


Article

Modeling of the Master Production Schedule for the Digital Transition of Manufacturing SMEs in the Context of Industry 4.0

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Abstract: The purpose of this article is to propose a guide for the digital transformation (4.0) of a manufacturing SME's medium-term production planning process, the master production schedule (MPS). A model of the current MPS process of a group of SMEs is presented as a starting point toward digitization. The current state of this process reveals a lack of tools to support decision making and the need to increase the reliability of input data and to make the process more agile. Industry 4.0 technologies and process modeling could increase agility in the planning process. However, the digital transformation of medium-term planning activities in SMEs has not been studied. To fill this gap, a group of six experts was consulted. The novelty of this study was to identify the Industry 4.0 technologies that could improve medium-term planning and integrate them into a standardized MPS process model. This model is an ultimate point of digitization that cannot be achieved immediately by any SME, but only after several cycles of planning, deployment, and improvement. Therefore, this research also provides a method to help SMEs determine how to start the digitization of their MPS process.

Keywords: production planning; MPS; industry 4.0; BPMN; SME



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1. Introduction

The digital technologies and tools related to the concept of Industry 4.0 offer companies various ways to execute, control, optimize, and automatize their processes. Thus, various objectives are at the heart of industrial projects of the digital transition, such as cost reduction, productivity improvement, increased quality and agility, and the proposal of more customized solutions [1–3]. The concept of “Industry 4.0” was introduced in 2011 at Hannover Fair. It refers to technologies that enable the gathering, storage, transmission, and processing of data. Cyber-physical systems, the Internet of Things, cloud computing, big data, cybersecurity, autonomous robots, virtual reality, simulation systems, machine-to-machine communication technologies, and artificial intelligence have been identified as the technological groups of this revolution [1]. Through these technologies, companies can retrieve internal and external data in real time in order to adapt decision making to current constraints and ensure customers' demands are met.

In recent years, SMEs have been looking to integrate 4.0 technological advances into their business processes. However, due to a lack of technical expertise, digital migration projects can be complex for these types of companies [4], and SMEs need methods to guide their digital transformation [5]. Despite growing research in that domain, few studies have focused on medium-term planning activities adapted to SMEs' specific industrial and organizational contexts [6].

Production planning activities are generally grouped into three levels of decision making, involving different planning horizons, levels of information granularity, and objectives. The operational level focuses on a short-term planning horizon (between one week and one month). In contrast, tactical planning addresses medium-term decisions (between 6 and 18 months) and the strategic level (between two and five years) covers long-term decisions.

These activities are based on two principles, priority and capacity management. Priority management is customer-centered. It determines the quantities of products to be delivered for a given date. The second principle, capacity management, is a response from the manufacturer to the customer. It compares the capacity of available resources, financial funds, and raw material availability with the demand to identify what the company requires to meet contractual deadlines [7]. Strategic planning (sales and operations plan) manages the satisfaction of the demand, taking into consideration the overall strategy of the company and providing a framework for lower levels of decision making. Tactical planning (MPS) defines, at the master item level, the quantity that must be produced in each period of the planning horizon to satisfy customer demand under optimal production conditions. Finally, operational planning (scheduling) manages the physical flows to ensure the availability of products in the production system according to what has been defined at the tactical level [8]. At each level, the definitions of priorities, available capacity, differences between priorities and capacity, and alternatives to resolve these discrepancies lead to the development of activities.

Within a medium-term planning horizon, MPS break down the sales and operations plan (S&OP) for individual products into a shorter planning horizon [9]. The planning horizon for the MPS must be at least as long as the longest cumulative lead time for supply and production [10]. The MPS is an important basis for communication between sales order management and production, as it allows the sales department to define the quantities that can be reserved for customers and the dates on which orders must be delivered [11]. Two of the three objectives of the MPS can be retrieved from this definition, to ensure customer satisfaction with respect to delivery times while controlling inventory levels [12].

As such, the MPS process has two main deliverables. The first output is a production plan that indicates the quantities of finished products to be manufactured per week within the MPS horizon. The second deliverable is an input plan for scheduling that indicates the production time for each production order. As mentioned by, Jonsson and Ivert [11], there is a difference between the results of the MPS and the goals that the company seeks to achieve with the MPS process. One of the most important outcomes of the MPS is a feasible production plan that indicates what is to be produced based on one or more of the following objectives: increase productivity, make the best use of the available capacity, improve customer service, and maintain inventory at the desired level. Master planners must also evaluate different MPS scenarios based on the feasibility of production [13]. The MPS itself does not guarantee the optimal use of resources or on-time delivery. It requires management systems that ensure responsiveness when disruptions arise [14]. This is a complex and essential process for translating strategic objectives into feasible production programs.

In terms of research, the MPS has mostly been tackled from a calculation point of view, with the exception of a few researchers. For instance, Jonsson and Ivert [11] surveyed Swedish manufacturing industries to measure the impacts of MPS methods for industrial performance based on three variables: plan feasibility, inventory turnover, and delivery service. Other researchers also proposed methods for improving the quality of MPS outputs. Chatras et al. [15] proposed a method for consolidating master items, so the MPS can be consistent with both technical and commercial constraints and, at the same time, be flexible in the frozen zone, and Hedenstierna and Disney [16] presented an approach to decrease the frequency of MPS updating.

As confirmed in the recent literature review [17], Industry 4.0 methods and tools are now emerging as new means to improve nearly all aspects of production management.

However, only a few papers have tackled the MPS level, as most research focuses on short-term decision making [18]. Among the few papers addressing the MPS level, Wocker et al. [19] proposed a method based on unsupervised learning algorithms to determine the optimal master production schedule. Wu and Shen [20] evaluated the impacts of the MPS and throughput on scheduling in production environments with CPSs and the IoT. Alemany et al. [21] presented a decision support tool based on a mathematical model to calculate the amount available to promise. Serrano-Ruiz et al. [22] proposed a conceptual framework of the MPS 4.0 based on digital twins and machine learning for zero-defect management in the supply chain. Despite these recent advances, the whole MPS process itself has still not been studied to take advantage of all technologies now available in the era of the fourth industrial revolution.

In this paper, we propose a model for integrating Industry 4.0 technologies in the master production schedule (MPS) process. Our industrial partner, Exxelia, is a designer and manufacturer of high-performance and innovative electronic and electromagnetic solutions. The group works in sectors with high requirements, such as aeronautical, space, defense, and medical industries. Today, Exxelia comprises 13 SMEs (4 in the United States, 6 in France, 2 in Morocco, and 1 in Vietnam). This research work was developed at one of the French sites, and it was addressed to production lines with the following characteristics: multiple assembly lines, batch manufacturing, mainly manual production, multiple components and raw material references, and assemble-to-order (ATO) or engineer-to-order (ETO) production strategies.

Our general methodology followed a typical business process re-engineering approach based on the modeling and evaluation of the current MPS process of our industrial partner. This article addresses the following three objectives:

- Mapping the current MPS process within a SME as a starting point of the digital transformation. This model, referred to as T0, is then used to identify several issues within the MPS process;
- Developing a standard to integrate Industry 4.0 technologies into the MPS process;
- Proposing a digital transformation approach that favors multiple iterative improvement steps to achieve a full Industry 4.0 MPS process.

Climate change is a global emergency that transcends national borders. Transformative action is urgently needed to put the world on a sustainable and resilient path. The Paris Agreement of the 12 December 2015 [23] sets long-term targets for reducing global greenhouse gas emissions to limit the global temperature increase to two degrees Celsius. To achieve this goal, the United Nations has developed the “2030 Agenda for Sustainable Development”, which defines seventeen goals to “transform our world” [24]. Our paper contributes to goal eight, which is to promote sustained shared and sustainable economic growth, full and productive employment, and decent work for all; and goal nine, which is to build a resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.

The article is structured as follows: Section 2 presents the research method. Section 3 presents a model describing the current process of our industrial partner, referred to as T0, using the BPMN 2.0 (business process modeling notation) process modeling standard. Section 4 proposes a revisited and improved model integrating Industry 4.0 technologies into the MPS process, referred to as Tn. As this ideal process cannot be implemented at once within any SME because of its high requirements for automation, technologies, competencies, and investment, a digital transformation approach that favors multiple iterative improvement steps to achieve a full Industry 4.0 MPS process is presented in Section 5. The Tn models and the method for moving from the current MPS to MPS 4.0 open the way to several research opportunities, and are presented in Section 6.

2. Research Method

In order to develop an appropriate guide for the transformation of the traditional MPS process within SMEs, it was first necessary to model the current MPS process of our industrial partner. We conducted a Delphi–Régner study with the participants of this process to identify the activities, tools, and issues. For this study, we selected 13 respondents who each held one of the following positions: master planner, scheduling manager, procurement manager, sales manager, production manager, or supply chain manager.

It is worth mentioning that Keeney et al. [25] considered that just because a person has a certain degree of knowledge of a particular subject, it does not mean that they are an expert. Nevertheless, they considered that participants who were willing to engage in a discussion would be more interested and involved in the study. For this reason, experts were selected from those directly involved in the MPS process of our industrial partner.

Regarding sample size, Loo [26] suggested the selection of 15–30 experts for a heterogeneous population and 5–10 for homogeneous populations. Considering that the experts were part of the same company, they could be listed as belonging to the same population.

Then, to model the planning process, we employed the BPMN 2.0 (business process modeling notation). This version was proposed in 2011 by the Object Management Group (OMG). We worked with the Lucid Chart software.

One of the advantages of this methodology is that the notation is easy to understand. The different parties (technical, developers, and business) and the modeler used a common modeling standard [27]. As mentioned by Geiger et al. [28], the use of this standard simplifies the transition between process modeling and its execution in information systems. Indeed, Dospinescu et al. [29] pointed out that the standard allows one to identify, model, develop, deploy, and manage processes that involve human interaction and employ information systems. The BPMN can be used to model, simulate, and modify processes in order to optimize the task execution. It is a process-centric standard.

Strimbei et al. [30] stated that this standard provides an understanding of the tasks of a process in detail and the type of information required to perform them. The standard is very flexible regarding the introduction of new information systems into a process that already uses other software.



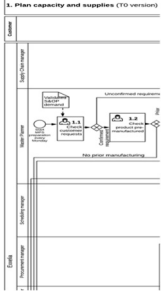






Hasic and Asensio [31] extended the scope of the BPMN beyond new software introduction. They demonstrated the benefits of using this standard in the context of IoT implementations in a business process. Mosser et al. [32] indeed presents several advantages of the BPMN in the context of process modeling with 4.0 technologies. This standard allows for the modeling of physical and information flows of the process and the interactions between the participants. In addition, the standard is applicable to event-driven and decision-driven approaches. It also allows for modelling the activities with a high level of granularity and at a low cost.

The notation elements of this methodology were grouped into four categories:

- Flow objects: Activities, events, and gateways are part of this category. Activities are the sequential decomposition of the work performed within a process. Events represent situations that occur during the execution of activities in a process. Gateways are used to represent the divergences and convergences found or levels of sequential flows of activities.
- Connectors: These are used to relate flow objects. They are used to define the sequence of execution of activities and to represent the exchange of messages.
- Corridors: These are used to model the participants in the process. Corridors of participants that are part of the same entity are grouped in a pool.
- Artifacts: These are data objects or databases that contain information necessary for the execution of activities.

In Table 1, we present the graphical elements we used in this study and their meanings:

Table 1. Graphic elements used.

Connection Objects	
Activity sequences	
Associations with files	
Organizational objects	
<p>The company is presented in the form of a pool. Inside, the different actors are represented by corridors.</p> 	
Activities	
Task	
Connections	
Exclusive (or)	
Parallel (and)	
Events	
Start of process	
End event	
Intermediate event	

We first modelled the current MPS process of our industrial partner. This model was referred to as T0. The planning process was performed for production lines with the following characteristics: several assembly lines, batch production, mainly handcrafted production, several components, raw material references, and assemble-to-order (ATO) or engineer-to-order (ETO) production strategies.

Our industry partner's current MPS process had two main subprocesses, capacity–supply planning and the MPS adjustment following the MRP. The participants or actors involved in the MPS were: the supply chain manager, the master planner, the scheduling manager, the procurement manager, the production manager, the sales manager, the engineering manager, and the methods manager.

Then, we proposed a standardized MPS process based on exploiting sales forecasts and firm orders. Based on this logic, the MPS (T1) process was integrated with four fundamental subprocesses as follows:

- Demand planning/demand management;
- Capacity and supply planning/management/preliminary MPS, aggregate capacity calculation, and scheduling;
- Hold a meeting about the MPS;
- Capacity management following the MRP calculations.

We incorporated an additional process and definitions of general MPS parameters.


For the modeling at the subprocess level, we kept the same group of interlocutors defined in the T0 model. This simplified for our industrial partner finding their way around when setting up the new activities.

Finally, with the help of the Industry 4.0 technology groups, we sought to improve the agility of the T1 MPS. Due to the lack of models for integrating Industry 4.0 technologies into medium-term planning approaches [18], it was necessary to consult with experts. We invited a group of six Industry 4.0 experts to two collaborative workshops.

Regarding the number of experts interviewed, Loo [26] suggested the selection of 15 to 30 experts for heterogeneous groups and 5 to 10 for homogeneous groups. Another study carried by Keeney et al. [25] states that the number of experts to interview depends on the purpose of the project and the time required to collect responses. Given the similarity in academic background, experience, and degree of knowledge about the research topic, the experts could be considered to have belonged to a homogeneous group. Thus, the research team selected 6 experts to be interviewed.

The first objective of the workshops with the experts was to identify the activities that could be improved by implementing Industry 4.0 technology. The second objective was to select the most suitable technology, and the third was to determine the scope of the MPS 4.0.

We considered the ten technologies that were identified by the CEFRIIO [1] as pillars of the fourth industrial revolution: cyber-physical systems (CPSs), the Internet of Things (IoT), cloud computing, big data, cybersecurity, autonomous robots/machines, augmented/virtual reality, simulation, machine-to-machine communication, and artificial intelligence (AI).

We modeled the integration of these technologies in the MPS using the BPMN methodology. We also added a lane named “4.0 Technologies”, in which we placed activities that used Industry 4.0 technologies. We also added the following symbol  in the lower right corner of these activities.

We then propose a revisited and improved model integrating Industry 4.0 technologies into the MPS process, referred to as Tn. As this ideal process cannot be implemented at once within any SME because of its high requirements of automation, technologies, required competencies, and investment, we proposed a digital transformation approach that favors multiple iterative improvement steps to achieve a full MPS 4.0 process. The method we presented to start the transition from MPS T0 to MPS 4.0 was consolidated through workshops with the supply chain manager, the Industry 4.0 expert of our industrial partner, and an academic expert in production planning and Industry 4.0. The Tn models and the method for moving from the current MPS (T0) to MPS 4.0 (Tn) opened the way to several research opportunities, which we discussed in the conclusion.

3. Results

In the following subsections, we first presented the current MPS process (T0) of our industrial partner. Then, an analysis based on the opportunities we found through the T0 models was proposed. The second subsection presents the integration of the Industry 4.0 technologies into the MPS (Tn).

3.1. Modeling the Current MPS Process (T0)

We started by modeling our partner’s current MPS process. This process supported an MPS for multiple assembly lines that included batch and artisanal production, and multiple reference components and raw materials, and one that has to support the assemble-to-order (ATO) or engineer-to-order (ETO) production strategies.

Our industrial partner’s current MPS process had two main subprocesses: planning capacity and supplies, and adjusting the MPS after the MRP (material requirements planning). Figure 1 presents the BPMN modeling of these subprocesses.

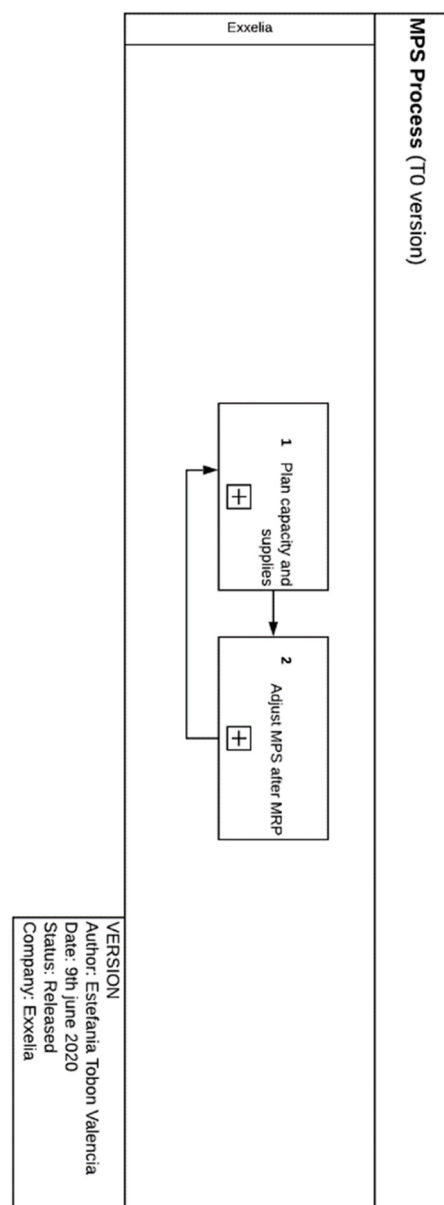


Figure 1. MPS T0 by subprocess.

The stakeholders or participants involved in the MPS were numerous and involved the supply chain manager, the master planner, the scheduling manager, the procurement manager, the production manager, the sales manager, the engineering department manager, and the methods manager.

A detailed description of the activities of each subprocess was presented hereafter. Note that each T0 subprocess had activities identified with numerical IDs (in brackets). These numerical IDs were used to guide the lectors when reading the figures.

3.1.1. Planning Capacity and Supplies Subprocess

Figure 2 illustrates the current planning capacity and supply subprocess.

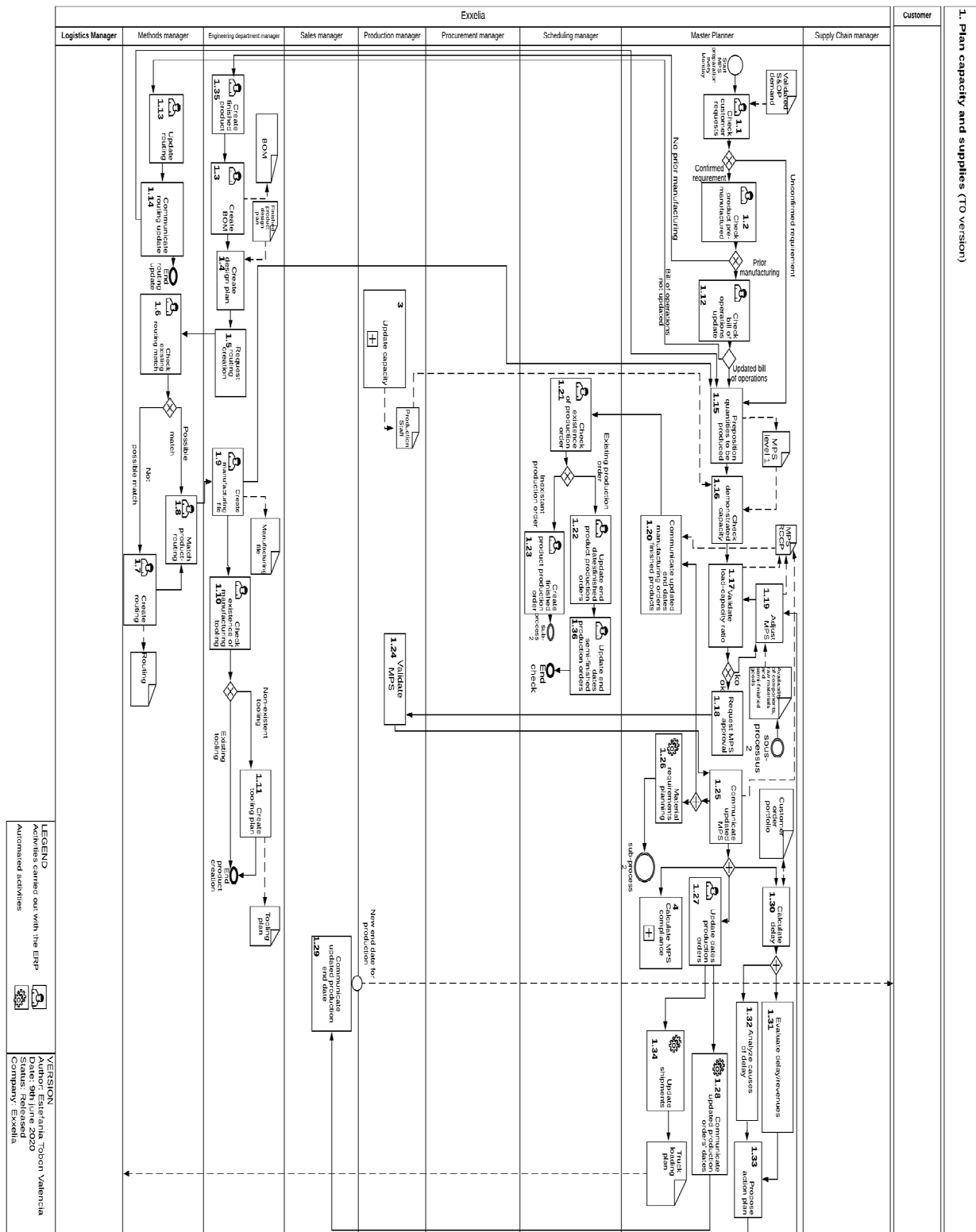


Figure 2. Planning capacity and supplies, T0.

1. Positioning the quantities to be produced according to customer needs, demonstrated capacity, and existing information (project, design, sales, procurement, engineering, etc.)

The master planner verified customer requirements based on the validated demand in the S&OP and using the ERP (1.1). If the requirement was not yet confirmed (customer order not approved but under negotiation), the master planner positioned the requirements at a distant date within the MPS horizon (1.15).

If the customer order was approved, the master planner verified the existing information related to the product ordered by the customer with the engineering department manager, the sales manager, and the methods managers. Thus, the master planner verified if the product was manufactured previously (1.2—T0). If the product was not manufactured in the past, the engineering department manager created the part number of the finished product in the ERP system (1.35—T0) and its BOM (1.3—T0). Once the CAD plan of the finished product (1.4—T0) was completed, the engineering department manager requested the creation of the routing from the methods manager (1.5—T0). At this point, the methods manager would check whether it was possible to associate the product with an existing routing (1.6—T0) from the ERP system. If it was impossible to associate the product with an existing routing, the methods manager created a routing for the product in the ERP (1.7—T0) and then associated the product with the routing (1.8—T0). Otherwise, the methods manager associated an existing routing with the product using the ERP (1.8—T0).

With the routing, the CAD plan, and the BOM, the engineering department manager created the product's manufacturing file (1.9—T0). The manager had to then check the existence of production tools to manufacture the product (1.10—T0). If the tools existed, the manager completed the creation of the product. Otherwise, he created the tooling plan using CAD (1.11—T0).

If the product was manufactured previously, the master planner would check the update of the product's routing (1.12—T0). If the routing was not up to date, the methods manager updated the routing in the ERP (1.13—T0) and communicated the update to the master planner (1.14—T0).

Once the previous activities were completed for all the products to be planned, the master planner prepositioned the quantities to be produced (1.15—T0) in the MPS level one file (Excel file). Using this file, he verified the demonstrated capacity (1.16—T0).

2. Update the production staff file (attendance, skills, and productivity) The production manager updated the workforce file for a nine-month horizon (Excel file) (3—T0). The following tasks were integrated in this subprocess:

- The production manager updated the attendance of the production staff.
- The production manager updated the skills of the production staff in a multi-skilling matrix.
- The production manager updated the productivity of the employees. A coefficient was associated with each employee for each planning week. The value of this coefficient changed each month according to the employee's learning curve.
- Finally, the file allowed the production manager to calculate the capacity per week and macro workstation automatically.

3. MPS level, load versus capacity

The master planner would check the demonstrated capacity using the MPS level one file and the production staff file (1.16—T0). The overall load analysis was conducted using the rough-cut capacity planning (RCCP) Excel file (1.17—T0).

If the load-to-capacity ratio was reasonable, i.e., there was no overload, so the master planner would request the approval of the MPS from the production manager (1.18—T0). The production manager validated the MPS (1.24—T0), and the master planner communicated the MPS (1.25—T0). Otherwise, the master planner adjusted the MPS. This adjustment concerned the repositioning of orders in different planning weeks (1.19—T0).

4. Update completion dates of finished product manufacturing orders and create manufacturing orders in the ERP system

The master planner communicated the updates to the completion dates of the finished product manufacturing orders to the scheduling manager through the MPS RCCP file

(1.20—T0). From the information entered into this file, the scheduling manager verified the existence of the manufacturing order in the ERP (1.21—T0). If the finished product's manufacturing order was already created, the scheduling manager would update the end dates in the ERP system (1.22—T0). It was also necessary to update the production dates of the semifinished products in the respective production orders (1.36—T0). If the scheduler forgot to update the end dates of the associated semifinished products, although it was necessary to produce them, a problem of material availability could arise when producing the finished product.

If the finished product manufacturing order was not created, the scheduler created it in the ERP system (1.23—T0). This mode of operation would often generate missing components at the time of manufacturing.

5. Validate MPS

The production manager validated the MPS (1.24—T0). Following this validation, the master planner communicated the adjusted MPS in the RCCP file (1.25—T0).

6. Update production dates of the customers' orders

The master planner updated the completion date of the customers' orders once a week in the ERP system (1.27—T0). A message was automatically generated when these changes were applied. Then, a message was transferred to the sales manager (1.28—T0), who communicated the changes in the delivery date to the customers (1.29—T0).

After having updated the completion dates, the master planner calculated the total backlog using the sales order portfolio (Excel file) (1.30—T0). A projection of the backlog on the turnover was calculated afterwards (1.31—T0). Then, the master planner analyzed the causes of delay (1.32—T0) and proposed an action plan for managing it (1.33—T0). This action plan included improvements for the adjustment of the MPS. However, the master planner often lacked the time to develop this action plan.

7. MPS implementation and monitoring

The master planner calculated the compliance of the production to the MPS (4—T0). This process involved the following tasks:

- The master planner checked the production order release plan;
- The master planner updated the stock of finished products and communicated it to the warehouse;
- The master planner compared the quantities of finished products declared by the production with those planned in the MPS.

8. Weekly release of the truck loading plan

The master planner updated the week's shipments based on changes in order completion dates (1.34—T0). An Excel file from ERP extractions was generated automatically (truck loading plan). This plan was communicated to the logistics manager.

9. Start MRP

The MRP was automatically generated by the ERP every Tuesday (1.26—T0).

3.1.2. Adjusting MPS after MRP

In Figure 3, we present the BPMN model of this subprocess.

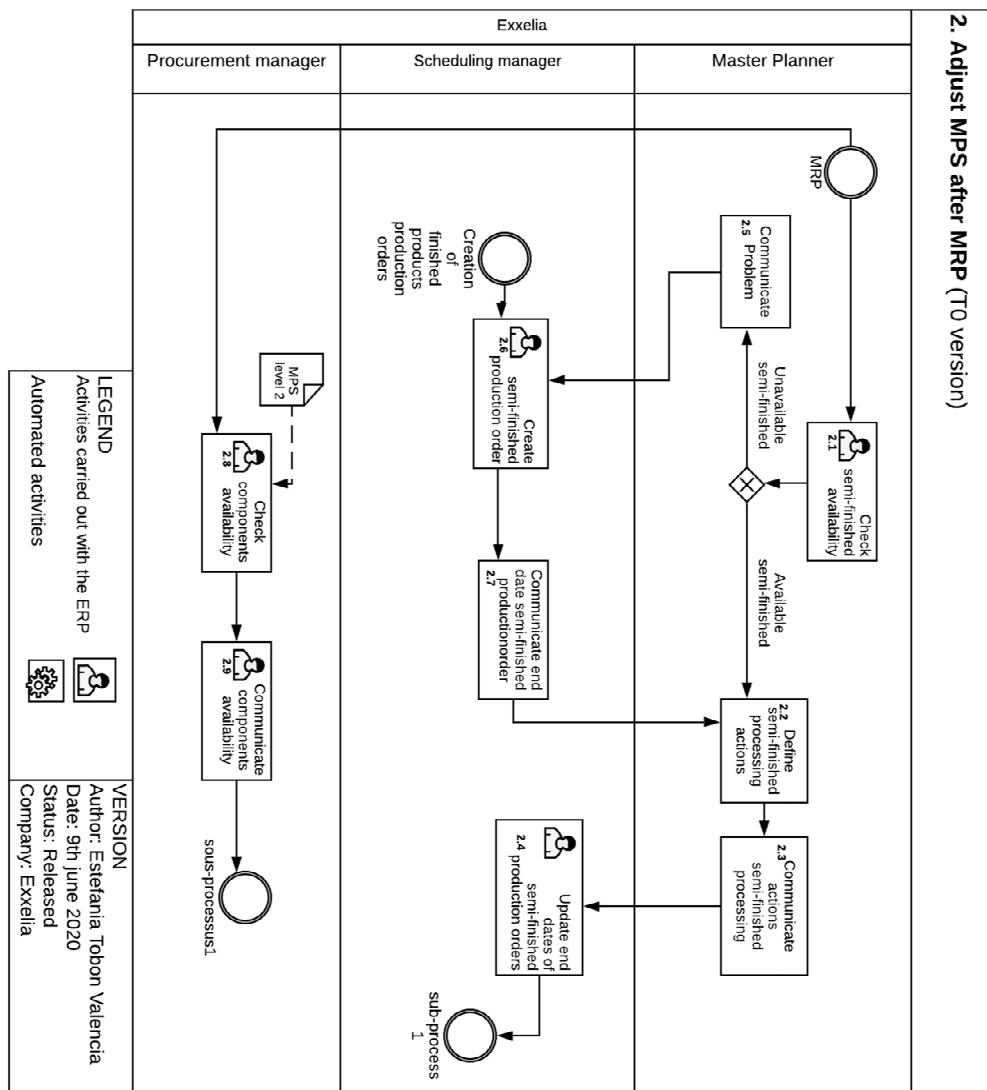


Figure 3. Adjusting MPS after MRP (T0).

1. Once MRP is executed, update completion dates of semifinished products' manufacturing orders

The master planner checked the availability of the semifinished products using the ERP (2.1—T0). If the semifinished product was available, the planner defined the actions for processing the semifinished product (2.2—T0) and communicated these actions to the scheduling manager (2.3—T0). Based on the instructions given by the chief planner, the scheduler would update the completion dates of the semifinished production orders (2.4—T0).

If the semifinished product was not available, which meant that production orders did not cover the requirement, the master planner would notify the scheduling manager (2.5—T0). The scheduler would create the production order for the semifinished product (2.6—T0) and communicate the best completion date to the master planner (2.7—T0).

2. Verify procurement availability

The procurement manager checked the availability of raw materials and/or components using the MPS level two file (Excel) and the MRP (2.8—T0). The MPS level two file extracted information from the ERP on the finished product manufacturing orders created by the scheduling manager.

The procurement availability was communicated weekly to the master planner (2.9—T0).

3. MPS readjustment based on the return of the procurement manager

The master planner updated the MPS based on the availability of raw materials, semifinished products, and components indicated by the procurement and scheduling managers (1.19—T0).

3.1.3. Analysis of the Current MPS Process

Based on the modeling of our industrial partner's current MPS process, we noticed a problem with the delegation of tasks and responsibilities. The master planner was responsible for several functions that other participants in the MPS process could perform. For instance, tasks such as checking the availability of semifinished products and defining their processing actions could be the responsibilities of the scheduling manager, with the oversight of the master planner. Similarly, all the tasks of checking the updating and the availability of the manufacturing file and the manufacturing routing should be performed by the person in charge of engineering and methods.

Other tasks, such as updating the due dates of production orders, require a lot of time from the master planner. This update was carried out manually in the ERP at the level of each order. By uploading the MPS into the ERP, this type of task could be automated.

Regarding the technologies and systems used in MPS activities, we noticed that most of the calculation activities were performed using custom Excel files. There was currently no Industry 4.0 technology employed in the planning process. According to the scale proposed by [1], the current MPS process was at the integrated level because an ERP supported it. However, the other IT tools used were not integrated with the ERP.

We also observed a lack of communication between the different participants. The master planner was at the core of all exchanges. Most information was transmitted orally or through emails without being recorded in a database or reports.

In the day-to-day life of the enterprise, many of the activities we modeled were not performed because of the master planner's lack of time.

After these findings, we proposed a standard MPS process model to guide the transformation plan of our industrial partner. Then, we sought to make the standard MPS more agile by integrating various Industry 4.0 technologies. The following section presents the Industry 4.0 technologies that could be incorporated into the future MPS process.

3.2. MPS 4.0 Process (Tn)

There are two main methods for MPS planning: stock management and using the information of future requirements [10]. The first method relies on inventory management methods to handle replenishments. The second method leverages sales forecasts and confirmed orders to calculate estimated stock and bases replenishment decisions on this information. This method can help to fulfill customer requirements and minimize the finished goods inventory.

We based our proposal on the method that uses sales forecasts and confirmed orders. Based on this logic, the MPS process consisted of four main subprocesses: demand planning, capacity and supply planning, holding a meeting about the MPS, and capacity management following the MRP. We added an extra subprocess: the definition of general MPS parameters. We present the relation between these subprocesses in Figure 4.

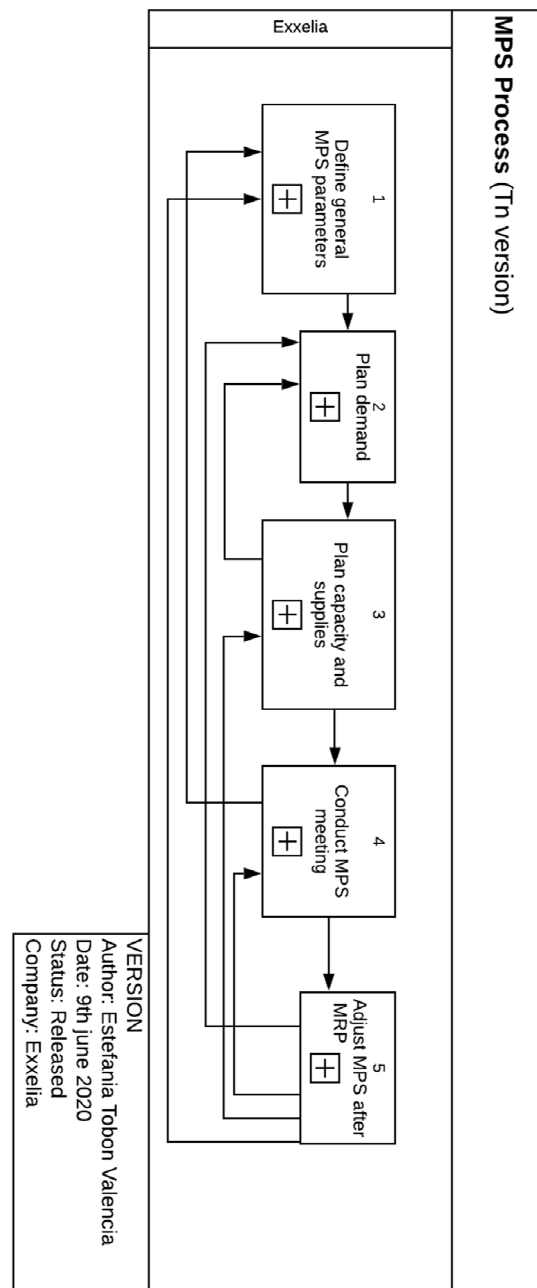


Figure 4. MPS Tn.

We considered four Industry 4.0 capability levels to determine the scope of MPS 4.0 improvements: monitoring, control, optimization, and autonomy. The authors of [1] defined these levels as follows:

- Monitoring capability allows the identification of changes in situations or in the process performance through sensors and external data sources;
- Control capability allows the system to respond automatically to specific predefined events;
- Optimization integrates the processing of data recovered from the monitoring level with the ability to propose alternatives on how to handle contingencies without degrading its performance;
- Autonomy capability combines all the previous levels so that the system can adapt in real time without the direct involvement of users.

With the integration of Industry 4.0 technologies in the MPS, we also sought to make this process agile. We considered the concept of agility proposed by [33], who indicated that agility in organizations is a synergic combination of the following dimensions:

- Robustness: the ability to maintain effectiveness across a range of tasks, situations, and conditions;
- Resilience: the ability to recover from or adjust to misfortune, damage, or a destabilizing perturbation in the environment;
- Responsiveness: the ability to react to a change in the environment in a timely manner;
- Flexibility: the ability to employ multiple ways to succeed and the capacity to move seamlessly between them;
- Innovation: the ability to perform new things and the ability to perform old things in new ways;
- Adaptation: the ability to change work processes and the ability to change the organization.

The MPS 4.0 (Tn) could address multiple dimensions of agility. As pointed out by [34], these dimensions are analytically distinct, but often interdependent.

In the next subsections, we summarized the results of the workshop with the experts and provided the model of each MPS 4.0 subprocess. These models were identified as the Tn, as we considered them to be the final level that the SME could reach after multiple cycles of the planning, implementation, and improvement of the digital transition toward the MPS 4.0. Activities and technologies were selected without considering financial and resource constraints.

3.2.1. Defining General MPS Parameters

During the workshop with the experts, we identified six activities of this subprocess that could benefit from Industry 4.0 technologies. Figure 5 presents the BPMN model for the definition of the general MPS parameters in Tn.

For the identification of critical resources (activity 1.1—Tn), the experts proposed to use simulations to generate multiple production flow scenarios. The simulation would enable the impacts of disruptions to the workshop to be evaluated, such as machine breakdowns, employee absenteeism, and the repositioning of employees in different workstations.

Workflow data could be retrieved through the IoT or CPS. Then, production flow verification could be carried out in nearly real-time conditions (activity 1.18—Tn). Access to these data would allow for evaluating production scenarios as soon as disruptions were detected, identifying if new bottlenecks appeared, and integrating the control, planning, and execution levels.

If the suppliers gave access to the procurement lead time data available in their information systems, it would be possible for the company to update this lead time with more reliability. The use of cloud computing and cybersecurity was proposed for activity 1.4—Tn.

Similarly, if disruptions were to occur in suppliers' production lines, component availability data could be shared in real time (Activity 1.26—Tn).

The definition of macrorouting (activity 1.9—Tn) could be performed using machine learning or simple segmentation techniques. The experts pointed out that using such techniques would make it possible to take into account the knowledge and experience of method and production managers, who are often consulted in the definition of macrorouting. The same techniques were proposed by the experts to define macro-BOM (activity 1.8—Tn).

The experts clarified that even if activities 1.8 and 1.9 of Tn used real-time production flow data, this did not imply that the macrorouting or the macro-BOM were updated in real time. The company must define the frequency at which these parameters were to be updated.



The association or updating of macrorouting and macro-BOM to master items could become an automated activity using machine learning (activity 1.10—Tn). The data related to the changes applied on the macrorouting and macro-BOM (activities 1.19 and 1.20—Tn) could be stored in a database to train these algorithms.

3.2.2. Demand Planning

The Tn version of the second subprocess, demand planning, is presented in Figure 6. From this figure, the intermediate events that we presented here as subprocesses (1–5) corresponded to those we presented in Figure 6.

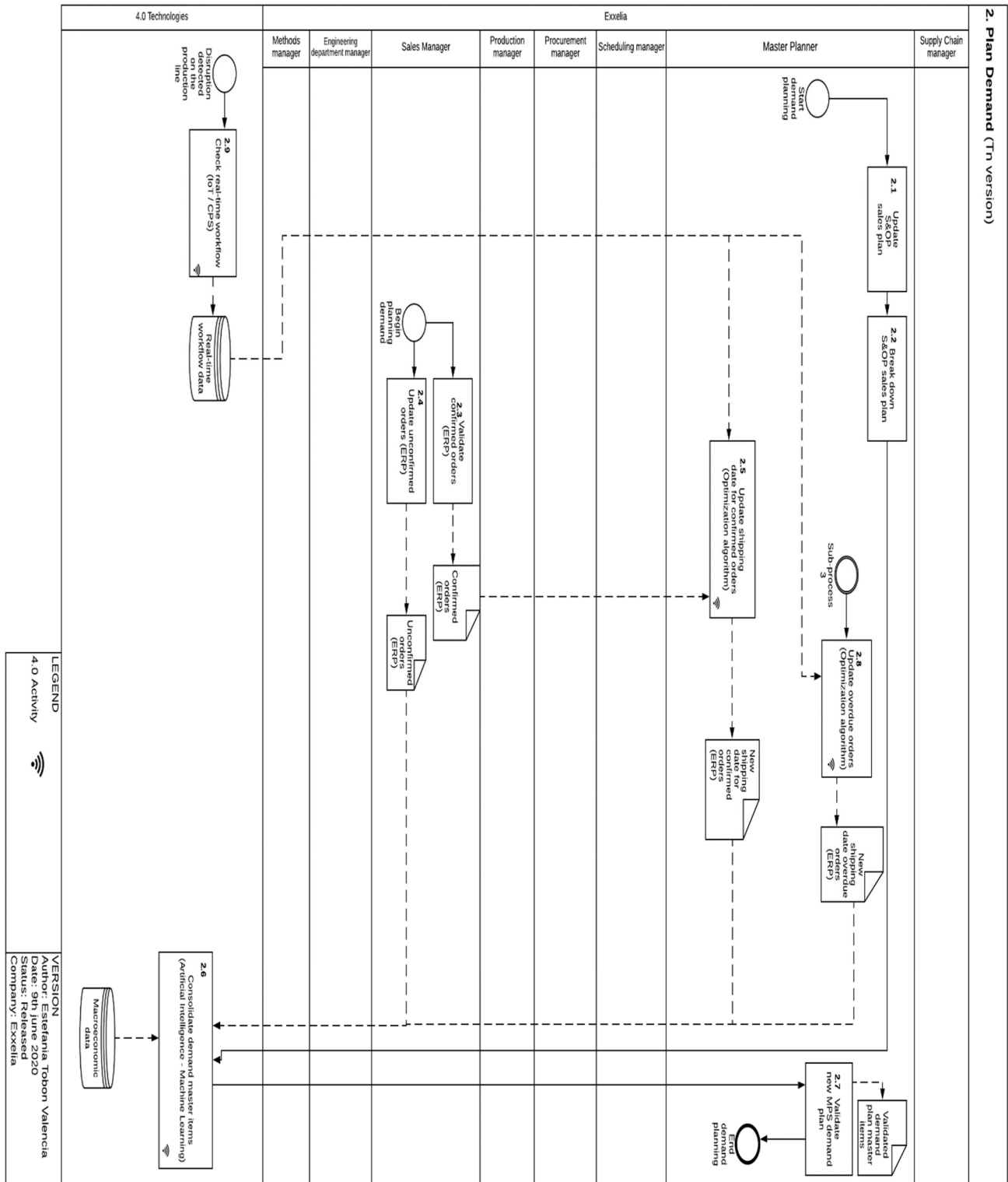


Figure 6. Demand planning (Tn).

For the demand consolidation of the master items (Activity 2.6—Tn), the experts proposed to use AI with machine learning techniques. This activity would need the following input data: the demand (backorders, confirmed orders, and nonconfirmed orders), the demand forecasts (S&OP sales plan disaggregated at the level of master items), and macroeconomic data that could influence the demand forecasts. Each company must identify these macroeconomic data that could lead to increases or decreases in sales forecasts. A machine learning algorithm would facilitate the analysis of these variables when defining the MPS demand forecasts. On the other hand, it would allow the identification of quantitative and qualitative trends in demand.

The use of optimization algorithms was considered relevant by the experts when updating the shipping dates of confirmed orders and backorders (activities 2.5 and 2.8—Tn).

Workflow data collected by the CPS or the IoT (activity 2.9—Tn) could be used to calculate new shipping dates for backorders (activity 2.8—Tn) and to update the shipping dates of confirmed orders. This would allow the master planner to estimate changes in shipping dates on a basis that would be very close to the reality of the shop floor. Additionally, the combination of demand data with real-time production flows would allow the master planner to optimally allocate resources when dealing with load variations.

3.2.3. Planning Capacity and Supplies

The BPMN model for this subprocess is presented in Figure 7. The activities were, subsequently, identified with the numbers we assigned in this figure.

To determine the cause of the poor performance of the previous week's MPS (activity 3.3—Tn), the experts suggested using machine learning. Using machine learning requires feeding the algorithm with data related to the causes of the poor performance and prior solutions. In this way, the algorithm could propose a solution according to the cause of the poor performance.

If the machine learning algorithm was to determine that the cause was related to the capacity, the simulation could be used to make adjustments to the capacity (activity 3.4—Tn) and to propose different capacity scenarios (subprocess 6—Tn). Then, the production manager could select the most appropriate scenario using optimization tools (activity 3.15—Tn).

If the machine learning algorithm was to determine that the cause of the poor performance of the MPS was linked to the load data, the simulation could be used in activity 3.5 of Tn to evaluate modifications in the macrorouting or in the macro-BOM. Using the production flow data recovered through the IoT or CPS (activity 3.10—Tn) would be important for updating the data used to calculate the load.

The IoT could also be useful when checking the availability of semifinished or internally manufactured supplies (activity 3.11—Tn). Similarly, the use of the IoT or CPS with cloud computing was proposed to verify the availability of components, raw materials, or semifinished supplies from suppliers (activity 3.12—Tn). The analysis of component inventory levels (activity 3.14—Tn) could use machine learning to determine forecasts on the availability of materials in the warehouse.

When proposing the MPS (activity 3.2—Tn), the experts proposed using a simulation with optimization tools to obtain a plan that respected several constraints, such as the load–capacity ratio, optimal use of available capacity, due date changes, and variations in capacity. The simulation would allow for studying several MPS scenarios.

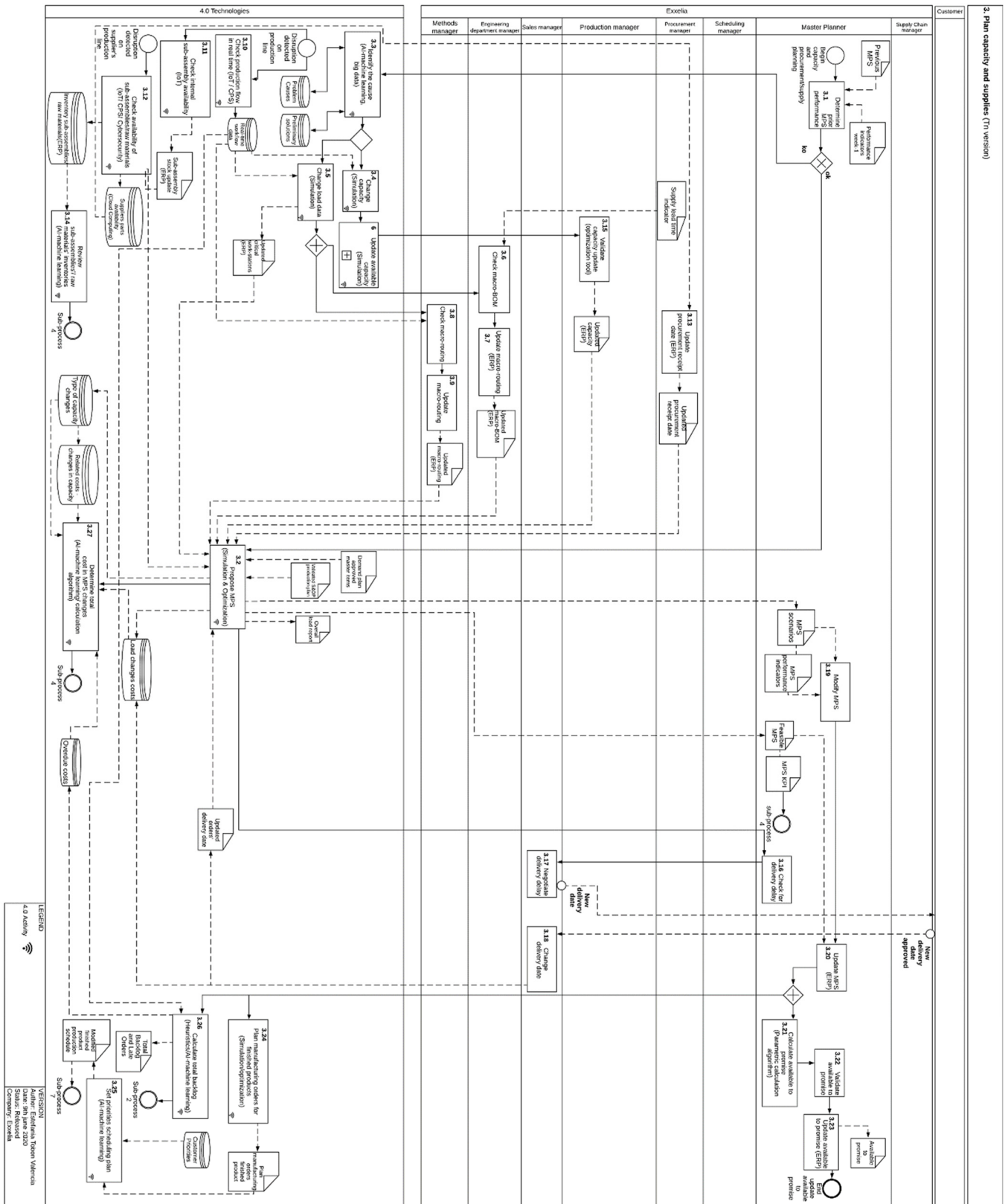


Figure 7. Planning capacity and supplies (Tn).

Then, optimization approaches (heuristic, metaheuristic, or hybrid) would allow for an evaluation of the scenarios based on MPS objectives for inventory levels and costs, delays, layoffs and hiring of operators, production rate, total production time, and capacity utilization.

Activity 3.2 of Tn could be fully automated and propose a feasible MPS that is uploaded in the ERP (3.20—Tn). Another alternative would be to propose multiple MPSs as a result of this activity (3.2—Tn) to allow the master planner to choose the most suitable MPS according to the production constraints at the time. The master planner would then be able to perform adjustments based on his knowledge (3.19—Tn). The choice between these two Industry 4.0 levels, automated and optimized, would depend on the Industry 4.0 scope (monitoring, control, optimization, and autonomy) sought by the company.

The costs of capacity changes, load repositioning, and delay are included in activity 3.27 of Tn—the determination of costs related to MPS changes. This activity could be performed using machine learning. The output of this algorithm would be an estimated cost, which would be more or less similar to the real cost depending on the quantity and quality of the input data.

The planning of the start and completion dates of finished product manufacturing orders (activity 3.24—Tn) could employ a simulation to integrate capacity variations. Optimization approaches would be necessary to choose the best manufacturing order plan according to the company's objectives.

The calculation of the backlog (activity 3.26—Tn) could be performed with machine learning. It is a prediction that considers many constraints and scenarios related to disruptions. Using a hybrid approach of machine learning with a heuristic or metaheuristic algorithm would allow the company to decrease the backlog and determine priorities for processing manufacturing orders (activity 3.25—Tn). The optimization approach would allow to verify the feasibility of the plan.

3.2.4. Conducting MPS Meeting

Figure 8 presents the Tn version of this subprocess.

The experts proposed to use machine learning to identify risks and problems related to the MPS (activity 4.9—Tn) and to define the actions to be launched (activity 4.10—Tn). A database of problems' causes associated with activity 4.9 would allow the algorithm to identify the problem related to the proposed MPS. This database could be fed with workflow data (activity 4.13—Tn) and with component availability (activity 4.14—Tn) collected in real time through the IoT or CPS. Similarly, activity 4.10 would require a database of prior solutions that would allow the algorithm to propose a solution to the problem or risk detected in the previous activity. This database could be updated with solutions proposed by the participants during the meeting.

3.2.5. Adjusting MPS after MRP

Most of the activities in this subprocess were associated with Industry 4.0 technologies. The model for this subprocess is presented in Figure 9.

The computation and validation of loads at all load stations (activities 5.1 and 5.2—Tn) could use simulations to study different load–capacity ratio scenarios. Fuzzy logic and/or heuristic algorithms could be used to select the best scenario. Real-time maintenance and workflow data are essential for the detailed load analysis.

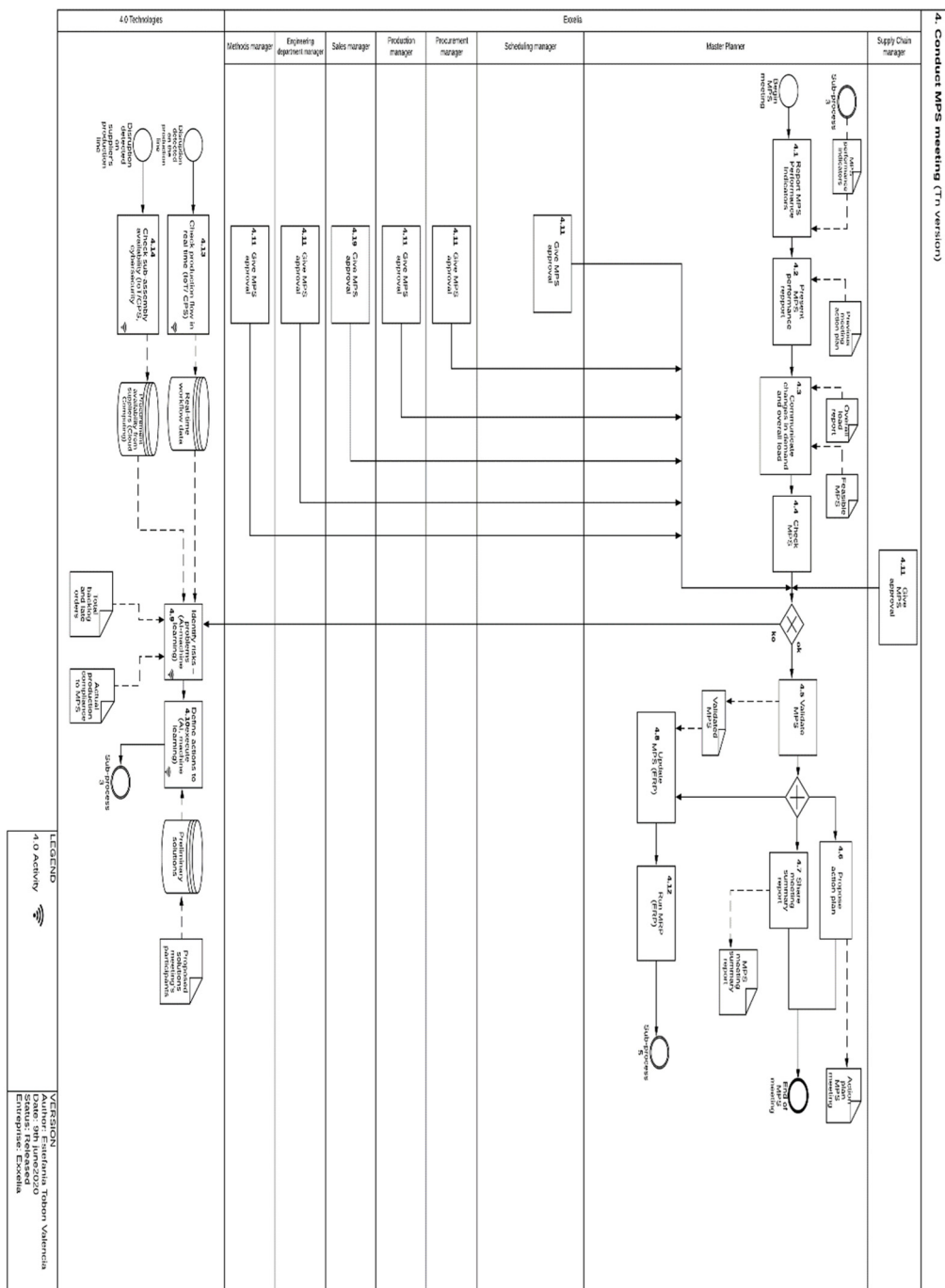


Figure 8. MPS meeting (Tn).

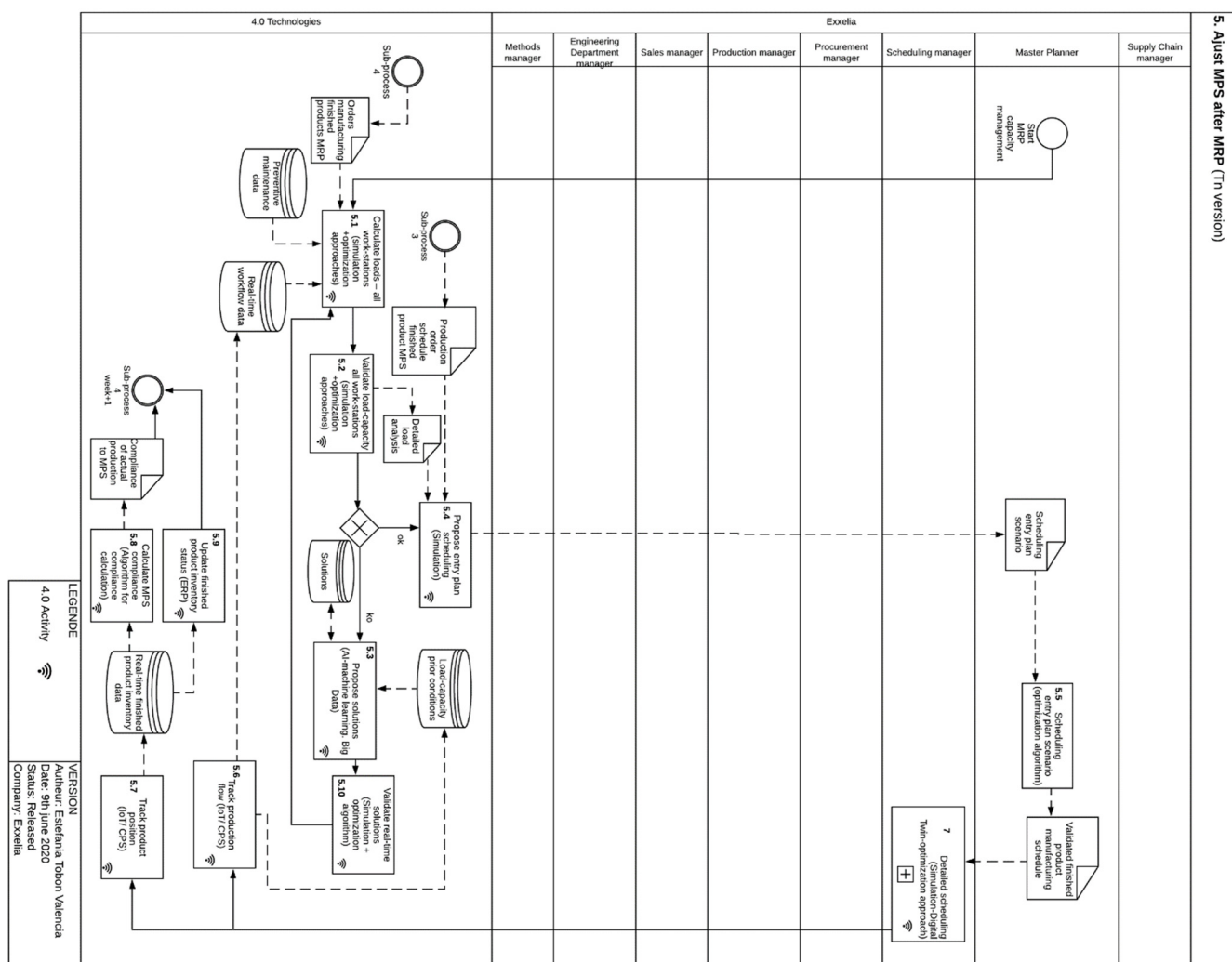


Figure 9. Adjusting MPS after MRP (Tn).

If the detailed load analysis was to not meet the company's objectives, machine learning could be used to propose solutions (activity 5.3—Tn). This algorithm requires a historical record of load-capacity conditions and a database of solutions for overload conditions. With these inputs, the algorithm could propose an adaptable solution to deal with the load-capacity balance situation. Once the solutions are proposed, a simulation could be employed to evaluate the impacts of their implementation in the production process.

For the scheduling (subprocess 7—Tn), digital twin simulations with optimization approaches were proposed by the experts.

The use of the IoT or CPS for workflow management (activity 5.6) would enable the collection of data of each resource, the cycle times of each workstation, the idle time, and the production shutdowns.

The experts proposed to use the IoT or CPS to monitor the positions of products in real time (activity 5.7—Tn). The data resulting from this activity would allow for the updating of the finished product stock in the ERP (activity 5.9—Tn). These data could also be used as the input for calculating the MPS compliance (activity 5.8—Tn).

4. Guiding the Transformation toward the MPS 4.0 Process

The results of the Delphi-Régnier study allowed us to model the MPS T0 (Section 3.1) of our industrial partner. These models (MPS T0) were presented to the supply chain

director and the Industry 4.0 expert. We also presented the MPS T1 models, which were the models of the standard MPS process. This allowed us to identify the areas of improvement in terms of activities, information flows, and exchanges in current practices. Then, the MPS 4.0 models were presented.

As part of its improvement programs, our industrial partner started to plan the integration of Industry 4.0 technologies within the MPS process by migrating from the T0 process (initial MPS) to Tn (Industry 4.0 technologies integrated). Recent studies have proved that Industry 4.0 technologies positively impact business results and promote continuous improvements in organizations [35,36]. In this section, we described the approach and the vision guiding this integration plan. We also discussed the implementation capacity for Industry 4.0 technologies of the SME considering the required expertise and financial resources.

4.1. Key 4.0 Technologies for the MPS Process

The main objective of the MPS is to define a feasible production plan that best meets the demand and integrates resource availability constraints (humans, machines, and components). There are many ways to model these objectives and constraints; however, in the context of operating an ERP, the load–capacity management model was translated into the form of:

- Workstations (capacity);
- Production ranges (load): pending production orders and coming production orders (from demand to the MRP).

In practice, the load–capacity analysis would rarely be carried out for each workstation. The theory of constraint suggests that only the bottleneck workstation(s) could be analyzed, as all flows were linked to their throughput. A such, there are several key elements to creating a realistic and feasible MPS:

- The quality of the capacity model;
- The quality of the load model;
- The reliability of the state of the operating system at instant T;
- The ability to identify the bottleneck workstation(s).

We believe that several technologies are critical to achieving these objectives:

- The Internet of Things: Real-time flow mapping improves the quality of the operating system's state. Recording flows in the form of a database can help refine the quality of the employed load–capacity model by improving the quality of the ranges.
- Simulations: The analysis of the selected scenarios allows for the identification of bottleneck workstations, especially if they are not fixed and depend on the product mix being released in the workshop. This technology could also be used to support the decision making of the master planner through the visualization of the impacts related to their choices.
- Big data: Machine learning could be an asset for the control of production processes, especially when many environmental variables can influence the quality of the product (humidity and temperature, for example).

Similarly, the quality of the capacity model is complex when several thousand batches are launched during the year, sometimes only once each. As a result, similarities between products are hardly detectable. Artificial intelligence could eventually help with this process.

4.2. Implementation Capability for Industry 4.0 Technologies

We proposed three criteria; the implementation capability, estimated cost, and expected financial gains; to evaluate the implementation capability of Industry 4.0 technologies. We characterized Industry 4.0 technologies in terms of an SME's capability to implement them. The capability was evaluated through two dimensions, one related to the required skills and the other related to the estimated cost of installing and running the technology.

Then, the evaluation of these criteria for each couple of Industry 4.0 technology and objective was carried by the supply chain manager, the Industry 4.0 expert of our industrial partner, and an academic expert in production planning and Industry 4.0. The scores were given from one (highly favorable) to four (highly unfavorable). Table 2 presents the results of this analysis. Finally, the general score was calculated with an average, as the expert panel considered all criteria to be of equal importance.

Table 2. Industry 4.0 technologies, related objectives, and evaluation.

MPS Subprocess	Activity ID	Technology	Objective	Capability	Estimated Cost	Estimated Gain	Score
P1-Tn	1.18	IoT	Track the production flows in real time	1	2	4	2.33
P1-Tn	1.4	Cloud computing	Real-time information sharing with suppliers	2	1	3	2
P1-Tn	1.26	IoT	Avoid inventory discrepancies and monitor inventory status (incoming and outgoing stocks)	1	1	3	1.67
P1-Tn	1.1	Simulation	Identify the bottleneck and analyze changes according to the product mix sold	1	3	3	2.33
P1-Tn	1.9	AI machine learning	Improve the quality of the capacity calculation model, in particular of the ranges, by increasing the accuracy of the predicted load times	3	2	4	3
P1-Tn	1.8	AI machine learning	Improve the quality of the BOM, including the identification of key returns	3	2	3	2.67
P2-Tn	2.6	AI machine learning	Within the framework of the S&OP, AI can suggest clusters by “macrofamily”. In the MPS, this is relevant for the load anticipation	3	2	4	3
P2-Tn	2.1	AI machine learning	Improve forecasting	3	2	4	3
P3-Tn	3.3	AI machine learning	Improve feedback related to MPS gaps	3	2	4	3
P3-Tn	3.2	Simulation	Improve responsiveness through the simulation of multiple possible scenarios	2	1	4	2.33
P3-Tn	3.10	IoT	Track in real time the position of flows and check the availability of semifinished products manufactured in-house	1	2	4	2.33
P3-Tn	3.27	AI machine learning	Support decision making regarding the cost related to a proposed change to the MPS	3	2	3	2.67
P3-Tn	3.25, 3.26	AI machine learning	Once the MPS and the expected objectives are defined, the AI enables real-time corrections to keep the objectives in line with the reality of the execution	3	3	4	3.33
P5-Tn	5.3	AI machine learning	Once the MPS and the expected objectives are defined, the AI enables real-time connective actions to integrate MRP results	3	3	4	3.33

5. Discussion

The workshop with the experts allowed us to identify two main axes for improving the MPS using Industry 4.0 technologies: monitoring and optimization capabilities.

The first axis concerns the reliability of input data (process parameters). The real-time control of production flows allows the company, on the one hand, to base forecasts on data closer to the actual situation, and, on the other hand, to improve the reactivity of plans when dealing with disruptions. The IoT and the CPS were the technologies the group of experts proposed to retrieve data in real time.

Cloud computing was another Industry 4.0 technology that the experts associated with the monitoring level. Data retrieval from suppliers' information systems, such as delivery dates of supplies, could be performed in real time using this technology. The experts also pointed out the importance of using cybersecurity to access information in the cloud and protect the company's information systems and those of suppliers.

Other uses of cloud computing in the MPS process include:

- The capacity to store workflow data when the company lacks space on its servers or when the company's computing power for simulations and optimization calculations is not enough;
- When the production network is geographically distributed, it enables access to real-time workflow data from all the manufacturing sites.

The second improvement axis involves using Industry 4.0 technologies for optimizing and/or supporting decision making. A simulation was one of the technologies proposed by experts. The experts pointed out that using heuristic and metaheuristic optimization approaches was essential for choosing the most suited scenario among those proposed by the simulation.

Another axis of improvement concerns using Industry 4.0 technologies to improve the decision-making process [37–40]. The authors of [40] studied data-driven decision making with 4.0 technologies in the context of production planning, scheduling, and control activities.

For the MPS 4.0 models (Tn), machine learning was proposed to support decision making. This technique was associated with MPS activities only when the decision maker was not able to model the influences of the different parameters on the object they were trying to calculate, for example, in the consolidation of demand forecasts (activity 3.3—Tn). As the system and the values of the parameters in the MPS process are often known, artificial intelligence techniques are scarcely used.

Besides the application of the IoT, CPS, cyber-security, and cloud computing for workflow management activities and simulation coupled with optimization algorithms or machine learning for decision-making support, the experts considered that there was no need to associate other Industry 4.0 technologies with the MPS activities. The plan's feasibility was the main condition that the group of experts related to the MPS. Accordingly, they considered that some of the Industry 4.0 technologies would be used, but it is essential to leave room for decision making by the various participants of the MPS.

In terms of agility, the MPS 4.0 process was flexible, responsive, and innovative. Flexibility was achieved through the use of simulations that allowed for evaluating manufacturing in different production lines. With the help of optimization approaches, MPS decision makers can select among production scenarios the one that allows to achieve the objectives within the system constraints at a given time. Reactivity is used through IoT and cyber-physical systems to drive production flows and check inventory availability in real time. These data are used to propose MPS plans (feasible MPS and the input plan for the scheduling activity) that incorporate changes in the internal (production floor) and external (suppliers) environments in a short time. Finally, MPS 4.0 promoted innovation. Machine learning algorithms propose production schedules that would lead the company to produce in a different way. Manufacturing within subcontractors could be proposed to solve problems of available capacity.

The research work in [41] proposed that SMEs are characterized by having managers who are involved in the decisions of the technostructure as much as in the operational center directly. Then, the research presented in [42] proved that SMEs are characterized by the management of proximity, in which the leader is a key element of change regarding Industry 4.0. In our research, we involved managers throughout our work modeling the MPS T0, MPS T1, and MPS 4.0 processes. Finally, we codesigned an approach to guide the transition from MPS T0 to MPS 4.0.

Considering this transformation toward the MPS 4.0 process, we analyzed our industrial partner's capacity to integrate Industry 4.0 technologies in terms of expertise and financial resources.

The Internet of Things seemed to us the most affordable key technology. The RFID technology could be easily implemented as the required skills are relatively simple. It could also be completely integrated with the ERP, as the tracking of production orders was already in place in the company. This technology could considerably improve the monitoring of the internal flows. At the same time, it could improve the control of the components' availability (entry/exit of the stock in particular) and the progress of production orders (passage from one production area to another).

Simulation was also considered a key technology. Several tools are available on the market, and the required computing capacity is available even for small and medium-sized companies. Most SMEs with an integrated MPS process have master planners with the expertise required to use simulation tools. Only the initial modeling (implementation) requires external help in some cases.

However, our industrial partner considered that most of the Industry 4.0 technologies are still very inaccessible and expensive. For example, big data analytics through machine learning algorithms are probably only a medium-term option for SMEs.

6. Conclusions

This paper provided multiple contributions to our field of research. First, we modeled the current MPS process of an SME (T0 model). As discussed earlier, the MPS was mostly presented as a calculation activity and not as a full business process. The mapping of this process allowed us to confirm that many key activities of the MPS process were not covered in the planning practice of our industrial partner. Only two of the five subprocesses were currently addressed (capacity–supply planning and the MPS adjustment after the MRP). This model also revealed the lack of agility within the current MPS process.

To model the MPS 4.0, we proposed a division into five subprocesses: the definition of the general parameters of the MPS, demand planning, capacity and supply planning, holding an MPS meeting, and the adjustment of the MPS after the MRP. We later integrated Industry 4.0 technologies into the MPS activities with the help of a group of experts (Tn subprocess models). The integration of Industry 4.0 technologies into MPS activities was mostly concerned with the monitoring and optimization capabilities. Monitoring functions could be improved by focusing on the capability and reliability of input data. The IoT, cyber-physical systems, cloud computing, and cyber security are technologies that could improve monitoring functions. The second improvement axis focused on using simulations with optimization approaches and artificial intelligence to re-engineer decision-making tasks. The proposed MPS 4.0 process also allowed for better support for the decision making of all participants by processing production flow data in real time.

The use of Industry 4.0 technologies also creates new way of conducting some MPS activities. With machine learning, it is possible to propose programs that lead the company to produce or subcontract differently to solve capacity problems.

From the MPS 4.0 models, we worked with our industrial partner to select the technologies to be deployed. This selection was based on the SME's capability to implement the proposed technologies, and their estimated costs and gains. We presented the results of our project to our industrial partner, particularly its supply chain department. Although the participants involved felt confident about the plan and the targeted end-state (Tn process),

the proposed plan may not be valid for all SMEs. Industry 4.0 technologies may be more or less easily implemented in different organizations, and gains would also vary from one SME to another based on their current state. Nevertheless, most of them recognized the MPS process as a core process, as it provided a common plan to all the stakeholders to meet the demand requirements.

This research had some limitations. The first limitation of this study was associated with the composition of the expert panel. Even though the panel included experts in production planning and Industry 4.0 technologies, and they were from the industrial and scientific communities, this choice included subjectivity bias.

Another limitation concerned the analysis of agility as the only objective for integrating Industry 4.0 technologies into the MPS process. However, other objectives have been previously associated with digital transformation projects, such as cost reduction, productivity improvement, and lead time reduction. It would, therefore, be relevant to analyze whether the proposed MPS 4.0 process would allow us to achieve other performance objectives.

The MPS 4.0 process (Tn) we proposed is suitable for a manufacturing SME with an ATO or ETO production strategy. However, it would be interesting to study whether this model would be applicable in other industrial contexts. Therefore, it would be relevant to study the modifications to be carried out in the MPS 4.0 models for SMEs with other production strategies and in other industrial sectors.

Another research perspective concerned the evaluation of the impact of the integration of Industry 4.0 technologies on scheduling and dimensioning (S&OP) activities.

The MPS 4.0 process was not tested or deployed by our industrial partner. The proposed MPS 4.0 models were exploratory research. The validation in the industrial field remains complicated, hence, the interest in relying on experts for proposing this model.

Regarding research perspectives and in order to pursue our goal to facilitate and guide the implementation of Industry 4.0 technologies within SMEs, it would be interesting to identify firm performance measures that could be influenced by Industry 4.0 technologies. We also considered it to be relevant to identify the operational skills required by each Industry 4.0 technology.

The research in these perspectives represents important steps in developing an Industry 4.0 transformation plan for an SME aligned with its targeted gains and skills development plan. Implementing this model in several SMEs to test its reliability and repeatability is another important research goal. In this regard, we recognize that supply chain and IT departments are increasingly linked. It would be interesting to study the relevance of mutualizing the implementation and use of the proposed technologies.

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