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Digital Twin Integration in Multi-Agent Cyber Physical Manufacturing Systems

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Abstract: Complex manufacturing and supply chain systems consist of concurrent labour-intensive processes and procedures with repetitive time-consuming tasks and multiple quality checks. These features may pose challenges for the efficient operation and management, while manual tasks may significantly increase human errors or near misses, having impact on the propagation of effects and parallel interactions within these systems. In order to handle the aforementioned challenges, a digital twin (DT) integrated in a multi-agent cyber-physical manufacturing system (CPMS) with the help of RFID technology is proposed. The proposed reference architecture tends to improve the trackability and traceability of complex manufacturing processes. In this research work, the interactions occurring both within a single complex manufacturing system and between multiple sites within a supply chain are considered. For the implementation of the integrated DT-CPMS, a simulation model employing the agent-based modelling technique is developed. A case study from a cryogenic supply chain in the UK is also selected to show the application and validity of the proposed digital solution. The results prove that the DT-CPMS architecture can improve system's performance in terms of human, equipment and space utilisations.

Keywords: Digital Twin; Cyber-Physical System; RFID; Agent-based modelling; Complex manufacturing.

1. INTRODUCTION

The integration of Digital Twins (DT), Cyber-Physical Systems (CPS) and the revolutionary information technologies such as the Internet of Things (IoT), cloud computing, and Artificial Intelligence (AI) has formed one of the main pillars of the fourth industrial revolution, known as Industry 4.0 (Schroeder, Steinmetz, Pereira, & Espindola, 2016). DT can be described as a digital representation of a real system. Haag and Anderl (2018) defined DT as "a comprehensive digital representation of an individual product that will play an integral role in a fully digitalised product life cycle". CPS can be described as a computer-based control system with an integrated network of hardware devices and software platforms. Physical devices communicate within the cyber network through a transportation layer of an IoT infrastructure. In the CPS context, DT can be defined as a cyber representation of a real system in real time. CPS allows the connectivity between physical and computational domains over the Internet and provides access to information and application services for the user (Josifovska, Yigitbas, & Engels, 2019). Accordingly, over the past decade, identification, and track and trace technologies have been advanced significantly from barcodes to smart RFID sensor tags and blockchain systems (Huang, Wang, Yan, & Fang, 2020). The next generation of such smart systems is capable of connecting with the wider cyberspace and other Industry 4.0 systems (Fernandez-Carames & Fraga-Lamas, 2018). For a System of Systems (SoS), deploying a DT requires a seamless interconnection of individual DT models. In this regard, the digital thread concept refers to a communication framework that allows such connectivity and integrity of data within the DT model. The digital thread concept aims at delivering "the right information to the right place at the right time" (Zhang, Guohui, & Yan, 2018). Developing such integrated DT-CPS model can also facilitate the new paradigm of smart manufacturing and supply chain systems. For complex manufacturing systems, the DT-based architecture of the CPS is composed of multiple digital representations for different cyber elements. In this context, the agent-based modelling technique can be applied effectively to develop the CPS, so-called multi-agent CPS (Farsi, Latsou, Erkoyuncu, & Morris, 2020). However, the challenge is to develop an integrated DT architecture that aggregates multiple cyber elements and allows data communication and integrity within a multi-agent CPS. Several other challenges are identified in the literature ahead of smart systems development. For instance, Tao et al. (2017) indicated that two-way communication between physical and virtual spaces is key for supporting a real-time interaction for smart manufacturing. Moreover, they argued that developing a seamless, secure and robust smart system is a challenging task due to the unpredictability, uncertainty and fuzziness of the physical space (Tao & Zhang, 2017).

This paper aims to present a DT architecture for a multi-agent CPS within the context of supply chains and complex manufacturing systems. The proposed DT represents the data flow for RFID tagged products being processed on a shop floor of a complex manufacturing system and as part of a supply chain. This paper focuses on an RFID-based CPS in order to provide interactivity in a different application. The authors would like to highlight that this research work extends the

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earlier study by the authors regarding development of a multi-agent CPS in Farsi, et al. (2020). The research also implements the hybrid Agent-Based Modelling (ABM)-Discrete Event Simulation (DES) simulation model, which was previously introduced and developed by the authors in Farsi, et al. (2019).

2. LITERATURE REVIEW

Although several research works around RFID-based CPS and DT have been carried out over the past decade, the studies that are focused on the integrated DT-based CPS models and architectures are sparse and relatively new. Over the past couple of years, the existing studies have focused on different aspects of DT-based CPS models, and in a variety of contexts; instances of these include: communication methodology for data exchange (Schroeder et al., 2016), cyber-physical production systems for SMEs (Uhlemann, Lehmann, & Steinhilper, 2017), smart manufacturing workshops (Leng et al., 2019), smart cities (Farsi, Daneshkhah, Hosseinian-Far, & Jahankhani, 2020), sustainable project scheduling (Chakrabortty, Rahman, Mo, & Ryan, 2019), prognostic health management (Park et al., 2019) and personalised production (Park, Lee, Kim, & Noh, 2020).

The important concept behind DT and CPS architectures is the cyber-physical connection. Tao et al. (2019) presented a thorough literature review to highlight the differences and similarities between DT and CPS. They highlighted that the CPS core elements are sensors and actuator. In contrast, DT elements are virtual models and data. Moreover, DT is more flexible to integrate with new IT platforms and at the system of systems level. Nevertheless, they both aim to enhance the capabilities of a system, by offering optimised solutions. Alam et al. (2017) presented a digital twin architecture for a cloud-based CPS reference model. Their proposed architecture composed of four elements, namely operational mode, physical level sensors-fusion mode, cyber level digital twin services-fusion mode, and deep integration of sensor services fusion mode. A product manufacturing digital twin architecture is proposed by Zhang et al. (2018). Their proposed DT consists of five models, namely product definition, geometric and shape, manufacturing attribute, behaviour and rule, and data fusion. Moreover, they presented the architecture with five layers of physical, network, database, model and application. A five-level architecture for the implementation of CPS is proposed by Lee et al. (2015) for Industry 4.0-based manufacturing systems. Their proposed architecture consists of smart connection level for acquiring data from physical components, data-to-information conversion level, cyber level as a central information hub, cognition level for generating knowledge of the component, and finally, configuration level for providing feedback from cyberspace to physical space.

The existing literature referred to the integration of CPS and DT models as a DT-based CPS (Chakrabortty et al., 2019; Ding, Chan, Zhang, Zhou, & Zhang, 2019; Park et al., 2020). Ding et al. (2019) argued that in production systems, the integrated DT-CPS enhances the interactivity between physical and cyber shop-floor. Moreover, they highlighted that implementing a DT-CPS is a challenging task due to the inadequate infrastructure for industrial networks and the deployment of relevant computing technologies. Negri et al. (2019) developed a set of simulation modules as a functional mock-up unit to replicate specific behaviours of the manufacturing equipment for CPS-DT. The proposed simulation modules support DT to effectively adapt in real-time. A multi-agent approach for developing an integrated CPS-DT for managing farms is presented by Laryukhin et al. (2019). Their proposed approach includes knowledge base with domain ontology, DT agent and data mining methods with a view to supporting decision-makers, i.e. farmers. Due to the complexities, dynamic and highly interactive nature of complex systems (Farsi, Erkoyuncu, Steenstra, & Roy, 2019), flexibility and adaptability for CPS-DTs are crucial. In this regard, Tran et al. (2019) proposed an approach for developing a smart cyber-physical manufacturing system (CPMS) to cope with the variations of the manufacturing environment. The main characteristics of smart CPMS are defined as self-organisation, self-diagnosis, and self-healing.

3. DIGITAL TWIN-BASED MULTI-AGENT CYBER-PHYSICAL MANUFACTURING SYSTEM

In a cryogenic supply chain including the procedures of collection, manufacturing, distribution and administration, the track and trace of cryogenically-stored materials can be particularly advantageous. Continuous monitoring and assessment of the location and condition of these materials can improve accuracy and quality of supply and logistics, ensure materials are handled properly and provide greater productivity. Moreover, the implementation of a logistics digital twin integrated in a cyber-physical monitoring and control system can enable more informed and responsive decision-making, improve logistics management and efficiency and optimise the overall supply chain operations. In this research work, a cryogenic supply chain from the cell and therapy (CGT) sector, consisting of the primary manufacturer, secondary manufacturer, and the end-user, is studied to develop a DT architecture for a multi-agent CPMS-RFID system. The RFID system selected in this study is installed at each stakeholder's site. Details about the RFID system architecture can be found in (Farsi, Latsou, et al., 2020). RFID readers are placed in the goods in and out areas collecting data on the arrival and dispatch of shippers, respectively. Additionally, the RFID readers in the cryogenic storage area capture data while cryo-materials are stored to the tanks after shippers' arrival or picked from the tanks before dispatch.

3.1 IoT Platform Architecture of Digital Twin-CPMS

In order to realise the DT-CPMS architecture with RFID application, a well-known five-layer IoT data structure, adopted by Lee et al. (2015), is developed. The DT architecture represents the data flow for RFID tagged products being processed on a shop floor or a supply chain. The DT enhances the interactivity between physical and digital spaces and allows data communication and integrity within a multi-agent CPMS. The architecture considers a sequential workflow from data acquisition to data analytics and optimisation for informed decision making. Moreover, feedback from the cyber to the physical space for on-demand predictive services, and from the physical to the cyber space for system's performance, and services optimisation are captured. The 5C architecture of the DT-CPMS, illustrated in Fig. 1, is outlined as:

1. Smart connection layer: captures the components existing in the physical space, which are the fundamental starting point for the construction of DT as they provide the necessary data for simulating their behaviours. Physical components may include site (i.e. terrain and buildings), and human, equipment and material resources. In addition, RFID hardware and equipment, including RFID tags and readers, antennas, sensors, routers and computer devices, are deployed. This layer is thus employed to obtain raw data from these physical components either from enterprise manufacturing systems or automatically from RFID sensors.

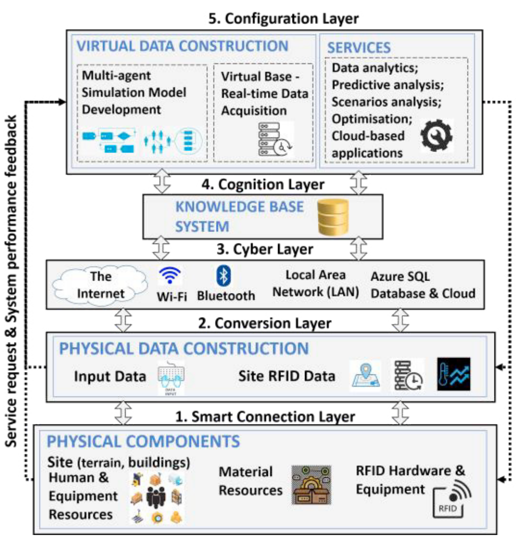

Fig. 1. DT-based cyber physical architecture of IoT.

2. Conversion layer: is used to pre-process raw data obtained from the physical components in the smart connection layer, so meaningful information to be extracted. This information retrieved from the interaction between the RFID system and the resources create the site RFID data, as seen in Fig. 1. Site RFID data may include task identification, supplier's and recipient's information once the RFID reading takes place within a site, date, time and location of RFID reading, order number, delivery location, sample types, batch number and quantity. Similarly, information from other input data may be associated with the number of human resources and equipment, operating hours, etc. Obtained information is then sent to the knowledge base system in the cognition layer through the cyber layer (Fig. 1).

3. Cyber layer: transfers information from the conversion to the cognition layer through a wired or a wireless network. Considered as a central information hub, this layer connects all 'things' including any physical component for sharing and exchanging data. The information from every connected component at each site within a supply chain is gathered and stored in a system database (DB) (Microsoft SQL). This DB is hosted on a Virtual Machine on Microsoft Azure Cloud enabling parallel communications and interconnections among different stakeholders within a supply chain. Advanced data analytics can be employed to process the stored information and compare it with historical data, providing a better insight for the tagged objects moving throughout a supply chain.

4. Cognition layer: captures multidimensional (e.g. product, time, storage) and heterogeneous data from multiple time periods and sources, i.e. from physical components and services as seen in Fig. 1. In order to effectively transfer knowledge to and from the decision-makers, data is presented in a structured form employing DB capabilities. This layer holds the system's knowledge with the help of the knowledge base system (KBS), consisting of three sub-DBs with: (i) site RFID data and (ii) input data obtained from the smart conversion layer; and (iii) historical data retrieved from the configuration layer. For the real-time data, a MS Excel file with the site RFID data is obtained via the Google Drive API. The file is automatically updated at a regular basis retrieving new data from the Azure and Google Drive APIs (cyber layer). The data is then processed with the help of auto-dynamic macros (Excel Visual Basic for Applications) generating a file with meaningful information, i.e. tags ID, date and time stamps and process time for performing tasks.

The Unified Modelling Language (UML) class diagram of the proposed DT-based multi-agent CPMS in Fig. 2 helps to better understand the architecture of the KBS in the cognition layer (represented by the red blocks). A built-in integrated DB so-called KBS is initially created. Data obtained from the conversion and/or configuration layer(s) is read by the KBS from a MS Excel spreadsheet file. A DB table is then generated automatically holding the data from the Excel file. DB views and DB view tables are also developed. A DB view is the result set of a query on the data stored in the DB table. A DB view table so-called virtual base is created when manufacturing components from the multi-agent simulation model request access to a DB view. Thus, the data in the virtual base, retrieved from a DB table following requests made via a DB view, provides input to the multi-level agents of the simulation model. Moreover, the system architecture considers an RFID detector element for the RFID hardware and equipment. In this research, the RFID detector should have a unique ID, location, ID number of scanned tags, and date and time detection, as viewed in Fig. 2 (grey block).

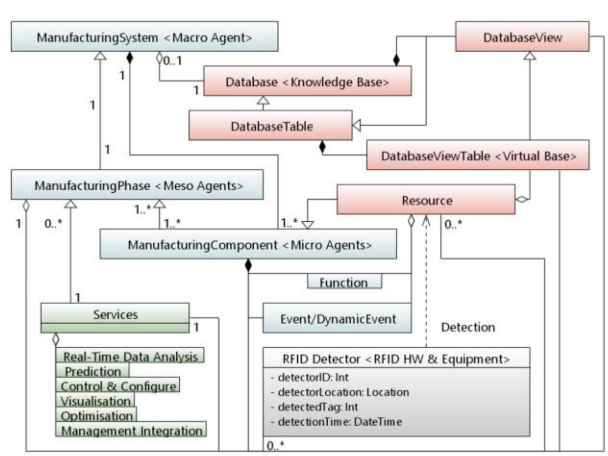

Fig. 2. UML class diagram of DT-based multi-agent CPMS.

5. Configuration layer: is the most interactive layer providing and receiving feedback to and from the smart connection and conversion layers, respectively. As viewed in Fig. 1, this layer comprises of two parts: virtual data construction; and services. The former part is for developing virtual models as exact replicas of physical components mimicking their physical geometries, properties behaviours and rules (Tao & Zhang, 2017). The behaviour of these virtual models is captured by retrieving data from the KBS, while reflected on the multi-agent simulation model, presented in Fig. 1. The data obtained from the KBS creates the virtual base as discussed earlier. By employing this virtual base data, process modelling and 2D/3D layouts of the physical space can be developed.

In this research study, a hybrid ABM-DES method has been employed to model complex manufacturing and supply chain systems. It is noted that these systems consist of multiple manufacturing phases in which various tasks may be performed at the same time, resulting in parallel interactions within the system. This increases the systems' complexity. The proposed ABM-DES system architecture is viewed in the UML class diagram in Fig. 2 (blue blocks). The proposed hybrid method that combines object and process-oriented approaches models the dynamic behaviour of complex manufacturing systems. A modular three-level multi-agent approach adopted by (Farsi et al., 2019; Farsi, Latsou, et al., 2020), is developed creating macro, meso and micro-level agents. A macro-level agent describing the global manufacturing system consists of multiple: (i) meso-level agents simulating the dynamic structure of manufacturing phases; and (ii) micro-level agents modelling the behaviour of manufacturing components. Meso-level agents are created as a single agent always existing within the current agent, while micro-level agents are created as a number of agents of the same type living in the same environment in the current agent. The ABM approach is employed at the meso and micro level agents, while the DES modelling approach is used to capture the discrete states of manufacturing phases. Moreover, the agents' behaviour existing at the micro-level is described by a resource type such as static, movable or portable. Human, equipment and material resources with their properties (capacity, rate, etc.) may be considered, as illustrated in Fig. 2. Finally, events for scheduling an action at some particular moment of time in the future and functions for describing algebraic rules can be added.

The services part in the configuration layer is created to provide added value services including real-time data analysis, evaluation, bottlenecks identification, estimation, optimisation and prediction, as illustrated in the UML class diagram in Fig. 2 (green blocks). Thus, added value algorithms and calculation models for processing requirements arising within a supply chain are considered. Services may allow better performance simulation, monitoring and visualisation, diagnosis and prognosis, scenarios analysis, optimisation and decision-making for resource planning, time-in-system and dispatch planning. Cloud-based applications may also be considered enabling multiple users with remote access to the model to conduct experiments and achieve better scenario management. Services, a key element of the architecture, act as a control system providing feedback (right arrows in Fig. 1) to the smart connection and conversion layers for making corrective and preventive decisions for performance improvement.

4. MODEL VALIDATION: A CASE STUDY IN CGT CRYOGENIC SUPPLY CHAIN

In this research, a complex manufacturing system at a CGT cryogenic warehouse is selected as the case study to: (i) test the validity of the proposed DT-CPMS architecture by its step-by-step application; and (ii) demonstrate the benefits of the RFID implementation to the system's performance in terms of the utilisation of human resources (HR), equipment resources (ER) and space zones (SZ). An agent-based simulation technique in the AnyLogic software package was implemented to model the proposed architecture.

4.1 System Description

The complex manufacturing system at the selected cryogenic supply chain consists of a primary manufacturer, a secondary manufacturer (cryogenic warehouse) and an end-user (patient). The focus is on the secondary manufacturer, who is responsible for receiving cryogenic material from the primary manufacturer, storing the material, and dispatching it when an order request is received from the end-user. The selected cryogenic warehouse consists of three manufacturing phases: (i) Receipt and Inventory; (ii) Storage; and (iii) Distribution. The UML activity diagram in Fig. 3 shows the execution of tasks, while highlighting these where RFID devices are implemented to capture information.

4.2 Results: Model Validation

The proposed DT-CPMS architecture is developed for the selected CGT cryogenic supply chain to demonstrate its applicability and validity. The DT represents the data flow for RFID tagged products being processed on the shop floor of the cryogenic warehouse within the studied supply chain. This DT enables bottlenecks identification employing real-time data or/and historical data in order to support decision-making between physical and digital spaces. The 5C architecture of the DT-CPMS, seen in Fig. 4, is defined as:

1. Smart connection layer: in this research, the physical components include the shop-floor of the selected CGT cryogenic warehouse with the corresponding HR, ER (e.g. trolleys, racks, tanks, etc.) and material resources (e.g. containers including shippers, vials, bags and boxes in which the biological material is stored and transferred throughout the cryogenic supply chain). RFID sensor tags, attached to the containers for tracking and tracing purposes, are also considered as physical components.

2. Conversion layer: for the physical data construction part, viewed in Fig. 4, real data was collected for the studied cryogenic warehouse. The input data, required for the micro-level agents of the ABM-DES simulation method, are 23 technicians (HR) for the execution of manufacturing tasks and 2 trolleys, and 4 cryo-carts (ER) for containers' transportation. The daily working hours are between 8:30am and 4:30pm. In addition, the cycle time distribution input for the manufacturing tasks is viewed in Table 1 (the asterisk denotes the RFID implementation). The site RFID data collected in this layer are tags ID, location, date and time stamps of each scanned tag. This is acquired from the containers movement with the help of the RFID system.

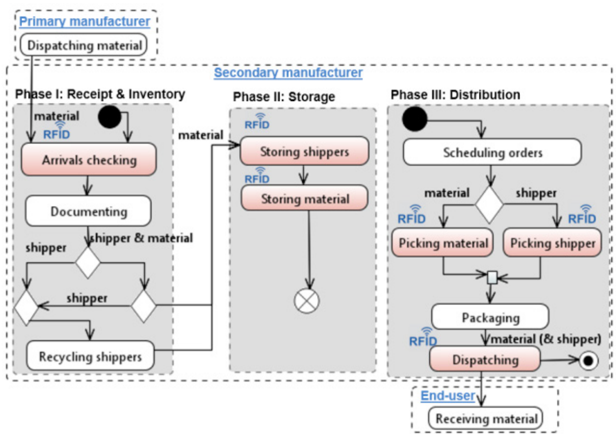

Fig. 3. UML activity diagram of a cryogenic supply chain with RFID.

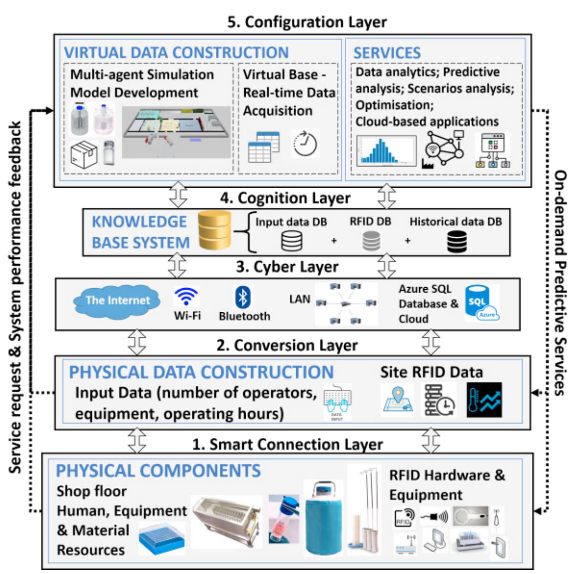

Fig. 4. DT-CPMS architecture of a cryogenic supply chain.

3. Cyber layer: information is transferred from the conversion to the cognition layer through the Internet, selected due to its global availability and affordability. At each site within the cryogenic supply chain, there exists a server PC that holds the system Microsoft SQL DB, while running a web service allowing devices with access to the same network to view and process the data. This DB is hosted on a Virtual Machine on MS Azure Cloud enabling parallel communications and interconnections between manufacturers and end-users.

4. Cognition layer: consists of three sub-DBs hosted in the KBS (Fig. 4). Data obtained from: human, equipment and material resources, and expert knowledge is stored to the input DB; RFID system is stored to the RFID DB; configuration layer including the simulation and optimisation results is stored to the DB of historical data.

Table 1. Input data – Cycle time distributions

Manufacturing phase	Manufacturing task	Distribution (minutes)
Phase I: Receipt and Inventory	Arrivals checking*	Uniform (2, 3)
	Documenting	Uniform (5, 10)
	Recycling shippers	Uniform (25, 70)
Phase II: Storage	Storing/picking shippers*	Uniform (5, 10)
	Storing/picking material*	Uniform (10, 30)
Phase III: Distribution	Scheduling orders	Uniform (35, 55)
	Packaging	Uniform (10, 20)
	Dispatching*	Uniform (1, 3)

5. Configuration layer: for the virtual data construction part, a simulation model following the hybrid ABM-DES method, discussed earlier in this work, is developed for the CGT cryogenic storage processes of the cryogenic warehouse in the UK. Employing the information stored in the input data DB and RFID DB of the KBS, virtual models for the material resources are developed. From the model simulation for a 5-week period, real data for the RFID cycle times is collected and the continuous probability distribution for each RFID task is listed in Table 2. This data demonstrates the ability of the architecture to obtain meaningful information, by mimicking the data flow of the RFID tags embedded to shippers. After implementing the RFID cycle times to the simulation model, real-time data analysis and evaluation is carried out in the services part of the configuration layer. Thus, the average utilisations of HR, ER and SZ for the three manufacturing phases are acquired. The RFID results are then compared against historical data obtained from the system operation without RFID and the reductions in the utilisations are summarised in Table 3. The computational results show that the RFID implementation can significantly reduce the times required for storing and picking materials and shippers, due to the reduction of the paperwork and an extra technician acting as a 'second witness'. Hence, the availability of human resources, equipment resources and space increases, resulting in reduced HR, ER and SZ utilisations. From the case study, it is found that the RFID tags integration with appropriate IT platform can effectively improve the cryogenic storage procedures, as they have great impact on the performance of the supply chain. The outcome from this study demonstrates reduction of HR, ER and SZ by ~41.3%, ~34.6% and ~43.3%, respectively. Following these observations, the deliveries and orders from the primary manufacturers and end-users respectively may increase as the secondary manufacturers are able to handle greater amount of materials. This would also have a direct impact on the costs of goods, making these cell and gene therapies more affordable. Analysing the simulation results, the following bottlenecks in the daily practices are identified: (i) shortage of HR in the recycling zone between 9:30am–5:00pm; and (ii) queues in the documenting zone, between 12:30pm–3:00pm, due to the interactive processes between receipt and distribution zones. Moreover, a 'what-if' scenario, in which the number of daily orders increased by four times, is examined. The results show that in addition to the aforementioned bottlenecks, the following new bottlenecks are: (i) shortage of HR while picking products and shippers for dispatching; and (ii) shortage in the number of validated shippers. Thus, current-state bottlenecks can be identified, while enhancement requirements can be highlighted by examining different scenarios. These outputs, obtained from the configuration layer, can be used as feedback to the conversion and smart connection layers helping in decision making to improve the system's performance.

Table 2. RFID input data – Cycle time distributions

Manufacturing phase	Manufacturing task	Distribution (minutes)
Phase I: Receipt and Inventory	Arrivals checking*	Uniform (0.17, 0.25)
Phase II: Storage	Storing/picking shippers*	Uniform (1, 3)
	Storing/picking material*	Uniform (2, 4)
Phase III: Distribution	Dispatching*	Uniform (0.17, 0.25)

Table 3. Average utilisations for the states 'Without RFID' and 'With RFID'

Phase	'Without RFID' (%)			'With RFID' (%)			Reduction %		
	HR	ER	SZ	HR	ER	SZ	HR	ER	SZ
I	4		3	2		1.5	50		50
II	15	13	5	8	8.5	2.5	46.7	34.6	50
III	81		1	59		0.7	27.2		30

5. CONCLUSIONS

This paper extends the application of agent-based approach in complex manufacturing and supply chain systems, proposing a DT architecture integrated in a hybrid multi-agent CPS with embedded RFID technology. The complexity of these systems, including labour-intensive processes, arise from the various manufacturing phases and components operating simultaneously and interact dynamically with each other. Hence, human error and near misses can greatly affect the system performance. To improve such performance, the proposed architecture enables effective inter-layer interactions between different manufacturing phases and among different stakeholders within a supply chain. A multi-layer data structure provides an IoT platform for the DT-CPMS with RFID application. The validity of the proposed architecture is demonstrated through its application to a case study from the cryogenic supply chain. The digital solution shows improvements in the trackability and traceability of complex manufacturing processes. Future work could: extend the current DT-CPMS architecture considering a vein-to-vein digital supply chain; explore the impact of the proposed architecture in terms of economic benefits and energy consumption; and examine how the DT architecture can improve systems' resilience once disruptive events occur.

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