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Designing a Digital Twin Prototype for an Addiction Treatments Clinic

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Abstract

Digital twins (DTs) are one of the highest technological trends. Although the first implementations were made in the manufacturing sector as an enabler of Industry 4.0, their evolution is already changing the face of various industries. Several applications of the concept of digital twins in services are provided by the scientific community. However, the application of DT in healthcare operations management is still in its infancy. In this research paper, we propose a digital twin prototype for healthcare operations management. Specifically, we analyze the impact of using a digital twin in a clinic that provides care and support services to marginalized people suffering from addiction. Following a "design science" research approach, we develop (i) an IoT prototype for real-time patient tracking, (ii) a hybrid simulation model, and (iii) integrate them to build our DT prototype. The IoT Lab is used as a testbed research environment to develop the IoT infrastructure and simulate the implementation of the DT. While the prototype is developed for a specific clinic, the approach can be applied to any other healthcare operational environment where real-time visibility and decision support based on simulation is needed.

Keywords: Simulation; Digital Twins, IoT, Healthcare operations management.

1. Introduction

The concept of Digital Twins (DTs) was introduced to the scientific community at the beginning of this millennium by Michael Grieves (Grieves, 2014) and described more formally in (Grieves and al. 2017). The idea behind a DT is that any object, process, or system can be replicated by a digital representation (Gartner 2019), thus creating two similar systems (twins) that are connected by a permanent real-time data exchange. The emergence of IoT technologies has contributed significantly to the development of DTs, and their application shows great potential for the management of operations in various sectors (Costello and Omale, 2019). The use of DTs is likely to become more common in various fields. According to a survey conducted by Gartner, 75% of surveyed organizations that already have IoT initiatives and infrastructure in place plan to launch digital twin projects within a year (Costello and Omale, 2019). The digital twin market was estimated to be worth $6.75 billion in 2021, with a projected growth rate of nearly 40% per year, reaching approximately $100 billion by 2029. It's clear that the digital twin will become more prevalent in organizations over the next decade, and an acceleration trend is expected for the technological tool represented by the digital twin.

Simulation tools have been used for decades in the context of healthcare operations management to identify problems, make what-if scenarios, and optimize the system under study based on the results obtained, without immediately altering the healthcare system under study (Maïzi & Bendavid, 2023); (Maïzi & Bendavid, 2021a); (Damnij & Damnij, 2010); (Kisliaskovski et al., 2017); (Cimino et al., 2022). Given the complexity of the healthcare system and the diversity of patients' condition, this ability to identify problems and test improvements without compromising the safety and security of staff or patients is essential and particularly relevant in the case of the present research project.

In this research study we are interested in the application of digital twins in healthcare environments. More specifically, among the different application cases that we are studying, we present a digital twin prototype to improve the daily management of operations in an addiction treatment clinic, where patients are dependent on opioids. It is essential that this clinic continuously adapts its support and care services to the needs of different users, while remaining efficient. The use of the Digital Twin (DT) is very promising and could be very useful to support real-time decision making.

The remainder of this paper is organized as follows: in Section 2, we review the existing literature on the DT, specifically regarding: i) the application of the DT concept in healthcare environments, ii) the IoT component in DTs, iii) hybrid simulation modeling as a DT component. In Section 3, we describe the "design science" methodological approach used to develop the physical prototype of the DT for daily clinic operations management. In Section 4, we present the design of the prototype. Finally, Section 5 discusses some of the expected results and Section 6 presents our concluding remarks.

2. Literature review

A digital twin is a virtual object or group of virtual objects that represents a physical object or group of physical objects. The physical object is equipped with technologies to retrieve and transmit data to its virtual replica in real time (Qi et al., 2021). This connection between the physical object and its virtual replica is usually established and maintained through the IoT.

In the manufacturing environment, the emergence of Industry 4.0 and the various technologies that support it have actively participated in the development and implementation of digital twins in this sector (Kritzinger et al., 2018). However, in other sectors, such as healthcare, the development and implementation of this technology is still in the cradle stage.

In the following, we will first address the literature review related to the concept of DTs in healthcare, secondly, we will review the literature related to the IoT component in DTs, and finally, we will address the simulation component in DTs.

2.1. DT concept application in healthcare

Approximately 4% of articles on digital twins are dedicated to their use in healthcare (Singh et al., 2022; Tao et al., 2022). This interest in the specific technology of DTs seems to be relatively recent, as is the case for other types of services: in the global literature reviews listed in recent years, the healthcare sector was often either absent (Jones et al., 2020; Liu et al., 2020) or barely mentioned in terms of its potential and opportunities, with at most one or a few articles mentioning healthcare (Fuller et al., 2020; Semeraro et al., 2021; Singh et al., 2021; Tao et al., 2019). By 2022, the coverage of the sector is much broader and different forms of DT are proposed for health subsectors: DT for physical activity and wellness, detection and prognosis of diseases and health problems, control and optimization of surgery, management of health facilities, management and study of public health, and integration and study of the entire human life cycle are listed (Alazab et al., 2022; Botín-Sanabria et al., 2022; Hassani et al., 2022; Khan et al., 2022; Patrone et al., 2020; Singh et al., 2022; Tao et al., 2022).

The literature shows a focus on the development of the digital patient, and therefore the interest is on the medical and physiological aspect, and very few articles actually address the management of a healthcare facility through the digital twin. However, researchers raise the importance of developing digital twins to support the daily management of healthcare operations. To the best of our knowledge, research on this type of application is lacking in the literature. In this study, we focus on designing a digital twin prototype to be used in a clinic that treats patients with addiction problems. Although this prototype is designed for a clinic that treats patients suffering from addiction. The IoT infrastructure developed for this prototype can be easily reused for other clinics with a few adjustments.

2.2. IoT Component in DTs

The concept of the Internet of Things (IoT) can be defined as an ecosystem that allows physical objects, software, and hardware to interact with each other (Ahmadi et al., 2019). The origin of the term is attributed to work on RFID technologies at the Massachusetts Institute of Technology (MIT) "Auto-ID Labs" (Wortmann & Flüchter, 2015). Over the past two decades, research on the topic has increased significantly with publications in top scientific journals and is being heard in various application areas including, but not limited to, smart cities, agriculture, supply chain management, and hospital management (Wang et al., 2021). The main idea behind the concept of IoT is to equip every physical object (living or not) with an electronic device that allows it to automatically communicate in real time with its environment (physical and software) to manage its own transactions (Bendavid et al., 2022). This then involves deploying this large number of objects, pumping and processing the captured data before returning feedback to their environment

(Sisinni et al., 2018; Bendavid et al., 2022). In order to connect objects, it is necessary to combine physical and software elements.

Figure 1. illustrates the different technology layers of an IoT infrastructure. At a high level, the model is composed of several layers, starting with layer one and two respectively for "object" identification (e.g., using RFID tags, sensors or wearables) and data collection. The third layer, connectivity, provides the link between the objects and the fourth layer, which in turn handles the storage and pre-processing of the data. To achieve a digital twin, in layer 5, the input data analysis is then performed to feed different hybrid simulation models developed using Discrete Event Simulation (DES), Agent-Based Modeling (ABM), and System Dynamics (SD). Finally, the last layer is used to analyze the simulation outputs and manage transactions accordingly.

Artificial Intelligence (AI) is used at all the layers. For instance, vision technology can be used for patient identification as well as for behavior analysis to detect any threatening pattern. AI algorithms can be used at layer 5 and 6, to analyze simulation outputs and automate decision making. Today, the concept of IoT is used in both manufacturing and services, and in all sectors. The integration of IoT in the manufacturing sector has ushered in Industry 4.0.

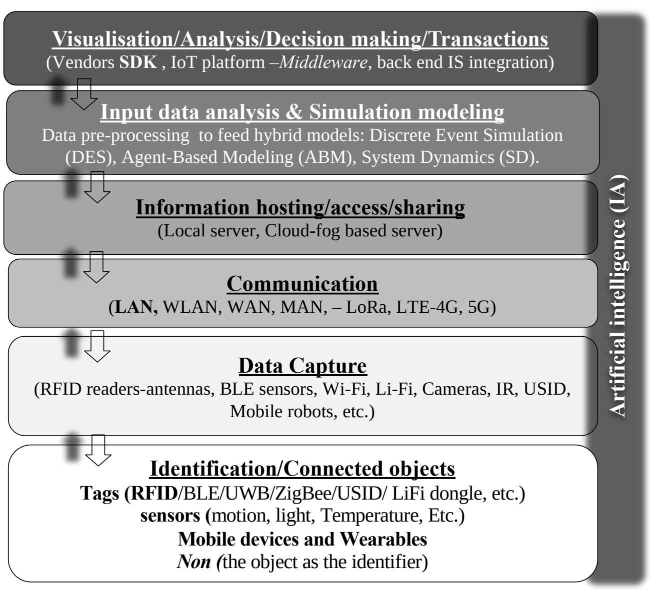

Figure 1. IoT Technology Layer (adapted from Maïzi and Bendavid, 2021b).

In the health sector, the integration of IoT is called Medicine 4.0 or Health 2.0, and IoT technologies dedicated to medical applications are called Healthcare Internet of Things (H-IoT) (Qadri et al., 2020).

2.3. Simulation Component in the DT

Simulation modeling has been used to design, observe, understand, analyze and improve large-scale complex systems, including several applications in healthcare (Salleh et al., 2017; Mei et al., 2015). Undeniably, its ease in capturing complex behaviors, interactions, and operations makes it a powerful tool for analyzing and improving the problems of large-scale healthcare operations management (Cimini et al., 2021). There is a wide range of methods used to build simulation models, and each of these methods/paradigms is predominantly used in its domain (Galvão et al., 2018). However, there are three methods that are widely used in the operations management and industrial engineering community and related fields to model and solve related problems: Discrete Event Simulation (DES), Agent-Based Modeling (ABM), and System Dynamics (SD). The inherent complexity of the processes associated with modern organizations, as well as the human behaviors that affect the performance of these processes, has led managers and researchers to combine these paradigms and use hybrid simulation approaches. Brailsford et al. (2019) define hybrid simulation as a modeling approach that combines two or more of the following methods: discrete event simulation, system dynamics, and agent-based modeling. Over the past decades, hybrid simulation modeling has been successfully used to model several processes related to manufacturing, supply chain and healthcare (Brailsford et al., 2019), most of which use a combination of discrete-event simulation and system dynamics modeling. Similarly, Galvão et al (2018) conducted a thorough literature review on hybrid simulation methods used in the industrial engineering community and related fields. The results of the study show that the combination of SD and DES has more than 40 years of history, while the integration of ABM in hybrid simulation modeling has a more recent history, but successful applications in healthcare operations management in combination with DES modeling. The motivation to use a hybrid modeling approach is derived from the complexity of the system under study and the difficulty in capturing its inherent characteristics when using a single modeling method, which could lead to limited modeling capabilities. Hybrid simulation applications have been particularly successful in healthcare due to the multidimensional complexity inherent in healthcare operations.

Simulation is an important component of the digital twin (Liu et al., 2022) and is the main decision support component in the prototype being developed in this research project.

In our study, we aim to bring the potential of hybrid simulation to the DT prototype. Indeed, the integration of the simulation component into the DT allows to reproduce the dynamics of the clinic in real time, in order to analyze the evolution of different needs from an operational perspective, as well as to predict future behaviors and to adapt the capacity of the clinic in response to continuous changes.

3. Methodological approach

In this research paper we follow a Design Science Research (DSR) approach (Peffers, et al., 2007). This methodology is widely used for research in the field of Information Technology (IT). It aims at solving concrete problems through the development of an artifact that solves problems and improves the environment in which it is instantiated (Peffers et al., 2020). **Figure 2.** illustrates the model of (Peffers et al., 2007) that we use in our research work. Given the scope of our research, we will limit our work to phase 4 (demonstration).

Specifically, we follow the Design Science Research Methodology (DSRM) process model shown in **Figure 2.**, which includes six steps: problem identification and motivation, goal definition for a solution, design and development, demonstration, evaluation, and communication.

The key steps of the methodological approach are described below:

In Phase 1, we recognize the importance of integrating the concept of DTs into a healthcare environment and emphasize the importance of having highly granular visibility into each step of the patient care process.

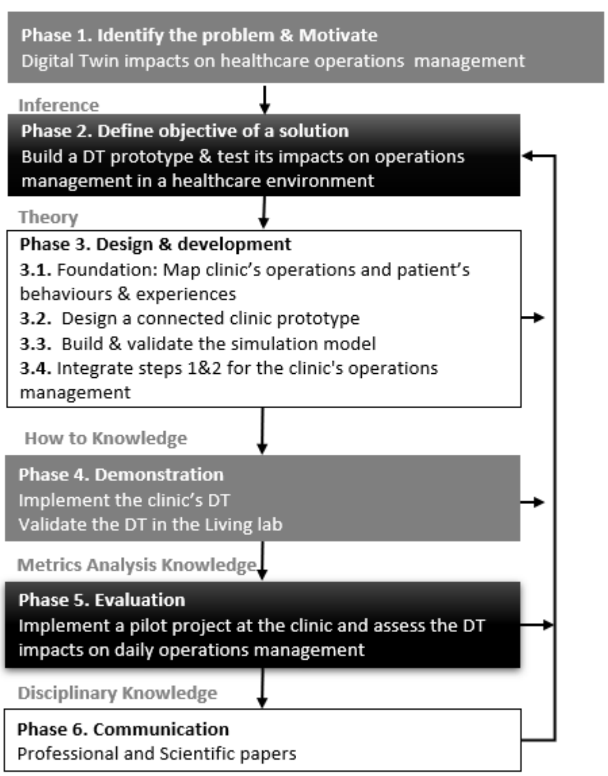

Figure 2. Design Science Research Methodology (DSRM) Process Model (adapted from Peffers *et al.*, 2007)

Since these patients suffer from addictions and can have very unpredictable behavior, it is important to continuously track and analyze every movement and behavior, to be able to react promptly to any change in behavior and to support the resource in charge of the patient with appropriate tools, but also to be able to continuously evaluate the performance of the process and its service level.

In Phase 2, we formalize the objectives for the design and development of an RFID/IoT prototype that is be used to support decision making in maintaining a safe environment for all staff as well as for the various patients, but also to continuously improve the performance of the clinic (e.g., by providing real-time visibility of patients, resources, and operations and the ability to assign new resources or reallocate resources when and where they are needed, especially when dangerous behavior is detected or reported by a resource).

In Phase 3, we gather data on patient flow, different patients' profiles, resource utilization and clinic settings. We then select the most appropriate technology for tracking patients at different stages of the process. Since we are looking for high detection performance - low value - disposable IDs, we select passive UHF RFID tags (from Avery Dennison and Zebra) using a badge form factor. Various fixed readers are also identified as potential candidates for tracking patient presence and direction. The next step is to build the connected prototype at the IoT lab in Montreal, where several RFID technologies are available. To facilitate the integration of data collection, we use the same product line from a single vendor (Impinj) with different passive RFID UHF fixed readers: (a) a multi-antenna R700 (Impinj 2023) fixed RFID reader to detect patients in different sub-zones (b) a xSpam (Impinj 2023) fixed reader equipped with technology to detect patient movement from one zone to another. All captured data is then streamed to a dedicated database using PTS ClearStream software (PTS, 2023).

In parallel, we build our simulation model. Any facility in a healthcare environment is a complex system (Brailsford et al., 2019) that requires the capture of multidimensional factors, especially in environments where patients may exhibit unpredictable behavior that could affect the performance of daily operations. For this research study, we adopt a hybrid simulation approach using AnyLogic 8.8.3 (AnyLogic, 2023), as it allows the integration of different methods in the same model. The discrete event simulation method is used to model the daily operations of the clinic, including the various care and support services provided to patients. The agent-based method allows us to capture the interactions between patients and different medical staff as well as the interactions between patients. These interactions are possible when agents are sent to the DES logic to receive different care and services. Patients can have different states for which they receive different services. These different states are modeled by state diagrams. Finally, the system dynamics method allows modeling the continuous emotions of patients in response to their interactions, but also in response to their perception of services they receive. Patients' emotions change continuously over time and are influenced by their interactions with different agents in the clinic but also by the effect of the opioid dose they receive. This continuous variation is naturally represented by an SD logic. It should be noted that this variation in emotions undoubtedly has an impact on the patient's condition and also on the performance of the support and care process. Therefore, it is important to constantly track and analyze this evolution through the digital twin.

In Phase 4, once the "best design" is selected (tag type, tag placement, reader configuration, antenna type and placement, etc.) and the technical performance of the solution is established (i.e., read rates, tag performance, % accuracy), the team runs different simulation scenarios (based on the hybrid simulation model developed in Phase 3) to assess the impact on patient care and support process performance. The testing of the RFID/IoT infrastructure in our IoT lab allows us to validate the choice of the main technologies required to ensure, on the one hand, the tracking of patient dynamics and, on the other hand, the real-time transmission of the collected data to be used by our simulation model. Within this paper, the scope of the research is limited to phase 4.

4. Prototype Design

4.1. Clinic's problems description and objectives statement

The clinic under study can benefit from several features of a DT, and thus many aspects of the clinic's daily operations could be improved. However, due to the limited scope of this research, we build a prototype that addresses some of the clinic's key issues. The clinic suffers from several sources of variability in its daily operations. Some of these variabilities are due to the characteristics of the patients and the type of care they require. To name a few, one of the main concerns is ensuring a safe and secure environment for all employees as well as for the various patients. Therefore, the goal of the prototype is to improve the speed of intervention when unforeseen and disruptive activities occur, while at the same time improving the overall security of the clinic environment and maintaining a high level of service quality.

To this end, a careful study of the different areas of the clinic was carried out, and certain areas were identified as riskier because they are isolated from the view of other staff and can be life-threatening. In fact, in such areas, if the variation in patient behavior is not detected quickly, either the health care worker risks his or her safety or the patient risks his or her life.

4.2. Building the IoT Infrastructure

The choice of technologies for our digital twin depends on the use case, keeping in mind that it's difficult to ask patients suffering from addictions such as opioids to wear sensors - at most we can give them an RFID tag, or a label stuck to their shirt.

For our prototype, we use RFID and BLE technologies from Impinj and Minew at the data identification and collection layer (in selected use cases as described below). The data is hosted in a local database on our middleware from ClearStream RFID. The input data is then pre-processed using a script developed in Python before populating new fields in the database and then passed to the hybrid simulation models.

To identify and track patients in the clinic, multiple RFID readers/antennas(R) are placed in specific areas where patients are located, such as the entrance, waiting area, registration area, and various treatment rooms and restrooms.

During a consultation, if stress is present, the professional opens the door to indicate a potential hazard. In this case, a Bluetooth BLE door sensor is used to automatically trigger an alarm.

When a patient is in the bathroom, it is necessary to monitor in case he or she becomes unconscious. In this case, a passive infrared sensor designed for body motion monitoring can be used to detect such a pattern and trigger an alarm.

5. Expected Outcomes

This is an ongoing research project. The next step is to integrate the simulation component into the DT prototype and validate the DT in the living lab.

We expect to demonstrate that the choice of the IoT infrastructure to collect multiple pieces of information and feed simulation models will enable behavioral variability to be detected more quickly, allowing managers to quickly adjust care and treatment. For example, detecting door movement in a treatment room may mean that the person treating the patient feels in danger or needs help and requires the presence of colleague or a physician. Or receiving an alarm from a panic button could mean that a security guard needs to be dispatched to the location where the signal was sent. As for the patient, if he or she is in an isolated area such as a washroom, the detection of a fall by appropriate sensors would send a signal that would immediately dispatch a rescue team to the restroom, allowing the patient to receive rapid care according to his or her precise needs. The variety of possible situations can be evaluated through the digital twin and help the clinic manager to reorganize workspaces and adjust resource allocation accordingly.

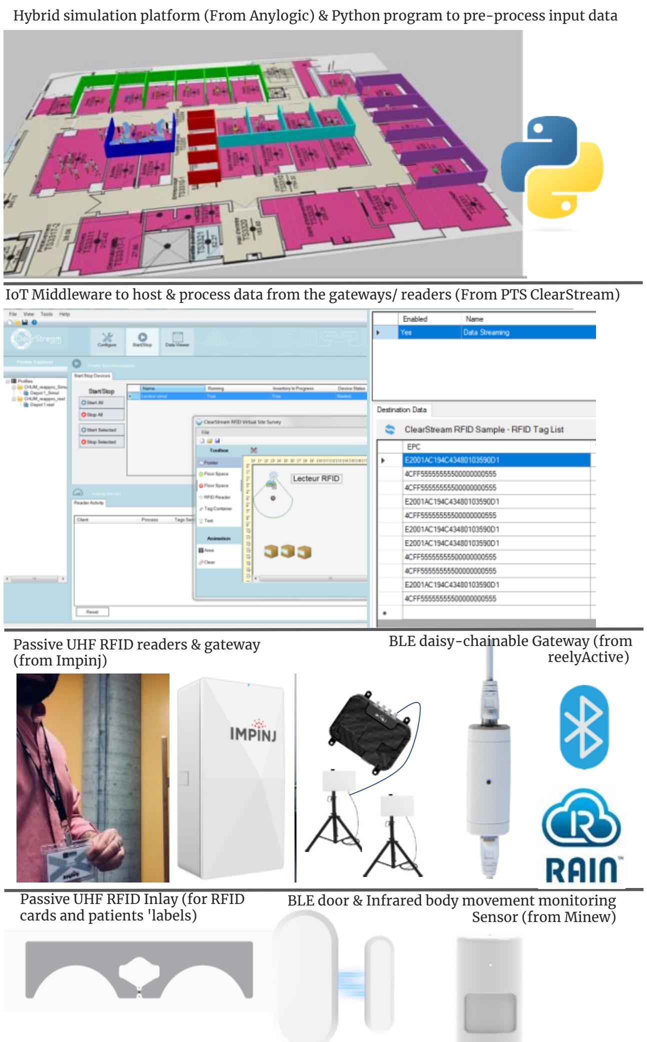

Figure 3. DT Prototype for improving clinic daily operations.

6. Conclusion

Digital Twins have been the focus of the scientific community for several years. Most of the applications have been focused on the Industry 4.0. In these last years, we observe a significant progression in the development of digital twins in services and more specifically in the healthcare system (Singh et al., 2022; Tao et al., 2022). Our analysis of the literature review shows a specific progression in digital patients, while the design of DT for decision support in healthcare processes remains in the cradle stage. In this research study, we propose the methodological approach to develop an IoT infrastructure for a DT prototype in a healthcare environment. More specifically, we analyze the impact of using the digital twin in a clinic that provides care and support services to marginalized people suffering from various addictions.

From a methodological point of view, this paper addresses the concerns of researchers (Singh et al., 2022; Tao et al., 2022) who call for research methods to address DTs issues in a healthcare environment and, more specifically, in the management of a healthcare facility.

From a broader perspective, this research helps to lay the foundation for the study of digital twins in the healthcare environment, where real-time data automatically captured and used as actionable insights can feed simulation models that run continuously to provide real-time support to hospital decision makers.

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https://www.sdginnovnetwk.com/

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