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Requirements for a Digital Twin for an Emergency Department

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Abstract. The Emergency Department (ED) represents the first stage of the path for some patients in a hospital. The JUNEAU project aims to propose a Digital Twin (DT) for the ED to both visualise the service behaviour in quasi real-time, forecast and anticipate its behaviour to control the “Emergency throughput time” indicator. This DT will be centred on the “patient pathway” view, which needs to first precise necessary data and information and decision support. The project will tackle this issue with a particular attention on exploring the DT architecture (with the help or holonic architecture), on coupling centralised and decentralised approaches to obtain a model as close as possible to the system dynamics and on managing DT evolution in a complex environment.

Keywords: Digital Twin · Emergency Department · Holonic System · Agent-Based Modelling.

1 Introduction

The Emergency Department (ED) is a strategic sector in the hospital chain. It welcomes some patients as their first stage of care in the hospital. Nevertheless, EDs have many limits, especially with the management of the flow of arrivals which strongly determines patient pathway. Optimising the patients’ pathway is a topic of growing interest addressed through data-driven approaches [9] or by integrating multi-agent systems into workflows [1]. Unfortunately, most published models are not implemented and used in EDs [5]. This lack of integration into operational systems shows the limits of such models, which have a good representation of flows and computing capacity, but are not connected to the physical system in order to monitor and control it.

These flows and priority management issues have been widely studied in the industrial field. In the current “Industry 4.0” dynamic, the approach based on Digital Twins (DT) is known to meet a need for control as close as possible to the system and also to better anticipate behaviour thanks to the integration of

simulation and artificial intelligence. A DT may be seen as an extension of the digital model of a product in the use phase. The notion of DT is currently being developed in the literature for production systems [23], [28]. Nevertheless, Melese *et al.* [22] present challenges that are still open for the design and deployment of DT on production systems, including: difficulties in building, understanding and controlling systems with precise multi-scale models and reliable, the lack of knowledge and methodology on these models, the difficulty of predicting the behaviour of complex systems, the difficulty of accessing the relevant data, the lack of synchronisation between the physical and digital worlds and the difficulty of maintaining the models and check and test their validity.

The application of a DT to a healthcare system context is currently arousing great interest. The benefits of using DTs are nevertheless clearly affirmed and demonstrated in these works, such as the reduction in the waiting time of patients or their length of stay, more efficient and precise planning of resources and so on. However, the challenges cited in [22] remain open in this context, with specifics related to the nature of EDs.

Therefore, the JUNEAU project³ aims to propose a DT for the ED allowing both to trace the data necessary to visualise the behaviour of the service in near real time but also to predict and anticipate its behaviour, by adding a simulation engine coupled to optimisation to respond to the hazards inherent in this type of service, in order to “enslave” and control the indicator “passage time for patients’ emergencies”. This indicator has been particularly observed by numerous research works on the modelling and simulation of emergency departments [27]. The objective of this paper is to discuss the requirements for such a DT and to present its architecture as proposed in JUNEAU Project.

The outline is as follows. Section 2 proposes an overview of the literature applied to ED organisation management on one hand, simulations and DT applied to ED on the other hand. Section 3 aims at synthesising the main requirements we identify for the DT architecture applied to ED. Section 4 gives details on specific scientific issues that will be tackled on this project and Section 5 will conclude

2 State of the Art

2.1 ED organisation and management

A particularly interesting indicator for the ED is the “average waiting time in hospital emergency services”. Our experience in the hospital world has shown us that the waiting time in the emergency room is one of the symptoms of the establishment’s maturity in the management of its processes, activity management and data management. This macro-indicator is multidimensional. Indeed, it is the reflection of the internal organisation of not only ED but also technical platforms (imaging, biology, operating room), related functions (stretcher

³ In French, JUNEAU stands for “JUmeau Numérique pour un sERvice d’Accueil des Urgences”, *i.e.*, DT for an ED.

among others) and intra-department organisation like procedure for taking care of patients in the ED, taking into account degrees of urgency.

It is also a mean of assessing the organisation of local primary care and the methods of recourse of the population to this care and to emergencies. The patient pathway in the ED can therefore be described (without being exhaustive) by the figure 1.

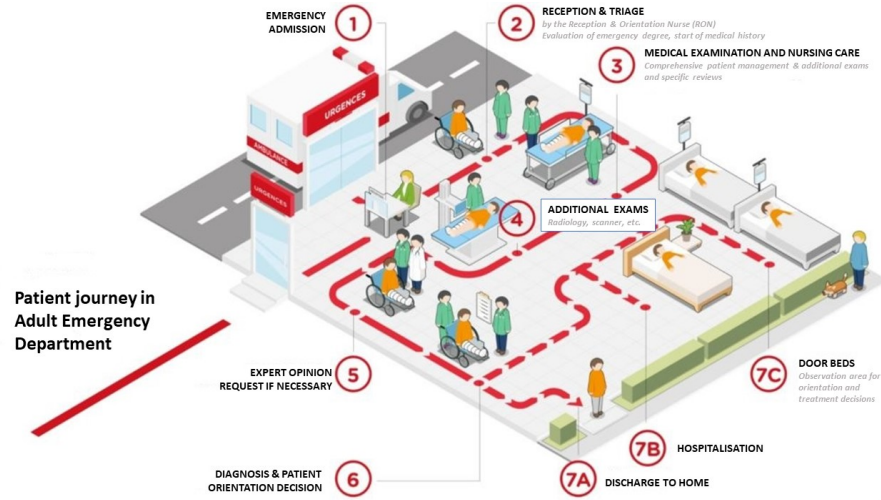


Fig. 1: Illustration of patient pathway in an ED (adapted from chl.lu)

The organisational complexity of the ED as well as its dependence on the availability of hospital beds could not be understood or explained by a study based only on the evaluation of static indicators. If we clearly perceive that the time of stay in the emergency room is one, even the parameter to be monitored for an effective management of the ED, it seems obligatory to consider this system in a dynamic form thus making it possible to model the decisions taken by the doctors, interns, external or other nurses, as well as their interactions.

For example, the current operation of the ED of Saint-Étienne University Hospital (France) is based on decentralised decision-making, generally based on priority management. Each caregiver selects their next patient based on the ED dashboard. As a first approximation, this choice is based on the level of severity of the patient: patients with severity levels 1 or 2 correspond to most urgent ones, where a doctor must be found as soon as possible, whereas patients with severity levels 3 to 5 will wait in the waiting room until a caregiver takes them by making a compromise (specific to each caregiver) between level gravity and order of arrival. More precisely, the different categories of caregivers all consult the same dashboard in which they select their next patient according to the care needed, the condition of the patient, etc.

In this context, the ED actors (doctors, nurses, patients and manipulators) are constantly brought to interact with each other and to learn from past experiences, thus influencing decision-making and the environment. In fact, the management of the patient journey in the ED is complex because, for example, the sequence of care is not known when the patient arrives, but is defined as the patient receives care and take exams. On the other hand, as described above, decision-making is highly decentralised as each caregiver selects their next patient based on the ED dashboard. For our project, it is therefore necessary to first clearly define the decision support that can be provided to each agent/carer.

2.2 Review of simulations and Digital Twins for healthcare systems

Simulation has been widely reported in the literature as a means to improve patient pathways, especially in EDs. This literature primarily includes Discrete Event Simulation (DES) [4] and Agent-Based Simulation (ABS) [20], with possible hybridisation DES+ABS [16]. Yet all these works on simulation mostly propose “what-if” scenarios for improvement, whereas these results are offline and the input of data into simulation models is known to be a very difficult and tedious task. As stated in the introduction, the DT approach seems promising to further develop the use of simulations directly connected to physical systems.

Kritzinger *et al.* [18] define a DT as a digital system with an automatic data flow both from and to a Physical Twin (PT). In fact, we think that a DT is the convergence of an Information System (IS) and a simulation or, in other words, the concept of DT increases the dynamism of an IS by not only recording the past and present states of the PT, but also forecasting its future by simulation.

The application of DT in the context of healthcare systems is currently garnering keen interest. While some authors focus on developing a DT for specific patients to improve their health in interaction with healthcare systems [2], we focus here on developing a DT for the ED system alone. Few works are in this field, for instance [15], [8], [7]; hence, the novelty of our work. The benefits of using DTs are nevertheless clearly affirmed in the aforementioned works, such as the reduction of patients’ waiting time or length of stay, the more efficient and precise planning of resources, and so on.

From [25], we understand that all previous work focuses on the fact that **simulation is the heart of a DT**, with data input in real-time from the PT through the internet of things. **Yet, no details on the architecture of DTs and the interactions with decision makers are provided.** Moreover, with the definitions proposed by Kritzinger *et al.* [18], one can say that simulation models described at the beginning at this section are **Digital Models** whereas the research works claiming to be Digital Twin are closer to **Digital Shadow**.

3 Requirements for a DT

Figures 2a, 2b and 2c recall how Kritzinger *et al.* [18] respectively define a digital model, a digital shadow and a DT, depending on how the digital system is connected to the physical system.

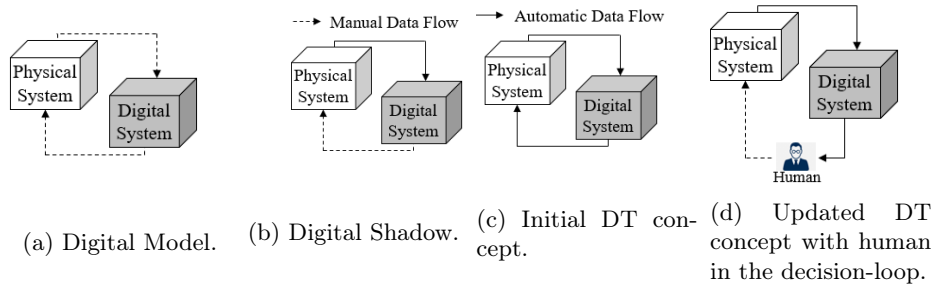


Fig. 2: Typology adapted from Kritzinger *et al.* [18].

In these definitions, physical system and PT are synonymous, but a digital system may not be a DT. Moreover, we think that Figure 2c deals with automation because the time delay is too short for humans to provide feedback. Since we want a DT for operational decisions – with a time range between minutes and weeks – we propose Figure 2d as an evolution of Figure 2c in order to include a human decision maker in the decision loop, because:

- *All models are false*: The digital system relies on a model which, by definition, is not a reproduction but a simplified representation of the reality. Some events occurring in PT (*e.g.*, failures, arrivals of patients, etc.) may be wrong or absent from the digital system, in which case the digital system has to resynchronize on the PT. On the other hand, if the digital system simulates events not present in the PT, then this system is wrong which, again, has to resynchronize on PT, not the other way around. This explains why the solutions generated by decision support systems (for planning, scheduling, etc.) are rarely applied to physical systems directly, and are often manually adapted beforehand.
- *Two systems cannot control each other*: If two systems control each other, then they need to do exactly the same thing, and may hence block each other and nothing happens in both of them. As a consequence of this point and the previous bullet points, PT has to be the master and the digital system a slave. This slave may suggest actions to PT, but cannot control it. This master/slave relationship complies with the next bullet point.
- *The digital system must be as non-invasive as possible*: This may not be the case for all kinds of production systems, but we assume that a healthcare system requires tools that suggest actions – rather than give orders – and these suggestions need to be updated whenever the digital system detects that they are not followed in PT. In fact, care givers – especially highly qualified staff such as doctors – already make decisions and may thus sometimes disagree with the suggestions of the digital system.

When including a human decision maker inside the decision loop, we aim at not only providing a framework making explicit all information needed by

the decision maker to make his/her decision (such a situation corresponds to a Digital Shadow), but also at capturing the complete decision inside the system PT+DT.

Attached to this definition of DT, other requirements are necessary. A DT is based on a strong knowledge of the processes in order to reproduce the behaviour of the PT as accurately as possible, which can be provided in different formalisms like UML or BPMN (Business Process Model and Notation) [28]. A DT is also based on an exchange of real data which assumes (1) the existence of these data in the IS, (2) their consistency and (3) their usability. In addition to the Process, Resources and Organisation views recommended by [3], we plan to enrich our model with a data view.

Because of the nature of an ED, its DT must be seen as a decision support tool and it is up to the various decision-makers of the ED to take advantage of this environment. Thus we aim to integrate the Human into the loop. This ambition is reflected here in the desire to offer hybrid control, which will combine centralised and distributed control.

At the same time, the DT should be as non-invasive as possible. This may be the case for many other types of production systems. To this end, we assume that a care production system requires tools that suggest actions — rather than give orders — and which update these suggestions each time the DT detects that its suggestions are not valid, not enforced in the physical twin. Indeed, caregivers are already making decisions and therefore may sometimes disagree with the suggestions of the DT.

We do not wish in this project to limit ourselves to the design phase of the DT but to integrate a complete vision of the life cycle of such a system. A strong challenge for a system such as the ED is to be able to trust the DT in a highly dynamic, uncertain and evolving context. One of the ambitions of the project is therefore to propose an environment for controlling differences in twinning and management associated with both organisational and technical developments.

4 Main scientific questions

As previously stated, the JUNEAU project aims to propose a DT for an ED allowing to both trace the data necessary to visualise the behaviour of the department in near real time, but also predict and anticipate its behaviour by adding a simulation engine coupled to optimisation. As summarised in Figure 3, such an ED should respond to the hazards inherent in this type of departments in order to pilot indicator “time spent by patients in ED”.

4.1 DT architecture

To meet the needs expressed above, we propose the digital system architecture of Figure 4. It is based on the distinction between two types of events triggering the transitions of the digital system:

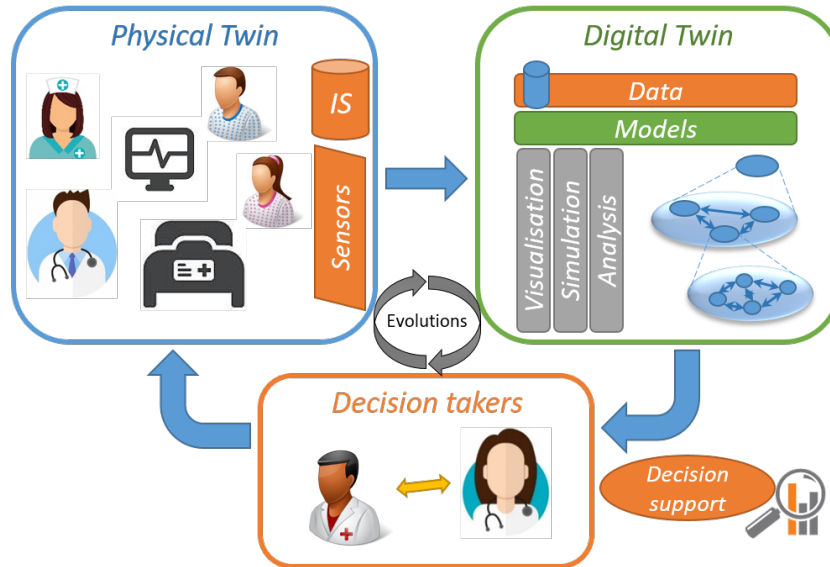


Fig. 3: Overview of Project JUNEAU.

- external events go up from the physical system to cause a re-synchronisation of the digital system on the physical;
- internal (i.e. inside the DT) events allow the operation of the digital system by causing it to simulate the possible future of the system.

Enabling transitions triggered by either or both of these event types causes our digital system to operate in one of three modes depicted in Figure 4:

- **Digital Shadow** (Figure 4a) : In this mode, only transitions triggered by external events (i.e. `ds_*` ones) are activated in the digital system. Therefore, it only displays to the human decision maker the current state of the physical system or, in other words, this mode makes it work like a dashboard.
- **Synchronised DT** (Figure 4b) : Transitions triggered by both transition types are enabled in this mode of the digital system. Consequently, the internal events cause it to simulate in accelerated a possible future of the physical system, until an external event re-synchronises the digital system on the present state of the physical system, then the internal events start again to simulate the future in accelerated starting from the new present state of the physical system until the arrival of the next external event and so on. In summary, a large number of internal events simulate the future between two external events and these external events re-synchronise the digital system on the physical.
- **Exploratory DT** (Figure 4c) : This mode only enables transitions triggered by internal events (i.e. `sim_*` ones). It therefore requires initialising the digital system on the current state of the physical, then the internal

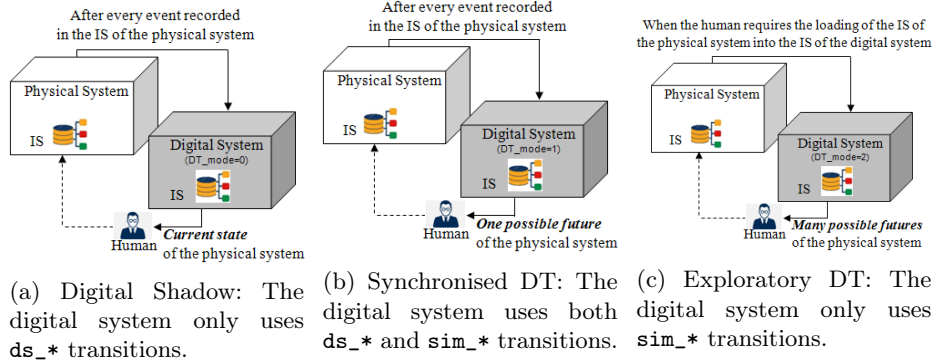


Fig. 4: The three operation modes of the digital system in Figure 2d.

transitions simulate the future of the physical system in accelerated mode without re-synchronisation at each external event going from the physical to the digital. This allows the decision maker to explore the variability of possible futures without being bothered by the regular re-synchronisations of the Synchronised DT mode.

Each of these operating modes requires the support of a detailed architecture, capable (1) of representing the behaviour of all the elements of the system, (2) of supporting the interaction with the various IS and physical elements of the hospital and (3) to interact with human decision-makers, in a way that is generic enough to support scaling. For this purpose, Project JUNEAU relies on the holonic paradigm initially proposed by Koestler [17]. Holonic approaches are well suited for the representation of production or even hospital systems, as shown in [13] on the adaptation of holonic systems to the drug circuit of a hospital. In the current state of the project, we imagine adapting a classic holonic architecture to digitise the ED. Compared to the literature, this architecture will propose innovations in the sense that it (1) will integrate the Human as a decision-maker and actor and (2) will have to allow the simulation of the studied system (through a specific holon for example, such as in the PROSIS approach [26]) for the realisation of what-if scenarios, used in modes (b) and (c) of our DT.

4.2 Hybrid and non-intrusive control

The architecture of the digital system depends on the organisation of the PT. Given the specificities of our PT, our second scientific objective is the proposition of a hybrid control by coupling centralised approaches (often modelled as NP-hard problems) and decentralised approaches (*e.g.*, based on multi-agent or holonic approaches, or some variant of game theory) in order to address the issue of the patient pathway. This will allow us to aim at the combination of the

best of both approaches: the efficiency of centralisation when there are no disturbances and the reactivity and resilience of the decentralisation to react after each disturbance [6]. Our hypothesis is that the application of this coupling to the management of patient pathway in an ED will make it possible to effectively manage this flow while coping with unpredicted events.

We plan to study the coupling of a centralised and a decentralised organisations to create a hybrid one able to switch between its centralised and decentralised modes. Switching from centralised to decentralised decision-making is easy because the agents start from the latest decisions received from the CA (Central Authority) as the starting point of their interactions; These inter-agent interactions correspond to the operation of the decentralised mode and represent the discussions of the agents agreeing on who does what and when. On the contrary, the switch in the other direction is more complicated because moving from decentralised decisions to centralised decisions requires that the CA takes into account what the agents are currently doing. For example, if the agents have agreed in a decentralised way to do tasks 1 to n for the next ten minutes, then (i) the CA has ten minutes to propose a new plan to the agents, (ii) this plan must take account of the fact that tasks 1 to n will have been carried out or will be in progress during the switch back to centralised decision-making and (iii) the agents will not all make this switch at the same time, but after everyone has completed their task (in the set of tasks 1 to n). In other words, the dynamic nature of the system to be controlled – *i.e.*, PT – is one of the main difficulties to be managed in the hybridisation. This is due to the fact that the dynamics of PT causes the model used by CA (in the digital system) to be late in comparison to the actual state of the caregivers in PT. Indeed, the decision support provided to CA at a given time is based on a previous state of the caregivers. During the duration of time between the evaluation of the state of ED and the decision support offered by CA, the (decentralised) decision-making carried out by the caregivers biases the perception that the CA has of the state of the ED and, consequently, may render the CA proposals inapplicable.

Then, the feedback from local systems (caregivers in the context of the ED) is another lever allowing hybridisation. This feedback raises questions about the quantity or volume of information to be reported, its delay, or even the absence of feedback and the consequences on the decision support offered by the CA.

Finally, the human dimension must necessarily be considered in a system in which the human is at the centre of the decision. For example, the acceptability of the system by humans (not taking into account and/or not questioning the decisions proposed, not reporting information, etc.), the human’s understanding of the decisions proposed by the human or taking into account the autonomy of caregivers remain scientific obstacles that are difficult to resolve, and not only within the ED but also in other types of production systems.

4.3 DT evolution management

A complex system such as a DT evolves during its life, as much by the specific dynamics of the physical twin as by the evolution of the modelling hypotheses

of the DT. The question of mastering such a system is strong, especially if we take into account the application system concerned.

Thus, through the study of the interactions between all the agents of the system and the understanding of the associated dynamic system, it is possible to obtain a modelling and an organisational control. Organisational morphology should be understood as the representation of the global state of the multi-agent system in the form of a representation in a geometric space [14]. The evolution of this representation makes it possible to quantify, through local interactions between agents, a global behaviour known as organisational. An application of this approach to a crisis situation has been proposed by Lachtar [19]. This idea makes it possible to approach modelling in an unusual form and linked to physics. Indeed, a certain number of physical approaches — notably those related to the re-normalisation group — make it possible to infer organisational behaviour. From a less dynamic system but more algebraic point of view, many works have focused on a characterisation most often via a spectral study of the Laplacian matrix of the graph representing the interactions between agents. We wish here to give geometric and/or topological invariants as they were introduced for example by [21] to characterise the cooperative system between agents in their decision-making.

On the other hand, to take advantage of this massification of data and ensure the evolution of DT over time, it is crucial to update the simulation models. In this context, the DDDS (Dynamic Data Driven Simulation) paradigm [10] interests us. The principle is that the simulation is continuously compared to the data of the real system in order to ensure its accuracy with respect to the real system and to obtain a better quality of prediction and analysis. DDDS approaches address two issues related to this principle: (1) when to perform the update and (2) how to perform it? Updating the simulation model requires evaluating the difference between the real and simulated systems at an instant t in time. This evaluation can for example be done via an adaptation function [11] or a control chart [24]. When this difference becomes significant, the update of the model can be done according to several modes. This can be (1) the reconstruction of a new simulation model if it was obtained by “black box” approaches of the neural network type or (2) the change of the parameters of the initial model if this one is made up of known primitives [12], via the assimilation of data reported from the field. However, this second type of approach is less able to automatically evolve the topology of the model. We therefore wish to propose a methodological approach ensuring the accuracy over time of the simulation models proposed by the JUNEAU Project, according to a procedure coupling adaptation of the simulation model by “white box” methods as long as this remains possible, then by “black box” in order to offer the user new topologies when the initial is no longer representative of the real system.

5 Conclusion

The Emergency Department is a complex organisation that needs improved ways to be managed and controlled, in order to enhance the patient pathway. Digital Twin, defined as a digital, accurate replication of a physical system with decision support capabilities for a set of stakeholders, seems to be a promising paradigm to tackle this issue. The JUNEAU project's aim is to contribute to the digital transformation efforts of the hospital by providing key constituting elements of such DT, in collaboration with a University Hospital. The expected results are various and with different dimensions: methodological, technical and economic.

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