, $S^2$FC MM allows a company to benchmark internal/external performance and practices within a specified domain (e.g., Shop Floor Control) and establish improvement roadmaps (ASDECKER; FELCH, 2018). Manufacturing companies, shop floor managers and professionals benefit from MM in four basic ways. First, $S^2$FC MM provides "*what to measure*" in the shop floor control highlighting the modeling of attributes (descriptive perspective/model) (RÖGLINGER; PÖPPELBUSS; BECKER, 2012). Second, $S^2$FC MM provides a "*measurement tool*" to assess the maturity of practices/capabilities (evaluation tool) on the Shop Floor Control function (prescriptive perspective/model) (METTLER; BALLESTER, 2021). Third, $S^2$FC MM delivers focus-areas, key factors, and capabilities to be implemented along with the maturity levels identified (maturity matrix/improvement roadmap). Fourth, $S^2$FC MM supports managers to position an "*as-is status*" against "*to-be status*" along with characteristic maturity levels within a domain (predictive/benchmarking perspective/model). Consistent $S^2$FC MM deployment enables shop floor managers and professionals problem-solving regarding upgrading ordering systems, scheduling, manufacturing execution and monitoring capabilities based on I4.0 technologies. Therefore, we address $S^2$FC MM as managerial artifacts to improve manufacturing companies' performance by implementing key factors and capabilities oriented by a highly technology-oriented shop floor environment (BASKERVILLE et al., 2018; HEVNER; GREGOR, 2022).

$S^2$FC MM implementation and usability were verified through a case study in a large steel manufacturing company endeavoring I4.0 projects. For Shop Floor Control function maturity in this company. $S^2$FC MM shows a maturity evaluation based on Level II – Digitalization. Regarding managerial/practical contributions, our study findings show that the model designed can evaluate the $S^2$FC MM's maturity, providing improvement capabilities at different focus-areas and maturity levels to shop floor managers and practitioners. Our study provides a maturity model that can help managers to move an $S^2$FC MM maturity level one stage further. For example, $S^2$FC MM identifies SS in Level II, and based on this is mapped the Strategy's key factors that are undeveloped such as SS3.1, SS3.4, and SS3.5. Analyzing these factors is possible to check capabilities that require development. Therefore, this evaluation and improvement path enables SFC function maturity progress.

Case study results show that our study has research contributions. Model design, tests, and implementation processes were continually developed with the steel manufacturing company and its managers' support for three years using mix-methods from iterative research processes. Also, we verify that DSR provides a path based on design, refinement, and testing that improve the MM robustness, measure precision, and reliability. Aligned on advances of recent MM such as Caiado et al. (2021) and Corrêa et al. (2014), we design a fuzzy rule-base self-assessment tool for $S^2$FC MM, advancing on presenting tools that well-capture the imprecision of managers about maturity into domain evaluated

Regarding limitations, our study is still not generalizable because $S^2$FC MM was applied only in a case study or company. According to Gokalp and Martinez (2021), additional case studies with different sectors, countries, and domain adoption levels are required to generalize a maturity model. Future studies should include the maturity evaluation in companies from different SFC environments (ETO, ATO, MTO, MTS) to verify the adherence and efficiency of $S^2$FC MM in companies dealing with varying environments of production, technology requirements, specific organizational and cultural characteristics, and contingent nature of production methods.

# 5 CONCLUSION

This Ph.D. Dissertation presented three articles, each corresponding to a specific objective. Figure 5.1 shows the relationship between the three articles of the Dissertation. While Article 01 addresses I4.0 capabilities for a smart PPC, Articles 02 and 03 seek to show how to design a Maturity Model for the Shop Floor Control function.

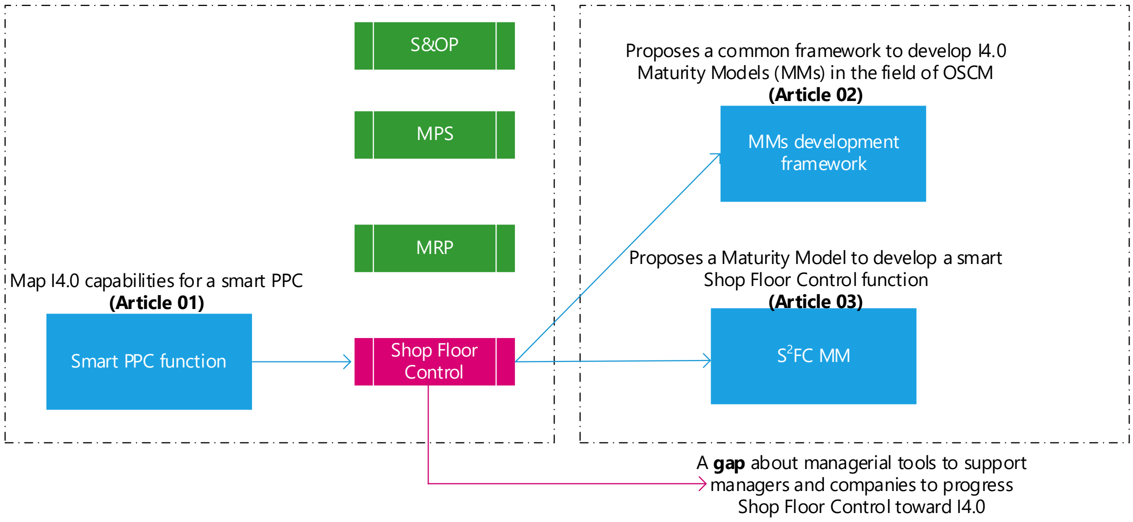



**Figure 5.1.** Articles' relationship

Article 01 presented a Systematic Literature Review (SLR) conducted on 102 articles to determine which smart capabilities from I4.0 technologies are explored by a smart PPC. Also, in this article, we verify contingency factors and performance indicators associated with smart PPC. In Article 02's findings, we presented a complete list of 18 smart capabilities for a smart PPC (e.g., real-time capabilities, adaptability and dynamicity, visibility and traceability, autonomy, smart scheduling, PPC-as-a-service); 13 performance indicators (e.g., manufacturing flexibility, agility, reliability); and environmental factor of smart PPC adoption (e.g., product, demand, and manufacturing process). We also propose a future agenda with ten research directions for PPC's study in the I4.0 context, where were found the gap for Articles 02 and 03.

Article 02 proposes a novel framework comprising elements, procedures, and recommendations determining a standard baseline for developing I4.0 Maturity Models (MMs) in the field of Operations and Supply Chain Management (OSCM). The framework proposed is organized into a workflow for operationalizing MM development. It was based on two building blocks:

*(i). nine elements or tasks of design*: problem-solving definition, MM comparison, meta-model definition, the decision to use a new architecture, or to use an existing one, mapping of I4.0 within OSCM-domain characteristics, MM design, assessment tool building, and follow-up;
*(ii). and seven iterative research aspects:* input (element to be designed), method, data and analysis (planning), element design, testing and validation, changes, and outputs (final element). The proposed framework is based on the shortcomings of existing ones, the contributions of previous architectures, and existing MMs. At last, we show a proof of concept of the framework, in which we demonstrate that designers could focus on the operationalization of their models (hands-on) by increasing the design redundancy and agility, design learning and transparency, and traceability and standardization of the development steps, thus also minimizing development efforts, time, and re-working.

The framework of Article 02 is used to develop the Maturity Model designed in Article 03

Finally, Article 03 presents the Smart Shop Floor Control Maturity Model – $S^2$FC MM. Article 03 uses previous articles' findings to design the Maturity Model proposed. Our findings show that our model supports the Shop Floor Control function maturity's modeling, fuzzy logic rule-based measurement, and progression into I4.0 environments. We implement $S^2$FC MM in a large Brazilian steel manufacturing company (rated in Level II - Digitalization), validating it and reaching a final version of MM. Still, our results contribute to design science research by applying a standardized/novel iterative research process built in Article 02. Lastly, our findings show that $S^2$FC MM provides a useful diagnostic tool based on focused-area, maturity key factors, and capabilities.

Therefore, the three articles that comprise this Dissertation attempt to understand the smart PPC concept, design a managerial artifact and propose paths that allow PPC/SFC managers to leverage I4.0 in manufacturing companies.

## 5.1. Contributions

Ph.D. Dissertation contributions are presented below:

**– Article 01**

The main theoretical contributions are concentred in Article 01. For the first time, this study defines a smart PPC from an I4.0 technologies perspective. Also, we define a theoretical framework linking 18 smart capabilities derived from five I4.0 technologies exploration by seven PPC activities/function. The OSCM community has adopted our framework in several studies.

***(i). theoretical implications:*** the main research contribution of Article 01 is to establish a theoretical framework for understanding the smart PPC concept based on I4.0 technologies. We verify that the researchers for this new study area are concentrated in Asian and European Universities, mainly from the Industrial/Production and Mechanical Engineering departments. Furthermore, these researchers are focusing on investigating key capabilities offered by IoT, CPS, (big) Data and Analytics/AI for Shop Floor Control, scheduling, inventory control, and capacity planning. Article 01 contributes to the PPC research field by organizing three drivers of smart capabilities: ***(i). digitalization capabilities*** **–** they address for example, real-time capabilities, synchronization of manufacturing stages, visibility and traceability; ***(ii). integration capabilities*** – they address the integration of systems and operational tasks for clustering smart capabilities for advantages in predictability, interoperability, servitization/PPC-as-service; ***(iii). automation*** capabilities: they address adaptiveness, responsiveness and robustness in PPC, automatic scalability, reconfiguration, distributed and ubiquitous PPC, and tools for intelligent PPC; ***(iv). smart capabilities:*** the mastering of all previous drivers/groups conjointly to the full development of people, cultural/organizational issues, and operational/managerial processes into I4.0 environments

Article 01 also makes theoretical contributions concerning future studies, presenting ten topics in a **Research Agenda** for smart PPC:

**(RT 1)** Research regarding how Industry 4.0 can support PPC activities for medium/long-term planning (strategic and tactical levels), such as smart S&OP/aggregate planning, MRP/ERP, and MPS;

**(RT 2)** Studies encompassing S&OP, MRP/ERP, and MPS/APS integration systems, frameworks, and models, based on BDA/AI, CPPS, and CMg ecosystems;

**(RT 3)** Research focusing on smart PPC as-a-service, and addressing capabilities such as scalability, collaboration, cooperation, modularity, and the trade-offs from adopting pay-as-you-go services based on CMg;

**(RT 4)** Research on the impact of AM on the reduction of overall smart PPC complexity;

**(RT 5)** Empirical research regarding end-to-end integration based on BDA/AI and CPPS, as applied to demand management and other PPC activities like smart shop floor scheduling and control;
**(RT 6)** Theoretical and empirical studies regarding the adoption level of Industry 4.0, maturity levels, and their influence on managers' awareness and their willingness to pay for the adoption of smart capabilities;
**(RT 7)** Studies on the effects of distributed manufacturing over the traditional PPC hierarchical structure discuss how new features of distributed manufacturing can affect the PPC configuration as to logistical objectives, degrees of autonomy, complexity, and effects on operations performance, like flexibility implementation;
**(RT 8)** Studies on how PPC design and autonomous manufacturing planning and control can be conceived periodicals with less expectation of re-planning or periodic planning at the tactical level (compression of front-end and engine PPC activities, owing to the more autonomous control on the shop floor and accurate PPC design afforded by I4.0);
**(RT 9)** Approaches to grounded theory through in-depth organizational investigation, e.g., use of theoretical lenses such as contingency theories with dynamic capabilities to jointly investigate the roles of moderating environmental factors with intangible asset factors on the applicability or development of smart PPC (endowed with smart capabilities) in different manufacturing environments;
**(RT 10)** Development of intelligent decision support systems, frameworks, architectures, and models to advance and consolidate smart manufacturing planning and control.

**– Article 02**

In this Dissertation, the main contribution of design theory and advances for DSR methodology is provided by Article 02 by proposing a novel framework to build MM. Our findings contribute for overcoming the challenges concerns MM development techniques, supproting designers and academics should on designing or investigating MMs. Our concept treats the construction of each MM element as an iterative research process, as recommended by DSR studies. This procedure is carried out using seven procedures from a cycle that includes, for example, design, tests/validation, and learning about the model element design. Furthermore, we combine three main phases for MM development, each one having specific elements that need to be built. Our framework also provides development recommendations to guide designers in creating their MMs.

Therefore, this study brings a comprehensive understanding of normative development frameworks, which support MM development in the OSCM field, thereby supplementing current MM-building literature. In summary, we provide evidence concerning "*what to design*" and "*how to design*" in the context of MM artifacts based on the DSR approach.

***(i). research implications:*** in this article, we contribute to design research theory on OSCM/SFC by proposing, building, validating, and applying a novel and common framework that synthesizes existing ones and adds details to the operationalization of MM building. We explore a variety of factors that influence MM development (architectures, current frameworks, and a list of recent MMs) to demonstrate the strengths and drawbacks of existing frameworks (shortcomings and main guidelines adopted).

A common method to create a maturity model is proposed. Our framework comprising elements, procedures, and recommendations determining a standard baseline for developing I4.0 maturity models; therefore, it contributes to research design theory, proposing new procedures to create new artifacts (MM) and expand the knowledge base of the subject. Since many new MMs are emerging in this field, comparing and using these tools is a challenge for scholars and practitioners, our goal was to contribute to a solid and repeatable foundation for MM development.

***(ii). practical implications:*** MM construction tools should assist designers in developing their models agilely, with minimum errors (due to test redundancy) and traceable and transparent steps. Our framework adds a second tier of procedures and details to current frameworks, upgrading them (for example, by adding the user viewpoint approach) and standardizing widely used recommendations into a single artifact. The results also confirm that managerial artifacts building needs quick follow-up in research and design, encompassing environmental changes based on technology, people, organizational culture, and value-creation processes, along with the OSCM domain. Aligned to this, we assigned the I4.0 footprint to the framework, intending to clarify the current smart technologies impacting the OSCM domain. We further emphasize that the DSR method enables creating artifacts based on MM in technologically new surroundings.

**– Article 03**

Article 03 brings the main managerial contributions of this Dissertation. In article 03, we present an innovative process of Maturity Model design based on five research iterations, from a mix-method approach oriented by DSR. Our study addresses how to design, test, and implement a Smart Shoop Floor Control Maturity Model ($S^2$FC MM) in manufacturing companies. For this, we used the Design Science Research approach comprising a reproducible and rigorous design process based on mix-methods: literature survey, qualitative methods, fuzzy inference system modeling, and a case study into a multinational steel manufacturing company. $S^2$FC MM is a critical managerial tool that can support shop floor managers and manufacturing professionals during I4.0 journey.

Aligned on advances of recent MM such as Caiado et al. (2021) and Corrêa et al. (2014), we design a fuzzy rule-base self-assessment tool for $S^2$FC MM, contributing and advancing on tools that well-capture the imprecision of managers about maturity into domain evaluated

***(i). managerial implications:*** regarding managerial/practical contributions, our study findings show that the model designed can evaluate the $S^2$FC MM's maturity, providing improvement capabilities at different focus-areas and maturity levels to shop floor managers and practitioners. Our study provides a maturity model that can help managers to move an $S^2$FC MM maturity level one stage further.

Shop floor managers and professionals should use $S^2$FC MM as a starting point to enhance the manufacturing and supply chain companies' practices and performance (GÖKALP; MARTINEZ, 2021) from I4.0 technologies (e.g., minimizing the lead times of orders and maximizing the reliability of scheduling carry out). Besides that, $S^2$FC MM allows a company to benchmark internal/external performance and practices within a specified domain (e.g., Shop Floor Control) and establish improvement roadmaps (ASDECKER; FELCH, 2018). Manufacturing companies, shop floor managers and professionals benefit from MM in four basic ways. First, $S^2$FC MM provides "*what to measure*" in the shop floor control highlighting the modeling of attributes (descriptive perspective/model) (RÖGLINGER; PÖPPELBUSS; BECKER, 2012). Second, $S^2$FC MM provides a "*measurement tool*" to assess the maturity of practices/capabilities (evaluation tool) on the Shop Floor Control function (prescriptive perspective/model)(METTLER; BALLESTER, 2021). Third, $S^2$FC MM delivers focus-areas, key factors, and capabilities to be implemented along with the maturity levels identified (maturity matrix/improvement roadmap). Fourth, $S^2$FC MM supports managers to position an "*as-is status*" against "*to-be status*" along with characteristic maturity levels within a domain (predictive/benchmarking perspective/model). Consistent $S^2$FC MM deployment enables shop floor managers and professionals problem-solving regarding upgrading ordering systems, scheduling, manufacturing execution and monitoring capabilities based on I4.0 technologies. Therefore, we address $S^2$FC MM as managerial artifacts to improve manufacturing companies' performance by implementing key factors and capabilities oriented by a highly technology-oriented shop floor environment (BASKERVILLE et al., 2018; HEVNER; GREGOR, 2022).

### 5.2. Limitations

The limitations of our Dissertation are as follows. First, for SLR findings, there is no consensus regarding the means of realization of I4.0. Second, the systematic review processes are naturally subject to the researchers' biases in extracting and analyzing the results. Third, in our review, we dedicate the analysis exclusively to journals and adopt an objective quality criterion (AJG/SJR index) that excludes searches of non-indexed sources, conference proceedings, among others. Finally, the number of studies addressing the propositions for moderating effects is insufficient for generalizing strong conclusions regarding this research question.

Artifacts development, such as frameworks (Article 02) and maturity models (Article 03), has a natural limitation of design choices from the development process, i.e., the (human) limitations of abilities, knowledge, resources, techniques and innovativeness of designers. Therefore, MM needs continuous follow-up for upgrading and releasing improved new versions.

Regards the Maturity Model study limitations, it is still not generalizable, because $S^2$FC MM was applied only in a case study or company. According to Gokalp and Martinez (2021), additional case studies with different sectors, countries, and domain adoption levels are required to generalize a maturity model. Future studies should include the maturity evaluation in companies from different SFC environments (ETO, ATO, MTO, MTS) to verify the adherence and efficiency of $S^2$FC MM in companies dealing with varying environments of production, technology requirements, specific organizational and cultural characteristics, and contingent nature of production methods. $S^2$FC MM needs to be applied to different countries to overcome the limitation of the study covering only a company in Brazil.

## REFERENCES


ACHILLAS, C.; AIDONIS, D.; IAKOVOU, E.; THYMIANIDIS, M.; TZETZIS, D. A methodological framework for the inclusion of modern additive manufacturing into the production portfolio of a focused factory. **Journal of Manufacturing Systems**, v. 37, n. October, p. 328–339, out. 2015. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0278612514000946>.

ACHILLAS, C.; TZETZIS, D.; RAIMONDO, M. O. Alternative production strategies based on the comparison of additive and traditional manufacturing technologies. **International Journal of Production Research**, v. 55, n. 12, p. 3497–3509, 18 jun. 2017. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2017.1282645>.

ADAMSON, G.; WANG, L.; MOORE, P. Feature-based control and information framework for adaptive and distributed manufacturing in cyber physical systems. **Journal of Manufacturing Systems**, v. 43, n. April, p. 305–315, abr. 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0278612516300905>.

AHMADOV, Y.; HELO, P. A cloud based job sequencing with sequence-dependent setup for sheet metal manufacturing. **Annals of Operations Research**, v. 270, n. 1–2, p. 5–24, 3 nov. 2018. Disponível em: <http://link.springer.com/10.1007/s10479-016-2304-3>.

ÅKERMAN, M. **Implementing Shop Floor IT for Industry 4 . 0 Implementing Shop Floor IT for Industry 4 . 0 Department of Industrial and Materials Science**. [s.l: s.n.]52 p.

AKTER, S.; WAMBA, S. F.; GUNASEKARAN, A.; DUBEY, R.; CHILDE, S. J. How to improve firm performance using big data analytics capability and business strategy alignment? ***(Define Capabilities). **International Journal of Production Economics**, v. 182, p. 113–131, dez. 2016. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527316302110>.

ALAMI, D.; ELMARAGHY, W. A cost benefit analysis for industry 4.0 in a job shop environment using a mixed integer linear programming model. **Journal of Manufacturing Systems**, v. 59, n. September 2020, p. 81–97, abr. 2021. Disponível em: <https://doi.org/10.1016/j.jmsy.2021.01.014>.

ALCÁCER, V.; RODRIGUES, J.; CARVALHO, H.; CRUZ-MACHADO, V. Industry 4.0 maturity follow-up inside an internal value chain: a case study. **International Journal of Advanced Manufacturing Technology**, n. 0123456789, 2022. Disponível em: <https://doi.org/10.1007/s00170-021-08476-3>.

ALEXOPOULOS, K.; SIPSAS, K.; XANTHAKIS, E.; MAKRIS, S.; MOURTZIS, D. An industrial Internet of things based platform for context-aware information services in manufacturing. **International Journal of Computer Integrated Manufacturing**, v. 31, n. 11, p. 1111–1123, 2 nov. 2018. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85050917823&doi=10.1080%2F0951192X.2018.1500716&partnerID=40&md5=64c0aa28e0b267fc6eb7f416a574935c>.

ALIEVA, J.; VON HAARTMAN, R. Digital MudA - The new form of waste by Industry 4.0. **Operations and Supply Chain Management**, v. 13, n. 3, p. 269–278, 2020.

ALTAF, M. S.; BOUFERGUENE, A.; LIU, H.; AL-HUSSEIN, M.; YU, H. Integrated production planning and control system for a panelized home prefabrication facility using simulation and RFID. **Automation in Construction**, v. 85, p. 369–383, 2018. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85033551039&doi=10.1016%2Fj.autcon.2017.09.009&partnerID=40&md5=f6911953dec38bd9400e3927b134c28f>.

ALVES, F.; VARELA, M.; ROCHA, A.; PEREIRA, A.; LEITÃO, P. A human centered hybrid MAS and meta-heuristics based system for simultaneously supporting scheduling and plant layout adjustment. **FME Transactions**, v. 47, n. 4, p. 699–710, 2019. Disponível em: <https://scindeks.ceon.rs/Article.aspx?artid=1451-20921904699A>.

ANAND, G.; KODALI, R. Development of a framework for implementation of lean manufacturing systems. **International Journal of Management Practice**, v. 4, n. 1, p. 95–116, 2010.

ANDERSSON, J.; JONSSON, P. Big data in spare parts supply chains: The potential of using product-in-use data in aftermarket demand planning. **INTERNATIONAL JOURNAL OF PHYSICAL DISTRIBUTION & LOGISTICS MANAGEMENT**, v. 48, n. 5, SI, p. 524–544, 2018.

ANSARI, F.; GLAWAR, R.; NEMETH, T. PriMa: a prescriptive maintenance model for cyber-physical production systems. **International Journal of Computer Integrated Manufacturing**, v. 32, n. 4–5, p. 482–503, 4 maio 2019. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85067308181&doi=10.1080%2F0951192X.2019.1571236&partnerID=40&md5=d1678c0461bce8140b714742ef2d6a28>.

ARBIX, G.; SALERNO, M. S.; ZANCUL, E.; AMARAL, G.; LINS, L. M. Advanced manufacturing: What is to be learnt from Germany, the U.S., and China [O Brasil E A nova onda de manufatura avançada]. **Novos Estudos CEBRAP**, v. 36, n. 03, p. 29–49, 2017.

ARKSEY, H.; O'MALLEY, L. Scoping studies: Towards a methodological framework. **International Journal of Social Research Methodology: Theory and Practice**, v. 8, n. 1, p. 19–32, 2005.

ASDECKER, B.; FELCH, V. Development of an Industry 4.0 maturity model for the delivery process in supply chains. **Journal of Modelling in Management**, v. 13, n. 4, p. 840–883, 5 nov. 2018. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/JM2-03-2018-0042/full/html>.

BABICEANU, R. F.; SEKER, R. Big Data and virtualization for manufacturing cyber-physical systems: A survey of the current status and future outlook. **Computers in Industry**, v. 81, p. 128–137, set. 2016. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361516300471>.

BAG, S.; GUPTA, S.; KUMAR, S. Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. **International Journal of Production Economics**, v. 231, p. 107844, jan. 2021. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527320302103>.

BÄNZIGER, T.; KUNZ, A.; WEGENER, K. Optimizing Human–Robot Task Allocation Using a Simulation Tool Based on Standardized Work Descriptions. **Journal of Intelligent Manufacturing**, v. 31, n. 7, p. 1635–1648, 3 out. 2020. Disponível em: <http://link.springer.com/10.1007/s10845-018-1411-1>.

BASKERVILLE, R.; BAIYERE, A.; GERGOR, S.; HEVNER, A.; ROSSI, M. Design Science Research Contributions: Finding a Balance between Artifact and Theory. **Journal of the Association for Information Systems**, v. 19, n. 5, p. 358–376, maio 2018. Disponível em: <http://aisel.aisnet.org/jais/vol19/iss5/3/>.

BAUTERS, K.; COTTYN, J.; CLAEYS, D.; SLEMBROUCK, M.; VEELAERT, P.; VAN LANDEGHEM, H. Automated work cycle classification and performance measurement for manual work stations. **Robotics and Computer-Integrated Manufacturing**, v. 51, p. 139–157, jun. 2018. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85039416654&doi=10.1016%252Fj.rcim.2017.12.001&partnerID=40&md5=837fbc4497fcbcd4405bd7d37fdad2bd>.

BECHARA, J.; VAN DE VEN, A. H. **Triangulating philosophies of science to understand complex organizational and managerial problems**. [s.l.] Emerald, 2011. v. 32343–364 p.

BECHTSIS, D.; TSOLAKIS, N.; BIZAKIS, A.; VLACHOS, D. A Blockchain Framework for Containerized Food Supply Chains. **Computer Aided Chemical Engineering**, v. 46, p. 1369–1374, 1 jan. 2019.

BECKER, J.; KNACKSTEDT, R.; PÖPPELBUSS, J. Developing Maturity Models for IT Management. **Business & Information Systems Engineering**, v. 1, n. 3, p. 213–222, 21 jun. 2009. Disponível em: <http://link.springer.com/10.1007/s12599-009-0044-5>.

BENDUL, J. C.; BLUNCK, H. The design space of production planning and control for industry 4.0. **Computers in Industry**, v. 105, p. 260–272, fev. 2019. Disponível em: <https://www2.scopus.com/inward/record.uri?eid=2-s2.0-85059233656&doi=10.1016%2Fj.compind.2018.10.010&partnerID=40&md5=3ec7aab7a2baebae2d9292a11f5b4026>.

BEVILACQUA, M.; CIARAPICA, F. E.; ANTOMARIONI, S. **Lean principles for organizing items in an automated storage and retrieval system: An association rule mining – Based approachManagement and Production Engineering Review**2019.

BIBBY, L.; DEHE, B. Defining and assessing industry 4.0 maturity levels – case of the defence sector. **Production Planning & Control**, v. 29, n. 12, p. 1030–1043, 10 set. 2018. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2018.1503355>.

BIONDI, M.; SAND, G.; HARJUNKOSKI, I. Optimization of multipurpose process plant operations: A multi-time-scale maintenance and production scheduling approach. **Computers & Chemical Engineering**, v. 99, n. April, p. 325–339, abr. 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S009813541730008X>.

BITKOM; VDMA; ZVEI. Implementation Strategy Industrie 4.0 Report on the results of the Industrie 4.0 Platform. **Bitkom e.V**, 2016.

BOGATAJ, D.; BOGATAJ, M.; HUDOKLIN, D. Mitigating risks of perishable products in the cyber-physical systems based on the extended MRP model. **International Journal of Production Economics**, v. 193, n. June, p. 51–62, nov. 2017. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85021821156&doi=10.1016%25252Fj.ijpe.2017.06.028&partnerID=40&md5=9f645c7d2a73440567cb82acf13015be>.

BONNEY, M. Reflections on production planning and control (PPC). **Gestão & Produção**, v. 7, n. 3, p. 181–207, dez. 2000. Disponível em: <http://www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-530X2000000300002&lng=en&tlng=en>.

BÜCHI, G.; CUGNO, M.; CASTAGNOLI, R. Smart factory performance and Industry 4.0. **Technological Forecasting and Social Change**, v. 150, n. October 2019, p. 119790, 2020. Disponível em: <https://doi.org/10.1016/j.techfore.2019.119790>.

BUENO, A.; FILHO, M. G.; CARVALHO, J. V.; CALLEFI, M. Smart Production Planning and Control Model. *In*: MESQUITA, A.; ABREU, A.; CARVALHO, J. V. **Perspectives and Trends in Education and Technology**. São Paulo: Springer Nature Singapore, 2022. p. 253–267.

BUENO, A.; GODINHO FILHO, M.; FRANK, A. G. Smart production planning and control in the Industry 4.0 context: A systematic literature review. **Computers and Industrial Engineering**, v. 149, n. August, p. 106774, 2020. Disponível em: <https://doi.org/10.1016/j.cie.2020.106774>.

BUER, S. V.; STRANDHAGEN, J. O.; CHAN, F. T. S. The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda. **International Journal of Production Research**, v. 56, n. 8, p. 2924–2940, 2018. Disponível em: <http://doi.org/10.1080/00207543.2018.1442945>.

CAIADO, R. G. G.; SCAVARDA, L. F.; GAVIÃO, L. O.; IVSON, P.; NASCIMENTO, D. L. de M.; GARZA-REYES, J. A. A fuzzy rule-based industry 4.0 maturity model for operations and supply chain management. **International Journal of Production Economics**, v. 231, n. November 2019, p. 107883, jan. 2021. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527320302401>.

CALABRESE, A.; DORA, M.; LEVIALDI GHIRON, N.; TIBURZI, L. Industry's 4.0 transformation process: how to start, where to aim, what to be aware of. **Production Planning and Control**, v. 0, n. 0, p. 1–21, 2020. Disponível em: <https://doi.org/10.1080/09537287.2020.1830315>.

CAMARINHA-MATOS, L. M. Collaborative smart grids – A survey on trends. **Renewable and Sustainable Energy Reviews**, v. 65, p. 283–294, 2016. Disponível em: <http://dx.doi.org/10.1016/j.rser.2016.06.093>.

CAÑAS, H.; MULA, J.; DÍAZ-MADROÑERO, M.; CAMPUZANO-BOLARÍN, F. Implementing Industry 4.0 principles. **Computers & Industrial Engineering**, v. 158, p. 107379, ago. 2021. Disponível em: <https://doi.org/10.1016/j.cie.2021.107379>.

CARALLI, R.; KNIGHT, M.; MONTGOMERY, A. Maturity Models 101: A Primer for Applying Maturity Models to Smart Grid Security, Resilience, and Interoperability Mark Knight, CGI Group and GridWise Architecture Council (GWAC) Member. n. November, p. 1–14, 2012. Disponível em: <https://resources.sei.cmu.edu/asset_files/WhitePaper/2012_019_001_58920.pdf>.

CARVALHO, J. V.; ROCHA, Á.; ABREU, A. Maturity Models of Healthcare Information Systems and Technologies: a Literature Review. **Journal of Medical Systems**, v. 40, n. 6, p. 131, 15 jun. 2016. Disponível em: <http://link.springer.com/10.1007/s10916-016-0486-5>.

CARVALHO, J. V.; ROCHA, Á.; VAN DE WETERING, R.; ABREU, A. A Maturity model for hospital information systems. **Journal of Business Research**, v. 94, n. August 2017, p. 388–399, jan. 2019. Disponível em: <https://doi.org/10.1016/j.jbusres.2017.12.012>.

CASTELO-BRANCO, I.; CRUZ-JESUS, F.; OLIVEIRA, T. Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. **Computers in Industry**, v. 107, p. 22–32, maio 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361518304081>.

CATTANEO, L.; FUMAGALLI, L.; MACCHI, M.; NEGRI, E. Clarifying Data Analytics Concepts for Industrial Engineering. **IFAC-PapersOnLine**, v. 51, n. 11, p. 820–825, 2018. Disponível em: <http://www.sciencedirect.com/science/article/pii/S2405896318315672>.

CHAPMAN, S. N. **The fundamentals of production planning and control**. Upper Saddle River, New Jersey: Pearson Prentice Hall, 2006.

CHERGUI, A.; HADJ-HAMOU, K.; VIGNAT, F. Production scheduling and nesting in additive manufacturing. **Computers & Industrial Engineering**, v. 126, n. December, p. 292–301, dez. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835218304649>.

CHOI, T.-M. M.; WALLACE, S. W.; WANG, Y. Big Data Analytics in Operations Management. **Production and Operations Management**, v. 27, n. 10, p. 1868–1883, out. 2018. Disponível em: <http://doi.wiley.com/10.1111/poms.12838>.

CIANO, M. P.; DALLASEGA, P.; ORZES, G.; ROSSI, T. One-to-one relationships between Industry 4.0 technologies and Lean Production techniques: a multiple case study. **International Journal of Production Research**, v. 59, n. 5, p. 1386–1410, 2021.

COHEN, Y.; NASERALDIN, H.; CHAUDHURI, A.; PILATI, F. Assembly systems in Industry 4.0 era: a road map to understand Assembly 4.0. **International Journal of Advanced Manufacturing Technology**, v. 105, n. 9, p. 4037–4054, 2019.

COLQUHOUN, H. L.; LEVAC, D.; O'BRIEN, K. K.; STRAUS, S.; TRICCO, A. C.; PERRIER, L.; KASTNER, M.; MOHER, D. Scoping reviews: Time for clarity in definition, methods, and reporting. **Journal of Clinical Epidemiology**, v. 67, n. 12, p. 1291–1294, 2014. Disponível em: <http://dx.doi.org/10.1016/j.jclinepi.2014.03.013>.

COMUZZI, M.; PATEL, A. How organisations leverage Big Data: a maturity model. **Industrial Management & Data Systems**, v. 116, n. 8, p. 1468–1492, 12 set. 2016. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/IMDS-12-2015-0495/full/html>.

CORRÊA, A. S.; DE ASSIS MOTA, A.; MOTA, L. T. M.; CORRÊA, P. L. P. A fuzzy rule-based system to assess e-government technical interoperability maturity level. **Transforming Government: People, Process and Policy**, v. 8, n. 3, p. 335–356, 2014.

CRESWELL, J. W.; CLARK, V. L. P. **Designing and Conducting Mixed Methods Research**. Los Angeles, CA: SAGE Publications, Inc., 2018. 628 p.

CRESWELL, J. W.; POTH, C. N. Qualitative Inquiry & Research Design: Choosing Among Five Approaches. **Sage Publications**, 2018.

CUI, Y.; KARA, S.; CHAN, K. C. Manufacturing big data ecosystem: A systematic literature review. **Robotics and Computer-Integrated Manufacturing**, v. 62, p. 101861, abr. 2020. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0736584519300559>.

DA SILVA SERAPIÃO LEAL, G.; GUÉDRIA, W.; PANETTO, H. Interoperability assessment: A systematic literature review. **Computers in Industry**, v. 106, p. 111–132, 2019. Disponível em: <https://doi.org/10.1016/j.compind.2019.01.002>.

DALENOGARE, L. S.; BENITEZ, G. B.; AYALA, N. F.; FRANK, A. G. The expected contribution of Industry 4.0 technologies for industrial performance. **International Journal of Production Economics**, v. 204, n. August, p. 383–394, out. 2018. Disponível em: <https://doi.org/10.1016/j.ijpe.2018.08.019>.

DALLASEGA, P.; ROJAS, R. A.; BRUNO, G.; RAUCH, E. An agile scheduling and control approach in ETO construction supply chains. **Computers in Industry**, v. 112, p. 103122, nov. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361519300284>.

DAS, A.; NARASIMHAN, R. Process-technology fit and its implications for manufacturing performance. **Journal of Operations Management**, v. 19, n. 5, p. 521–540, 2001.

DE BRUIN, T.; ROSEMANN, M.; FREEZE, R.; KULKARNI, U. Understanding the main phases of developing a maturity assessment model. In: ACIS 2005 Proceedings - 16th Australasian Conference on Information Systems, 2005, [...]. 2005.

DE CAROLIS, A.; MACCHI, M.; KULVATUNYOU, B.; BRUNDAGE, M. P.; TERZI, S. Maturity Models and tools for enabling smart manufacturing systems: Comparison and reflections for future developments. **IFIP Advances in Information and Communication Technology**, v. 517, p. 23–35, 2017.

DE LAS MORENAS, J.; GARCIA-HIGUERA, A.; GARCIA-ANSOLA, P. Shop Floor Control: A Physical Agents Approach for PLC-Controlled Systems. **IEEE Transactions on Industrial Informatics**, v. 13, n. 5, p. 2417–2427, 2017. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85021917663&doi=10.1109%2FTII.2017.2720696&partnerID=40&md5=57976ca92367adab28414a71a892cad3>.

DENKENA, B.; DITTRICH, M.-A.; JACOB, S. Methodology for integrative production planning in highly dynamic environments. **Production Engineering**, v. 13, n. 3–4, p. 317–324, 23 jun. 2019. Disponível em: <http://link.springer.com/10.1007/s11740-019-00889-0>.

DENNO, P.; DICKERSON, C.; HARDING, J. A. Dynamic production system identification for smart manufacturing systems. **Journal of Manufacturing Systems**, v. 48, p. 192–203, jul. 2018. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85046378998&doi=10.1016%252Fj.jmsy.2018.04.006&partnerID=40&md5=2d9193882d5e4f1c693d28c750cdd163>.

DEV, N. K.; SHANKAR, R.; QAISER, F. H. Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. **Resources, Conservation and Recycling**, v. 153, 2020. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85075058351&doi=10.1016%2Fj.resconrec.2019.104583&partnerID=40&md5=c216612fd4c98370f181e631277c950d>.

DING, K.; CHAN, F. T. S.; ZHANG, X.; ZHOU, G.; ZHANG, F. Defining a Digital Twin-based Cyber-Physical Production System for autonomous manufacturing in smart shop floors. **International Journal of Production Research**, v. 57, n. 20, p. 6315–6334, 2019. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85060183300&doi=10.1080%2F00207543.2019.1566661&partnerID=40&md5=48dcfb42b127a895337b828382c50255>.

DOLGUI, A.; IVANOV, D.; SETHI, S. P.; SOKOLOV, B. Scheduling in production, supply chain and Industry 4.0 systems by optimal control: fundamentals, state-of-the-art and applications. **International Journal of Production Research**, v. 57, n. 2, p. 411–432, 17 jan. 2019. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2018.1442948>.

DOMBROWSKI, U.; DIX, Y. An Analysis of the Impact of Industrie 4.0 on Production Planning and Control. *In*: **IFIP Advances in Information and Communication Technology**. [s.l: s.n.]p. 114–121.

DUMAN, M. C.; AKDEMIR, B. A study to determine the effects of industry 4.0 technology components on organizational performance. **Technological Forecasting and Social Change**, v. 167, n. February, p. 0–3, 2021.

ELIBAL, K.; ÖZCEYLAN, E. Comparing industry 4.0 maturity models in the perspective of TQM principles using Fuzzy MCDM methods. **Technological Forecasting and Social Change**, v. 175, n. May 2021, 2022.

ELLIOTT, S. Proof of Concept Research. **Philosophy of Science**, v. 88, n. 2, p. 258–280, 1 abr. 2021. Disponível em: <https://www.cambridge.org/core/product/identifier/S0031824800017189/type/journal_article>.

FANG, C.; LIU, X.; PARDALOS, P. M.; PEI, J. Optimization for a three-stage production system in the Internet of Things: procurement, production and product recovery, and acquisition. **The International Journal of Advanced Manufacturing Technology**, v. 83, n. 5–8, p. 689–710, 30 mar. 2016. Disponível em: <http://link.springer.com/10.1007/s00170-015-7593-1>.

FARERI, S.; FANTONI, G.; CHIARELLO, F.; COLI, E.; BINDA, A. Estimating Industry 4.0 impact on job profiles and skills using text mining. **Computers in Industry**, v. 118, p. 103222, 2020. Disponível em: <https://doi.org/10.1016/j.compind.2020.103222>.

FARHAT, H.; ILIEV, P.; MARRIAGE, P.; ROLLAND, N. An Added Value Alternative to RAIN RFID Items Characterization in Retail. **IEEE Access**, v. 6, p. 32430–32439, 2018. Disponível em: <https://ieeexplore.ieee.org/document/8375671/>.

FAROOQUI, A.; BENGTSSON, K.; FALKMAN, P.; FABIAN, M. Towards data-driven approaches in manufacturing: an architecture to collect sequences of operations. **International Journal of Production Research**, v. 58, n. 16, p. 4947–4963, 17 ago. 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2020.1735660>.

FEDERAL MINISTRY OF ECONOMIC AFFAIRS AND ENERGY. Alignment Report for Reference Architectural Model for Industrie 4 . 0 / Intelligent Manufacturing System Architecture. **Federal Ministry of Economic Affairs and Energy Germany**, p. 1–36, 2018.

FERA, M.; FRUGGIERO, F.; LAMBIASE, A.; MACCHIAROLI, R.; TODISCO, V. A modified genetic algorithm for time and cost optimization of an additive manufacturing single-machine scheduling. **International Journal of Industrial Engineering Computations**, v. 9, n. 4, p. 423–438, 2018. Disponível em: <http://www.growingscience.com/ijiec/Vol9/IJIEC_2018_1.pdf>.

FRANK, A. G.; DALENOGARE, L. S.; AYALA, N. F. Industry 4.0 technologies: Implementation patterns in manufacturing companies. **International Journal of Production Economics**, v. 210, n. January, p. 15–26, abr. 2019. Disponível em: <https://doi.org/10.1016/j.ijpe.2019.01.004>.

FROGER, M.; BÉNABEN, F.; TRUPTIL, S.; BOISSEL-DALLIER, N. A non-linear business process management maturity framework to apprehend future challenges. **International Journal of Information Management**, v. 49, n. June, p. 290–300, 2019. Disponível em: <https://doi.org/10.1016/j.ijinfomgt.2019.05.013>.

FU, W.; CHIEN, C.-F. UNISON data-driven intermittent demand forecast framework to empower supply chain resilience and an empirical study in electronics distribution. **Computers & Industrial Engineering**, v. 135, p. 940–949, set. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835219303936>.

GAVIÃO, L.; BRITO, G.; LIMA, A. Indicadores De Sustentabilidade Para a Educação Básica Por Modelagem Fuzzy. **Indicadores De Sustentabilidade Para a Educação Básica Por Modelagem Fuzzy**, v. 19, n. 3, p. 274–297, 2015.

GEBAUER, H.; PAIOLA, M.; SACCANI, N.; RAPACCINI, M. Digital servitization: Crossing the perspectives of digitization and servitization. **Industrial Marketing Management**, v. 93, p. 382–388, 2021.

GHADGE, A.; DANI, S.; KALAWSKY, R. Supply chain risk management: present and future scope. **The International Journal of Logistics Management**, v. 23, n. 3, p. 313–339, 2 nov. 2012. Disponível em: <http://www.emeraldinsight.com/doi/10.1108/09574091211289200>.

GHADGE, A.; KARANTONI, G.; CHAUDHURI, A.; SRINIVASAN, A. Impact of additive manufacturing on aircraft supply chain performance. **Journal of Manufacturing Technology Management**, v. 29, n. 5, p. 846–865, 13 ago. 2018. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/JMTM-07-2017-0143/full/html>.

GHOBAKHLOO, M. The future of manufacturing industry: a strategic roadmap toward Industry 4.0. **Journal of Manufacturing Technology Management**, v. 29, n. 6, p. 910–936, 15 out. 2018. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/JMTM-02-2018-0057/full/html>.

GHOBAKHLOO, M. Determinants of information and digital technology implementation for smart manufacturing. **International Journal of Production Research**, v. 58, n. 8, p. 2384–2405, 17 abr. 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2019.1630775>.

GHOBAKHLOO, M.; IRANMANESH, M. Digital transformation success under Industry 4.0: a strategic guideline for manufacturing SMEs. **Journal of Manufacturing Technology Management**, v. 32, n. 8, p. 1533–1556, 2021.

GILCHRIST, A. **Industry 4.0**. Berkeley, CA: Apress, 2016.

GOECKS, L. S.; DE SOUZA, M.; LIBRELATO, T. P.; TRENTO, L. R. Design Science Research in practice: Review of applications in Industrial Engineering. **Gestao e Producao**, v. 28, n. 4, p. 1–19, 2021.

GÖKALP, E.; MARTINEZ, V. Digital transformation capability maturity model enabling the assessment of industrial manufacturers. **Computers in Industry**, v. 132, p. 103522, nov. 2021. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361521001299>.

GONZÁLEZ-VIDAL, A.; JIMÉNEZ, F.; GÓMEZ-SKARMETA, A. F. A methodology for energy multivariate time series forecasting in smart buildings based on feature selection. **Energy and Buildings**, v. 196, p. 71–82, ago. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0378778818338775>.

GOODALL, P.; SHARPE, R.; WEST, A. A data-driven simulation to support remanufacturing operations. **Computers in Industry**, v. 105, p. 48–60, 2019. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85057063260&doi=10.1016%2Fj.compind.2018.11.001&partnerID=40&md5=a1d957cf6c616e5397797c577180137d>.

GRAESSLER, I.; POEHLER, A. Integration of a digital twin as human representation in a scheduling procedure of a cyber-physical production system. In: IEEE International Conference on Industrial Engineering and Engineering Management, 2017, [...]. 2017. p. 289–293.

GRASSI, A.; GUIZZI, G.; SANTILLO, L. C.; VESPOLI, S. **The manufacturing planning and control system: A journey towards the new perspectives in industry 4.0 architectures**. [s.l: s.n.]v. 289193–216 p.

GRASSI, A.; GUIZZI, G.; SANTILLO, L. C.; VESPOLI, S. A semi-heterarchical production control architecture for industry 4.0-based manufacturing systems. **Manufacturing Letters**, v. 24, p. 43–46, abr. 2020b. Disponível em: <https://doi.org/10.1016/j.mfglet.2020.03.007>.

GRASSI, A.; GUIZZI, G.; SANTILLO, L. C.; VESPOLI, S. Assessing the performances of a novel decentralised scheduling approach in Industry 4.0 and cloud manufacturing contexts. **International Journal of Production Research**, v. 0, n. 0, p. 1–20, 7 ago. 2020c. Disponível em: <https://doi.org/00207543.2020.1799105>.

GRÖGER, C. Building an Industry 4.0 Analytics Platform. **Datenbank-Spektrum**, v. 18, n. 1, p. 5–14, 17 mar. 2018. Disponível em: <http://link.springer.com/10.1007/s13222-018-0273-1>.

GRUNDSTEIN, S.; FREITAG, M.; SCHOLZ-REITER, B. A new method for autonomous control of complex job shops – Integrating order release, sequencing and capacity control to meet due dates. **Journal of Manufacturing Systems**, v. 42, p. 11–28, jan. 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0278612516300711>.

GUSTAFSSON, E.; JONSSON, P.; HOLMSTRÖM, J. Digital product fitting in retail supply chains: maturity levels and potential outcomes. **Supply Chain Management: An International Journal**, v. ahead-of-p, n. ahead-of-print, p. 574–589, 22 jun. 2019. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/SCM-07-2018-0247/full/html>.

HAJIPOUR, V.; KAZEMI, A.; MOUSAVI, S. M. A fuzzy expert system to increase accuracy and precision in measurement system analysis. **Measurement: Journal of the International Measurement Confederation**, v. 46, n. 8, p. 2770–2780, 2013. Disponível em: <http://dx.doi.org/10.1016/j.measurement.2013.04.015>.

HAMADA, T. Determinants of Decision-Makers' Attitudes toward Industry 4.0 Adaptation. **Social Sciences**, v. 8, n. 5, p. 140, 6 maio 2019. Disponível em: <https://www.mdpi.com/2076-0760/8/5/140>.

HAMISTER, J. W.; MAGAZINE, M. J.; POLAK, G. G. Integrating Analytics Through the Big Data Information Chain: A Case From Supply Chain Management. **Journal of Business Logistics**, v. 39, n. 3, p. 220–230, set. 2018. Disponível em: <http://doi.wiley.com/10.1111/jbl.12192>.

HELO, P.; HAO, Y. Cloud manufacturing system for sheet metal processing. **Production Planning & Control**, v. 28, n. 6–8, p. 524–537, 11 jun. 2017. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2017.1309714>.

HELO, P.; HAO, Y.; TOSHEV, R.; BOLDOSOVA, V. Cloud manufacturing ecosystem analysis and design. **Robotics and Computer-Integrated Manufacturing**, v. 67, n. March 2019, p. 102050, fev. 2021.

Disponível em: <https://doi.org/10.1016/j.rcim.2020.102050>.

HELO, P.; PHUONG, D.; HAO, Y. Cloud manufacturing – Scheduling as a service for sheet metal manufacturing. **Computers & Operations Research**, v. 110, p. 208–219, out. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0305054818301564>.

HERMANN, M.; PENTEK, T.; OTTO, B. Design Principles for Industrie 4.0 Scenarios. In: 2016 49th Hawaii International Conference on System Sciences (HICSS), 2016, [...]. IEEE, 2016. p. 3928–3937.

HERNÁNDEZ, E.; SENNA, P.; SILVA, D.; REBELO, R.; BARROS, A. C.; TOSCANO, C. Implementing RAMI4.0 in Production - A Multi-case Study. **Lecture Notes in Mechanical Engineering**, p. 49–56, 2020. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85083067657&doi=10.1007%2F978-3-030-29041-2_6&partnerID=40&md5=dac45322cf9328da7a2187de9e688bd8>.

HEVNER, A.; CHATTERJEE, S. **Design Research in Information Systems**. Boston, MA: Springer US, 2010. v. 2262–72 p.

HEVNER, A.; GREGOR, S. Envisioning entrepreneurship and digital innovation through a design science research lens: A matrix approach. **Information & Management**, v. 59, n. 3, p. 103350, abr. 2022. Disponível em: <https://doi.org/10.1016/j.im.2020.103350>.

HEVNER; MARCH; PARK; RAM. Design Science in Information Systems Research. **MIS Quarterly**, v. 28, n. 1, p. 75, 2004. Disponível em: <https://www.jstor.org/stable/10.2307/25148625>.

HOFFMANN, M. **Smart Agents for the Industry 4.0**. Wiesbaden: Springer Fachmedien Wiesbaden, 2019.

HOLMSTRÖM, J.; HOLWEG, M.; KHAJAVI, S. H.; PARTANEN, J. The direct digital manufacturing (r)evolution: definition of a research agenda. **Operations Management Research**, v. 9, n. 1–2, p. 1–10, 18 jun. 2016. Disponível em: <http://link.springer.com/10.1007/s12063-016-0106-z>.

HOLMSTRÖM, J.; KETOKIVI, M.; HAMERI, A. P. Bridging practice and theory: A design science approach. **Decision Sciences**, v. 40, n. 1, p. 65–87, 2009.

HOWALDT, J.; KOPP, R.; SCHULTZE, J. Why Industrie 4.0 Needs Workplace Innovation—A Critical Essay About the German Debate on Advanced Manufacturing. *In*: **Workplace Innovation**. Cham: Springer, 2017. p. 45–60.

HUANG, S.; GUO, Y.; ZHA, S.; WANG, Y. An internet-of-things-based production logistics optimisation method for discrete manufacturing. **International Journal of Computer Integrated Manufacturing**, v. 32, n. 1, p. 13–26, 2 jan. 2019. Disponível em: <https://www2.scopus.com/inward/record.uri?eid=2-s2.0-85057605956&doi=10.1080%2F0951192X.2018.1550671&partnerID=40&md5=f4c0aa25a5181f92b68ad428239a8b4b>.

HWANG, Y.-M.; KIM, M. G.; RHO, J.-J. Understanding Internet of Things (IoT) diffusion. **Information Development**, v. 32, n. 4, p. 969–985, 9 set. 2016. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84982913060&doi=10.1177%25252F0266666915578201&partnerID=40&md5=5a321ec7c71ecf6c2406d83963ff8784>.

IVANOV, D.; DOLGUI, A.; SOKOLOV, B.; WERNER, F.; IVANOVA, M. A Dynamic Model and an Algorithm for Short-Term Supply Chain Scheduling in the Smart Factory Industry 4.0. **International Journal of Production Research**, v. 54, n. 2, p. 386–402, 17 jan. 2016. Disponível em: <http://www.tandfonline.com/doi/full/10.1080/00207543.2014.999958>.

JACOBS, F. R.; BERRY, W. L.; WHYBARK, D. C.; VOLLMANN, T. E. **Manufacturing planning and control for supply chain management: The CPIM Reference**. [s.l.] McGraw-Hill Education, 2018. 640 p.

JANSEN, S. A focus area maturity model for software ecosystem governance. **Information and Software Technology**, v. 118, p. 106219, fev. 2020. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0950584919302290>.

JI, W.; WANG, L. Big data analytics based fault prediction for shop floor scheduling. **Journal of Manufacturing Systems**, v. 43, p. 187–194, 2017. Disponível em:

<https://www.scopus.com/inward/record.uri?eid=2-s2.0-85017029120&doi=10.1016%2Fj.jmsy.2017.03.008&partnerID=40&md5=d02cb5c9a38da78d9d9870b37c041d9d>.

JIANG, H.; GAO, S.; ZHAO, S.; CHEN, H. Competition of technology standards in Industry 4.0: An innovation ecosystem perspective. **Systems Research and Behavioral Science**, v. 37, n. 4, p. 772–783, 2020.

JIANG, R.; KLEER, R.; PILLER, F. T. Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. **Technological Forecasting and Social Change**, v. 117, p. 84–97, abr. 2017. Disponível em: <http://dx.doi.org/10.1016/j.techfore.2017.01.006>.

JIANG, T.; ZHANG, C.; SUN, Q. M. Green Job Shop Scheduling Problem with Discrete Whale Optimization Algorithm. **IEEE Access**, v. 7, p. 43153–43166, 2019.

JIANG, Z.; JIN, Y.; E, M.; LI, Q. Distributed Dynamic Scheduling for Cyber-Physical Production Systems Based on a Multi-Agent System. **IEEE Access**, v. 6, p. 1855–1869, 2018. Disponível em: <https://ieeexplore.ieee.org/document/8168335/>.

JONSSON, P.; MATTSSON, S. The implications of fit between planning environments and manufacturing planning and control methods. **International Journal of Operations & Production Management**, v. 23, n. 8, p. 872–900, ago. 2003. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/01443570310486338/full/html>.

JOSLIN, R.; MÜLLER, R. Identifying interesting project phenomena using philosophical and methodological triangulation. **International Journal of Project Management**, v. 34, n. 6, p. 1043–1056, 2016.

KAGERMANN, H.; HELBIG, J.; HELLINGER, A. **Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working GroupAcatech**. [s.l: s.n.].

KAMALAHMADI, M.; PARAST, M. M. A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. **International Journal of Production Economics**, v. 171, p. 116–133, jan. 2016. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527315004041>.

KAMPKER, A.; FRANK, J.; EMONTS-HOLLEY, R.; PHILIPP JUSSEN. **Advances in Production Management Systems. Smart Manufacturing for Industry 4.0**. Cham: Springer International Publishing, 2018. v. 536477–484 p.

KANG, H. S.; NOH, S. Do; SON, J. Y.; KIM, H.; PARK, J. H.; LEE, J. Y. The FaaS system using additive manufacturing for personalized production. **Rapid Prototyping Journal**, v. 24, n. 9, p. 1486–1499, 12 nov. 2018. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/RPJ-11-2016-0195/full/html>.

KASSNER, L.; GRÖGER, C.; KÖNIGSBERGER, J.; HOOS, E.; KIEFER, C.; WEBER, C.; SILCHER, S.; MITSCHANG, B. The Stuttgart IT Architecture for Manufacturing. n. 2017, p. 53–80, 2017.

KATCHASUWANMANEE, K.; BATEMAN, R.; CHENG, K. Development of the Energy-smart Production Management system (e-ProMan): A Big Data driven approach, analysis and optimisation. **Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture**, v. 230, n. 5, p. 972–978, maio 2016. Disponível em: <http://journals.sagepub.com/doi/10.1177/0954405415586711>.

KENDIG, C. E. What is Proof of Concept Research and how does it Generate Epistemic and Ethical Categories for Future Scientific Practice? **Science and Engineering Ethics**, v. 22, n. 3, p. 735–753, 2016.

KIEL, D.; MÜLLER, J. M.; ARNOLD, C.; VOIGT, K.-I. SUSTAINABLE INDUSTRIAL VALUE CREATION: BENEFITS AND CHALLENGES OF INDUSTRY 4.0. **International Journal of Innovation Management**, v. 21, n. 08, p. 1740015, 11 dez. 2017. Disponível em: <https://www.worldscientific.com/doi/abs/10.1142/S1363919617400151>.

KIM, H.-J. Bounds for Parallel Machine Scheduling with Predefined Parts of Jobs and Setup Time. **Annals of Operations Research**, v. 261, n. 1–2, p. 401–412, fev. 2018. Disponível em: <http://link.springer.com/10.1007/s10479-017-2615-z>.

KIM, S.; PÉREZ-CASTILLO, R.; CABALLERO, I.; LEE, D. Organizational process maturity model for IoT data quality management. **Journal of Industrial Information Integration**, n. xxxx, 2021.

KLIR, GEORGE, J.; YUAN, B. **Fuzzy sets and fuzzy logic: Theory and applications**. Upper Saddle River: Prentice Hall PTR, 1996. v. 2044 p.

KOCH, J.; GRITSCH, A.; REINHART, G. Process design for the management of changes in manufacturing: Toward a Manufacturing Change Management process. **CIRP Journal of Manufacturing Science and Technology**, v. 14, p. 10–19, ago. 2016. Disponível em: <http://dx.doi.org/10.1016/j.cirpj.2016.04.010>.

KONDRATENKO, Y.; KONDRATENKO, G.; SIDENKO, I. Multi-criteria decision making for selecting a rational IoT platform. **Proceedings of 2018 IEEE 9th International Conference on Dependable Systems, Services and Technologies, DESSERT 2018**, p. 147–152, 2018.

KONG, X. T. R.; FANG, J.; LUO, H.; HUANG, G. Q. Cloud-enabled real-time platform for adaptive planning and control in auction logistics center. **Computers & Industrial Engineering**, v. 84, p. 79–90, jun. 2015. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835214003660>.

KRUMEICH, J.; WERTH, D.; LOOS, P. Prescriptive Control of Business Processes. **Business & Information Systems Engineering**, v. 58, n. 4, p. 261–280, 7 ago. 2016. Disponível em: <http://link.springer.com/10.1007/s12599-015-0412-2>.

KUNOVJANEK, M.; REINER, G. How will the diffusion of additive manufacturing impact the raw material supply chain process? **International Journal of Production Research**, v. 58, n. 5, p. 1540–1554, 3 mar. 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2019.1661537>.

KUSIAK, A. Smart manufacturing. **International Journal of Production Research**, v. 56, n. 1–2, p. 508–517, jan. 2018.

LACERDA, D. P.; DRESCH, A.; PROENÇA, A.; ANTUNES JÚNIOR, J. A. V. Design Science Research: A research method to production engineering. **Gestao e Producao**, v. 20, n. 4, p. 741–761, 2013.

LACERDA, T. C.; VON WANGENHEIM, C. Systematic literature review of usability capability/maturity models. **Computer Standards & Interfaces**, v. 55, n. December 2016, p. 95–105, jan. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0920548916302355>.

LAMBA, K.; SINGH, S. P. Modeling big data enablers for operations and supply chain management. **The International Journal of Logistics Management**, v. 29, n. 2, p. 629–658, 14 maio 2018. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/IJLM-07-2017-0183/full/html>.

LEE, C.-Y.; LIANG, C.-L. Manufacturer’s printing forecast, reprinting decision, and contract design in the educational publishing industry. **Computers & Industrial Engineering**, v. 125, p. 678–687, nov. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835218302584>.

LEE, J.; BAGHERI, B.; KAO, H.-A. A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. **Manufacturing Letters**, v. 3, p. 18–23, jan. 2015. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S221384631400025X>.

LEVY, Y.; J. ELLIS, T. A Systems Approach to Conduct an Effective Literature Review in Support of Information Systems Research. **Informing Science: The International Journal of an Emerging Transdiscipline**, v. 9, p. 181–212, 2006. Disponível em: <https://www.informingscience.org/Publications/479>.

LEWIS, M. W. Iterative triangulation: A theory development process using existing case studies. **Journal of Operations Management**, v. 16, n. 4, p. 455–469, 1998.

LI, Q.; KUCUKKOC, I.; ZHANG, D. Z. Production planning in additive manufacturing and 3D printing. **Computers & Operations Research**, v. 83, p. 157–172, jul. 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0305054817300138>.

LI, Q.; TANG, Q.; CHAN, I.; WEI, H.; PU, Y.; JIANG, H.; LI, J.; ZHOU, J. Smart manufacturing standardization: Architectures, reference models and standards framework. **Computers in Industry**, v. 101, n. April, p. 91–106, 2018. Disponível em: <https://doi.org/10.1016/j.compind.2018.06.005>.

LI, Q.; ZHANG, D.; WANG, S.; KUCUKKOC, I. A dynamic order acceptance and scheduling approach for additive manufacturing on-demand production. **The International Journal of Advanced Manufacturing Technology**, v. 105, n. 9, p. 3711–3729, 14 dez. 2019. Disponível em: <http://link.springer.com/10.1007/s00170-019-03796-x>.

LIAO, W.; WANG, T. A Novel Collaborative Optimization Model for Job Shop Production–Delivery Considering Time Window and Carbon Emission. **Sustainability**, v. 11, n. 10, p. 2781, 15 maio 2019. Disponível em: <https://www.mdpi.com/2071-1050/11/10/2781>.

LIAO, Y.; DESCHAMPS, F.; LOURES, E. de F. R.; RAMOS, L. F. P. Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. **International Journal of Production Research**, v. 55, n. 12, p. 3609–3629, 18 jun. 2017. Disponível em: <http://dx.doi.org/10.1080/00207543.2017.1308576>.

LIBONI, L. B.; CEZARINO, L. O.; JABBOUR, C. J. C.; OLIVEIRA, B. G.; STEFANELLI, N. O. Smart industry and the pathways to HRM 4.0: implications for SCM. **Supply Chain Management**, v. 24, n. 1, p. 124–146, 2019.

LICHTBLAU, K.; STICH, V.; BERTENRATH, R.; BLUM, M.; BLEIDER, M.; MILLACK, A.; SCHMITT, K.; SCHMITZ, E.; SCHRÖTER, M. **IMPULS: INDUSTRIE 4.0-READINESS**. [s.l: s.n.].

LIN, F.; WONG, M. C.; GE, M. Development of the digital model of the jewellery production process for resource optimisation and prediction. **HKIE Transactions**, v. 25, n. 4, p. 229–236, 2 out. 2018. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/1023697X.2018.1535284>.

LIN, P.; LI, M.; KONG, X.; CHEN, J.; HUANG, G. Q.; WANG, M. Synchronisation for smart factory - towards IoT-enabled mechanisms. **International Journal of Computer Integrated Manufacturing**, v. 31, n. 7, p. 624–635, 3 jul. 2018. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/0951192X.2017.1407445>.

LIN, P.; SHEN, L.; ZHAO, Z.; HUANG, G. Q. Graduation manufacturing system: synchronization with IoT-enabled smart tickets. **Journal of Intelligent Manufacturing**, v. 30, n. 8, p. 2885–2900, 18 dez. 2019. Disponível em: <http://link.springer.com/10.1007/s10845-018-1429-4>.

LIN, Y.; CHONG, C. S. Fast GA-based project scheduling for computing resources allocation in a cloud manufacturing system. **Journal of Intelligent Manufacturing**, v. 28, n. 5, p. 1189–1201, 8 jun. 2017. Disponível em: <http://link.springer.com/10.1007/s10845-015-1074-0>.

LIU, P.; HUANG, S. H.; MOKASDAR, A.; ZHOU, H.; HOU, L. The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis. **Production Planning & Control**, v. 25, n. 13–14, p. 1169–1181, 26 out. 2014. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2013.808835>.

LOLLI, F.; BALUGANI, E.; ISHIZAKA, A.; GAMBERINI, R.; RIMINI, B.; REGATTIERI, A. Machine learning for multi-criteria inventory classification applied to intermittent demand. **Production Planning & Control**, v. 30, n. 1, p. 76–89, 2 jan. 2019. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2018.1525506>.

LONGO, F.; NICOLETTI, L.; PADOVANO, A. Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. **Computers and Industrial Engineering**, v. 113, p. 144–159, 2017. Disponível em: <https://doi.org/10.1016/j.cie.2017.09.016>.

LU, Y.; MORRIS, K.; FRECHETTE, S. **Current Standards Landscape for Smart Manufacturing Systems**. [s.l: s.n.]v. 810739 p.

LUCATO, W. C.; PACCHINI, A. P. T.; FACCHINI, F.; MUMMOLO, G. Model to evaluate the Industry 4.0 readiness degree in Industrial Companies. **IFAC-PapersOnLine**, v. 52, n. 13, p. 1808–1813, 2019. Disponível em: <https://doi.org/10.1016/j.ifacol.2019.11.464>.

MA, A.; NASSEHI, A.; SNIDER, C. Anarchic manufacturing. **International Journal of Production Research**, v. 57, n. 8, p. 2514–2530, 18 abr. 2019. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85053542258&doi=10.1080%252F00207543.2018.1521534&partnerID=40&md5=c5d72fd22f28dcce02ed1434e2512b0b>.

MACHADO, C. G.; WINROTH, M.; CARLSSON, D.; ALMSTRÖM, P.; CENTERHOLT, V.; HALLIN,

M. Industry 4.0 readiness in manufacturing companies: Challenges and enablers towards increased digitalization. **Procedia CIRP**, v. 81, p. 1113–1118, 2019. Disponível em: <https://doi.org/10.1016/j.procir.2019.03.262>.

MAESTRINI, V.; LUZZINI, D.; MACCARRONE, P.; CANIATO, F. Supply chain performance measurement systems: A systematic review and research agenda. **International Journal of Production Economics**, v. 183, p. 299–315, jan. 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527316303292>.

MAIER, A. M.; MOULTRIE, J.; CLARKSON, P. J. Assessing organizational capabilities: Reviewing and guiding the development of maturity grids. **IEEE Transactions on Engineering Management**, v. 59, n. 1, p. 138–159, 2012.

MAMDANI, E. H.; ASSILIAN, S. An experiment in linguistic synthesis with a fuzzy logic controller. **International Journal of Man-Machine Studies**, v. 7, n. 1, p. 1–13, 1975.

MAN, L. C. K.; NA, C. M.; KIT, N. C. IoT-Based Asset Management System for Healthcare-Related Industries. **International Journal of Engineering Business Management**, v. 7, p. 19, 3 fev. 2015. Disponível em: <http://journals.sagepub.com/doi/10.5772/61821>.

MANAVALAN, E.; JAYAKRISHNA, K. A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. **Computers & Industrial Engineering**, v. 127, n. November 2017, p. 925–953, jan. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835218305709>.

MARNEWICK, C.; MARNEWICK, A. L. The Demands of Industry 4.0 on Project Teams. **IEEE Transactions on Engineering Management**, v. 67, n. 3, p. 1–9, 2019. Disponível em: <https://ieeexplore.ieee.org/document/8673643/>.

MATHABA, S.; ADIGUN, M.; OLADOSU, J.; OKI, O. On the use of the Internet of Things and Web 2.0 in inventory management. **Journal of Intelligent & Fuzzy Systems**, v. 32, n. 4, p. 3091–3101, 29 mar. 2017. Disponível em: <http://www.medra.org/servlet/aliasResolver?alias=iospress&doi=10.3233/JIFS-169252>.

METTLER, T. Thinking in Terms of Design Decisions When Developing Maturity Models. **International Journal of Strategic Decision Sciences**, v. 1, n. 4, p. 76–87, out. 2010. Disponível em: <http://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/jsds.2010100105>.

METTLER, T.; BALLESTER, O. Maturity Models in Information Systems: A Review and Extension of Existing Guidelines. n. 2017, p. 1, 2021. Disponível em: <https://www.researchgate.net/publication/355350937>.

MEYER, G. G.; (HANS) WORTMANN, J. C.; SZIRBIK, N. B. Production monitoring and control with intelligent products. **International Journal of Production Research**, v. 49, n. 5, p. 1303–1317, mar. 2011. Disponível em: <http://www.tandfonline.com/doi/abs/10.1080/00207543.2010.518742>.

MITTAL, S.; KHAN, M. A.; ROMERO, D.; WUEST, T. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). **Journal of Manufacturing Systems**, v. 49, n. June, p. 194–214, out. 2018. Disponível em: <https://doi.org/10.1016/j.jmsy.2018.10.005>.

MODICA, T.; COLICCHIA, C.; TAPPIA, E.; MELACINI, M. Empowering freight transportation through Logistics 4.0: a maturity model for value creation. **Production Planning and Control**, v. 0, n. 0, p. 1–16, 2021. Disponível em: <https://doi.org/10.1080/09537287.2021.1988176>.

MOEUF, A.; PELLERIN, R.; LAMOURI, S.; TAMAYO-GIRALDO, S.; BARBARAY, R. The industrial management of SMEs in the era of Industry 4.0. **INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH**, v. 56, n. 3, p. 1118–1136, 2018.

MOHER, D.; LIBERATI, A.; TETZLAFF, J.; ALTMAN, D. G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. **PLoS Medicine**, v. 6, n. 7, p. e1000097, 21 jul. 2009. Disponível em: <https://dx.plos.org/10.1371/journal.pmed.1000097>.

MOONEY, J. G.; GURBAXANI, V.; KRAEMER, K. L. A Process Oriented Framework for Assessing the Business Value of Information Technology. **Data Base for Advances in Information Systems**, v. 27, n. 2, p. 68–81, 1996.

MOURTZIS, D.; VLACHOU, E. A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance. **Journal of Manufacturing Systems**, v. 47, p. 179–198, abr. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0278612518300700>.

MUIR, M.; HADDUD, A. Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain. **Journal of Manufacturing Technology Management**, v. 29, n. 2, p. JMTM-01-2017-0004, 28 dez. 2017. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/JMTM-01-2017-0004/full/html>.

NAHMIAS, S.; OLSEN, T. L. **Production and Operations Analysis**. [s.l: s.n.]840 p.

NAYERNIA, H.; BAHEMIA, H.; PAPAGIANNIDIS, S. A systematic review of the implementation of industry 4.0 from the organisational perspective. **International Journal of Production Research**, 2021. Disponível em: <https://doi.org/10.1080/00207543.2021.2002964>.

NEFF, A. A.; HAMEL, F.; HERZ, T. P.; UEBERNICKEL, F.; BRENNER, W.; VOM BROCKE, J. Developing a maturity model for service systems in heavy equipment manufacturing enterprises. **Information and Management**, v. 51, n. 7, p. 895–911, 2014. Disponível em: <http://dx.doi.org/10.1016/j.im.2014.05.001>.

NING, C.; YOU, F. Data-driven decision making under uncertainty integrating robust optimization with principal component analysis and kernel smoothing methods. **Computers & Chemical Engineering**, v. 112, p. 190–210, abr. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0098135418300693>.

NORAN, O. Using Reference Models in Enterprise Architecture. *In*: **Reference Modeling for Business Systems Analysis**. [s.l.] IGI Global, 2011. p. 0–24.

NORMANN ANDERSEN, K.; LEE, J.; METTLER, T.; MOON, M. J. Ten misunderstandings about maturity models. **ACM International Conference Proceeding Series**, p. 261–266, 2020.

OLHAGER, J. Evolution of operations planning and control: from production to supply chains. **International Journal of Production Research**, v. 51, n. 23–24, p. 6836–6843, 18 nov. 2013. Disponível em: <http://www.tandfonline.com/doi/full/10.1080/00207543.2012.761363>.

OLHAGER, J.; RUDBERG, M. Linking manufacturing strategy decisions on process choice with manufacturing planning and control systems. **International Journal of Production Research**, v. 40, n. 10, p. 2335–2351, jan. 2002. Disponível em: <http://www.tandfonline.com/doi/abs/10.1080/00207540210131842>.

OLUYISOLA, O. E.; BHALLA, S.; SGARBOSSA, F.; STRANDHAGEN, J. O. Designing and developing smart production planning and control systems in the industry 4.0 era: a methodology and case study. **Journal of Intelligent Manufacturing**, n. 0123456789, 2021.

OLUYISOLA, O. E.; SGARBOSSA, F.; STRANDHAGEN, J. O. Smart Production Planning and Control : Concept , Use-Cases and Sustainability Implications. 2020.

ORELLANA, F.; TORRES, R. From legacy-based factories to smart factories level 2 according to the industry 4.0. **International Journal of Computer Integrated Manufacturing**, v. 32, n. 4–5, p. 441–451, 4 maio 2019. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/0951192X.2019.1609702>.

OZTEMEL, E.; GURSEV, S. Literature review of Industry 4.0 and related technologies. **Journal of Intelligent Manufacturing**, v. 31, n. 1, p. 127–182, 2020.

PACAUX-LEMOINE, M. P.; TRENTESAUX, D.; ZAMBRANO REY, G.; MILLOT, P. Designing intelligent manufacturing systems through Human-Machine Cooperation principles: A human-centered approach. **Computers and Industrial Engineering**, v. 111, p. 581–595, 2017. Disponível em: <http://dx.doi.org/10.1016/j.cie.2017.05.014>.

PACCHINI, A. P. T.; LUCATO, W. C.; FACCHINI, F.; MUMMOLO, G. The degree of readiness for the implementation of Industry 4.0. **Computers in Industry**, v. 113, p. 103125, dez. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361519303835>.

PAGH, J. D.; COOPER, M. Supply Chain Postponement and Speculation Strategies: How to choose the right strategy. **Journal of Buesiness Logistics**, v. 19, n. 2, p. 13, 1998.

PALASCIANO, C.; THIEDE, B.; TAISCH, M.; HERRMANN, C. **Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing**. Cham: Springer International Publishing, 2017. v. 513

PARENTE, M.; FIGUEIRA, G.; AMORIM, P.; MARQUES, A. Production scheduling in the context of Industry 4.0: review and trends. **International Journal of Production Research**, v. 58, n. 17, p. 5401–5431, 1 set. 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2020.1718794>.

PARIDA, V.; SJÖDIN, D. R.; LENKA, S.; WINCENT, J. Developing global service innovation capabilities :How global manufacturers address the challenges of market heterogeneity. **Research Technology Management**, v. 58, n. 5, p. 35–44, 2015.

PASETTI MONIZZA, G.; BENDETTI, C.; MATT, D. T. Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry. **Automation in Construction**, v. 92, p. 270–285, ago. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0926580517305642>.

PEFFERS, K.; TUUNANEN, T.; ROTHENBERGER, M. A.; CHATTERJEE, S. A design science research methodology for information systems research. **Journal of Management Information Systems**, v. 24, n. 3, p. 45–77, 2007.

PETERS, V. J. T.; MEIJBOOM, B. R.; DE VRIES, E. Interfaces in service modularity: a scoping review. **International Journal of Production Research**, v. 56, n. 20, p. 6591–6606, 2018. Disponível em: <https://doi.org/10.1080/00207543.2018.1461270>.

PILLER, F. **Sustainability Ten propositions how digital business models foster sustainability The working group " Digital Business Models " of**. [s.l: s.n.]. Disponível em: <https://ssrn.com/abstract=3996223 1>.

PLOMP, M. G. A.; BATENBURG, R. S. Measuring chain digitisation maturity: An assessment of Dutch retail branches. **Supply Chain Management**, v. 15, n. 3, p. 227–237, 2010.

PÖPPELBUSS, J.; RÖGLINGER, M. What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management. **19th European Conference on Information Systems, ECIS 2011**, p. Pöppelbuß, J., Röglinger, M. (2011). What makes, 2011.

PRATHIMA, B. A.; SUDHA, P. N.; SURESH, P. M. Shop floor to cloud connect for live monitoring the production data of CNC machines. **INTERNATIONAL JOURNAL OF COMPUTER INTEGRATED MANUFACTURING**, v. 33, n. 2, p. 142–158, 2020.

QU, T.; YANG, H. D.; HUANG, G. Q.; ZHANG, Y. F.; LUO, H.; QIN, W. A case of implementing RFID-based real-time shop-floor material management for household electrical appliance manufacturers. **Journal of Intelligent Manufacturing**, v. 23, n. 6, p. 2343–2356, 4 dez. 2012. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84870947362&doi=10.1007%2Fs10845-010-0476-2&partnerID=40&md5=1984c4a630a68a61cb46d94b218802e9>.

QU, Y. J.; MING, X. G.; LIU, Z. W.; ZHANG, X. Y.; HOU, Z. T. Smart manufacturing systems: state of the art and future trends. **International Journal of Advanced Manufacturing Technology**, v. 103, n. 9–12, p. 3751–3768, 2019.

RAFAEL, L. D.; JAIONE, G. E.; CRISTINA, L.; IBON, S. L. An Industry 4.0 maturity model for machine tool companies. **Technological Forecasting and Social Change**, v. 159, n. July, p. 120203, out. 2020. Disponível em: <https://doi.org/10.1016/j.techfore.2020.120203>.

RAFF, S.; WENTZEL, D.; OBWEGESER, N. Smart Products: Conceptual Review, Synthesis, and Research Directions. **Journal of Product Innovation Management**, v. 37, n. 5, p. 379–404, 2020.

RĂILEANU, S.; ANTON, F.; BORANGIU, T.; ANTON, S.; NICOLAE, M. A cloud-based manufacturing control system with data integration from multiple autonomous agents. **Computers in Industry**, v. 102, p. 50–61, nov. 2018. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85052998214&doi=10.1016%2Fj.compind.2018.08.004&partnerID=40&md5=54b0fc76e8fe4bf346a20950279a312d>.

RAJ, A.; DWIVEDI, G.; SHARMA, A.; LOPES DE SOUSA JABBOUR, A. B.; RAJAK, S. Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective. **International Journal of Production Economics**, v. 224, p. 107546, jun. 2020. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S092552731930372X>.

RAMAKRISHNAN, R.; GAUR, L.; SINGH, G. Feasibility and Efficacy of BLE Beacon IoT Devices in Inventory Management at the Shop Floor. **International Journal of Electrical and Computer Engineering (IJECE)**, v. 6, n. 5, p. 2362, 1 out. 2016. Disponível em: <http://www.iaescore.com/journals/index.php/IJECE/article/view/1164>.

RAMOS, L.; LOURES, E.; DESCHAMPS, F.; VENÂNCIO, A. Systems evaluation methodology to attend the digital projects requirements for industry 4.0. **International Journal of Computer Integrated Manufacturing**, v. 33, n. 4, p. 398–410, 2 abr. 2020. Disponível em: <https://doi.org/10.1080/0951192X.2019.1699666>.

RAUCH, E.; DALLASEGA, P.; MATT, D. T. Complexity reduction in engineer-to-order industry through real-time capable production planning and control. **Production Engineering**, v. 12, n. 3–4, p. 341–352, 15 jun. 2018. Disponível em: <http://link.springer.com/10.1007/s11740-018-0809-0>.

REHSE, J.-R.; DADASHNIA, S.; FETTKE, P. Business process management for Industry 4.0 Three application cases in the DFKI-Smart-Lego-Factory. **IT-INFORMATION TECHNOLOGY**, v. 60, n. 3, p. 133–141, jun. 2018.

REINHARD, G.; JESPER, V.; STEFAN, S. Industry 4.0: Building the digital enterprise. **2016 Global Industry 4.0 Survey**, 2016.

RODEN, S.; NUCCIARELLI, A.; LI, F.; GRAHAM, G. Big data and the transformation of operations models: a framework and a new research agenda. **Production Planning & Control**, v. 28, n. 11–12, p. 929–944, 10 set. 2017. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2017.1336792>.

RÖGLINGER, M.; PÖPPELBUSS, J.; BECKER, J. Maturity models in business process management. **Business Process Management Journal**, v. 18, n. 2, p. 328–346, 2012.

ROMERO-SILVA, R.; HERNÁNDEZ-LÓPEZ, G. Shop-floor scheduling as a competitive advantage: A study on the relevance of cyber-physical systems in different manufacturing contexts. **International Journal of Production Economics**, v. 224, n. November 2019, p. 107555, jun. 2020. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527319303895>.

RONDEAU, P. J.; LITTERAL, L. a. Evolution of manufacturing planning and control systems: from reorder point to enterprise resources planning. **Production and Inventory Management Journal**, v. 42, n. 2, p. 1–7, 2001.

ROSEMANN, M.; DE BRUIN, T. Towards a business process mangement maturity model. **Proceedings of the 13th European Conference on Information Systems, Information Systems in a Rapidly Changing Economy, ECIS 2005**, n. January, 2005.

ROSSIT, D. A.; TOHMÉ, F.; FRUTOS, M. A data-driven scheduling approach to smart manufacturing. **Journal of Industrial Information Integration**, 2019a. Disponível em: <https://www2.scopus.com/inward/record.uri?eid=2-s2.0-85065042772&doi=10.1016%2Fj.jii.2019.04.003&partnerID=40&md5=66fde6a66bc8817dc71ddb436b4317f6>.

ROSSIT, D. A.; TOHMÉ, F.; FRUTOS, M. Production planning and scheduling in Cyber-Physical Production Systems: a review. **International Journal of Computer Integrated Manufacturing**, v. 32, n. 4–5, p. 385–395, 4 maio 2019b. Disponível em: <https://www2.scopus.com/inward/record.uri?eid=2-s2.0-85064663595&doi=10.1080%2F0951192X.2019.1605199&partnerID=40&md5=d567b61c3068bd70f32864fd2701de35>.

ROSSIT, D. A.; TOHMÉ, F.; FRUTOS, M. Industry 4.0: Smart Scheduling. **International Journal of Production Research**, v. 57, n. 12, p. 3802–3813, 18 jun. 2019c. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2018.1504248>.

ROSSIT, D. A.; TOHMÉ, F.; FRUTOS, M. A data-driven scheduling approach to smart manufacturing. **Journal of Industrial Information Integration**, v. 15, p. 69–79, set. 2019d. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S2452414X18300475>.

SAAD, S. M.; BAHADORI, R.; JAFARNEJAD, H. The smart SME technology readiness assessment methodology in the context of industry 4.0. **Journal of Manufacturing Technology Management**, v. ahead-of-p, n. ahead-of-print, 2021.

SALAH, D.; PAIGE, R.; CAIRNS, P. An Evaluation Template for Expert Review of Maturity Models. *In*: JEDLITSCHKA, A.; KUVAJA, P.; KUHRMANN, M.; MÄNNISTÖ, T.; RAATIKAINEN; MIKKO, J. M. **Product-Focused Software Process Improvement**. [s.l.] Springer, 2014.

SANTOS, M. Y.; OLIVEIRA E SÁ, J.; ANDRADE, C.; VALE LIMA, F.; COSTA, E.; COSTA, C.; MARTINHO, B.; GALVÃO, J. A Big Data system supporting Bosch Braga Industry 4.0 strategy. **International Journal of Information Management**, v. 37, n. 6, p. 750–760, dez. 2017. Disponível em: <http://dx.doi.org/10.1016/j.ijinfomgt.2017.07.012>.

SANTOS, R. C.; MARTINHO, J. L. An Industry 4.0 maturity model proposal. **Journal of Manufacturing Technology Management**, v. 31, n. 5, p. 1023–1043, 9 dez. 2019. Disponível em: <https://www.emerald.com/insight/content/doi/10.1108/JMTM-09-2018-0284/full/html>.

SAUNDERS, B.; SIM, J.; KINGSTONE, T.; BAKER, S.; WATERFIELD, J.; BARTLAM, B.; BURROUGHS, H.; JINKS, C. Saturation in qualitative research: exploring its conceptualization and operationalization. **Quality and Quantity**, v. 52, n. 4, p. 1893–1907, 2018.

SAUNDERS, M. N. K.; LEWIS, P.; THORNHILL, A. **Research Methods for Business Students**. New York, USA: Pearson, 2019.

SCHMITZ, S.; HAGEMANN, M. **How to transform manufacturing companies: Industrie 4.0 at scale**. [s.l: s.n.]. Disponível em: <www.i40mc.de>.

SCHUH, G.; ANDERL, R.; GAUSEMEIER, J.; TEN HOMPEL, M.; WAHLSTER, W. **Industrie 4.0 Maturity IndexAcatech Study**. [s.l: s.n.].

SCHUMACHER, A.; EROL, S.; SIHN, W. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. **Procedia CIRP**, v. 52, p. 161–166, 2016. Disponível em: <http://dx.doi.org/10.1016/j.procir.2016.07.040>.

ŞEN, E.; İRGE, N. T. Industry 4.0 and Agile Firms. *In*: **Agile Business Leadership Methods for Industry 4.0**. [s.l.] Emerald Publishing Limited, 2020. p. 209–231.

SHAMSUZZOHA, A.; TOSCANO, C.; CARNEIRO, L. M.; KUMAR, V.; HELO, P. ICT-based solution approach for collaborative delivery of customised products. **Production Planning & Control**, v. 27, n. 4, p. 280–298, 11 mar. 2016. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2015.1123322>.

SHI-WAN, L.; BRADFORD, M.; JACQUES, D.; GRAHAM, B.; CHIGANI, A.; MARTIN, R.; MURPHY, B.; CRAWFORD, M. The Industrial Internet of Things Volume G1 : Reference Architecture. **Industrial Internet Consortium White Paper**, v. Version 1., p. 58 Seiten, 2017.

SIMCHI-LEVI, D.; WU, M. X. Powering retailers' digitization through analytics and automation. **INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH**, v. 56, n. 1–2, SI, p. 809–816, 2018a.

SIMCHI-LEVI, D.; WU, M. X. Powering retailers' digitization through analytics and automation. **International Journal of Production Research**, v. 56, n. 1–2, p. 809–816, 17 jan. 2018b. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2017.1404161>.

SJÖDIN, D. R.; PARIDA, V.; LEKSELL, M.; PETROVIC, A. Smart Factory Implementation and Process Innovation. **Research-Technology Management**, v. 61, n. 5, p. 22–31, 3 set. 2018. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/08956308.2018.1471277>.

SKYTTNER, L. **General Systems Theory: Problems, Perspectives, Practice**. [s.l.] World Scientific Publishing Co. Pte Ltd, 2005.

SOARES, G. P.; TORTORELLA, G.; BOUZON, M.; TAVANA, M. A fuzzy maturity-based method for lean supply chain management assessment. **International Journal of Lean Six Sigma**, 2021.

SOFTWARE ENGINEERING INSTITUTE. CMMI for Development, Version 1.3. **Software Engineering Process Management Program**, n. November, p. 1–520, 2010.

SONI, G.; KODALI, R. **A critical review of supply chain management frameworks: Proposed framework**. [s.l: s.n.]v. 20263–298 p.

SONY, M.; NAIK, S. Critical factors for the successful implementation of Industry 4.0: a review and future research direction. **Production Planning and Control**, v. 31, n. 10, p. 799–815, 2020a. Disponível em: <https://doi.org/10.1080/09537287.2019.1691278>.

SONY, M.; NAIK, S. Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model. **Technology in Society**, v. 61, n. March, p. 101248, 2020b. Disponível em: <https://doi.org/10.1016/j.techsoc.2020.101248>.

SOTO SETZKE, D.; BÖHM, M.; KRCMAR, H. The Role of Openness and Extension Modularization in Value Capture for Platform-Based Digital Transformation. *In*: **Lecture Notes in Business Information Processing**. [s.l: s.n.]p. 145–156.

SOUSA, R.; VOSS, C. A. Contingency research in operations management practices. **Journal of Operations Management**, v. 26, n. 6, p. 697–713, nov. 2008. Disponível em: <http://doi.wiley.com/10.1016/j.jom.2008.06.001>.

SPENHOFF, P.; WORTMANN, J. C.; SEMINI, M. EPEC 4.0: an Industry 4.0-supported lean production control concept for the semi-process industry. **Production Planning and Control**, v. 0, n. 0, p. 1–18, 2020. Disponível em: <https://doi.org/10.1080/09537287.2020.1864496>.

SRAI, J. S.; KUMAR, M.; GRAHAM, G.; PHILLIPS, W.; TOOZE, J.; FORD, S.; BEECHER, P.; RAJ, B.; GREGORY, M.; TIWARI, M. K.; RAVI, B.; NEELY, A.; SHANKAR, R.; CHARNLEY, F.; TIWARI, A. Distributed manufacturing: scope, challenges and opportunities. **International Journal of Production Research**, v. 54, n. 23, p. 6917–6935, 16 dez. 2016. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2016.1192302>.

STICH, V. P.; HERING, N.; MEISSNER, J. Cyber Physical Production Control. *In*: UMEDA, S AND NAKANO, M AND MIZUYAMA, H AND HIBINO, H AND KIRITSIS, D AND VONCIEMINSKI, G. **ADVANCES IN PRODUCTION MANAGEMENT SYSTEMS: INNOVATIVE PRODUCTION MANAGEMENT TOWARDS SUSTAINABLE GROWTH (AMPS 2015), PT I**. IFIP Advances in Information and Communication Technology. HEIDELBERGER PLATZ 3, D-14197 BERLIN, GERMANY: SPRINGER-VERLAG BERLIN, 2015. p. 308–315.

STONEBRAKER, M.; ILYAS, I. F. Data Integration: The Current Status and the Way Forward. **IEEE Data Eng. Bull.**, 2018.

STRANDHAGEN, J. W.; ALFNES, E.; STRANDHAGEN, J. O.; VALLANDINGHAM, L. R. The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study. **Advances in Manufacturing**, v. 5, n. 4, p. 344–358, 2 dez. 2017. Disponível em: <http://link.springer.com/10.1007/s40436-017-0200-y>.

SUBRAMANIYAN, M.; SKOOGH, A.; SALOMONSSON, H.; BANGALORE, P.; BOKRANTZ, J. A data-driven algorithm to predict throughput bottlenecks in a production system based on active periods of the machines. **Computers & Industrial Engineering**, v. 125, p. 533–544, nov. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835218301608>.

TABESH, P.; MOUSAVIDIN, E.; HASANI, S. Implementing big data strategies: A managerial perspective. **Business Horizons**, v. 62, n. 3, p. 347–358, maio 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S000768131930028X>.

TANG, D.; ZHENG, K.; ZHANG, H.; ZHANG, Z.; SANG, Z.; ZHANG, T.; ESPINOSA-OVIEDO, J. A.; VARGAS-SOLAR, G. Using autonomous intelligence to build a smart shop floor. **International Journal of Advanced Manufacturing Technology**, v. 94, n. 5–8, p. 1597–1606, 2018.

TAO, F.; ZHANG, M. Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. **IEEE Access**, v. 5, p. 20418–20427, 2017. Disponível em: <http://ieeexplore.ieee.org/document/8049520/>.

TAO, F.; ZHANG, M.; NEE, A. Y. C. **Digital Twin Driven Smart Manufacturing**. Cennai: Elsevier, 2019.

TEJESH, B. S. S.; NEERAJA, S. Warehouse inventory management system using IoT and open source framework. **Alexandria Engineering Journal**, v. 57, n. 4, p. 3817–3823, dez. 2018. Disponível em:

<https://linkinghub.elsevier.com/retrieve/pii/S1110016818301765>.

TERRAZAS, G.; FERRY, N.; RATCHEV, S. A cloud-based framework for shop floor big data management and elastic computing analytics. **Computers in Industry**, v. 109, p. 204–214, ago. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361518306808>.

TEZEL, A.; AZIZ, Z. From conventional to it based visual management: A conceptual discussion for lean construction. **Journal of Information Technology in Construction**, v. 22, p. 220–246, 2017. Disponível em: <https://www.itcon.org/papers/2017_12-ITcon-Tezel.pdf>.

THOBEN, K.-D.; WIESNER, S.; WUEST, T. "Industrie 4.0" and Smart Manufacturing – A Review of Research Issues and Application Examples. **International Journal of Automation Technology**, v. 11, n. 1, p. 4–16, 5 jan. 2017. Disponível em: <https://www.fujipress.jp/ijat/au/ijate001100010004>.

THÜRER, M.; PAN, Y. H.; QU, T.; LUO, H.; LI, C. D.; HUANG, G. Q. Internet of Things (IoT) driven kanban system for reverse logistics: solid waste collection. **Journal of Intelligent Manufacturing**, v. 30, n. 7, p. 2621–2630, 7 out. 2019. Disponível em: <http://link.springer.com/10.1007/s10845-016-1278-y>.

TRANFIELD, D.; DENYER, D.; SMART, P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. **British Journal of Management**, v. 14, n. 3, p. 207–222, set. 2003. Disponível em: <http://doi.wiley.com/10.1111/1467-8551.00375>.

TRENTESAUX, D. Distributed control of production systems. **Engineering Applications of Artificial Intelligence**, 2009.

TSAI, W.-H. Green Production Planning and Control for the Textile Industry by Using Mathematical Programming and Industry 4.0 Techniques. **Energies**, v. 11, n. 8, p. 2072, 9 ago. 2018. Disponível em: <http://www.mdpi.com/1996-1073/11/8/2072>.

TSAI, W.-H.; LAI, S.-Y. L. Green production planning and control model with ABC under industry 4.0 for the paper industry. **Sustainability (Switzerland)**, v. 10, n. 8, 2018.

TSAI, W.-H.; LU, Y.-H. A Framework of Production Planning and Control with Carbon Tax under Industry 4.0. **Sustainability**, v. 10, n. 9, p. 3221, 8 set. 2018. Disponível em: <http://www.mdpi.com/2071-1050/10/9/3221>.

TUFANO, A.; ACCORSI, R.; GARBELLINI, F.; MANZINI, R. Plant design and control in food service industry. A multi-disciplinary decision-support system. **Computers in Industry**, v. 103, p. 72–85, dez. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361518303968>.

URBINATI, A.; BOGERS, M.; CHIESA, V.; FRATTINI, F. Creating and capturing value from Big Data: A multiple-case study analysis of provider companies. **Technovation**, v. 84–85, p. 21–36, jun. 2019. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166497218300361>.

VAN GEEST, M.; TEKINERDOGAN, B.; CATAL, C. Design of a reference architecture for developing smart warehouses in industry 4.0. **Computers in Industry**, v. 124, p. 103343, jan. 2021. Disponível em: <https://doi.org/10.1016/j.compind.2020.103343>.

VAN HILLEGERSBERG, J. Part II - Models. *In*: BERGENER, K.; RÄCKERS, M.; STEIN, A. **The Art of Structuring: Bridging the Gap Between Information Systems Research and Practice**. Cham: Springer International Publishing, 2019. p. 145–151.

VAN LOOY, A.; DE BACKER, M.; POELS, G.; SNOECK, M. Choosing the right business process maturity model. **Information and Management**, v. 50, n. 7, p. 466–488, 2013. Disponível em: <http://dx.doi.org/10.1016/j.im.2013.06.002>.

VAN LOOY, A.; POELS, G.; SNOECK, M. Evaluating business process maturity models. **Journal of the Association for Information Systems**, v. 18, n. 6, p. 461–486, 2017.

VAN STEENBERGEN, M.; BOS, R.; BRINKKEMPER, S.; VAN DE WEERD, I.; BEKKERS, W. Improving IS Functions Step by Step: The use of focus area maturity models. **Scandinavian Journal of Information Systems**, v. 25, n. 2, p. 35–56, 2013.

VD/VDE; ZVEI. **Reference Architecture Model Industrie 4.0 (RAMI4.0)ZVEI – German Electrical and Electronic Manufacturers VDI/VDE Society Measurement and Automatic Control (GMA)**. [s.l: s.n.]. Disponível em:

<https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2016/januar/GMA_Status_Report__Reference_Archtitecture_Model_Industrie_4.0__RAMI_4.0_/GMA-Status-Report-RAMI-40-July-2015.pdf>.

VDI; VDE; ZWEI. Industrie 4.0 – Technical Assets: Basic terminology concepts, life cycles and administration models. n. March, p. 28, 2016. Disponível em: <https://www.vdi.de/fileadmin/vdi_de/redakteur_dateien/gma_dateien/6092_PUB_E_TW_GMA_Status_Report_ZVEI_-_Industrie_4_0_-_Technical_Assets_Internet.pdf>.

VEILE, J. W.; KIEL, D.; MÜLLER, J. M.; VOIGT, K. I. Lessons learned from Industry 4.0 implementation in the German manufacturing industry. **Journal of Manufacturing Technology Management**, v. 31, n. 5, p. 977–997, 2020.

VEILE, J. W.; SCHMIDT, M. C.; VOIGT, K. I. Toward a new era of cooperation: How industrial digital platforms transform business models in Industry 4.0. **Journal of Business Research**, v. 143, n. February, p. 387–405, 2022. Disponível em: <https://doi.org/10.1016/j.jbusres.2021.11.062>.

VERGARA, L.; GAVIÃO, L.; LIMA, G. Suporte à decisão para modelo de maturidade de processo utilizando lógica fuzzy a partir da perspectiva do ciclo PDCA. **Exacta**, v. 14, n. 2, p. 269–284, 1 jul. 2016. Disponível em: <http://periodicos.uninove.br/index.php?journal=exacta&page=article&op=view&path[]=6357>.

VEZZETTI, E.; VIOLANTE, M. G.; MARCOLIN, F. A benchmarking framework for product lifecycle management (PLM) maturity models. **International Journal of Advanced Manufacturing Technology**, v. 71, n. 5–8, p. 899–918, 2014.

VOLLMANN, T. E.; BERRY, W. L.; WHYBARK, D. C.; JACOBS, F. R. **Manufacturing Planning and Control for Supply Chain Management**. New York: McGraw-Hill, 2005.

VOLLMER, T.; ZHOU, B.; HEUTMANN, T.; KIESEL, R.; SCHMITT, R. Roadmap for production planning and control [Entwicklung der Produktions-IT]. **WT Werkstattstechnik**, v. 107, p. 11–12, 2017.

WAGIRE, A. A.; JOSHI, R.; RATHORE, A. P. S.; JAIN, R. Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice. **Production Planning & Control**, v. 32, n. 8, p. 603–622, 11 jun. 2021. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537287.2020.1744763>.

WAN, J.; CHEN, B.; WANG, S.; XIA, M.; LI, D.; LIU, C. Fog Computing for Energy-Aware Load Balancing and Scheduling in Smart Factory. **IEEE Transactions on Industrial Informatics**, v. 14, n. 10, p. 4548–4556, out. 2018. Disponível em: <https://ieeexplore.ieee.org/document/8323243>.

WAN, J.; TANG, S.; LI, D.; IMRAN, M.; ZHANG, C.; LIU, C.; PANG, Z. Reconfigurable Smart Factory for Drug Packing in Healthcare Industry 4.0. **IEEE Transactions on Industrial Informatics**, v. 15, n. 1, p. 507–516, jan. 2019. Disponível em: <https://ieeexplore.ieee.org/document/8371642/>.

WANG, G.; GUNASEKARAN, A.; NGAI, E. W. T.; PAPADOPOULOS, T. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. **International Journal of Production Economics**, v. 176, p. 98–110, jun. 2016. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925527316300056>.

WANG, J.; LI, D. Task Scheduling Based on a Hybrid Heuristic Algorithm for Smart Production Line with Fog Computing. **Sensors**, v. 19, n. 5, p. 1023, 28 fev. 2019. Disponível em: <https://www.mdpi.com/1424-8220/19/5/1023>.

WANG, M.; ALTAF, M. S.; AL-HUSSEIN, M.; MA, Y. Framework for an IoT-based shop floor material management system for panelized homebuilding. **International Journal of Construction Management**, v. 20, n. 2, p. 130–145, 3 mar. 2020a. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/15623599.2018.1484554>.

WANG, X.; ONG, S. K.; NEE, A. Y. C. A comprehensive survey of ubiquitous manufacturing research. **International Journal of Production Research**, v. 56, n. 1–2, p. 604–628, 17 jan. 2018. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85038090085&doi=10.1080%2F00207543.2017.1413259&partnerID=40&md5=d40b2ed6d4e22b31c69fb0d6c3d86919>.

WANG, X.; YEW, A. W. W.; ONG, S. K.; NEE, A. Y. C. Enhancing smart shop floor management with ubiquitous augmented reality. **International Journal of Production Research**, v. 58, n. 8, p. 2352–2367, 17 abr. 2020b. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85067597275&doi=10.1080%2F00207543.2019.1629667&partnerID=40&md5=ee93a41eeee4a8cf37b2441c3fb0b8b3>.

WEBER, C.; KÖNIGSBERGER, J.; KASSNER, L.; MITSCHANG, B. M2DDM – A Maturity Model for Data-Driven Manufacturing. **Procedia CIRP**, v. 63, p. 173–178, 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S2212827117304973>.

WEBSTER, J.; WATSON, R. Analyzing the past fo prepare for the future: writing a literature review. **MIS quarterly**, v. 26, n. 2, p. xiii-xxiii/June, 2002. Disponível em: <https://www.cs.auckland.ac.nz/courses/compsci705s2c/resources/litreview.pdf>.

WENDLER, R. The maturity of maturity model research: A systematic mapping study. **Information and Software Technology**, v. 54, n. 12, p. 1317–1339, dez. 2012. Disponível em: <http://dx.doi.org/10.1016/j.infsof.2012.07.007>.

WHEELWRIGHT, S. C.; HAYES, R. H. Link Manufacturing Process and Product Life Cycles. **Harvard Business Review**, n. January, p. 133–140, 1979.

WIENDAHL, H.-H.; VON CIEMINSKI, G.; WIENDAHL, H.-P. Stumbling blocks of PPC: Towards the holistic configuration of PPC systems. **Production Planning & Control**, v. 16, n. 7, p. 634–651, 21 out. 2005. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/09537280500249280>.

WIERINGA, R. J. **Design science methodology: For information systems and software engineering**. [s.l: s.n.]1–332 p.

WILLNER, O.; GOSLING, J.; SCHÖNSLEBEN, P. Establishing a maturity model for design automation in sales-delivery processes of ETO products. **Computers in Industry**, v. 82, p. 57–68, out. 2016. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0166361516300689>.

XU, L. Da; XU, E. L.; LI, L. Industry 4.0: state of the art and future trends. **International Journal of Production Research**, v. 56, n. 8, p. 2941–2962, 18 abr. 2018. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2018.1444806>.

XU, Y.; CHEN, M. An Internet of Things based framework to enhance just-in-time manufacturing. **PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART B-JOURNAL OF ENGINEERING MANUFACTURE**, v. 232, n. 13, SI, p. 2353–2363, nov. 2018.

YANG, Y.; CHI, H.; TANG, O.; ZHOU, W.; FAN, T. Cross perishable effect on optimal inventory preservation control. **European Journal of Operational Research**, v. 276, n. 3, p. 998–1012, ago. 2019. Disponível em: <https://www2.scopus.com/inward/record.uri?eid=2-s2.0-85061655651&doi=10.1016%2Fj.ejor.2019.01.069&partnerID=40&md5=4ac44725bb2bd68b67d192c0cd598e9e>.

YANG, Z.; ZHANG, P.; CHEN, L. RFID-enabled indoor positioning method for a real-time manufacturing execution system using OS-ELM. **Neurocomputing**, v. 174, p. 121–133, 22 jan. 2016. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0925231215011352>.

YERPUDE, S.; SINGHAL, T. K. Augmentation of effectiveness of vendor managed inventory (VMI) operations with IoT Data - A research perspective. **International Journal of Applied Business and Economic Research**, v. 15, n. 16, p. 469–482, 2017.

YIN, P.-Y.; CHAO, C.-H. Automatic selection of fittest energy demand predictors based on cyber swarm optimization and reinforcement learning. **Applied Soft Computing**, v. 71, p. 152–164, out. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S1568494618303764>.

YIN, R. K. **Case study research and applications: Design and methods**. California: SAGE Publications Inc., 2018. v. Six Editio

YIN, Y.; STECKE, K. E.; LI, D. The evolution of production systems from Industry 2.0 through Industry 4.0. **International Journal of Production Research**, v. 56, n. 1–2, p. 848–861, 17 jan. 2018. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2017.1403664>.

YLI-OJANPERÄ, M.; SIERLA, S.; PAPAKONSTANTINOU, N.; VYATKIN, V. Adapting an agile manufacturing concept to the reference architecture model industry 4.0: A survey and case study. **Journal**

**of Industrial Information Integration**, v. 15, n. October 2018, p. 147–160, 2019. Disponível em: <https://doi.org/10.1016/j.jii.2018.12.002>.

YU, C.; MOU, S.; JI, Y.; XU, X.; GU, X. A delayed product differentiation model for cloud manufacturing. **Computers & Industrial Engineering**, v. 117, p. 60–70, mar. 2018a. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0360835218300263>.

YU, C.; ZHANG, W.; XU, X.; JI, Y.; YU, S. Data mining based multi-level aggregate service planning for cloud manufacturing. **Journal of Intelligent Manufacturing**, v. 29, n. 6, p. 1351–1361, 19 ago. 2018b. Disponível em: <http://link.springer.com/10.1007/s10845-015-1184-8>.

YUAN, M.; DENG, K.; CHAOVALITWONGSE, W. A.; CHENG, S. Multi-objective optimal scheduling of reconfigurable assembly line for cloud manufacturing. **Optimization Methods and Software**, v. 32, n. 3, p. 581–593, 4 maio 2017. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/10556788.2016.1230210>.

YUE, Q.; LIU, F.; DIAO, Y.; LIU, Y. Research and Application of a Big Data-Driven Intelligent Reservoir Management System. **Journal of Coastal Research**, v. 82, p. 270–279, 2 set. 2018. Disponível em: <http://www.bioone.org/doi/10.2112/SI82-039.1>.

ZADEH, L. A. Fuzzy sets. **Information and Control**, v. 8, n. 3, p. 338–353, jun. 1965.

ZENG, J.; LI, J. Operations simulation as a cloud based service. In: 2013 IEEE Conference Anthology, ANTHOLOGY 2013, 2013, [...]. IEEE Computer Society, 2013.

ZHANG, H.; ZHANG, G.; YAN, Q. Digital twin-driven cyber-physical production system towards smart shop-floor. **Journal of Ambient Intelligence and Humanized Computing**, v. 10, n. 11, p. 4439–4453, 2019. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85057330632&doi=10.1007%2Fs12652-018-1125-4&partnerID=40&md5=f998720a74a664b779b8115f75af694a>.

ZHANG, X.; ZHU, W. Application framework of digital twin-driven product smart manufacturing system: A case study of aeroengine blade manufacturing. **International Journal of Advanced Robotic Systems**, v. 16, n. 5, p. 172988141988066, 1 set. 2019. Disponível em: <http://journals.sagepub.com/doi/10.1177/1729881419880663>.

ZHANG, Y.; LIU, S.; LIU, Y.; YANG, H.; LI, M.; HUISINGH, D.; WANG, L. The ‘Internet of Things’ enabled real-time scheduling for remanufacturing of automobile engines. **Journal of Cleaner Production**, v. 185, p. 562–575, jun. 2018. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0959652618303676>.

ZHANG, Y.; QU, T.; HO, O.; HUANG, G. Q. Real-time work-in-progress management for smart object-enabled ubiquitous shop-floor environment. **International Journal of Computer Integrated Manufacturing**, v. 24, n. 5, p. 431–445, 2011. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-79957498356&doi=10.1080%2F0951192X.2010.527374&partnerID=40&md5=26d73fe6f4efebf160a1d08869fac899>.

ZHANG, Y.; WANG, J.; LIU, Y. Game theory based real-time multi-objective flexible job shop scheduling considering environmental impact. **Journal of Cleaner Production**, v. 167, p. 665–679, nov. 2017. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S0959652617317845>.

ZHANG, Y.; ZHANG, G.; WANG, J.; SUN, S.; SI, S.; YANG, T. Real-time information capturing and integration framework of the internet of manufacturing things. **International Journal of Computer Integrated Manufacturing**, v. 28, n. 8, p. 811–822, 3 ago. 2015. Disponível em: <http://www.tandfonline.com/doi/full/10.1080/0951192X.2014.900874>.

ZHAO, X.; ZHANG, W.; MENG, H.; HE, F.; REN, S. A framework for shop floor material delivery optimization based on RFID-enabled production big data. **Advances in Intelligent Systems and Computing**, v. 885, p. 699–705, 2019. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85061107311&doi=10.1007%2F978-3-030-02804-6_91&partnerID=40&md5=04c41ff9163993bba9f16ba9af4009b2>.

ZHENG, M.; WU, K. Smart spare parts management systems in semiconductor manufacturing. **Industrial Management & Data Systems**, v. 117, n. 4, p. 754–763, 8 maio 2017. Disponível em:

<http://www.emeraldinsight.com/doi/10.1108/IMDS-06-2016-0242>.

ZHENG, P.; WANG, H.; SANG, Z.; ZHONG, R. Y.; LIU, Y.; LIU, C.; MUBAROK, K.; YU, S.; XU, X. Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. **Frontiers of Mechanical Engineering**, v. 13, n. 2, p. 137–150, 2018.

ZHONG, R. Y.; HUANG, G. Q.; DAI, Q. Y.; ZHANG, T. Mining SOTs and dispatching rules from RFID-enabled real-time shopfloor production data. **Journal of Intelligent Manufacturing**, v. 25, n. 4, p. 825–843, 25 ago. 2014. Disponível em: <http://link.springer.com/10.1007/s10845-012-0721-y>.

ZHONG, R. Y.; LAN, S.; XU, C.; DAI, Q.; HUANG, G. Q. Visualization of RFID-enabled shopfloor logistics Big Data in Cloud Manufacturing. **International Journal of Advanced Manufacturing Technology**, v. 84, n. 1–4, p. 5–16, 2016. Disponível em: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84939421306&doi=10.1007%2Fs00170-015-7702-1&partnerID=40&md5=1405ea01a795450c919c6b223735d3e0>.

ZHONG, R. Y.; XU, C.; CHEN, C.; HUANG, G. Q. Big Data Analytics for Physical Internet-based intelligent manufacturing shop floors. **International Journal of Production Research**, v. 55, n. 9, p. 2610–2621, 2017. Disponível em: <http://dx.doi.org/10.1080/00207543.2015.1086037>.

ZHONG, R. Y.; XU, X.; KLOTZ, E.; NEWMAN, S. T. Intelligent Manufacturing in the Context of Industry 4.0: A Review. **Engineering**, v. 3, n. 5, p. 616–630, out. 2017c. Disponível em: <https://linkinghub.elsevier.com/retrieve/pii/S2095809917307130>.

ZHOU, G.; ZHANG, C.; LI, Z.; DING, K.; WANG, C. Knowledge-driven digital twin manufacturing cell towards intelligent manufacturing. **International Journal of Production Research**, v. 58, n. 4, p. 1034–1051, 16 fev. 2020. Disponível em: <https://www.tandfonline.com/doi/full/10.1080/00207543.2019.1607978>.

ZHUANG, C.; LIU, J.; XIONG, H. Digital twin-based smart production management and control framework for the complex product assembly shop-floor. **International Journal of Advanced Manufacturing Technology**, 2018.

## APPENDIX A

### – TABLES OF $S^2$FC MATURITY MODEL DEVELOPMENT: STEPS AND RESEARCH'S ITERATIONS

**Table A1.** $S^2$FC MM – design research elements (**Step 1 – RI #1**)

| Procedures | Tasks |
|---|---|
| **— Input (s)**<br>**(Element to be designed)** | **1.** Problem-solving<br>**2.** Comparison of existing maturity models<br>**3.** Definition of I4.0 technologies and OSCM domain<br>**4.** Meta-model (scope of the model): model requirements, research design, and preliminary elements<br>**5** and **6.** Reference model |
| **— Method** | **1, 2, 3, 4, 5, and 6.** *(i)*. Systematic Literature Review and snowballing forward and backward<br>*(ii)*. scoping review<br>*(iii)*. meetings of research team/designers<br>*(iv)*. MM development literature |
| **— Data/Analysis** | **1, 2, 3, 4, 5, and 6.** *(i)*. time frame: until July 2021<br>*(ii)*. databases: *(a)*. previous SLR (102 articles) (BUENO; GODINHO FILHO; FRANK, 2020) and 18 additional articles searched by snowballing forward and backward -2021 year (see the file "Database Literature Survey" at the: https://bityli.com/UbCZBqv); *(b)* 20 maturity models analyzed from scoping review (Tables 3.3 and 3.4, Chapter 3); *(c)* eight development frameworks for MM building (Table 3.2, Chapter 3), *(d)*. five architectures of I4.0 implementation/adoption in manufacturing companies (Table 3.1, Chapter 3)<br>*(iii)*. technique of analysis: content analysis |
| **— Elements' design** | **1.** By problem-solving paths delimitation<br>**2.** By follow-up of the 20 MM standard elements<br>**3.** By analysis of the I4.0 technologies used in the SFC literature (120 articles)<br>**4.** — Preliminary category elements and their relationships<br>— five preliminary maturity levels<br>— comparison of the most adherent research design<br>— choose of MM development framework to follow and model type definition<br>— implementation and institutionalization issues<br>**5 and 6.** Based on the smart PPC model (BUENO et al., 2022) |
| **— Test/Validation** | Meetings of the $S^2$FC MM's research team |
| **— Changes** | — |
| **— Outputs**<br>**(Element validated)** | **1.** Problem-solving definition: *shop floor control maturity into I4.0*<br>**2.** Comparison of existing maturity models*: 20 MM presented in Table 3.3* |

| | |
|---|---|
| | **3.** I4.0 technologies for the S$^2$FC MM function: *(i) technologies*: CPS, IoT, CMg, (big) data and analytics, ICT/ancillary technologies (Table 3.5, Chapter 3)<br>*(ii) OSCM domain*: SFC function<br>**4.** S$^2$FC MM meta-model: *(i). identification of elements of design*: - relationships between the main elements (*preliminary category list*)<br>- preliminary progression maturity levels<br>- key I4.0 technologies orientation<br>-preliminary focus-areas<br>- preliminary key factors<br>- maturity matrix draft<br>*(ii). research method definition*: Design Science Research methodology. *Seven development procedures* and nine tasks for elements design were adopted; these two building blocks were synthesized from eight MM development frameworks and the analysis of the 20 MM<br>- *seven procedures (how to design):* 1. definition of the designed element (input), 2. method, 3. data/analysis, 4. model's element design, 5. test/validation, 6. changes, 7. outputs (validated element for model structure)<br>- *nine elements (what to design):* 1. problem-solving, 2. comparison of existing maturity models, 3. I4.0 and OSCM domain characteristics, 4. meta-model, 5 and 6. to adapt or develop a reference model/architecture, 7. design, 8. measurement/evaluation tool, 9. usability and follow-up<br>*(iii). model type:* Prescriptive (P)<br>*(iv). implementation and institutionalization issues*: centered on SFC/PPC managers' roles and responsibilities<br>**5 and 6.** *(i).* reference architecture/model for S$^2$FC [(see Bueno et al. (2022)] |

**Table A2.** $S^2$FC MM – model design and test (**Step 2 – RI #2**)

| Procedures | Tasks |
|---|---|
| **— Input (s) (Element to be designed)** | **1.** Model design and test |
| **— Method** | *(i).* Qualitative methods (see the protocols in Appendix C): focus groups, expert interviews and a panel, practitioners' interviews, workshops/practitioners' meetings, direct observation |
| **— Data/Analysis** | *(i).* time frame: until December 2021<br>*(ii).* — 20 maturity models were analyzed (Tables 3.3 and 3.4, Chapter 3);— three focus groups with manufacturing practitioners (refinement), — 11 interviews (experts and practitioners, see Tables B1 and B2 in Appendix B), — one workshop, six meetings with managers in a steel manufacturing industry, and direct observation in a steel manufacturing industry<br>*(iii).* technique of analysis: - content analysis<br>- analysis/triangulation of the set of evidence obtained through Qualitative Methods to verify category list items saturation<br>- the convergence/acceptance of the $S^2$FC MM design verified from overall scores extracted from Salah et al.' (2014) questionnaire applying |
| **— Elements' design** | **—** *six focus-area: (i).* Sensing and Networking, *(ii).* Big Data and Analytics, and Optimization, *(iii).* Skills and Organizational Culture, *(iv).* ICTs and Smart Technologies of Supporting, *(v).* Fit and Legacy Systems, *(vi).* Value-Creation.<br>**—** *18 key factors*:<br>*Digital data-collection infrastructure on the shop floor* — *Shop floor (big) data-collection*<br>*Connectiveness from shop floor* — *Shop floor (big) data integration and databases*<br>*Interoperability of shop floor assets and systems* — *Shop floor (big) data analytics and optimization*<br>*Shop floor cybersecurity* — *ICTs and ancillary technologies*<br>*Skills development and training on Industry 4.0* — *Fit of the legacy systems and manufacturing physical assets*<br>*Shop Floor Control change management* — *Fit of the Shop Floor Control methods and environment*<br>*Projects and teams for Industry 4.0 initiatives on Shop Floor Control* — *Manufacturing execution and monitoring*<br>*Digital and data-driven culture on Shop Floor Control* — *Production scheduling*<br>*Industry 4.0 strategy on Shop Floor Control* — *Order release, progress, and feedback*<br>**—** *five maturity levels:* Nonexistent, Digitalized, Integrated, Autonomous, Smart |
| **— Test/Validation** | *(i).* panel with five experts (category list test)<br>*(ii).* four practitioners' interviews (model design test)<br>*(iii).* one focus group with practitioners (model validation)<br>*(iv).* meetings with $S^2$FC MM's research team (model validation) |
| **— Changes** | *(i).* there were changes in the name of all focus-area initially designed (e.g., Value-Creation → Digital Value-Creation)<br>*(ii).* there was a decrease in focus areas (6→5)<br>(iv) some key factors exchanged of focus area (e.g., *Shop Floor Control ICTs and smart technologies*)<br>*(v).* there was an increase in key factors (18→20) |

| | |
|---|---|
| **— Outputs (Element validated)** | **—** *five focus-area: (i).* Sensing and Networking (SN), *(ii).* Data and Analytics (DA), *(iii).* Strategy and Systems (SS), *(iv).* Skills and Culture (SC), *(v).* Digital Value-Creation (VC)<br>**—** *20 key factors*: see a full description of factors and examples in Tables D2 - D6 in Appendix D<br>***SN****: Digital data sensing infrastructure on the shop floor*<br>*Connectiveness from the shop floor*<br>*Interoperability of shop floor assets and systems*<br>*Shop floor cybersecurity*<br><br>***DA****:(big) Data-collection from shop floor*<br>*Shop floor (big) data integration and databases*<br>*Shop floor data analytics and optimization*<br><br>***SC****: Data skills and training for people on Shop Floor Control*<br>*Shop Floor Control change management*<br>*Projects and teams for Industry 4.0's solutions on Shop Floor Control*<br>*Data-driven and digital culture on Shop Floor Control*<br><br>***SS****: Fit of the legacy systems and manufacturing assets*<br>*Fit of the Shop Floor Control methods and environment*<br>*Industry 4.0 strategy on Shop Floor Control*<br>*Integration of systems and assets from Shop Floor Control*<br>*Shop Floor Control ICTs and smart technologies*<br><br>***VC****: Smart order release, progress, and feedback*<br>*Smart production scheduling and sequencing*<br>*Smart manufacturing execution and*<br>*New digital business processes*<br><br>**—** *Five maturity levels:* Level I – Non-existent, Level II – Digitalization, Level III – Integration, Level IV – Automation, Level V – Smart |

**Table A3.** $S^2FC$ MM – maturity matrix design and test (**Step 3 – RI #3**)

| Procedures | Tasks |
|---|---|
| **— Input (s)**<br>**(Element to be designed)** | **1.** Maturity matrix design and test (roadmap) |
| **— Method** | *(i).* Literature survey methods (performed in RI #1)<br>*(ii).* Qualitative Methods: focus group, direct observation from a steel manufacturing company |
| **— Data/Analysis** | *(i).* time frame: until December 2021<br>*(ii).* – 120 articles analyzed (see the file "Database_ Literature Survey" at: https://bityli.com/UbCZBqv); — one focus group with manufacturing managers (refinement),<br>*(iii).* technique of analysis: - content analysis<br>- analysis/triangulation of the set of evidence obtained through Qualitative methods to verify maturity matrix saturation |
| **— Elements' design** | Maturity matrix roadmap was built: 110 indicators were initially designed |
| **— Test/Validation** | *(i).* one focus group with four managers of a steel manufacturing company (refinement)<br>*(ii).* meetings with SFC MM's research team (validation) |
| **— Changes** | Twelve indicators were excluded or synthesized from one remaining |
| **— Outputs**<br>**(Element validated)** | Maturity matrix roadmap: 98 indicators (see the file "Database_Maturity Matrix" at: https://bityli.com/NrlaCiS)<br>SN: eight indicators;<br>DA: 12 indicators;<br>SS: 32 indicators;<br>SC: 20 indicators;<br>VC: 26 indicators |

**Table A4.** $S^2$FC MM – maturity evaluation tool design and test (**Step 4 – RI #4**)

| Procedures | Tasks |
|---|---|
| **— Input (s)<br>(Element to be designed)** | **1.** Maturity evaluation tool design and test |
| **— Method** | *(i).* Knowledge acquisition and rules base design<br>*(ii).* Fuzzy inference/expert system modeling (by MATLAB)<br>(iii). Maturity questionnaire (by Survey Monkey)<br>*(iii).* Pilot test (by a biorefinery company) |
| **Data/Analysis** | *(i).* time frame: until September 2022<br>*(ii).* questionnaire: 20 key factors (answered by three practitioners of a biorefinery company)<br>*(iii).* technique of analysis: fuzzy rule-based global maturity score (for the pilot test) |
| **— Elements' design** | Evaluation tool design was carried out based on the procedures of Caiado et al. (2021) and Correa et al.'s (2014) for fuzzy inference systems |
| **— Test/Validation** | *(i).* pilot test in three industrial companies: biorefinery, food industry, seeds processing industry<br>*(ii).* meetings with SFC MM's research team |
| **— Changes** | – Two indicators were not configured as fuzzy: Digital data sensing infrastructure on the shop floor; New digital business processes<br>– Eighteen key factors were answered using fuzzy linguistic/value variables<br>– For rule-base building optimization, SS and SC focus areas were partitioned into four sub-areas with related factors:<br>(SS) Strategy: *Fit the legacy systems and manufacturing assets*<br>*Fit of the Shop Floor Control methods and environment*<br>*Industry 4.0 strategy on Shop Floor Control*<br>(SS) Systems*: Integration of systems and assets from Shop Floor Control*<br>*Shop Floor Control ICTs and smart technologies*<br>(SC) Skills*: Data skills and training for people on Shop Floor Control*<br>*Projects and teams for Industry 4.0's solutions on Shop Floor Control*<br>(SC) Culture: *Shop Floor Control change management*<br>*Data-driven and digital culture on Shop Floor Control*<br>– Rules for global maturity index calculation were developed (from seven FIS outputs) |
| **— Outputs<br>(Element validated)** | Fuzzy Expert System (maturity evaluation tool):<br>*(i).* rules-base: SN: 125 rules DA: 125 rules VC: 125 rules<br>SS: 150 rules (125 related to strategy sub-area; 25 related to systems sub-area)<br>SC: 50 rules (25 related to skills sub-area; 25 related to culture sub-area)<br>*(ii).* linguistic variables, inputs/outputs, and parameters of the maturity model: see Table 4.1 (Chapter 4)<br>*(iii).* fuzzy inference system: Cascaded hierarchical fuzzy tree with nine fuzzy inference systems - FIS (Mamdani-style fuzzy inference)<br>– Maturity model's questionnaire (see https://pt.surveymonkey.com/r/S86LWJ8)<br>– Software implementation of Fuzzy Inference/Expert System Model (MATLAB) |

**Table A5.** S²FC MM – implementation, evaluation, and follow-up (**Step 5 – RI #5**)

| Procedures | Tasks |
|---|---|
| **— Input (s)**<br>**(Element to be designed)** | **1.** S²FC MM |
| **— Method** | *(i).* Case study |
| **— Data/Analysis** | *(i).* time frame: until October 2022<br>*(ii).* questionnaire: 20 key factors<br>*(iii).* interviews: four steel manufacturing managers – a plant manager - a senior ICT manager, a manufacturing manager, and an industrial engineer<br>*(iii).* technique of analysis – by the focus-areas, dimensions, and global maturity index calculation provided by S²FC MM<br>– recommendations based on the maturity matrix |
| **— Elements' design** | — |
| **— Test/Validation** | *(i).* maturity measurement and recommendations for a steel manufacturing company |
| **— Changes** | — |
| **— Outputs**<br>**(Element validated)** | S²FC MM (final version) |

## APPENDIX B

### – TABLES OF EXPERT PROFILES THAT PARTICIPATED IN THE STUDY

**Table B1.** Experts' interviews: profile and times

| ID | Position | Country | SFC/Manufacturing experience | I4.0 experience | Documentation analysis (duration) | Interviews (duration) |
|---|---|---|---|---|---|---|
| #1 | CEO of a manufacturing technology company and ABII director | Brazil | >25 years | >6 years | 0:15 min. | 24 min. |
| #2 | Academic of Shop Floor Planning and Control | USA | >25 years | >3 years | 1:05 h | 15 min. |
| #3 | Industrial ICT systems consultant and ABII director | Brazil | >25 years | >5 years | 2:00 h | 36 min. |
| #4 | IT and Manufacturing Digitalization Manager/ABBI director | Brazil | >20years | >6 years | 1:00 h | 25 min. |
| #5 | Academic Shop Floor Planning and Control | Canada | >20 years | >7 years | 3:00h | 54 min. |
| #6 | Supply Chain Planning Lead Manager | Brazil | >20 years | >5 years | 0:40 min | 28 min. |
| #7 | ERP/MES/I4.0 Consultant | Brazil | >25 years | >5 years | 0:30 min. | 50 min. |

**Table B2.** Practitioners' profiles and their I4.0 initiatives

| ID | Position | SFC/Manufacturing Experience | I4.0 project on the company (ongoing) |
|---|---|---|---|
| #8 | Planning and Control Analyst | > 5 years | pricing of beef carcasses to livestock suppliers |
| #9 | Senior Planning and Control Analyst | >10 years | automatic input/output control/report in cold rooms (visibility of manufacturing flow with PPC synchronizing) |
| #10 | Planning and Logistics Manager | >10 years | pattern recognition in the seed selection process in the production process |
| #11 | Manufacturing Manager | >15 years | I4.0 initiative in the steel industry (integration and digitalization of manufacturing, people, and systems) |

*Note:* Practitioners' interviews lasted between 40 minutes and 90 minutes

## APPENDIX C

**– PROTOCOLS USED TO CONDUCT THE QUALITATIVE METHODS**

**Table C1.** Focus Group Protocol

| | |
|---|---|
| *Federal University of São Carlos*<br>*UFSCar* | *Department of Industrial Engineering*<br>*PLACOP/GEPRELT* |

### Smart Shop Floor Control Maturity Model – Focus Group Protocol

**1. Participant Information's**

Name (Optional): ____________________ Date: ________

*Last* *First* *M.I.*

Organization/ Companies (Optional): **1.** ________ Country: ________

Position: **1.** **2.** **3.** **4.** ________ Email (Optional): **1.** **2.** **3.** **4.** ________

Professional Experience (time): **1.** **2.** **3.** **4.**

**2. Introductory Comments**

*1. Introduce of Moderator*
*2. Talk about recognition and importance of participation in research*
*3. Presentation of participation time: 40 min.*
*4. Brief overview of the research and goals of the Focus Group*
*5. Presentation of basic guidelines for the Focus Group*
*Confidentiality statement: The moderator will be taking notes about what is discussed, but that individual names or identifying information will not be attached to comments.*
*6. Brief overview of the research, procedures, and goals of the Focus Group*
*7. Present the Questions that will be applied to the participants in the Focus Group process. Highlight the key-questions*
*8. Distribute the SFC MM Form, ask participants to answer it, and discuss their assigns/responses. From this, the Group should reach a consensus for evaluated items*
*9. Distribution of consent form*
*10. Filling and collect of consent form. Thank everyone for their participation*

**3. Structured Questions**

*Please answer the following questions if you judge necessary*

| **Criteria** | **Strongly Disagree** | **Slightly Disagree** | **Neither Disagree Nor Agree** | **Slightly Agree** | **Strongly Agree** |
|---|---|---|---|---|---|
| MATURITY LEVELS | | | Choose an item | | |

| | | | | | |
|---|---|---|---|---|---|
| The maturity levels are sufficient to represent all maturation stages of the **Smart Shop Floor Control domain (Sufficiency)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| There is no overlap detected between descriptions of maturity levels **(Accuracy)** | ☐ | ☐ | ☐ | ☐ | ☐ |

| FOCUS AREA, KEY FACTORS AND CAPABILITIES | Choose an item | | | | |
|---|---|---|---|---|---|
| The focus area/key factors and capabilities matrix are relevant to the **Smart Shop Floor Control domain (Relevance)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| Key-factors and capabilities matrix cover all aspects impacting/involved in the **Smart Shop Floor Control domain (Comprehensiveness)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| Key factors and capabilities matrix are clearly distinct between **Smart Shop Floor Control** focus-area **(Mutual exclusion)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| Key factors and capabilities matrix are correctly assigned to their respective maturity levels **(Accuracy)** | ☐ | ☐ | ☐ | ☐ | ☐ |

| MATURITY MODEL | | | | | |
|---|---|---|---|---|---|
| **— Understandably** | Choose an item | | | | |
| The maturity levels are understandable | ☐ | ☐ | ☐ | ☐ | ☐ |
| The assessment guidelines are understandable | ☐ | ☐ | ☐ | ☐ | ☐ |
| The documentation is understandable | ☐ | ☐ | ☐ | ☐ | ☐ |
| **— Easy of Use** | Choose an item | | | | |
| The scoring schema is easing to use | ☐ | ☐ | ☐ | ☐ | ☐ |
| The assessment guidelines are easy to use | ☐ | ☐ | ☐ | ☐ | ☐ |
| The documentation is understandable | ☐ | ☐ | ☐ | ☐ | ☐ |
| **— Usefulness and Practicality** | Choose an item | | | | |
| The maturity model is useful conducting assessments | ☐ | ☐ | ☐ | ☐ | ☐ |
| The maturity model is practical for use within the shop floor control/industry | ☐ | ☐ | ☐ | ☐ | ☐ |

## 4. Semi-structured Questions

*Please answer the following questions.*

**Q1 —** Would you add any maturity scale point or level? If, so please explain What and Why?

Answer:

**Q2 —** Would you update the maturity scale or level description? If, so please explain What and Why?

Answer:

**Q3 —** Would you add any focus area, key factors or actions/capabilities? If, so please explain What and Why?

Answer:

**Q4** — Would you remove any of the focus area, key factors or actions/capabilities? If, so please explain What and Why?

Answer:

**Q5** — Would you redefine/update any of the focus area, key factors or actions/capabilities? If, so please explain What and Why?

Answer:

**Q6** — Would you suggest any updates or improvements related to the scoring scheme? If, so please explain What and Why?

Answer:

**Q7** — Would you suggest any updates or improvements related to the assessment guidelines? If, so please explain What and Why?

Answer:

**Q8** — Would you like to elaborate on any of your answers? If, so please explain What and Why?

Answer:

**Q9** — Could the model be made more useful? How?

Answer:

**Q10** — Could the model be made more practical? How?

Answer:

## 5. Not-structure Questions

*Please answer the following questions.*

***Questions***

1. Improvements suggested for: - Focus area, key factors and capabilities
2. - Maturity Levels
3. - Maturity Model

Signature: ______________________ Date: ______________

**Table C2.** Field observation protocol

| | |
|---|---|
| *Federal University of São Carlos*<br>*UFSCar* | PPGEP Programa de Pós Graduação em Engenharia de Produção<br>*Department of Industrial Engineering*<br>*PLACOP/GEPRELT* |

**Field Observation Protocol** – steel manufacturing company

## 6. Descriptive Notes

When (Date):
Who (People and responsabilities):
How long:
Problem/situation:
Department involved:
Sector/Machine:
SFC MM's relationships:
Literature contrast:
Material and Methods:
Records: Report of main contributions from site/problem observed:
Triangulation with other data-collection sources:

## 7. Reflexive Notes

The reflexive description must always be guided/framed in the three axes of the SFC MM and its sub-items:
**1.** Maturity Level Design insights/contributions;
**2.** Category List Design insights/contributions;
**3.** Maturity Matrix Design insights/contributions
**4.** Maturity Model Design insights/contributions

**Table C3.** Expert/practitioners' interviews protocol

**Expert Information**

Name (Optional): ____________________________________________ Date:__________

*Last* *First* *M.I.*

Organization/ Company (Optional): ______________________________ Country: __________

Position:______________________________ Email (Optional): ______________________________

Experience (time):____________________________________________

| Criteria | Strongly Disagree | Slightly Disagree | Neither Disagree Nor Agree | Slightly Agree | Strongly Agree |
|---|---|---|---|---|---|
| MATURITY LEVELS | Choose an item | | | | |
| The maturity levels are sufficient to represent all maturation stages of the **Smart Shop Floor Control domain (Sufficiency)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| There is no overlap detected between descriptions of maturity levels **(Accuracy)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| FOCUS AREA, KEY-FACTORS AND CAPABILITIES | | Choose an item | | | |
| The focus area/key-factors and capabilities matrix are relevant to the **Smart Shop Floor Control domain (Relevance)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| Key-factors and capabilities matrix cover all aspects impacting/involved in the **Smart Shop Floor Control domain (Comprehensiveness)** | ☐ | ☐ | ☐ | ☐ | ☐ |
| Key-factors and capabilities matrix are clearly distinct between **Smart Shop Floor Control** focus-area **(Mutual exclusion)** | ☐ | ☐ | ☐ | | ☐ |
| Key-factors and capabilities matrix are correctly assigned to their respective maturity levels **(Accuracy)** | ☐ | ☐ | ☐ | | ☐ |

| MATURITY MODEL | | | Choose an item | | |
|---|---|---|---|---|---|
| — **Understandably** | | | | | |
| The maturity levels are understandable | ☐ | ☐ | ☐ | | ☐ |
| The assessment guidelines are understandable | ☐ | ☐ | ☐ | | ☐ |
| The documentation is understandable | ☐ | ☐ | ☐ | | ☐ |
| — **Easy of Use** | | | Choose an item | | |
| The scoring schema is easing to use | ☐ | ☐ | ☐ | | ☐ |
| The assessment guidelines are easy to use | ☐ | ☐ | ☐ | | ☐ |
| The documentation is understandable | ☐ | ☐ | ☐ | | ☐ |
| — **Usefulness and Practicality** | | | Choose an item | | |
| The maturity model is useful conducting assessments | ☐ | ☐ | ☐ | | ☐ |
| The maturity model is practical for use within the shop floor control/industry | ☐ | ☐ | ☐ | | ☐ |

## Semi-structured Questions

*Please answer the following questions if you judge necessary.*

**Q1 —** Would you add any maturity scale point or level? If, so please explain What and Why?

Answer:

**Q2 —** Would you update the maturity scale or level description? If, so please explain What and Why?

**Answer:**

**Q3 —** Would you add any focus area, key-factors or actions/capabilities? If, so please explain What and Why?

Answer:

**Q4 —** Would you remove any of the focus area, key-factors or actions/capabilities? If, so please explain What and Why?

Answer:

**Q5 —** Would you redefine/update any of the focus area, key-factors or actions/capabilities? If, so please explain What and Why?

Answer:

**Q6 —** Would you suggest any updates or improvements related to the scoring scheme? If, so please explain What and Why?

Answer:

**Q7 —** Would you suggest any updates or improvements related to the assessment guidelines? If, so please explain What and Why?

Answer:

**Q8 —** Would you like to elaborate on any of your answers? If, so please explain What and Why?

Answer:

**Q9 —** Could the model be made more useful? How?

Answer:

**Q**10 **—** Could the model be made more practical? How?

Answer:

## Unstructured Questions

1. Improvements suggested for: - Focus area, key-factors and capabilities
2. - Maturity Levels
3. - Maturity Model

Signature: ______________________ Date: ____________

## APPENDIX D

### – $S^2$FC MATURITY MODEL: CATEGORY LIST DESCRIPTION

#### — Focus-area

**Table D1.** Focus area description

| |
|---|
| **Sensing and Networking – SN** |
| It comprises key factors and smart capabilities related to creating a reliable, secure, and scalable manufacturing data-sensing infrastructure. High digitalization, data sensing and transmission platform are some maturity indicators in this focus-area. Sensing and networking area concentrate efforts to create digitalization processes (e.g., manufacturing data sensing, digital data collection), and sensing and networking processes (e.g., real-time data transmission platform, M2M communication) based mainly on Industrial IoT technologies/ecosystem. Therefore, to reach a high maturity level in this area, an SFC function must master key factors such as: digital data-collection/sensing infrastructure; connectiveness of physical assets, people, and systems; cybersecurity; interoperability of systems between smart devices, digital machines, manufacturing execution systems, automation/transport systems, and enterprise systems (e.g., ERP). In summary, this area comprises sensing and networking infrastructure for smart Shop Floor Control's function. |
| **Data and Analytics – DA** |
| It concerns the shop floor's data management capabilities, such as processing, warehousing/storage, analytics/optimization, data-value capture, and data-driven decisions. SFC's data-driven workflow is the main goal. (big) Data management enables analytics tasks using AI technologies coupled with optimization tools (e.g., machine learning algorithms, metaheuristics, statistical techniques, data science/business analytics tools, big data/optimization software). They work to aid production scheduling, order management, manufacturing execution, and maintenance/capacity management with new possibilities for improvements by real-time monitoring, pattern recognition, best/worst-case scenarios, and optimization of resource use (smart grid). At the lowest maturity level, this focus area has its efforts around digitalization capabilities' harnessing, designing the data management strategies/plan, and defining value-creation ways, parameters, and KPIs, that is, defining ground capabilities for a smart Shop Floor Control function. At SFC's maturity higher levels, this focus area is concerned with capabilities related to mature data governance, standards for the (big) data and analytics platform (data integration), plug and play tools use, data-driven shop floor control, dashboards and data visualization, use of extensible and open-source big data/analytics/AI tools, machine learning tools use, and optimization capabilities. In summary, this area comprises a data management infrastructure/platform (transmission, processing, analytics) for Shop Floor control. |
| **Strategy and Systems – SS** |
| The capabilities to develop a digital structure within a smart decision support system depend on integrated ICTs (e.g., MES, ERP, SAP, CRM, inventory and capacity planning and control system) working with smart technologies (e.g., cloud services ecosystem, CPPS) on Shop Floor Control. At the lowest maturity levels, it is concerned with mastering of computerized resources for manufacturing automation and monitoring (e.g., PLCs/SCADA), digitalization of machines (e.g., sensors), and data and IS integration (e.g., networking and MES). Also, it is concerned with the full-use and mastering of digital technologies for smart manufacturing, and supporting systems for smart SFC.<br>In this focus area, some designed actions/capabilities are concerned with the fit of legacy systems and manufacturing assets. Also, it concerned to the fit of shop floor control methods and production environments to smart planning and control concept, i.e., how to set the route definition, operation, activities using I4.0 capabilities; how to fit the digitalized work instructions (e.g., orders release, its tasks, operations, progress, feedbacks); how to balance the cells/production lines with the support of smart technologies (e.g., data analytics tools); how supporting and enabling operators 4.0, managers with digital fluency, top-management, CIOs, CEOs, and owners with data citizens; how thinking or redesign the shop floor control in the smart manufacturing planning and control scope, from an adaption process requirements around I4.0 strategy. In summary, this area is centered on the SFC's organizational processes |

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| development towards smart environments based on the adjustment of manufacturing systems, assets, methods, and also I4.0 strategy deployment. |
| **Skills and Culture – SC** |
| In this focus-area, capabilities concern the creation of digital and data-driven culture by the people working on shop floor. It is based on initiatives such as data science projects, and digital fluency skills development. It is concerned with the data skills and training for all of employees; data science projects focused on value-creation; internal education programs to qualify employees such as data scientists and data citizens; change management program; a clear data-driven manufacturing strategy. This focus area is centered on the people, which drives the organizational culture changes towards data-driven manufacturing and digital culture in the shop floor control function. In summary, this area deals with I4.0 skills and culture development by people of the Shop Floor Control function. |
| **Digital value-creation – VC** |
| Capabilities in this focus area are concerned with value-creation based on the Shop Floor Control function. Technological infrastructure, data sensing, processing, analytics, I4.0 technologies and strategy, smart systems, and organizational changes support the smart capabilities development for value-creation in front-end SFC activities such as manufacturing execution, production scheduling, and order release. Smart SFC also supports new digital business and process propositions (innovation). Therefore, in high maturity levels in this area, SFC activities are fed by manufacturing data from reliable IoT data-collection infrastructure, with new possibilities for manufacturing systems improvements, which are based on data, events, and learning. From this, the manufacturing systems get to take most conditions to prioritize links within a digital thread, from data pipeline and analytics, and cloud services harnessing. This digital thread bonds manufacturing with the planning and control decisions, actions, and policies, which afford better platforms for making decisions for value-adding to products, processes, and manufacturing business. The internal manufacturing chain, the in-plant logistics and informational flow (material, parts, vehicles, products, conveyors, humans), and decision support systems are digitalized, integrated, and automated. This provides both the manufacturing execution and control function (SFC) with high leverage of flexibility, agility, visibility, traceability, and customization. These smart capabilities provide, sustain, and improve key performance indicators and value creation. In summary, this area is centered on smart Shop Floor Control value-creation proposal, performing in high maturity level smart manufacturing execution and monitoring, smart scheduling, and smart ordering, supported by the flexibility of new digital business proposition. |

**— Key factors**

**Table D2.** Sensing and Networking (SN)

| Key Factor **(KF#)** | **Literature** |
|---|---|
| Digital sensing infrastructure on shop floor<br><br>**Description:** This key factor concerns in the **digitalization** of manufacturing assets, systems, products, and entire **shop floor infrastructure sensing**. From this, it is possible the digital (and real-time, near real-time) data generation and collection of the **manufacturing execution, order monitoring,** and **scheduling plan**, which can feed the **data-driven Shop Floor Control decision-making**. Furthermore, manufacturing **digitalization** is **a primer-requirement** for **Industry 4.0 concept'** implementation in the Shop Floor Planning and Control Function. Therefore, a digital data-collection by Shop floor Control is centered on the high use and value-creation from the Industrial IoT technologies ecosystem.<br><br>**Required smart capabilities:** shop floor digitalization; manufacturing infrastructure sensing; digital and real-time shop floor data-collection; manufacturing assets context-awareness; shop floor visibility | Machado et al. (2019)<br>Ghobakhloo (2020)<br>Calabrese et al. (2020) |
| Connectiveness from shop floor<br><br>**Description:** Sensing infrastructure (Industrial IoT) on the Shop Floor needs **to be connected** to its systems (information and communication technologies—ICTs) and people (decision-making) by an **established industrial internet network and infrastructure** (operational technology—OT). Industrial Internet networking enables **linking** digital manufacturing assets, Industrial IoT devices, ICTs, and people in **real-time** on the shop floor control. Industrial Internet network provides a **dual-channel integration** that supports **digital data transmission** of **manufacturing execution assets**, **in-plant logistics assets** information, data about **products and parts**, **orders completion/status**, **scheduling plan status**. Furthermore, it supports **real-time information** and **commands from decision-makers** by the shop floor control systems like **MES, APS, ERP**, **autonomous machines/workshops**. Therefore, a smart shop floor connectiveness is based on **networking** of manufacturing infrastructure, i.e., the building of a **reliable industrial internet network**, its integration/interoperability with legacy ICTs systems, local networks, automation/transport systems, and people. Shop floor control connectiveness is based on industrial IoT networking technologies, and integration of systems techniques.<br><br>**Required smart capabilities:** networking of the shop floor assets and ICTs; stable network connectivity; reliable data/information transmission; network reliability | Gilchrist (2016)<br>Kusiak (2018)<br>Manavalan and Jayakrishna (2019) |
| Interoperability of shop floor assets and systems<br><br>**Description:** This key factor concerns required actions for interoperability and integration feasibility (vertical/horizontal/end-to-end) regards to digital manufacturing assets and shop floor/PPC/business systems/enterprise information system. **Interoperability capability** (i.e., technical, syntactical, semantic, and organizational) between different factory' systems and layers, from the digital manufacturing assets, SFC systems/software, associate managerial functions, and devices operated by people, enables these **manufacturing entities to "talking**". In addition, it enables the **real-time exchange of data/information** for shop floor managerial and control tasks (order progress, scheduling | Åkerman et al. (2018)<br>Cui et al. (2020)<br>Cañas et al. (2021) |

| Key Factor **(KF#)** | **Literature** |
|---|---|
| status, manufacturing execution and maintenance, and monitoring activities). Therefore, the interoperability between digital manufacturing assets, systems, and managerial functions/activities/people on shop floor control is a base requirement for integration of systems (vertical, horizontal, and end-to-end).<br><br>**Required smart capabilities**: shop floor connectiveness; enterprise modeling systems capabilities; interoperability capabilities. | |
| Shop floor control cybersecurity<br><br>**Description:** Cybersecurity is a key factor for the stable working of the smart shop floor control regarding **data/information integrity**, **privacy**, and **availability** of **shop floor control services/tasks**. Its roles play protection against threats to ICT infrastructures, avoiding cyberattacks, and providing required **digital operational stability** to the smart manufacturing systems (**reliability**). For high cybersecurity patterns in smart shop floor control, the Industry 4.0 projects must be able to **design a reliable security system** along with shop floor' digitalization, networking and integration processes deployment. Furthermore, this **security system** must be able to predict **(events), map** (risks), **correcting** (countermeasures plan) the **critical vulnerabilities** in both the **physical and cyberspace of the manufacturing systems**, i.e., ICT infrastructure, factory/manufacturing infrastructure, network infrastructure, Industrial Control Systems— ICS infrastructure (e.g., SCADA/PLC).<br><br>**Required smart capabilities:** industrial internet network defense system; shop floor hosting defense system (physical and cyber manufacturing assets, and their systems); cybersecurity culture. | Lezzi et al. (2018)<br>Ullah and Babar (2019)<br>Amrollahi et al. (2020) |

**Table D3.** Data and Analytics (DA)

| Key Factor **(KF#)** | **Literature** |
|---|---|
| big) Data-collection from shop floor<br><br>**Description:** This key factor concerns **(big) data-collection (capture)** from **heterogeneous sources** like the digital manufacturing assets, ICT and network infrastructures, automation and control systems, products, orders, people, and devices, i.e., from the **entire shop floor (big) data collection**, **extraction, transmission**, and **analytics platform**. From this, it is possible to a **manufacturing execution optimization**, **data order visualization** and **analytics**, **simulation** and **optimization** of (re) **scheduling plan**, **shop floor predictability**, and **real-time KPIs management**. Furthermore, algorithms based on **artificial intelligence embedded** on software, applications, and systems of the Shop Floor Planning and Control Function are a requirement for **advanced analytics and learning capabilities** supporting based on big data, shop floor control events' predictability (e.g., machine wear, order completion or lateness, downtime, scheduling deviations). Therefore, a smart shop floor control (big) data-collection is based on focused use and value-creation from the Industrial Big Data-Collection and Processing technologies ecosystem with Artificial Intelligence tools (data mining, machine learning, et cetera).<br><br>**Required smart capabilities:** data-driven shop floor control decision-making; (big) data-collection, processing capabilities, and platform; optimization and simulation capabilities; AI/machine-learning capabilities. | Ji and Wang (2017)<br>Cui et al. (2020)<br>Farooqui et al. (2020) |
| Shop floor (big) data integration and databases<br><br>**Description:** Industrial data could be generated with **different granularity/dimensions/types** from multiple and **heterogeneous sources** of **digital manufacturing systems** (e.g., different machines, devices, API, middleware, systems, people, et cetera). Therefore, these data **needs cleaning, integration, and standardization** for **useful processing and analytics**. Besides that, the **(big) manufacturing data management** requires a **warehouse and workflow/dataflow** based on a **secure and integrated data platform**. Furthermore, ICTs systems, responsibilities roles (e.g., manufacturing managers), and data science projects teams (e.g., to a shop floor machine-learning project) need **reliable data** for the data-driven shop floor value-creation. **Multiple shop floor data sources** and external data (customer, suppliers, and delivery logistics) require **integration** and cleaning aiming at precise decision-making for the manufacturing execution, order release and progress, and scheduling activities. The **data silos of different functions, legacy systems, new digital systems and assets, and shop floor activities must be integrated** and managed into a secure and consistent database. A **digital shop floor control' data management platform** must be established with standardized dimensions, patterns, granularity, schemas/architectures, systems/ICTs, governance, and **protected by security systems and policy**. Therefore, a smart shop floor control (big) data integration, storage/warehouse, and management are based on focused use of industrial (big) data management and integration technologies and AI (database integration techniques/tools, e.g., NoSQL/MongoDB), and cybersecurity tools.<br><br>**Required smart capabilities:** (big) data cleaning, integration, and warehouse capabilities; data integration capabilities; data accuracy; data management platform capability; AI/machine-learning capabilities; data security capability; cloud computing capabilities; scalability capability). | Zhong et al. (2017)<br>dos Santos et al. (2017)<br>Stonebraker and Ilyas (2018) |
| Shop floor data analytics and optimization<br><br>**Description:** This key factor concerns using **tools, techniques, and algorithms/systems** to **analyze large data sets** to support shop floor control activities during the plan and execution/monitoring steps. During the **plan step,** Shop Floor Control has centered on **data-driven manufacturing** | Akter et al. (2016)<br>Ji and Wang (2017)<br>Gröger (2018) |

**system capabilities** based on data analytics like **predictability, simulation**, and **optimization**. On the other hand, during the **manufacturing execution/monitoring step**, data analytics is centered on **patterns recognition** of **real-time monitoring signals** and **data/KPIs visualization** capabilities. According to Ji and Wang (2017), **dynamism, flexibility**, and **adaptability** are the core features of a smart shop floor control. For example, a scheduling task based on data analytics can perform optimal task rearrangement face **unexpected events**. Furthermore, Data Analytics is the key to **discovering shop floor control knowledge** about **data patterns**, which must be interpreted and enrich the shop floor control **managers' and analysts' learning**. Therefore, **predictability**, **adaptability/dynamics**, **flexibility**, shop floor' data **knowledge discovery**, and **learning** about **patterns** are **key capabilities** provided by **data analytics/AI technologies** to the smart shop floor control. In last, data analytics in Shop Floor Control can be performed about purpose diagnostic (for root cause analysis), prescriptive (e.g., for the employee assignment optimization and generation of concrete action recommendations for a defined function goal), and predictive (e.g., order completion forecasting/prediction). Therefore, a smart shop floor control uses the (big) data analytics and optimization focused on Industrial Data Analytics technologies and AI algorithms/techniques; dashboards and digital devices for data visualization; business intelligence/plug-and-play tools (e.g., RapidMiner, Power BI).

**Required smart capabilities:** shop floor predictability; shop floor control advanced data analytics; real-time indicators manufacturing monitoring; data and manufacturing KPIs visualization; flexible, adaptable and dynamics scheduling; flexible, adaptable and dynamics ordering system; knowledge discovery from shop floor data; learning based on patterns/AI capabilities; shop floor/manufacturing simulation and optimization.

**Table D4.** Strategy and Systems (SS)

| **Key Factor (KF#)** | **Literature** |
|---|---|
| Industry 4.0 strategy on Shop Floor Control<br><br>**Description:** Shop floor control' digitalization must be linked to **a clear** and **well-designed** smart manufacturing/factory/shop floor control' **strategy plan** (e.g., **design**, **development**, and **implementation**). In addition, issues about the correct **digital technologies implementation,** deployment status, key-requirements mapping, technological readiness level (**TRL**) **evaluation**, assessment of **budget/financial resources** required, mapping of **key performance indicators/goals** impacted, and determining of smart manufacturing/**factory spending** and **maintenance costs. Furthermore,** issues/policies about **education** and **training programs**, data governance, and **cybersecurity systems/policy**, **green**/sustainable **manufacturing**, automation/autonomy investments/risks, **productivity** and **profitability** yields, **vertical/horizontal integration strategy**, **end-to-end integration strategy**, flow material/products **traceability** and **visibility strategy**, **openness** and **innovation management** issues.<br>Therefore, KF-13 is a key factor in building a **digital strategy** to **implement/deploy Industry 4.0' initiatives** on the **shop floor control function.** A strategy plan must cover and be deployed to consider specificities at each one of the **maturity levels** designed in **S$^2$FC MM**: computerized, digitalized, integrated, autonomous, smart. Often, PPC/SFC Function deploys the strategy company; therefore, for a company to deploy a digital strategy on the shop floor control, it must follow some **strategic decisional processes**: **Technology strategy adoption for** digital manufacturing (for linking new digital business specifications and market requirements changes with smart manufacturing tasks), a**lignment the digital manufacturing strategy and manufacturing tasks** (tasks digitalization, integration, automation), **alignment the digital manufacturing tasks and manufacturing process** (fit and re-design for embedded Industry 4.0 technologies/solutions), a**lignment of the digital manufacturing process and PPC/SFC function** (PPC/SFC tasks digitalization, integration, automation), a**lignment of digital PPC/SFC and manufacturing performance** (definition and evaluation of core performance indicators for a digital manufacturing environment). **To support** the shop floor control's **strategic planning process towards Industry 4.0** can be used, well-known tools as **SWOT**, **PEST**, **BSC**, **Growth-Share matrix**, **OKR**, **Pareto Analysis**, among others.<br><br>**Required smart capabilities:** strategic planning capability; Industry 4.0 strategic processes deployment capability; alignment of digital strategic processes; strategic planning tools use; project management capabilities; top management engagement capability. | Santos and Martinho (2019)<br>Raj et al. (2020)<br>Bueno et al. (2021) |
| Integration of system and assets from Shop Floor Control<br><br>**Description: Vertical, horizontal**, and e**nd-to-end integration** are the main types of integration for manufacturing companies. Integration leads to requirements development that makes possible Cyber-Physical Systems (CPS) conception. It is based on **integrating systems, assets, people, factory**, **supply chain, customers**, which comprise some key relationships with shop floor control function. Therefore, there three main integration types from shop floor control function perspective: 1. **vertical integration between machines** and **equipment, systems**; 2. **horizontal integration of manufacturing and business processes, shop floor control activities** with other key companies and supply chains; 3. **end-to-end integration among manufacturing companies, shop floor control activities, and customers**. Besides that, it links interoperability practices, cloud services, enterprise architectures, and other Industry 4.0 resources (THOBEN; WIESNER; WUEST, 2017; XU; XU; LI, 2018). A critical aspect of mastering this factor is the **interoperability of assets**, systems and digital platforms (digital machines, automation systems, ICTs system, etc.), i.e., **data and information exchange** (DA SILVA SERAPIÃO LEAL; GUÉDRIA; PANETTO, 2019). Therefore, integration is based on network capabilities, | Bueno et al. (2022)<br>Bueno et al. (2020)<br>Frank et al. (2018) |

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| smart devices embedded with IoT, interoperability, web/cloud services, APIs/middleware, enterprise architectures (e.g., SOA), process mapping and integration (SCHUH *et al.*, 2017). An outcome possible from shop floor control function integration is the **synchronization of ERP**, **MES, APS**, machine-to-machine (M2M), and smart objects make ordering systems more reliable for **real-time operations execution monitoring** (LIN *et al.*, 2018). For example, the **vertical integration of the physical assets** with manufacturing execution systems (MES) and ERPs **optimize manufacturing performance** by integrated systems, **providing visibility and traceability of one order** by all of the company's layers and departments aligned to shop floor operations (TAO; ZHANG, 2017; ZHONG *et al.*, 2017c). For example, with high integration levels, the shop floor control function manages an **ordering system integrated and synchronized** to manufacturing operations, scheduling activity, and enterprise/business information systems. **Order monitoring to be real-time**. Resources for the **order completion have full traceability and visibility**. Integration enables to the **Production Scheduling and Sequencing tasks are fully-connected** and can receive real-time shop floor data. It provides real-time information about schedule progress with integrated systems for they support precise changes with real-time (re) scheduling (adaptability). Integration practices enable scheduling-as-a-service capabilities (e.g., APS on cloud, and/or APS with machine learning resources), collaboration, and sharing resources.<br><br>**Required smart capabilities:** interoperability; processes mapping; processes standardization; common protocols; middleware and devices; alignment of digital strategic processes; strategic planning tools use; project management capabilities; top management engagement capability; cloud and capabilities; web-services enterprise architectures. | |
| Shop Floor Control ICTs and smart technologies<br><br>**Description:** This key factor concerns the use of **ICTs**, **automation systems**, and **ancillary Industry 4.0 technologies** in **addition** to main Industrial **IoT** infrastructure and **(big) data analytics platform** (focus area 1 and 2), which must role-play the "midfield" between **digital shop floor infrastructure** and its **decision-makers**, providing specific smart capabilities to specific requirements of the Production Control environments. Besides that, **ICTs** are critical systems for manufacturing companies' operations management and control. ICTs support the manufacturing strategies and decision-making on shop floor control, where the main is MES, APS, ERPs, software/TI systems. Thus, **ICTs**, **automation systems** (e.g., PLC/SCADA, virtual commissioning/simulation), and **smart ancillary technologies** must support the shop floor control in **specific Industry 4.0 solutions** and **performance goals** for contingent problems in different manufacturing planning and control environments. The first example, **digital twins** of CNC (nesting tasks shadow integrating CAD/CAM and scheduling) within shop floor environments based on make-to-order (**MTO**), Second, **augmented reality** of digital product fitting for **mass customization** in assemble-to-order environments (**ATO**). Third, testbed systems for aeronautical components (e.g., aircraft turbines) can be based on **machine-learning algorithms** for early wear/stress patterns detection within the engine-to-order environments **(ETO),** avoiding for the shop floor control several problems before assembly (e.g., rework, order lateness, recall/return, loss customer reliability). Fourth, critical spare parts by **additive manufacturing** for the MRO in the **continuous processing** maintenance environments (e.g., sugarcane biorefineries, hospitals, hydroelectric plants). Fifth, **auto-ID technologies** with **a CPS system for material/resources flow traceability, visibility, virtualization** for **project planning and control environments**. Other emerging smart technologies use in digital manufacturing execution and control environments are **machine-to-machine communication**, **smart grid**, **smart robots/co-bots**, **smart products**/parts/materials/conveyors, and **cloud-services.** Therefore, a smart shop floor control is based on **digital value-creation** from the intensive use of ICTs technologies, automation systems, and focused applications of **ancillary Industry 4.0's technologies** in the different manufacturing planning and control environments. | Tao and Zhang (2017)<br>Lin et al. (2018)<br>Gustafsson, Jonsson and Holmström (2019) |

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| **Required smart capabilities:** mass customization capability by the shop floor control; virtualization capability (e.g., digital twins); web and cloud-services capabilities; wearables devices capabilities; shop floor automation/autonomy capabilities; smart products/resources capabilities; decision support systems capability; ICTs capability (e.g., MES/APS/ERP); smart grid/sustainable/green capabilities; holonic/distributed manufacturing capabilities (e.g., smart robots); cloud manufacturing capabilities (e.g., services/computing platforms); cooperation and collaboration capabilities; scalability, and (re) configuration capabilities (e.g., M2M); shop floor resources as-a-service/servitization (e.g., MES-as-a-service); shop floor control systems and assets synchronization to remain factory layers (e.g., vertical MES synchronization to ERP/S&OP). | |
| Fit of the Legacy Systems and Manufacturing Assets<br><br>**Description:** This factor concerns **shop floor control upgrading policy/initiatives** for **Industry 4.0-concept**. In this key factor are described all of the **actions required**, **capabilities desired**, **organizational strategic alignment**, and **resources of supporting** for the **operational fit (upgrading)** of the **shop floor legacy physical assets and** systems/network to **Industry 4.0-concept**. The **fit process** can occur in **two ways**: ***(i).*** **little and incremental changes/innovations** by **adjustments** made for **getting digital capabilities** on **legacy physical assets** and systems on the shop floor (e.g., PADs adoption to operator monitoring the CNC' KPIs in real-time, and/or; ***(ii).*** the **radical fit of the manufacturing and systems** changes/innovation by **bought of new and native digital assets**/technologies and systems. The **fit process aims** to link the **correct capabilities of digital technology'** solutions with legacy manufacturing environment requirements for **performance increase** (**profile and off-profile** gains), and/or a **goal achievement** (e.g., digitalization, integration, automation). In summary, the shop floor fitting is regards the **plan of how to adjust/upgrade** (if possible) the **legacy physical manufacturing assets** and **systems/network to** the **Industry 4.0-concept** based on in two ways: radical change by **building/buying entirely new digital manufacturing assets** and **systems** (infra) strucuture and, or else, by the option of the **minimal replacement** and **maximal digitalization/integration/automation**, reaching all of the equally smart capabilities provided by a native new digital assets or system that could be bought. These incremental fit premises are grounded on in fact that the most of manufacturing assets can be **digitally adjusted** in many industries, requiring **embedding of a few/incremental smart capabilities** towards to Industry 4.0-concept. In an **Industry 4.0' evolutional plan** for the shop floor, a **fine-evaluation** must **be done** regards the **fit range of machines, production lines, conveyors, ICTs** and **automation systems** because sometimes **few adjustments** and **workers knowledge** are able to **provide the required digitalization, integration, and automation** to **digital manufacturing**. The incremental **fit process avoids great investments**, **risks**, **failures**, and **efforts** in new and not experimented assets, saving time and resources, boosting Industry 4.0 initiatives with minimal changes/efforts. Thus, all manufacturing assets and systems must be rigorously evaluated with regard to **the incremental innovation** and **fitting possibility** for cheaper and quick digitalization, integration, and automation options. For example, a sensor embedded in a legacy CNC machine avoids buying a native digital machine model, enabling equal integration **to new integrated IoT-MES systems** enabling real-time KPIs/OEE' monitoring. Over again, **Industry 4.0 experts' knowledge** conjointly to shop floor **workers tacit knowledge** can generate "**home-made" solutions** well-thinking/designed towards significant **incremental adjustments and innovativeness**, which in turn, **save costs, time, and resources**.<br><br>Therefore, some legacy systems **fit actions** can comprise: ***(i).*** contingency plan for failure and disruptions during the fit process; ***(ii).*** defining a **technical workflow** for the fit process (roles and responsibilities, timeline, core assets); ***(iii).*** **actions roadmap** of fit of legacy systems, and physical manufacturing assets (What, why, how, and Hhw much?); ***(iv).*** the **fitness of communication protocols** and **interoperability requirements** of the legacy systems/device/network to the new digital systems; ***(v).*** fit of the **network infrastructure** of legacy systems to new networking requirements/smart technologies/devices; ***(vi).*** **fit the legacy TICs** (ERPs, CRM/SCM, MES/APS), automation systems and transport systems (PLC/SCADA, robot systems, AGVs) **to smart technologies-concept** (IIoT, BDA/AI, Cloud, CPPS); ***(vii).*** **fit** (if possible) **gradually of all** | Orellana and Torres (2019)<br>Hoffmann (2019)<br>Ramos et al. (2020) |

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| **physical legacy assets** (machines, conveyors, processes, lines, products, parts) **to Industry 4.0-concept**, applying the process of digitalization, integration, automation, servitization; ***(viii)*. fit processes of assets and systems** must be **aligned to organizational Industry 4.0's strategy**.<br><br>**Required Smart Capabilities:** incremental fit/innovation capabilities; radical and fit/innovation capabilities; equipment/assets replacement evaluation capabilities; fit plan capability; upgrading capability; change management capability; project management capability; organizational Industry 4.0's strategy alignment capability. | |
| Fit of the Shop Floor Control Methods and Environment<br><br>This key factor concerns to **fit** or (re) **design** of shop floor control **intangible assets**, i.e., "**how do/developing digitally**" the shop floor control regards to **digital manufacturing execution (**tasks/operations, processes and equipment) and **digital SFC managerial task/activities**, methods, tools, organization, supervision/coordination, roles and responsibilities, employees' digital skills, smart operators. The development of these **digital intangible assets is critical to performance**, heavily depending on the **internal company's efforts** (fit processes, continuous improvements/change management programs). **Environment fit** regards to adjustments of focused smart technologies to **environmental characteristics** of a **digital shop floor's planning and control**, i.e., it is critical to consider the planning and control environments characteristics adherence (e.g., projects/jobbing, continuous, ETO, ATO, MTO, MTS, cell and group technology, and hybrids) to Industry 4.0 technologies benefits/capabilities/projects. This assessment aids in the **right SFC environment fit/design execution** by **correct smart technologies choice**, the **highest leverage of digital capabilities**, and seamlessly reaching strategic alignment and performance.<br>In this key factor, **all designed actions/capabilities** are concerned with the **fit** of **shop floor control' methods and environments** (e.g., digitalization of managerial tasks, automatic errors detections tasks, and autonomous making decisions), i.e., grounded on **smart planning and control concept**. In detail, the fit of shop floor control' methods and environments to Industry 4.0 are both linked to **manufacturing execution** and **monitoring** (how "**running the manufacturing digitally**"), as-well-as concerns to activities of **manufacturing managerial control function** (how "**running the production control digitally**") like scheduling/dispatching, sequencing, order release, progress and monitoring), and also the integrated interfaces (purchasing, inventory management, quality, maintenance, MRP, CAD/CAM, et cetera).<br>**Some examples** of issues about digital fitness of shop floor control methods and environment to Industry 4.0 are: **i)** (how) **adjust** and set the **routing scheduling** to automatic way; **ii)** (how) **adjust** and to **operate** with **real-time monitoring**; **iii)** (how) **adjust** and to **trace** the **supply materials for critical orders**; **iv)** (how) **adjust** and to **run** the production control with **digitalized work instructions** (e.g., digital machine documentation/instructions); **v)** (how) **adjust** and to **balance the cells/production lines** with the support of **smart technologies** (e.g., data analytics tools and **optimization**); **vi)** (how) **adjust** the **training programs** for operators 4.0 development (**smart operators**), **managers** with **digital fluency**, top-management, CIOs, CEOs, and owners as **data analytics skills/competencies**. **In summary**, this method/environment fit process is centered on thinking (how) the (re) design/fit of shop floor control activities within the smart manufacturing planning and control scope. Therefore, this key factor is centered on fitting the SFC's organizational processes.<br><br>Therefore, some **actions/capabilities** that can be endeavor in the shop floor control to **intangible assets fit processes are**: **i)** Defining **a clear roadmap** of What, Why, How Shop Floor Control methods/tools/activities/tasks can be fitted for Industry 4.0 initiatives; **ii) Fitting of Shop Floor Control methods/tools** and **programs to** the **new digital environment** organization (e.g., lean move towards to lean 4.0); **iii)** (Re) **design/fit** of **worker tasks** to digital environment requirements; **iv)** Define **benchmarking** and **KPIs** for Shop Floor Control for managing the fit process (**As-Is** and **To-Be**); **v) smart capabilities development**, which is centered on both digital resources provided by Industry 4.0' | Kagermann et al. (2013)<br>Strandhagen et al. (2017)<br>Romero-Silva and Hernández-López (2020) |

technologies adoption, and also in Smart Manufacturing/Smart Shop Floor Control practices' domain; **vi) fit processes** of **methods** and **environment** must be **aligned to** organizational **Industry 4.0's strategy**.

**Required Smart Capabilities:** digital capabilities development; fit plan capability; environment upgrading capability; change management capability; project management capability; PPC/SFC methods (re) design capabilities; planning and control environment features mapping capabilities; capabilities of innovation along with SFC methods and environment; organizational Industry 4.0's strategy alignment capability.

**Table D5.** Skills and Culture (SC)

| Key Factor (KF#) | Literature |
|---|---|
| Shop Floor Control change management<br><br>**Description:** Change management's key factor **c**oncerns **changes in the business models**, **activities, processes**, **mindset**, and **skills** that enable reaching all benefits of the **full deployment** of the **new digital technologies** within the shop floor control function. It is the **start point** for the **maturity path** towards the Industry 4.0 concept, conceiving the shop floor control function's changes **from analogical to smart status**. Therefore, to reach a smart shop floor control, a manufacturing company **must formulate an Industry 4.0-based change management planning** and **execute** it accurately. Shop Floor Control Change Management towards Industry 4.0 must comprise the following **key actions: i) Definition** about What, Why, How, and Where **starting** the Shop Floor **Change**. This step is based on a **short number of priorities** (driven by analysis about key systems, manufacturing assets, activities/tasks, methods/tools, people/teams/projects, costs, time, risks, efforts), and also the **Mapping of a List of objectives** with clear motivate goals for Industry 4.0 adoption; **ii) Planning** the Shop Floor Control **transition processes** by the designed stages (computerized, digitalized, integrated, autonomous, smart); **iii) Formulation of a migration/fit strategy** for manufacturing assets, ICTs and automation systems (MES, APS, ERP, PLC/SCADA) to the new smart capabilities of Industry 4.0; **iv)** Documentation and **Roadmap about learning lessons** through Shop Floor Control Change Management process towards Industry 4.0. Therefore, a smart shop floor control is based on an **accurate manufacturing change management plan and migration strategy of systems** from **managerial methods** (e.g., 5W1H; CANVAS, scrum, agile methods; project management tools), **engineering change tools** (migration systems strategy, technological readiness level-TRL; risks, costs, and budget plan and assessment; financial/economics engineering), and **organizational change** capabilities;<br><br>**Required Smart Capabilities:** manufacturing change management capabilities; system migration capabilities; project management capabilities; agile methodologies capabilities; leadership capabilities. | Koch et al. (2016)<br>Machado et al. (2019)<br>Roblek et al. (2020) |
| Data-driven and digital culture on Shop Floor Control<br><br>**Description:** This factor concerns key issues for **avoiding failures** or **poor performance** from **Industry 4.0 projects/initiatives,** i.e., **cultural and organizational/social aspects.** Along with Operations Management development, its literature based on empirical evidence relates that **failure** and ineffectiveness of continuous improvement programs (e.g., **lean**) or managerial programs (**total quality management**) are linked mainly to **cultural resistance** and **organizational changes** related to lack of **employee engagement**, lack of **top management support**, lack of **strong leadership role**, and failure of **effective communication between functions/activities**. In addition, **organizational factors** and **structure** (e.g., hierarchies, managers mindset, education, and motivational aspects), and **social aspects** (e.g., values) also are important to consider in a **profound transformational** initiative like Industry 4.0. Thus, the first step for **digital culture and data-driven decisions** establishment in the Shop Floor Control is grounded on **top-management engagement to the Industry 4.0 Initiatives/projects**, e.g., required resources and changes for made it feasible. **Map** and **eliminate the barriers** for **digital** and **data-driven Culture** on Shop Floor Control can be a second step. The third step is the development/selection of **engaged Leadership** to conducting Industry 4.0 initiatives and cultural changes for a digital Shop Floor Control. The fourth step is the **continuous employees' education, engagement, and awareness programs** for Industry 4.0 projects and operation's environment: a **best practice** for easy this step is a **building of cultural change roadmap** (encompassing preparation, involvement, roles and | Lamba and Singh (2018)<br>Kampker et al. (2018)<br>Tabesh et al. (2019) |

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| responsibilities assignment, mapping of leadership skills required, cultural changes desired, reached results assessment). Therefore, **an in-depth understanding** of **organizational structure** and **culture** is required by those manufacturing companies and their **leadership roles** that endeavor to **scale maturity paths towards smart Factories**, Smart Manufacturing, and Smart Shop Floor Control. For smart status reaching, **profound organizational** and **cultural efforts changes** (transformational mindset) need to be performing to awareness the human resources (at all levels) about digital Production Control activities benefits on the shop floor. Once overcoming the organizational and cultural barriers for Industry 4.0 concept, digital and data-driven culture can be established gradually on organizational practices. After **Industry 4.0 acculturation** and **digital culture consolidation**, the **employees** can **run** the **shop floor control** activities and **manufacturing tasks** based on **data-driven decision-making**. Strong digital culture/skills and data-driven shop floor control activities are core characteristics of the smart shop floor control within the organizational culture perspective.<br><br>**Required smart capabilities:** organizational change capability; cultural change capability; data-driven capabilities; digital fluency capabilities; organization learning capability; education and training capabilities; leadership capability to changes; employees’ engagement; digital skills. | |
| Data skills and training for people on Shop Floor Control<br><br>**Description:** This key factor concerns, firstly, **employees’ skills development**, **roles** and **responsibilities to Industry 4.0 concept deployment** and running a Smart Shop Floor Control. Secondly, the shop floor control function must have a **continuous qualification program** to leverage the Industry 4.0 requirements related to employees' skills development, i.e., an **enterprise education system** to the **Industry 4.0 skills development** and **support**. In the manufacturing execution and monitoring activities, **smart operators** hold core features and skills for smart Shop Floor environments. Therefore, smart operators’ skills need to be developed (technical and digital skills associated). Both ordering system management and production scheduling activity require a program for **employees’ digital fluency** and **data-driven skills development**, i.e., **training** of manufacturing **leaders, supervisors, analysts, technicians, engineers**, as well as the **middle** and **top managers**. Last, the main skillsets required by a smart shop floor control working and its interface functions/activities are based on besides classical/technical skills, in the **computationa**l, **technological, digital**, and **soft skills**. Therefore, **Industry 4.0 skills** on shop floor control are based on **employees’ training, development,** and **continuous professional education program** with the purpose of intensive use of **ICTs technologies**, **automation systems**, and **focused applications** of **Industry 4.0 technologies** for different manufacturing planning and control environments.<br><br>**Required smart capabilities:** digital skills capabilities; soft skills capabilities; computational skills capabilities; technological skills capabilities; professional training and education capabilities into Industry 4.0-context. | Longo et al. (2017)<br>Pacaux-Lemoine et al.(2017)<br>Liboni et al. (2019) |
| Projects and teams for Industry 4.0’s solutions on Shop Floor Control<br><br>**Description:** A smart Shop Floor Control in the **people dimension** is characterized by **dedicated, interdisciplinary, and expert teams** (e.g., data scientists, virtual commissioning analysts and engineers, digital twin scientists and developers, additive manufacturing engineers and operators) working on **creation-value projects** based on Industry 4.0 technologies capabilities. **Teams and projects** focused on providing **digital solutions** to shop floor control must have **top-management support** for Industry 4.0 initiatives as a primer requirement. Besides that, **Industry 4.0 projects** for the shop floor need to have a **precise scope**. **Interdisciplinary teams’ formation** is also a requirement (e.g., business domain specialists and data scientists for manufacturing data analytics projects). In the Industry 4.0 pilot initiatives/projects, these projects and teams must use the **PoC** | Veile et al. (2020)<br>Marnewic and Marnewic (2019)<br>Şen and İrge (2020) |

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| **cycle steps** (Pilot, Refine, Establish, Extend and Standardize), i.e., develop and implement the digital pilot solution and expand it gradually. **Agile methodology** and its **tools (kanban, SCRUM, Lean, CANVAS)** handling by teams along Industry 4.0 projects can increase its success rate on the shop floor. Lastly, benchmarking and KPIs must be established to monitor **Industry 4.0 projects** implementation **progress** by **clear** and **managed metrics**. Therefore, a smart shop floor control is based on **dedicated and interdisciplinary teams for** Industry 4.0 projects, i.e., it is grounded in **project management techniques** and the **teams' competencies/skills** for Industry 4.0 deployment.<br><br>**Required Smart Capabilities:** project management capability; agile methodologies' capabilities; interdisciplinary knowledge expert teams; PoC cycle deployment capabilities; teamwork and soft skills capabilities. |

**Table D6.** Digital value-creation

| Key Factor (KF#) | Literature |
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| New digital business processes<br><br>**Description:** New digital business processes should be **agile,** and supported by a smart Shop Floor Control function. This factor closely relates to **innovation practices**, **digital business**, the **offer, creation, and capture of value** utilizing Shop Floor Control function activities and tasks. For example, by using additive manufacturing-based unitizing processes along with a unique workstation, manufacturing managers decrease the lead times by minimizing delivery time windows to customers (offer value). For a **sustainable new digital business**, an **integrated shop floor management (vertically, horizontally, end-to-end)** should **support new digital capabilities** such as throughput real-time management, materials traceability and control, synchronizing of all shop floor activities and tasks (e.g., quality, materials inventory, organization, manufacturing processes execution, scheduling, and ordering). The shop floor's smart assets (tangible and intangible) should support **changeable value-creation requirements** (e.g., flexibility). Besides that, the shop floor control function should work in an integrated manner with all remain function towards **performance achievements** and **digital value-capture strategies**. For sustaining optimized and sustainable offers, the creation, and capture of new business processes based on Industry 4.0, it is required an **integrated and collaborative shop floor management**. These practices enable **flexibility, responsiveness, and agility** to changes concerning new digital business, creating **resilience and alignment** to production strategy in Industry 4.0. Therefore, this factor concerns **new digital business process propositions** supported by shop floor management practices and aligned to the manufacturing company's **business strategy.**<br><br>**Required smart capabilities:** innovation; integration; collaboration; Industry 4.0 strategy; business processes alignment; digital value-offer strategy; digital value-creation; digital-value capture; performance management; digital shop floor management. | Berman (2012)<br>Meißner et al. (2020)<br>Veile et al. (2022)<br>Piller (2022) |
| Manufacturing execution and monitoring<br><br>**Description:** This factor concerns **Smart Manufacturing practices** within shop floor control. This **bundle of practices** based **on Industry 4.0 technologies** provides several smart capabilities to manufacturing processes, execution, and maintenance task**s**. Thus, the main smart practices and its derived capabilities are: **i) advanced automation** for **autonomous manufacturing lines** (e.g., sensors integrated to microcontrollers can alert or stop the line/machine in out-specifications parts/products events), **robotics/co-bots** operations practices, **virtual commissioning** practice, and **collaborative man/machine** work; **ii) flexibility (FMS) and** and **autonomous manufacturing lines; iii) product modularity** and **agile manufacturing** for **mass-customization** of a wide-range of product variety in short lead times (e.g., **additive manufacturing** has capabilities for integrating entire products projects steps around quick customization, from digital design to manufacturing at **3-D printers**); **iv)** internal **traceability** and **visibility** for **manufacturing logistics flow (**e.g., **traceability RFID systems** generate data for inputs simulation models to adapt changes within a smart factory including the staff levels, WIP, and process plans); **v) virtual manufacturing practices** based on **CPPS systems (**by the establishment of **a digital-thread** linking **IIoT,** (big) **data management, cloud solutions**, **decision support systems,** and **people,** e.g., a **digital twin** is a standard technology employed for shop floor environment **virtualization)**; **vi) vertical integration** and **interoperability practices** between operational (OT) technology of sensing and network, physical assets, automation and ICTs systems (PLC, MES, APS, MES, ERPs);**vii) data management**, **analytics**, and **optimization** to support **data-driven manufacturing execution** tasks/operations, processes, and decision- | Zheng et al. (2018)<br>Qu et al. (2019)<br>Frank et al. (2019) |

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| making (better making decisions on execution, monitoring, and maintenance); **viii) sustainable/green manufacturing** and **energy management practices** for **saving** and **optimization resources (e.g., smart grid** system embedded on **CNC machines groups** for **intelligent change** of **power consumption energy** according to the materials shear force requirement in the sheet cutting task— nesting; **ix)** Definition of **key performance indicators** and **benchmarking** for shop floor control in Smart Manufacturing environments (agility/responsiveness, productivity/profitability, reliability, flexibility, costs/lead times, quality/customer satisfaction, inventory, complexity, green/sustainability); **x)** Use of **smart devices** (HMI, tablets, mobile, PAD, AR/VR) and **digital skills** for operators within Smart Manufacturing execution, maintenance, and monitoring practices. Furthermore, in advanced Smart Manufacturing environments are the predominance of **autonomous manufacturing practices** as self-sensing, self-adaptive, self, organization, and self-decision (for more details, see Qu et al 2019).<br>Therefore, **Smart Manufacturing** enabling **digital value-creation** by focused Industry 4.0' technologies adoption within manufacturing execution operations, its maintenance, and monitoring. For this, some **actions/capabilities** that can be endeavor in the shop floor control to **Smart Manufacturing execution practices ' domain** are: **i) lean manufacturing** and continuous improvement (e.g., agile/QRM) initiatives/programs deployment harnessing Industry 4.0' technologies (**Lean 4.0**); **ii) real-time manufacturing execution and logistic flow information**, **traceability** and **visibility**: machines, vehicles, operations progress, lines, orders completion/lateness, logistic flow (AGVs/conveyors, material handling, smart products/PEID, parts/raw material, tools/equipment, inventory/supply, WIP, lead time/cycle time, throughput, setup, OEE, efficiency/yield), and workers and decisions; **iii) modelling and simulation** supports to the **data-driven manufacturing decision-making** and **advanced optimization** (predictive, prognostics, and prescriptive capabilities) based on smart technologies; **iv) adaptive manufacturing**: flexibility and self-configured/autonomy lines (self-monitoring and self-optimizing lines based on event-triggered control); **vi) manufacturing execution synchronization** between different assets/systems in line with **dynamics changes** triggered by the shop floor control systems/business needs (e.g., machine load minimization automatically at more expensive power times via designation of smart grid algorithms and profitability simulation, or else, by breakdown of stock capacity or lack of raw materials); **vii) performance indicators** and **benchmarking** for digital/Smart Manufacturing; **viii) green/sustainable Smart Manufacturing** practices.<br><br>**Required smart capabilities:** autonomous manufacturing capabilities; dynamics/synchronization manufacturing capabilities; data-driven manufacturing capabilities; smart manufacturing performance measurement capabilities; real-time manufacturing capabilities; logistics flow manufacturing capabilities (visibility, traceability); optimization manufacturing capabilities; shop floor modeling and simulation; lean manufacturing capabilities; virtual/CPPS capabilities; predictive manufacturing capabilities; | |
| **KF- VC5.3:** Production scheduling and sequencing<br><br>**Description:** This factor concerns **Smart Scheduling practices** within shop floor control. A **bundle of practices** based **on Industry 4.0 technologies** provides several **smart capabilities** to production scheduling activities. Scheduling is a Production Control activity that performing the **allocation** of **resources** (e.g., workers, machines, teams/crews) to **tasks/operations** of manufacturing in a **defined sequence**, **route**, and **time**. Thus, **Smart Scheduling** harnesses **Industry 4.0' technologies** to improve production scheduling activities performance and to **value-creation** by an **intelligent scheduling**, **sequencing/routing**, **dispatching**, and **balance line tasks**. Therefore, the main **smart practices** required for Smart Scheduling are based on CPPS systems and Big Data/AI ecosystem, i.e., smart technologies to the (big) data management and decision support system (DSS): | Mourtzis et al. (2018)<br>Bauters et al. (2018)<br>Rossit et al. (2019c)<br>Cohen et al. (2019)<br>Jiang et al. (2019)<br>Parente et al. (2020)<br>Grassi et al. (2020c)<br>Spenhoff et al. (2020) |

***(i).* decentralized/distributed decision-making' scheduling**, e.g., in cloud-connected, CPPS systems, **autonomous robots** carry out their **own optimal scheduling** in a decentralized setting. In this case, **CPPS system** can be defined as a combination of physical shop-floor agents, i.e., machines, robots, humans, capable of **collaborative work** as machine-to-machine and **human-robot collaboration** (co-bots) integrated with **sensing** and **networking platforms** (IoT, sensors, gateways, middleware, WSN, web/cloud-services), and **intelligent manufacturing agents**. This practice is based **on CPPS systems capabilities**. Therefore, CPS, big data, ancillary technologies (e.g., robots/co-bots, 3-D printers) join in a **digital thread** as a high-level **Decision Support System**, which embeds the **production self-scheduling, collaboration** and **cooperation,** and **autonomy capabilities** from shop floor control.

**Big data**, **data analytics**, and **AI applications** provide the capabilities to effectively convert that **data** into **learning** and **knowledge**, which can be used to support **real-time decisions** of **supervisors** and **schedulers** on different problems related to **scheduling environments** as single machine, parallel machine, flow and job shop, projects (e.g. real-time analyzing and monitoring to avoid out-conformance patterns in sheets metal bending to deliver on due date; or to establish predictive CNCs maintenance planning based on Machine Learning use, avoiding unscheduled downtime, job delays, and decreasing of **scheduling tasks performance**: 1. Meet due dates, 2. Minimize work-in-process (WIP) inventory, 3. Minimize the average flow time through the system, 4. provide for high machine/worker time utilization/ minimize machine/worker idle time, 5). provide accurate job status information, 6). reduce setup times. 7). minimize production and worker costs. Big data ecosystems can be connected to digital thread of decision support systems based on CPPS system. Therefore, big data ecosystem is a part into CPPS system that is related to data/information collection, transmission, processing, analytics, and optimization practices for production scheduling supporting.

***(ii).* modeling** and **simulation** are **practices** able to provide **optimization**, **predictability**, **accuracy**, and **learning/knowledge** capabilities to smart agents and people in scheduling tasks. For example, **intelligent optimization** of nesting in at CNC **synchronized** to schedules in the virtual world by APS software can improve **sequencing tasks' reliability**. Modeling and simulation provide **optimization** from **scenarios** and **patterns** designed by an association of **data science techniques** as **AI tools** and **machine learning algorithms**, **operations research models**, and **statistics tests** applied conjointly to **manufacturing/operations management knowledge**. In turn, the first benefit of **optimization practices** use is the learning and knowledge to **accurately performing scheduling tasks**: balancing, dispatching, sequencing/routing.

***(iii).* dynamic** and **data-driven (re) scheduling** is **a set** of **practices** enabled by the **data management ecosystem** and its **technologies**. Therefore, by data management technologies use, production scheduling activity can **dynamically** by **predictability capability** provide **data-driven quick changes**, e.g., supporting **detailed job shop schedule** to meet the specification of production quantities from **MRP/ERP system driven** by **real-time demand changes** linked to **S&OP** or **horizontal/end-to-end-integration**. **Predictability** is a ground capability of production scheduling to predict demand and manufacturing events, and then react to them (e.g., the requirement of **greater predictability** of **completion time for dispatching tasks** in flow shops or the mass **customization job arrival patterns**). Furthermore, **adaptative scheduling** is a **second-order capability** from dynamic and data-driven scheduling practice**. Adaptive scheduling** is the capability to **re-generate alternative** and **feasible schedules** driven by **real-time shop-floor conditions**. Mourtzis et al. (2018) describe an example of adaptive scheduling where once the manufacturing monitoring system detects a deviation in the shop-floor conditions, all the available monitoring data including machine tools status and availability, as well as the status of the tasks are sent to the smart algorithm in purpose to generate new feasible schedules. **Flexible production**

**scheduling** is the output performing of practices mentioned above, representing a **high level** of both **Industry 4.0 technologies** implementation and **smart practices** domain.

***(iv).* production scheduling synchronization** is a capability enabled by **integration practices**, for example, **scheduling tasks synchronization** with managerial functions interfaces (e.g., inventory, purchasing, S&OP) interoperable ICTs (MES, ERPs, CRMs), and business layers aim value-creation by holistic scheduling embedded with full capabilities of integration, traceability, and visibility along with supply chain. Horizontal, Vertical, and end-to-end integration support **holistic scheduling**, which considers more supply chain information and also the higher hierarchical' levels of the decision included in the scheduling process. This aligns the production schedule to tactical and strategic goals within the manufacturing company (e.g., end-to-end, real-time JIT synchronization of jobs schedule along with systems, suppliers, and customers in the car assembly supply chain). Therefore, these practices harness of IoT ecosystem (RFID, sensors, WSN), cloud manufacturing (cloud and web-services), and integration tools (SOA, NoSQL, middleware, MQTT/IPv6 protocols, 5G) to feasible full integrated and synchronized smart production scheduling task and systems (APS, MES, MRP/ERP, CRM, logistics/supply chain systems).

***(v).* scheduling-as-a-service** is a practice enabled by **cloud/web services** encompassing IoT ecosystems, vertical integration, virtualization and **servitization capabilities**. **Production Scheduling** as-a-service is an online way for execution and monitoring of sequencing, dispatching, and balancing tasks. Thus, cloud and (big) data capabilities interact to support smart scheduling needs, e.g., **scalable computational requirements** of **complex scheduling simulation** problems (scalability requirements), as well as the processing and analytics of the large amounts of data generated in shop floor environment (big data and analytics platforms). Another capability provided by production scheduling-as-a-service practice is the **sharing and collaboration process** of routine, resources, and real-time information of scheduling execution tasks.

***(vi).* production scheduling complexity minimization** is **a practice** based on **ancillary technologies** as **AM** and **AR/VR/MR** coupled to AI tools. They can be used for the **routing/workstation layout self-configured**, and **smart assistance in design, manufacturing**, and **assembly**. Often, **production scheduling is a complex task** from a computational view (NP-Hard problems, high computer processing requirements, programming skills, and in operations research) as well as in its operationalization (e.g., a high number of products, routes options, layout and combinatorial constraints, teams/crews' specificities, modularization' requirements). Smart technologies as AM provide practices that can minimize scheduling production complexity since design (product, process, manufacturing/assembly). For example, a 3D-printer unify a series of operations and process in an only workstation comprising few manufacturing operations and minimizing the most of the complexities inherent to scheduling (routing and layout, balancing, sequencing/assignment, dispatching). Therefore, **AI algorithms** and wearables as **AR/VR/MR** can **help shop floor professionals** in a **realistic simulation** of integrated product design, manufacturing process, and assembly aiming the complexity minimization of production scheduling tasks. In last, an example presented in Cohen (2019) is an **assembly system 4.0** that uses **real-time optimization models** and **machine learning algorithms** to **automatically self-configuring**. In this way, the assembly line is embedded with **self-scheduling** and **self-balancing**, which are defined **in real-time**, utilizing an **optimal product sequence** and **task assignment**, considering the workers' skills, the inventory level of components/parts, and the available machinery capacity. In **manual assembly**, augmented reality (AR) can use smart glasses to display a real image seen by the worker, over virtual holograms artificially created by software, it is highly beneficial for aid manual assembly tasks into performing the assembly scheduled by PPC**.** For an additional example of AR, AI, and simulation in manual assembly in smart workstations, see Bauters et al (2018).

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| ***(vii).* Green/sustainable production scheduling** is a practice based on the application of **optimization algorithms**, models, and technologies aiming at **energy** and **resource-saving** from balancing, sequencing, dispatching/assignment, routing tasks. This practice uses **big data** and **machine learning tools**, **smart grid algorithms/systems**, **metaheuristics algorithms** (e.g., see Jiang et al. 2019), **simulation techniques** (see Goodall et al. 2019), **circular economy**, **cleaner production concepts** and **tools**. For example, Moon and Park (2014) built smart production scheduling embedded in a **Smart Grid application** that found simultaneously an optimal solution for both production and energy schedule aiming to minimize manufacturing and energy total costs. Therefore, **green production scheduling** concerns with new optimization criteria and green requirements embedded in models, algorithms, simulation tools (e.g., APS software), and manufacturing systems that harnessing **advances** in **computational/programming techniques** in response to an **emerging industrial mindset** that incorporates **sustainable issues** into **performance goals** (e.g., resources saving, energy, wasting minimization, sustainability, and circular economy).<br><br>**Required smart capabilities:** autonomous (re) production scheduling capabilities; dynamics/synchronization production scheduling capabilities; data-driven production scheduling capabilities; real-time production scheduling capabilities; visibility and traceability capabilities; optimization production scheduling capability; production scheduling' modeling and simulation capabilities; green optimization capability; CPPS/DSS capability; predictive capabilities; adaptive and flexible production scheduling capabilities; production scheduling-as-a-service capability; holistic production scheduling capabilities. | |
| Order release, progress, and feedbacks<br><br>**Description:** This factor concerns **smart order practices** within shop floor control. Smart order activity links **manufacturing execution on real-time**, to **production/order schedule plan**, **detailed planning activities** (e.g., MRP), **demand forecasting/S&OP activities**, and **business goals/performance**, i.e., it is representing the **customer requirements realization** over smart manufacturing processes/operations and smart scheduling tasks/practices. It **complements, effective, a**nd **monitor** the realization of smart **manufacturing operations** and **scheduling tasks** through of ICTs and Industry 4.0' technologies of supporting. For this, the **practices** based on **Industry 4.0' technologies** provide a **bundle of smart capabilities**. Smart Ordering activities in a complex shop floor control' environment is performed on following activities/sub-activities: i) **Order Release** → Shop packet; ii) **Order Scheduling** → Dispatching list; iii) **Order Progress** → Management Reports & Factory Data-Collection System→ 1. Raw material and Components, 2. Work Centers/Stations, 3. WIP, 4. Finished Products. Brinding smart scheduling and smart manufacturing execution, a smart ordering activity can be performed along with **CPPS** as **a high level** of **Decision Support System**. **MRP and MPS activities** can be **integrated** with Production Control Activities as Order Management, and their **systems** (CAD/CAM, APS, MES, ERP, CRM), **assets/resources** of execution (machines and tools), and **Industry 4.0 technologies** of support, **leveraging smart capabilities** of **virtualization**, **integration**, **synchronization**, **autonomy**, **simulation** and **optimization**, **real-time monitoring**, **data-driven decisions**, **traceable** and **visible order status, resources**, and **logistics flow**. Thus, the **CPPS system** constitutes a core **DSS** in supporting a **digital thread** that bonds from S&OP to detailed capacity planning, the purchasing system, capacity and inventory, to shop floor control activity and systems in the bottom, which release, schedule, and monitor the routine of production orders (execution and status).<br><br>**Smart order** activities execution are often operationalized on **ICT systems** as Manufacturing Execution System (**MES**) and Enterprises Resources Planning (**ERP**) connected by **CPPS systems' digital thread**. These systems typically respond to online inquiries concerning the **status of order release**, **order scheduling**, and **progress**. In a smart shop floor environment, furthermore classical MES system capabilities, order management is | Zhang et al. (2011)<br>Qu et al. (2012)<br>Zhong et al. (2016)<br>Zhong et al. (2017)<br>Tao and Zhang (TAO; ZHANG, 2017)<br>Grundstein et al. (2017)<br>Lin et al. (2018)<br>Rossit et al. (2019d)<br>Zhou et al. (ZHOU *et al.*, 2020)<br>Wang et al. (2020b)<br>Alami and ElMaraghy (2021) |

empowered with a **generation of digital process' instructions** to worker/workshop, **digital** and **real-time order manufacturing annotations** by the operator, **order progress integrated** to **real-time inventory/supply monitoring**, **real-time capacity monitoring** and **predictability** of **machine** and **tool status/availability, labor** and **workload traceability**, **real-time quality statistic control metrics**, **costs transparency**, **OEE** and **productivity KPIs monitoring** and **optimization**, **WIP level monitoring** and **management**. In addition, a **smart MES** can support the order management, providing links to interfaces function modules into manufacturing companies' information system, such as **quality control**, **maintenance**, energy management (**smart grid**), and **optimization**.

Therefore, **smart ordering practices** are related to: ***(i).*** **intelligent monitoring** of orders based on smart manufacturing objects (see Zhong et al. 2017); ***(ii).*** **WIP management**: resources visibility and traceability to order completion/progress supporting (see Zhang et al. 2011); ***(iii).*** **real-time feedback** and **messages** about **order status reporting/events.** For example, Qu et al. (2011) showed an application where product outputs captured at the end of the assembly line are used in connection with the product's BOM structure to calculate the line's real-time material consumption, thus, quantities of materials have been replenished to line are captured by an RFID- Gateway at the buffer gate, therefore, real-time line-side stocks could be easily traced); ***(iv).*** **CPPS** as a **high level DSS** for **real-time ordering system** working with order **visibility** and **traceability** capabilities (see Rossit et al. 2019a); **v) digital order handling** and order **information feeding** into **smart devices** on shop floor (see Longo et al. 2017; Lin et al. 2019); ***(vi).*** **order synchronization** and **integration** (Lin et al. 2018; 2019). Order synchronization is a practice that enables data/information synchronization, **sharing**, and **collaboration** between systems, devices/assets, and people along with the shop floor's **key value-adding points**, and also **digital order transmission** and **filling**, order status changes by operators, and order progress monitoring (e.g., HMI communication, mobiles devices, PADs, computers). **Order integration** is based on **vertical/horizontal integration of systems**; ***(vii).*** **order flexibility** is based on the **quick change/increment capability** of orders in **attending to customized requirements**, i.e., order flexibility to custom configuration and **mass customization** (Mourtzis et al. 2019; Yu et al. 2018); ***(viii).*** **KPIs designed to smart ordering system performance** assessment within shop floor control, e.g., delivery-on-time, production lead-time, order lead-time, plan versus realized production, sales versus capacity, WIP and inventory level (see Orellana and Torres 2019); ***(ix).*** **modeling, simulation**, and **analytics** apply to **order making-decision support, forecasting** and shop floor **scenarios building** (advanced modeling and simulation employing AI tools, ML, data science tools, metaheuristics, statistics tools, operations research techniques, and advanced analytics tools) (see Shao and Kibira 2019). A **key capability** derived from modeling and simulation practice is **predictability** (in supporting of order resources management, maintenance, inventory/supply, capacity, logistics flow) (see Prathima et al. 2019); ***(x).*** **autonomous/automatic order release** and **monitoring** (see Grundstein et al. 2017). This practice also covers **autonomous agents** use, which are embedded with self-capabilities (sensing, adaptative, organization, decision) and responses to the order change or logistic flow changes (e.g., smart products and smart equipment interact autonomously for dynamic optimization in real-time) (see Zhong et al. 2016; Qu et al. 2019).

**Required smart capabilities:** automatic order release capability; autonomy/self-capabilities; real-time ordering capabilities; predictive ordering system capability; order optimization capability; order performance measure capability; order transparency/visibility and traceability capability; order flexibility capability; WIP management capability; integration of system capabilities; order modelling, simulation and analytics capabilities; digital order monitoring and handling capabilities; order synchronization capability; CPPS/DSS capabilities; responsiveness capabilities.