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An agent-based architecture of the Digital Twin for an Emergency Department

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Abstract

The Digital Twin (DT) concept seems to be one of the ways to improve the management of patient pathways in Emergency Departments (ED). This article proposes an agent-based architecture of a DT designed for that purpose. The core of this DT is its Information System (IS), which is regularly synchronised in the IS of the Physical Twin (PT). The agents model the ED's resources (equipment and staff) and patients in the DT, and update this information in the DT's IS. This article shows how such a DT may operate in three modes: (0) "Digital Shadow" to monitor the ED's current state in real-time, (1) "Synchronised DT" to monitor the ED current and future states according to a predictive simulation, and (2) "Exploratory DT" in order to perform "What-if" analyses. The proposition is illustrated on a emulation of the ED to demonstrate the capabilities.

Keywords: Architecture of Digital Twin, Agent-Based Simulation (ABS), AnyLogic 8, Information System, patient pathway

1 Introduction

Improving patient flows in organisations or care pathways has been a topic of increasing interest for decades. Most studies and research focus on the hospital system and not on the care system as a whole. The multitude of actors and their interactions are such that it is still difficult to adequately address this issue. The hospital and its gateway, the Emergency Department (ED), is therefore the main system in which a significant improvement of the patient pathway may be envisaged. Today, with the renewed interest in AI methods, we are witnessing a new era in the management of hospital systems organisation and patient flow. This digital transformation is often likened to that of Industry 4.0. Of all the concepts and approaches encompassed in the Industry 4.0 paradigm, **Digital Twin** (DT) is a particularly promising path to improve ED performance. It offers faster access to data captured on the floor and provides a digital support framework enhanced with simulations and data analysis [1].

An abundant literature exists on DT applied to various domains [2]. One definition is that “*DT consists of a virtual representation of a production system that is able to run on different simulation disciplines, characterised by the synchronisation between the [digital] and [physical] systems, by means of data and connected smart devices, mathematical models and real time data elaboration*” [3]. DTs are used when there is a need for (i) a control as close as possible to the physical system and (ii) anticipation of its behaviour, through the integration of simulation. We base our work on the work of Kritzinger et al. [4] who define a DT as a digital system with an automatic data flow both from and to the PT. In their definitions, PT and physical system are synonymous, but not DT and digital system. For instance, a Digital Shadow is a digital system monitoring a PT that is not a DT. We use the same definitions as [4], except for DT which we refine as “Synchronised DT” and “Exploratory DT”.

The contribution of this work is to **propose an architecture of DT that relies on agent-based simulation**, *i.e.* all aspects of communication, infrastructure and data modelling lie beyond the scope of this paper. To focus on the simulation architecture without being disturbed by these aspects, we emulate the PT rather than using a real one.

In this context, the transitions of our digital agents¹ have a name starting either with `ds_` (for “Digital Shadow”) when they take part in the synchronisation with PT, or with `sim_` (for simulation) when they are involved in interactions with other agents.

We show below that our **digital system may operate in one of three modes depending on the type(s) of transition activated**:

- 0 *Digital Shadow* (only `ds_*` transitions) is a **visualisation/monitoring** of current PT performance,

¹In this article, the word “agent” always refers to the digital counterpart of a patient or (human or material) resource.

- 1 *Synchronised DT* (both `ds_*` and `sim_*` transitions at the same time) provides a “**real-time**” **predictive image** of the future of the system, allowing for performance trajectories to be tracked and for decision-makers to anticipate potential problems,
- 2 *Exploratory DT* (only `sim_*` transitions) provides the various types of AnyLogic experiments (Monte Carlo simulations with parameter variations, optimisation with the OptQuest engine, etc.) to analyse “**What-If**” **scenarios**.

The outline is as follows. Section 2 reviews the literature on simulation and DT applied to EDs. Section 3 presents the proposed architecture of a DT and an application to an emulated ED. Section 4 discusses this proposition. Section 5 concludes.

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) [5, 6] and Agent-Based Simulation (ABS) [7–9], with possible hybridisation DES+ABS [10, 11]. 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.* [4] define a DT as a digital system with an automatic data flow both from and to a PT. When this flow is automatic from the PT to the digital system only, and manual in the other direction, they call the digital system a digital shadow. Below, we reproduce their figures in Figures 1a, 1b and 1c as we base our work on their definitions. In fact, we think that a DT is the convergence of an 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 [12], [13] focus on developing a DT for specific patients to improve their health in interaction with healthcare systems, we focus here on developing a DT for the ED system alone. In 2019, Patrone *et al.* [14] reviewed the literature on DT and/or simulation involved in decision support systems and applied to healthcare systems. Only three papers were explicitly about DT [15–17]. Since that review, the subject has gained interest [18–20] (*cf.* DT for Healthcare by GE²); hence, the novelty of our work. The benefits of using DTs are nevertheless clearly affirmed and

²<https://www.gehccommandcenter.com/digital-twin>

demonstrated in these 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 Patrone *et al.*'s review, 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 details on the architecture of DTs and the interactions with decision makers are not provided.**

Unlike most of the literature on DTs for production systems, we think that ABS is more relevant than traditional DES because:

(i) *ABS allows various levels of abstraction*: The developers of AnyLogic [21, p. 13] claim that ABS allows for both higher and lower abstraction levels than does traditional DES, which allows for a DT to be started with a coarse model, and then gradually refined;

(ii) *DT as a system of systems*: We think that DTs will be linked up to make other DTs. For instance, the DTs of various resources (based on CAD or DES models for example) and patients (modelling their genome, physiological characteristics or lifestyle) may be connected to one another to produce the DT of a production system such as an ED. The interactions (discussion and inclusion) between such models are what agents (especially, holons) focus on.

The next section explores all these facets in order to propose our architecture of a DT.

3 Architecture of a Digital Twin (DT)

Subsection 3.1 first details our adaptation of the typology of digital systems by Kritzinger *et al.* [4]. Next, Subsection 3.2 shows the implementation in agents of the three modes of operation of the digital system. Finally, Subsection 3.3 applies what precedes to an emulated ED.

3.1 DT typology

Figures 1a, 1b and 1c recall how Kritzinger *et al.* [4] respectively define a digital model, a digital shadow and a DT, depending on how the digital system is connected to the physical system (PT). In these definitions, physical system and PT are the same, but a digital system may not be a DT. Moreover, Figure 1c 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 1d as an evolution of Figure 1c to include a human decision maker in the decision loop. The main reasons for this is that we think

- *All models are false*. Indeed 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 based on the PT. On the other hand, if the digital

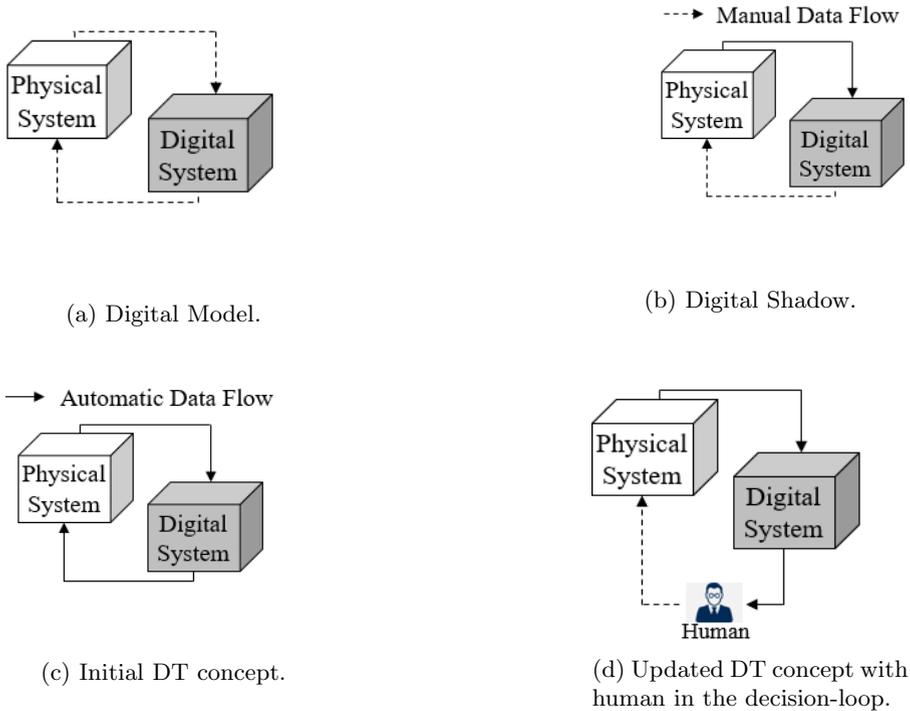


Fig. 1: Typology adapted from Kritzingner *et al.* [4].

system simulates events not present in the PT, then it is wrong and, again, the digital system 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.

- Also, *two systems cannot control each other*. If two systems control each other, then they block each other and nothing happens in both of them. As a consequence of this point and the previous bullet point, the physical system has to be the master and the digital system a slave. This slave may suggest actions to – but cannot control – the physical system. This master/slave relationship complies with the next bullet point.
- And finally *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 that update these suggestions whenever the digital system detects that they are not followed in the PT. In fact, care givers already make decisions and may thus sometimes disagree with the suggestions of the digital system.

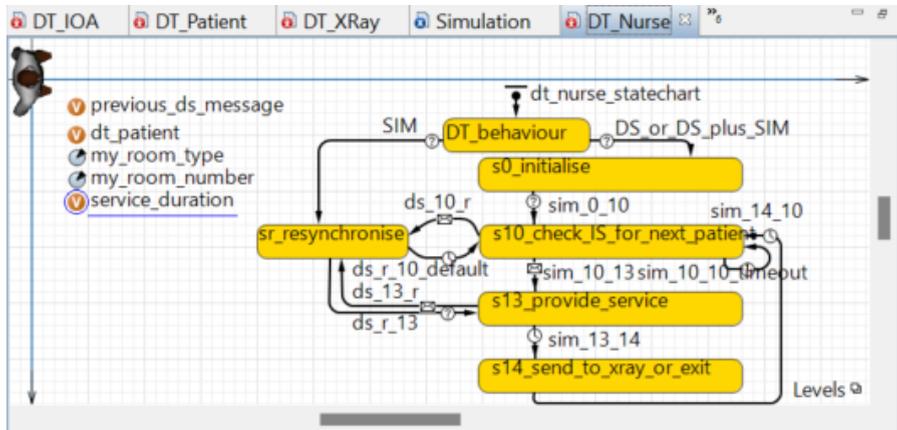


Fig. 2: The transitions of a DT_Nurse with a name starting by `ds_*` are activated when `DT_mode ≤ 1`, and the transitions starting by `sim_*` are activated when `DT_mode ≥ 1`.

When including a human decision maker inside the DT, we aim at not only providing a framework making explicit all information that the decision maker may need 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, and hence updating as automatically as possible both PT and DT.

3.2 Technical architecture of digital agents

To present the three modes of operation of the digital system, we first introduce the two main types of transitions in an agent, as illustrated by Figure 2 below.

3.2.1 `sim_*` transitions

The first step of development of a digital system is the implementation of an Agent-Based Simulation (ABS) of the PT which is not connected to the PT. More precisely, we have created agents with a behaviour modelled as states and transitions. We have given the transitions a name starting with `sim_`, and the states a name starting with `sXX_` (here “s” means “state” and “XX” is the order of activation of this state, *e.g.*, `s13_provide_service` is after `s12` in an agent not shown in this article – Only the four states `s0_initialise`, `s10_check_IS_for_next_patient`, `s13_provide_service` and `s14_send_to_xray_or_exit` were added in this first step).

More precisely, `sim_*` transitions model interactions between agents. Some of these transitions are waiting times modelling the duration of a task (shown by a clock on their arrow in Figure 2, *e.g.*, `sim_13_14`), and the others (shown by an envelope, *e.g.*, `sim_10_13`) model the reception of a message sent by another agent.

In order to deactivate `sim_*` transitions in the next step of development, we have added `DT_mode ≤ 1` to their condition.

3.2.2 ds_* transitions

In the second development step, we have first set `DT_mode = 2` to put the digital system in mode “Exploratory DT”. Next, we have added State `sr_resynchronise` and pairs of transitions with a name starting with `ds_` connected to `sr_resynchronise`. In every pair of `ds_*` transitions, (i) the transition from a state `sXX_*` to `sr_resynchronise` is the reception of a message from the PT whenever an event was recorded in its IS, while (ii) the transition in the other direction makes the DT agent be in the same state as its PT counterpart (*i.e.*, a nurse in the case of Figure 2, but this counterpart may be another type of resources or a patient).

Similarly to the other type of transitions, all `ds_*` transitions include the condition `DT_mode ≥ 1`.

Shortly, `sim_*` transitions model interactions with other agents in order to perform simulation, while `ds_*` transitions resynchronise the agents on the PT. (State `DT_behaviour` and transitions `SIM` and `DS_or_DS_plus_SIM` initialise the agent differently, depending on the operating mode of the digital system.)

The activation of `sim_*` and/or `ds_*` transitions selects one of the three modes of the digital system detailed in Figures 3. We recall them here such that:

1. *Digital Shadow.* In Figure 3a, only `ds_*` transitions are activated when `DT_mode = 0`. The names of these transitions come from “Digital Shadow” which means that the state of agents monitors only the state of their PT counterparts.
2. *Synchronised DT.* In Figure 3b, both `ds_*` and `sim_*` transitions are activated when `DT_mode = 1`. We call “synchronised” this DT because the `ds_*` transitions resynchronise its agents on PT whenever an event is saved in the IS of the PT. Between two such events, `sim_*` transitions make its agents simulate one possible future when `DT_acceleration_factor > 1`. (Please notice that `DT_acceleration_factor = 0` makes the synchronised DT behave like a Digital Shadow.) Section 4 discusses the possibility to simulate other possible futures in Monte Carlo simulations.
3. *Exploratory DT.* In Figure 3c, only `sim_*` transitions are activated when `DT_mode = 2`. Since `ds_*` transitions are not used, this mode requires first that all agents be initialised according to a file saving the content of the IS of the PT, and next that `sim_*` transitions simulate as many futures as wished (Monte Carlo simulations) with various parameters.

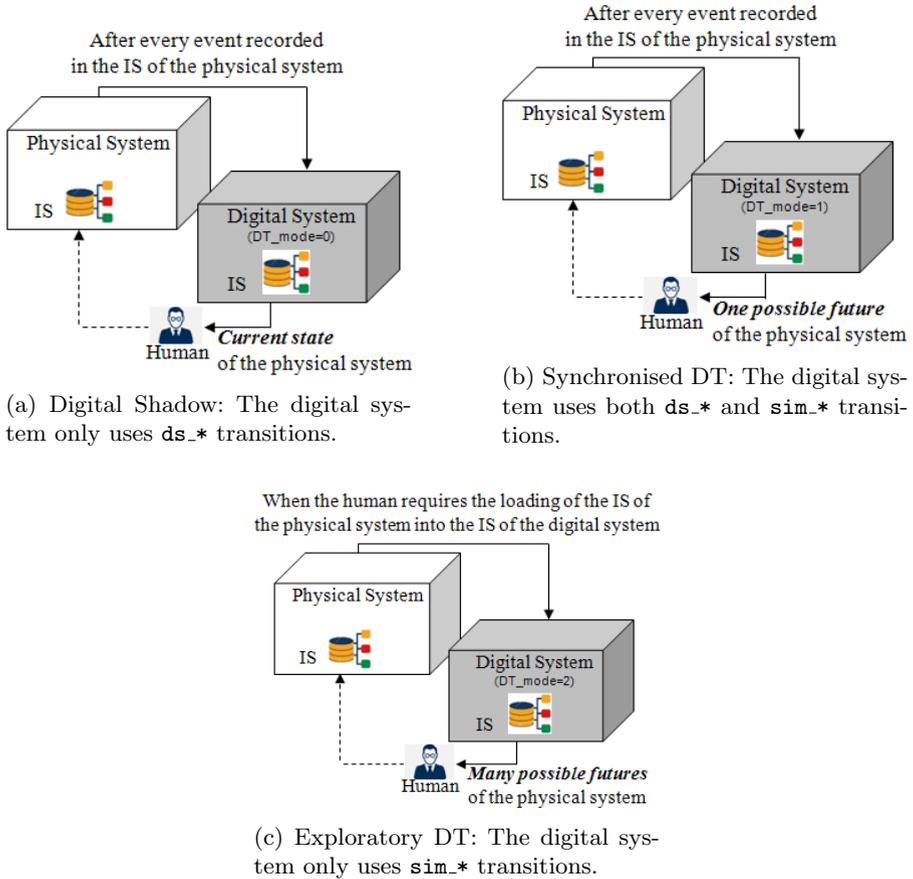


Fig. 3: The three operation modes of the digital system in Figure 1d.

3.3 Use case of an Emergency Department (ED)

The 3D window on top of Figure 4 shows the use case considered for our PT. The seven numbers between parentheses in this figure show the following steps of the process: (1) a patient arrives at the ED (left door) and (2) enters the waiting line of the IOA (*Infirmière d'Organisation de l'Accueil*, *i.e.*, triage nurse); (3) once available, the IOA determines the class of path (UG when the severity is 1 or 2 for serious cases, or UF when severity equals 3, 4 or 5 for light problems); (4) the patient goes to the waiting room; (5) once available, a nurse calls the patient to a box and prescribes care; (6) potentially, the patient may go to the X-Ray room when available, and (7) the patient leaves the ED.

The lower half of Figure 4 shows the digital system. It is running in mode “Synchronised DT” (*cf.* `DT_behaviour = 1`) and twice as fast as PT (*cf.* `DT_acceleration_factor = 2`). The lower 3D window shows three patient agents with a red disk at their feet because each of them corresponds to a real

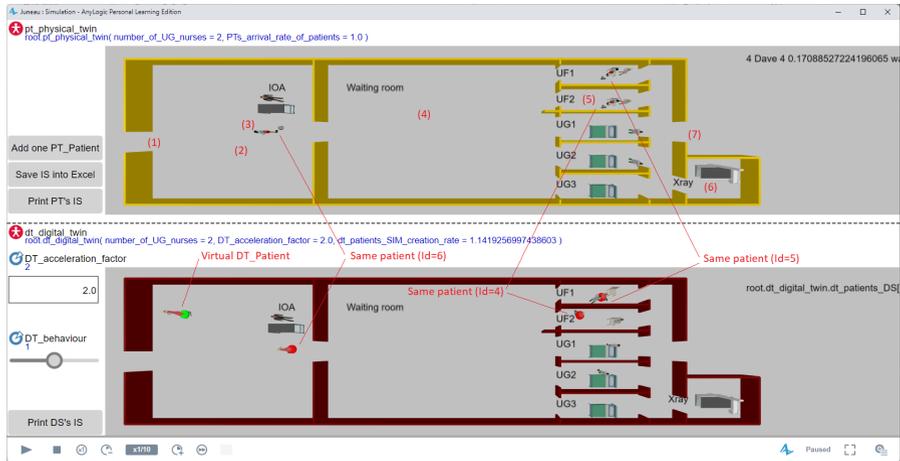


Fig. 4: Emulation of the physical (top) and digital systems (bottom) - Annotations are written in red and digits between parentheses are explained in the text.

patient. A fourth patient agent has a green disk showing that it is virtual, in the sense that it does not correspond to a real patient in the PT. Of course, all agents exist only in the digital system, but the word “virtual” means here that the green agents are randomly created by the digital system to simulate future arrivals of patients and these ones are destroyed with each synchronisation of the digital system on the PT.

We have just seen in Figure 4 that $DT_acceleration_factor = 2$, but a typical use of the Synchronised DT will use a much larger value, in which case red patient agents quickly disappear and are replaced by green agents. The IS of the digital systems reflects this evolution and is hence different from the IS of the PT as long as no information is saved in the IS of the PT. Whenever saving in the IS of the PT does occur, the entire digital system is resynchronised on the IS of the PT: (i) all green patient agents are removed; (ii) the state of every red patient agent is resynchronised according to the information saved in the IS of the PT (*i.e.*, according to a real patient); (ii') similarly, care giver agents are also resynchronised; and (iii) the content of the IS of the digital system is resynchronised on the IS of the PT.

When the decision maker wants to change the mode of the digital system for “Exploratory DT”, (s)he clicks the button “Save IS into Excel”. The content of the Excel file shown in Figure 5 can then initialise the agents of an Exploratory DT.

Id	Name	Severity	Arrival time at ED	Location	Start time of service	nurseDuration	needsXRays
4	Dave	4	0,170885272	at UF2	2,24	2,65560433	false
5	Eve	4	0,432734841	at UF1	2,53	2,281374036	false
6	Sara	-4444	2,176103347	at IOA	2,465	2,440589727	false

Fig. 5: Excel exporting the IS of the PT in Figure 4 to initialise an Exploratory DT.

4 Discussion and future work

The proposed architecture aims at providing several interaction types to decision-makers and stakeholders more precisely and more consistently. Nevertheless, some issues are still open with our propositions.

First, the digital system is behind the PT because it synchronises according to the PT whenever a change is recorded in the IS of the PT. This delay may be short if care givers update patients' file after each medical treatment, or long when care givers first take care of all their patients, then update the IS at the end of their working day. This problem is the same as in industrial maintenance, where technicians also do their "real duty" first and the "paper work" as late as possible. The use of tablets with voice recognition motivates technicians to report their work more fully in the IS of their workshop, and we expect that tablets will incur the same improvement in EDs.

Next, the Synchronised DT in Figure 3b shows the current state of our implementation in which only one possible future is shown to the decision maker. Figure 6 shows how to modify this digital system in order to (1) perform Monte Carlo simulations (*i.e.* replicate the same simulation to show the variety of possible futures) and (2) study the expected impact of decisions (*e.g.* what may happen if Alice leaves at hh:mm):

Monte Carlo simulations: Replication of the variety of possible futures in a Synchronised DT can be obtained by (α) using n digital systems in parallel. Each of these simulates one replication, that is, one possible future, as shown in Figure 6, and (β) restarts each of the n digital systems when it has simulated a given duration (*e.g.* the next 24 hours for an ED) in order to make each digital system perform more than just one replication.

After each replication has finished simulating this duration, some KPIs (Key Performance Indicators) will be saved to show histograms of the KPIs of all replications to the decision maker.

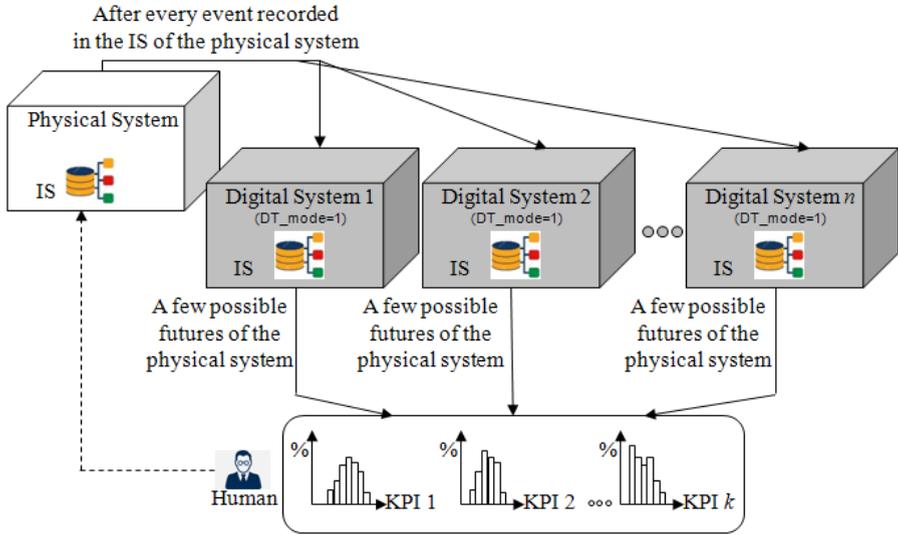


Fig. 6: Improvement on Figure 3b enabling Synchronised DT to carry out Monte Carlo simulations.

Next, Point β requires resynchronising each digital system on the PT after each end of a replication. Such a resynchronisation can be obtained like in our Exploratory DT which uses an Excel file such as the one in Figure 5.

“What-If” analyses: We have not implemented the possibility to dynamically change decision variables in our digital system. More precisely, it is possible to change them (for instance, in AnyLogic experiments of the “Parameter variation” and “Optimisation” type) but they will be constant during a simulation run. Nevertheless, the dynamic nature of the Synchronised DT makes it more interesting to have decisions such as “Change this parameter at this time” (*e.g.*, “keep the same number of UG nurses as in the Excel file until hh:mm, next remove one nurse” in order to study the consequence on the ED if Alice leaves at hh:mm).

Moreover, the histograms in Figure 6 do not show that they can be updated regularly. That is, whenever an event is recorded in the IS of PT, the distribution of each KPI will be recomputed from the new state of PT. The evolution of every KPI will thus be visible and used similarly to control charts, *e.g.*, it will be possible to identify trends in order to detect problems before their occurrence [22, 23].

Finally, an ED system is first a human-based organisation. The capture of the decision and the update of the PT are so much more complex than what has been proposed in this article, since all stakeholders have a liberty space to perform their tasks and a consensus has to be found very often. As a consequence, to really define a DT of an ED, we need an indirect capture of the decisions and an analysis of the system dynamics is promising [24].

5 Conclusion

Taking advantage of the current digitisation trend, the Digital Twin (DT) concept is seen as an opportunity to improve the control and management of complex organisations, especially Emergency Departments (EDs). A DT relies on simulation to anticipate the behaviour of the Physical Twin (PT). Yet few initiatives have been developed in this respect. Our research focuses on the architecture and the development of the specifications of the simulation core of a DT for an ED connected to an emulation of the PT. We use an Agent-Based Simulation (ABS) as it is recognised in the literature as a better reflection of the emergence of complex behaviours. Our architecture proposes three operational modes to provide a decision maker with not only a 3D real-time visualisation (i.e. Digital Shadow) of the organisation's behaviours, but also the analysis of what-if scenarios allowed by DT (as defined by [4]) with the possibility to track the decisions taken.

This work is a very first step towards a full DT for an ED. Future research will focus on the other classical dimensions of a DT: communication, data modelling, interoperability with hospital IS, human interfaces, and so on. Furthermore, since ED organisation is primarily based on human actions and decisions with various levels of knowledge, we will take advantage of the DT environment to analyse more closely the dynamics of an ED, the stability of decisions, and so on.

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