

Towards a Digital Twin for Cyber-Physical Production Systems: A Multi-Paradigm Modeling Approach in the Postal Industry

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Towards a Digital Twin for Cyber-Physical Production Systems: A Multi-Paradigm Modeling Approach in the Postal Industry

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ABSTRACT

This paper presents our early-stage research on a Multi-Paradigm Modeling (MPM) approach as an initial step towards the definition of a Digital Twin (DT) for Cyber-Physical Production Systems (CPPSs). This work takes place in the context of the digitalization of the mail sorting process at La Poste, the French national postal service company. Indeed, La Poste is currently investing on robotics modules for automatically loading mail containers. The main objective is to reduce the painful work for human operators while optimizing the robots usage. We already worked on targeting such a balance in a past effort that resulted in the production of different kinds of models of the La Poste CPPS. However, these models were defined separately and are not directly related to the underlying business process in particular. Thus, we propose an MPM approach starting from this business process as now modeled explicitly in a BPMN model. Then, we refine the high-level business activities into finer-grained activities represented in a UML Activity model. From these latest, we derive the specification of a Multi-Agent System (MAS) developed with the JADE framework and emulating the behavior of the La Poste CPPS. Our longer term objective is to pave the way for supporting the definition of a DT for this CPPS, and potentially for other CPPSs in different contexts in the future.

CCS CONCEPTS

• **Software and its engineering → Design languages**; **Unified Modeling Language (UML)**; **Software design engineering**; • **Computer systems organization → Robotic components**.

KEYWORDS

Cyber-Physical Production Systems, Multi-Paradigm Modeling, Business Process Modeling, Activity Modeling, Agent-based Modeling, Digital Twin.

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1 INTRODUCTION

Nowadays, industrial and service companies are progressively moving towards the digitalization and larger automation of their regular business activities. Such a transformation process often requires to address many different and complex dimensions of corresponding Cyber-Physical Systems (CPSs) [30]. This makes the continuous development, validation and evolution of these CPSs a complex engineering activity [1]. In this context, the idea of building Digital Twins (DTs) of the concerned CPSs emerged in order to more efficiently manage their daily running and better predict their future evolution [28]. Recently, this has resulted in the development of more and more structuring initiatives in this domain such as the OMG Digital Twin Consortium [24] or the ISO 23247 group for a Digital Twin Framework for Manufacturing [15].

In this overall context, La Poste (French postal service) [25] started an innovation project dedicated to the design of a control system for Cyber-Physical Production Systems (CPPSs). More particularly, they intend to deal with their new generation of postal sorting centers, i.e., their production systems as a postal industry. To this end, they want to introduce automated robots and make them actively collaborate with human actors. A longer term objective is to specify and implement a DT for these sorting centers (i.e. for these CPPSs) and use it in their industrial setup. However, the realization of such a DT is a complex task requiring an extensive knowledge and understanding of many different aspects of the CPPSs. To this end, Multi-Paradigm Modeling (MPM) [22] appears to be particularly appropriate as it already proved to be relevant for the design and operation of complex CPSs/CPPSs [26].

In a research work at La Poste, three kinds of models have already been specified [27]. A first model was designed to express performance indicators according to the current situation. Then,

heuristic models were specified to support the discovery of an optimal sorting process. Finally, a simulation model was realized to simulate this new sorting process (including robots). While these models helped to understand, analyze and simulate the behavior of the La Poste CPPS, they have been defined independently from each other and are not explicitly interrelated.

In this paper, we go further and pave the way to the definition of a DT for CPPS by proposing an initial MPM phase in which we correlatively model complementary aspects of the system under study. We start by using the BPMN notation to specify the sorting business process at La Poste. Then, we propose a mapping between the BPMN model and an intermediate UML Activity diagram describing finer-grain activities. Afterwards, we derive an implementation of these activities as corresponding agents in a Multi-Agent System (MAS) [29]. From a more global perspective, the proposed approach is driven by the business expertise in order to make validation easier prior to the DT design and implementation.

The remainder of the paper is organized as follows. Section 2 motivates our work by presenting the La Poste context and the challenges related to their use case. Then, Section 3 describes the MPM approach we proposed in order to go from the business process to a Multi-Agent System (MAS) emulating the CPPS. Section 4 discusses the current state of our work according to its general context. Then, Section 5 identifies open research problems and introduces our next steps by relying on existing related work. Finally, Section 6 concludes the paper.

2 CONTEXT AND MOTIVATION

La Poste (French postal service) [25], as many companies, is interested in transitioning towards Industry 4.0 [17]. To this end, La Poste is working on robotizing the loading step of part of the mail flow orientation process by focusing on high-traffic destinations only (so far). This loading step is currently fully achieved by human operators. The main objectives of La Poste are both to improve work conditions of their human operators and to optimize the mail and package sorting capabilities, as deployed in its different sorting centers located across the country. They also want to amortize their investment in terms of robot purchase and deployment costs.

Practically, this loading step consists in loading into carts the containers which are full of mails / packages and already waiting on conveyors (as coming from a sorting ring). A specific destination is assigned to each cart and, once full, the cart is then sent to the corresponding location inside (e.g., for further processing) or outside (for future transport and delivery) the sorting center. To this day, the different destinations of each pusher conveyor, i.e. the conveyor descending from the loop conveyor and assigned to the different carts placed around it, are predefined. The operators have to handle and manually load the different containers from the pusher conveyor to the carts. They have to repeat this task several times a day which turns out to be very painful, especially when the containers are full with heavy mails / packages. To give an idea of the capabilities of the system, the flow rate of the sorting ring and of the pusher conveyor are 12000 containers/hour and 1200 containers/hour (respectively).

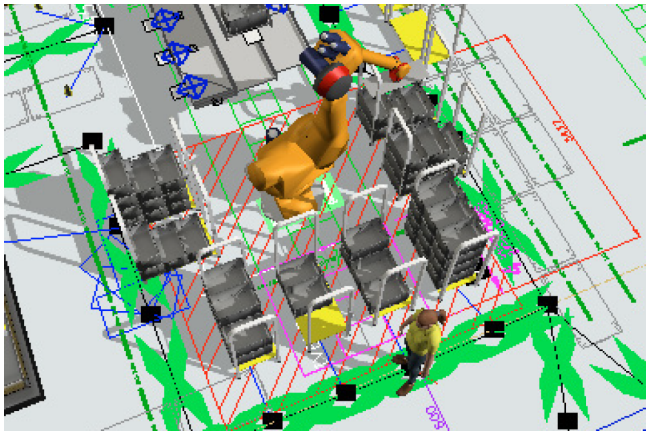


Figure 1: Automated mail loading robot at La Poste, modeled using FlexSim [23].

To assist the operators, La Poste is working on several robotics modules automatically loading containers from the pusher conveyors to the carts whenever possible. In this context, a first research effort has been made on which tasks would better be assigned to robots vs. humans [27]. To this end, various models were designed to 1) represent performance indicators for the loading process, 2) specify heuristics for discovering a more optimal sorting process and 3) simulate this optimized sorting process prior to its actual implementation. As an illustration, Figure 1 shows an excerpt of the 3D physical model realized with FlexSim, a 3D flow simulation and analysis tool [23]. A full-length video of the actual simulation of this model in FlexSim is also available[1]. As introduced in Section 1, this initial modeling effort already allowed to better understand, analyze and simulate the behavior of the La Poste CPPS. However, it is still difficult to capitalize on the produced models as defined separately and not explicitly interrelated to each other. In particular, La Poste is lacking an overall business vision over the associated workflow in order to be able to validate it at the business-level first (i.e. prior to its deployment in the real technical environment). Generally, such a business perspective is necessary for taking better strategic decisions that will then directly impact various cyber and physical components of the CPPS. We are strongly convinced of the importance of a clear separation of concerns between the business process, cyber and physical aspects of the CPPS. For this reason, we decided to rely on an MPM approach that starts directly from the business perspective. This way, we aim at fostering a closer collaboration between business experts and software engineers from early stages of the DT development process.

In the future, this separation of concerns should facilitate a good synchronization between the business processes and the DT from one side, and between the DT and the underlying CPPS from another side. Thus, we propose in Section 3 an initial MPM phase in which we correlatively model complementary aspects of the CPPS. Our final objective is to pave the way for supporting the definition

[1]Cf. slide 15 of the presentation downloadable from https://uncloud.univ-nantes.fr/index.php/s/omEAc8zTAPrZ2Ns

of a DT for the La Poste CPPS, and potentially other CPPSs from other companies in the future.

3 A MULTI-PARADIGM MODELING APPROACH

As previously motivated in Section 2, the MPM approach we followed in the context of the La Poste CPPS starts at a high abstraction level. The primary focus is set on the modeling of the business behavior of the system under study, regardless of the underlying technical environment and constraints. On the long run, from this business model, we aim at progressively deriving the different layers and components required in order to design and implement a DT of the La Poste CPPS.

Up to our current knowledge, the scientific literature does not provide a unique nor standardized definition of the Digital Twin (DT). As explained in a recent survey on the DT topic concept [3], there are works that define it as a virtual entity that can be substituted to the actual system in order to perform (at least some of) its tasks. In other works, a DT is described as a digital representation of a system for observation and prediction purposes mostly. In some cases, it is even simplistically presented as a very realistic and complete model of the system. However, the characteristics commonly associated to the DT are that it must be able to 1) behave like the real system during its entire life cycle, 2) allow to predict possible failures and 3) take autonomous decisions accordingly. Moreover, it appears to be fundamental to have a seamless connection and synchronization between the DT and the system (cf. Section 4 for related discussions).

In what follows, we present the different consecutive steps of our MPM approach as an initial phase towards the realization of such a DT. Firstly, we decided to use the Business Process Modeling Notation (BPMN) in order to identify and represent all the involved business entities and related activities (cf. Subsection 3.1). Secondly, we opted for the UML Activity diagram in order to describe only the corresponding control system that we obtained by mapping from the global BPMN model (cf. Subsection 3.2). Thirdly, we chose to use a UML Class diagram in order to derive the modeling of the Multi-Agent System (MAS) from the UML Activity model (cf. Subsection 3.3).

3.1 Business Process Modeling

The business process modeling of the La Poste CPPS was realized based on the results of the heuristics defined in a past work to describe a more optimal sorting process [27]. The main objective of these heuristics is to send as many containers as possible to the robotic arms in order to release the pressure from the human operators. Moreover, we also applied the concept of *Cyber-Physical System nodes (CPSn)* [18] that consists in explicitly modeling each manufacturing resource (MR) and its relationships with the others in order to provide a simple guideline to visualize independently the Manufacturing Resources (MRs).

This resulted in the complete BPMN model (Figure 2), where in two distinct pools, we distinguished between the *Robotic Arm* and the *TCC* (*Tri et Convoyage de Contenant* in French, meaning *Container Sorting and Conveying*). In both cases, the pool is divided into two lanes representing the *Physical Space* (i.e., all the activities done by sensors, cameras and humans) and its Cyber / *Digital Counterpart* (i.e., the Control System that manages, commands and regulates the behavior of the physical object).

The mail sorting process starts when a container (called *BAC*) arrives at the *TCC*. A message carrying the *BAC* information is sent to the *Digital Counterpart* that then calculates the Most Frequent Destination or *MFD*: the most frequent destination corresponding to the 10 carts surrounding the *Robotic Arm* (its maximum capacity) and loaded in the so-called *CE30*. Note that the *MFD* calculation is performed for any arriving *BAC* in order to check if there is any new destination to add in the list of potential destinations. However, this *MFD* is not updated (*Update MFD*) until there is a cart containing enough *BAC*s and not being used (Least Recently Used or *LRU*). In case the destination of the container does not belong to the *MFD*, a message carrying the decision to perform the process of handling the *BAC* manually is sent to the *Physical Space* of the *TCC*. Otherwise, its Control System (i.e. the *Digital Counterpart* of the *TCC*) checks if there are *BAC*s going to the same destination before sending a message carrying the decision to send the *BAC*s to the *Robotic Arm*. If there is not any, a message carrying the decision to keep the *BAC* waiting in the *TCC* is sent back. In order to avoid the overloading of *BAC*s in the *TCC*, it is regularly checked whether there is more than a maximum number of *BAC*s not being treated in the *TCC*. If so, the Control System chooses *BAC*s from the *LFD* and sends a message for human operators to perform the corresponding handling process manually.

Once arrived to the *Robotic Arm*, an arrival notification message is sent from its *Physical space* to its *Digital counterpart*. Thus, this latter (i.e., the Control System of the *Robotic Arm*) can update the *CE30* destination in which the arm will have to automatically position the *BAC*. After that, it also checks if the corresponding *CE30* is available. If this is the case, it then sends a message to position the *BAC* in the appropriate *CE30*. Otherwise, it sends a message to position the *BAC* in the *Buffer Zone* and to ask for a human operator to change the *CE30*. Once this change is done, she/he has to report its availability to the Control System. Thanks to this action, the Control System can send a message for the *Robotic Arm* to take back the *BAC* from the *Buffer Zone* and position it accordingly in the appropriate *CE30*.

3.2 From Business Process to Activities

In order to derive a UML Activity diagram of the CPPS control system from the global BPMN model specified in the previous step, we followed general mapping rules found from the existing work in the literature [9, 14]. It is interesting to note that, like the initial BPMN model [12], the intermediate UML Activity model produced at this step can also be made executable for different purposes (e.g. simulation) [6, 19]. The considered mapping rules are mostly model-to-model transformation rules where many of the involved concepts are quite similar in the BPMN model and the UML Activity model. However, the set of provided rules appeared to be insufficient in our case since there was no mapping rule for BPMN *intermediate events*. Intermediate events are important to consider since they trigger changes that directly affect the execution of the business process and thus impact the supporting CPPS. As a consequence, it is necessary to take them into account when realizing our mapping,

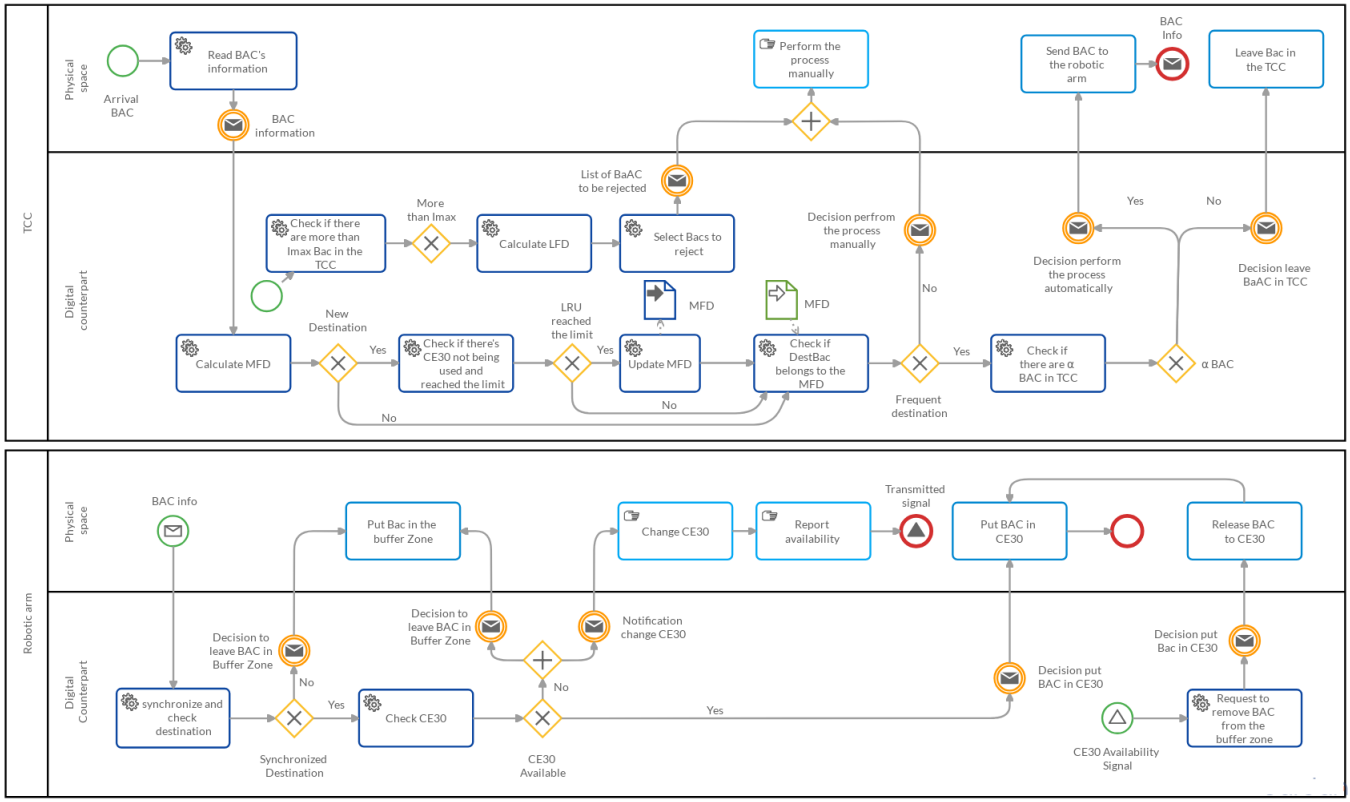


Figure 2: Business process model (in BPMN) of the La Poste mail loading process.

and also afterwards when deriving the MAS from the resulting UM Activity model. For example, after the *Select BACs to reject* activity in the BPMN model (cf. Figure 2), there is an intermediate message containing the *List of BACs to be rejected*. This kind of intermediate message between the Physical space and its Digital counterpart has to be mapped to action nodes starting with *Send* in the resulting UML Activity model.

By applying this specific rule for intermediate events in addition to the original set of mapping rules [14], we obtained the UML Activity model shown in Figure 3:

- Both pools and lanes in the BPMN model are represented as partitions in the UML Activity model. Thus, each Manufacturing Resource (MR), TCC and Robotic Arm, is represented by a distinct partition. Then, each partition is divided into two sub-partitions representing the *Physical space* and the *Digital counterpart* of each MR.
- The BAC arrival, represented by a Start event in the BPMN model, is represented as the Initial node in the UML Activity model. Tasks in the BPMN model are represented as action nodes in the UML activity model, e.g., *Send arrival message*, *Calculate MFD*, etc.
- Data objects in the BPMN model, e.g., *MFD*, are represented as object nodes in the UML Activity model.

However, there are several occurrences of Start and End events in the BPMN model which do not have direct equivalences in the UML Activity model. In such particular situations, we decided to perform the following mapping:

- Start events in the BPMN model (e.g., messages, signals) can be represented as the combination of a start node followed by an action node in the UML Activity model. This is the case for the *infoBAC* message start event that is transformed into a start node and a *send* action node, or for the *CE30 availability* signal start event that is transformed into a start node and a *receive signal* action node.
- Similarly, End events in the BPMN model (e.g., messages, signals) can be represented as an action node followed by a final node in the UML Activity model. This is the case for the *Bac info* message end event that is transformed into a *send* action node and a final node, or for the *Transmitted signal* signal end event that is transformed into a *receive signal* action node and a final node.

3.3 From Activities to Multi-Agent System

A Multi-Agent System (MAS) was used to emulate the sorting CPPS. The use of a MAS is motivated by its capacity to resolve conflicts in complex contexts thanks to the ability of the agents to communicate, cooperate and negotiate in terms of both scalability and robustness [29]. A Multi-Agent System (MAS) is a system composed of a population of autonomous agents where each agent pursues

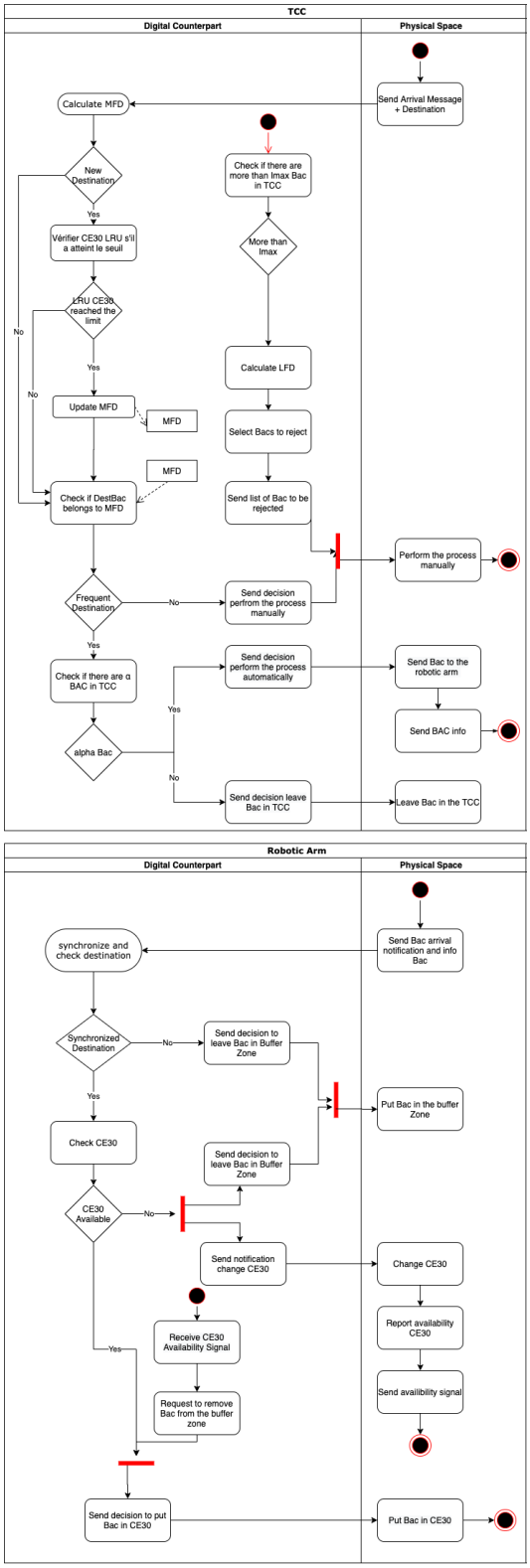


Figure 3: UML Activity model of the La Poste mail loading process, derived from the BPMN model in Figure 2.

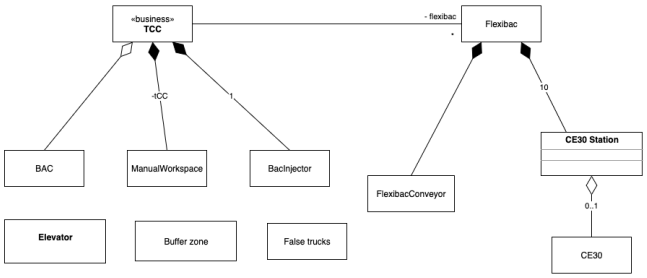


Figure 4: Agent model (in UML) of the La Poste mail loading process, derived from the UML Activity model in Figure 3.

its individual objectives and cooperates with others to achieve common goals [20]. Some of the best known platforms to develop a MAS include RepastHPC, Madkit, NetLogo, FLAME and JADE.

We selected the Java Agent DEvelopment (JADE) framework, an open-source project initially developed by Telecom Italia and that provides a middleware facilitating the MAS development under the FIPA standard [4]. Our program is implemented using the IDE Netbeans 11.2 and the agents are implemented using Java language (JDK 11). JADE allows the implementation of cognitive or reactive agents and each agent can have one or more behaviours implementing services/functionalities. There are simple (*one-shot behaviour,cyclic behaviour,generic behaviour, WakerBehaviour, TickerBehaviour*) and complex behaviours (*SequentielBehaviour, FSMBehaviour, parallelBehaviour*).

While preliminary work already studied in the past the possibility of directly mapping BPMN models to agent ones [13], we rather use a UML Activity model(cf. Section 3.2) in order to model the agents and their features. Such a model is particularly appropriate to represent the system behavior. Notably, concepts like Swim Lane can be used to group the activities according to the entity, in our case agent, that will perform them. The messages exchanged between agents are then modeled as links between different activities across the Swim Lanes. Finally, the methods and activities of each agent are more detailed in each Swim Lane via corresponding actions and conditions.

Complementary to this system behavior modeling, the structure of the MAS has also been represented as a UML Class model that we derived from both the initial BPMN model and previous UML Activity model (notably by identifying the main flow objects and data/artifacts involved in the process). Figure 4 shows the resulting model and how it represents the different entities (or agents) of the system as well as their various relationships.

4 GENERAL DISCUSSION

In Section 3, we proposed an initial MPM phase as a first step towards the definition of a Digital Twin architecture for the La Poste sorting center. This proposed MPM approach relies on an initial business process modeling effort that explicitly separates the physical space from its digital / cyber counterpart in the CPPS. Based on that, we have been able to obtain a clear separation of concerns between the (business) process, cyber and physical aspects of the La Poste CPPS. From this business process modeling, we have been able to derive a model of the corresponding control

system as a UML Activity diagram. In order to perform a first basic evaluation of our mapping and of the resulting UML Activity model, we manually compared it to a similar model [2] previously derived from the FlexSim simulation model introduced in Section 2. We observed that the BPMN model and its derived UML Activity model specify additional features which were not represented in the UML Activity model derived form the FlexSim model. These additional features are the following:

- An explicit connection between the digital / cyber and physical spaces of the modeled CPPS.
- Each manufacturing resource of the CPPS is explicitly specified as CPS-node resources.
- Tasks performed at the physical level are explicitly represented in both the physical and the digital / cyber space, as decisions in the latter.

We also noticed in our initial modeling that data and communications items were generally distributed between the digital / cyber and the physical layers. To go further with our MPM approach, these items should be explicitly identified right from the business-level as they are in fact necessary for the specification of a DT. Indeed, a general 4-layer architecture for DTs has already been proposed [5]. It notably includes data- and connection-specific layers among the following:

- *Cyber-Physical Layer* describes the CPPS handled by the DT;
- *Data Layer* - stores and shares the required (DT) data;
- *Connection Layer* - ensures the inter-layer connection;
- *Application Layer* - contains the business logic of the DT.

5 NEXT STEPS AND RELATED WORK

By following the previously mentioned 4-layer architecture, from a refined BPMN model we should be able to elaborate on an appropriate architecture for a DT at La Poste in the future. To this end, the future objectives we currently consider to address in our next steps directly relate to complementary MPM research areas [21]:

- First of all, automate (at least partially) the different steps of our MPM approach by implementing corresponding mappings as a chain of model-to-model transformations (for example) [2]. This should also result in a better consistency and synchronisation between the various models representing the design time aspects (notably business) and runtime aspects of the CPPS [7].
- Then, from our models, automate (at least partially) the generation of different software components such as the target MAS in our present case or various software artifacts of the Application Layer in the context of a future DT at La Poste (e.g., micro-services directly implementing various features of the CPPS or micro-services that can be used as agents emulating components of the CPPS [16]).
- Provide appropriate views to different stakeholders (e.g., business expert, DT architect, software engineer) over the set of possibly large and heterogeneous models resulting from our MPM approach or from the definition of the future DT at La Poste [8]. Blended Modelling techniques could also be envisioned in order to enable the various stakeholders to better interact with the views and underlying models [10].
- Based on such views, provide an automated and possibly visual assistance to these different stakeholders while they perform their engineering tasks (e.g., for business experts, to support them in building and adapting their BPMN models more easily thanks to recommendation patterns indicating how to appropriately map business concerns into correct process models [11]).

Once available, the results of these next steps of our work could be progressively integrated and used in practice in an experimental set up at La Poste. However, we will pay a particular attention to keep the proposed MPM approach as generic as possible in order to facilitate its adaptation and possible reuse in other different industrial contexts. More generally, in order to finally deploy such an MPM approach and resulting DT, in the La Poste production environment or any other industrial context, having a DT reference architecture could help significantly. In this respect, initiatives such as the OMG Digital Twin Consortium [24] or the ISO 23247 group that works on a Digital Twin Framework for Manufacturing [15] appear to be interesting to follow in the near future.

6 CONCLUSION

This paper presents our early-stage research on a MPM approach towards the definition of a Digital Twin for Cyber-Physical Production Systems. To this end, we propose an initial MPM phase in which we correlatively model complementary aspects of the system under study. We developed and applied this approach in practice by working in the context of the digitalization of the mail sorting process at La Poste, the French national postal service company. Previously, a first research effort was already made to determine a better distribution of tasks between the new robotic arms and the human operators [27].

In this paper, we are going one step forward by proposing a MPM approach completely driven by the business process. We believe such an approach can be highly beneficial to industrial companies for several reasons: (i) An easier consideration of (and capitalization on) the business requirements through explicit modeling; (ii) A clear separation of the business process from both the cyber / digital and physical aspects of the CPPS; (iii) Thanks to that, an easier validation by business experts prior to the future DT design and implementation; (iv) Additionally, a closer collaboration between business experts and the future DT architects and engineers; (V) A possibly improved synchronization between the business processes and the DT from one side, and between the DT and the underlying CPPS from another side.

We are strongly convinced that such an MPM approach coupled with easy interactions with business deciders will help to pave the way for supporting the definition of a DT for CPPSs in different contexts in the future.

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