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Design and Use of Human Operator Digital Twins in Industrial Cyber-Physical Systems: Ethical Implications

Olivier Cardin*, Damien Trentesaux**

* LS2N UMR 6004, IUT de Nantes, Nantes University, Nantes, France

** LAMIH UMR 8201, UPHF, Valenciennes, France

Abstract: The development of future Industrial Cyber-Physical Systems is highly connected to the need for Digital Twins. Integrating machines and information systems in such twins is a difficult task, but the integration of human operators usually constitutes an even harder challenge. However, this challenge is generally seen as a sum of technical or scientific issues, when the actual challenge might have a broader scope. This paper aims at identifying the benefits and risks of this activity from an ethical point of view. An illustrating example is provided to exhibit how an apparently beneficial process can be deflected and used for negative purposes.

Keywords: industrial cyber-physical systems, Digital Twin, human factor, ethics.

1. INTRODUCTION

Beyond the traditional control of industrial systems, industrial cyber-physical systems (ICPS) are meant to become a generic solution able to implement intelligent and learning industrial systems. Inspired by the definitions proposed (Monostori, 2014) and (Cardin, 2019), the definitions of CPS (Cyber-physical Systems – on a broader scope) and CPPS (Cyber-Physical Production Systems – on a more narrow scope) can be specified to define an ICPS as follows:

Industrial Cyber-physical Systems consist of physical elements with their control systems, offering and consuming services along a value chain, integrated with digital systems with means for online analysis and reconfiguration of these elements. They have various degrees of autonomy, connect and cooperate with each other and with humans according to the situation, via information systems, in order to improve actions and decision-making processes in real time, react to unforeseen conditions and facilitate the integration of industrial system evolutions over time.

It is important to note that, in this definition, humans are present (in literature, the term Cyber-Physical and Human System – CPHS – is used to explicitly refer to the presence of humans (Kim et al., 2011), see for example the eponymous IFAC workshop series). Depending on their involvement in the transformation, decision or analysis functions assigned to the ICPS, they may either appear in the physical part or be modelled in the cyber part.

Between physical and cyber parts, a mandatory function consists in modeling the system of interest in the cyber world, in order to mirror it (and get a digital mirror) and make adequate decisions of potential reconfigurations of the assets or of the control system (Putnik et al., 2019). This function is directly connected to one of the main properties of the concept of Digital Twin. In our work, a Digital Twin is defined as *a set of adaptive models that emulate the behavior of a physical*

system in a virtual system getting real time data to update itself along its life cycle. The Digital Twin replicates the physical system to predict failures and opportunities for changing, to prescribe real time actions for optimizing and/or mitigating unexpected events observing and evaluating the operating profile system (Semeraro et al., 2021).

This paper is focused on the way humans belonging to the physical part of ICPS are modeled and mirrored in a Digital Twin, and how these models can be used in the Cyber part and their consequences for the physical part. Starting from the fact that these models are mandatory for an actual Digital Twin (and thus an actual ICPS) to be developed, it is discussed why those developments are getting increasingly questionable with time from an ethical point of view.

The remainder of this paper is structured as follows. After identifying the related concepts and applications in other scientific fields, an analysis of the human modelling activities in Digital Twins is presented. Potential ethical risks of such a modelling are presented. Before an application on an actual industrial study is presented, a short discussion about ways to mitigate these risks is provided. Finally, some insights about future perspectives of this analysis are provided.

2. RELATED WORK

Simulation has been proposed for decades to model systems and test alternative decisions before their applications. The concept of simulation has more recently evolved towards the one of Digital Twin, to integrate more elaborated functionalities powered by several technological advances. Digital twins enable now not only to simulate systems and test strategies, but also to supervise them by mirroring a reality in real time, to integrate learning mechanisms exploiting huge quantities of data through Information and Communication Technology (ICT) system integrations, to anticipate and predict possible behaviors of the mirrored systems and even to act on real systems. As their ability to sense increases, the accuracy of their mirroring and prediction increases.

Consequently, more and more equipment are connected, more and more Digital Twins are connected with each other, and now, a Digital Twin is even intended to mirror the human operator (Bécue et al., 2020; Graessler & Poehler, 2017; Pairet et al., 2019; Sparrow et al., 2019). Sensing the human is now widely proposed by authors in the context of Industry 4.0 or ICPS (Paredes-Astudillo et al., 2020). From our point of view, *a human Digital Twin is a Digital Twin devoted to the mirroring of human physical and mental characteristics, state and behavior.*

One can find the concept of digital human in the social media and videogames fields. Even if these fields can be seen as far from the industrial field, they demonstrate the interest of designing digital humans to support interaction among humans and artificial entities (Okubo & Komatsu, 2018). The concept of human Digital Twin has also been studied in medicine (Nyholm, 2021), and major ethical questions were discussed (de Kerckhove, 2021). However, the main objective was clearly organizational (Angulo et al., 2019), in a context close to the context of ICPS.

Its application in industrial systems is more recent. A set of specifications can be found in (Sparrow et al., 2019), where a human Digital Twin is intended to *allow natural interaction with the human senses and facilitate the capture and digitization of data from human workers, for use by other digital entities.* One can find some close concepts in literature: Operator 4.0 (Peruzzini et al., 2020), Human Holons (Sun & Venuvinod, 2001), social holonic manufacturing systems (Valette et al., 2021), to name a few. Very few considerations are made about ethics in this application field. There exist industrial regulation mechanisms, such as the Corporate social responsibility (CSR) or the EU General Data Protection Regulation (GDPR), but these tools are not sufficient. For example, the CSR addresses mainly ethics at the business level, not the operational one. The GDPR addresses a specific aspect relevant to ethics which is data right and usage management, only in Europe, and without any consideration paid to other elements than data

3. MODELLING HUMANS IN DIGITAL TWINS AND ICPS

Humans are present all along the value chain of an industrial system. As the Digital Twin is meant to be an exact replica of the behavior of the industrial system, humans are naturally involved in the modelling perimeter. One may face different ways to consider the Digital Twinning of the human. It can be relevant to physical aspects (forces, ergonomics, movements...), physiological (stress, fatigue), mental (mental workload, decisional mechanisms...) or behavioral (skills, rules, ...) (Bevilacqua et al., 2020).

3.1 Humans in an ICPS

A representation of a generic ICPS is provided in Fig. 1. In an ICPS, humans can have different roles, that have to be considered in the Digital Twin. Even if humans (mostly making decisions of reconfigurations) are present in the cyber part of ICPS (cyber-decision makers), this paper is only focused on the humans acting in the physical part. In the physical part, two types of human can be found. First, the humans as operators contributing to the added value of the industrial process. For sake of simplicity, these operators will all be denoted as *transformation operators* in the remainder of this paper, as they are involved in the transformation of the product or service the industry provides. A second type are the humans as operators that connected to the control system. It is rare to consider industrial systems where this control system is fully automated. Usually, automated decision-making systems are implemented (seen as sociotechnical systems that encompass models, resolution algorithm and global inputs (Battaglini & Rasmussen, 2019)), but are driven and adjusted by human operators at least in charge of parameterization, verification and application of the results of the decision-making system. These activities can be performed at various stages of the company value chain, from the organizational services to the shop floor (concept of team leaders). Again, as the activities of those operators are similar all along the decisional chain, a common terminology was chosen. For sake of simplicity, all these operators will be denoted as *decision operators* in the remainder of this paper.

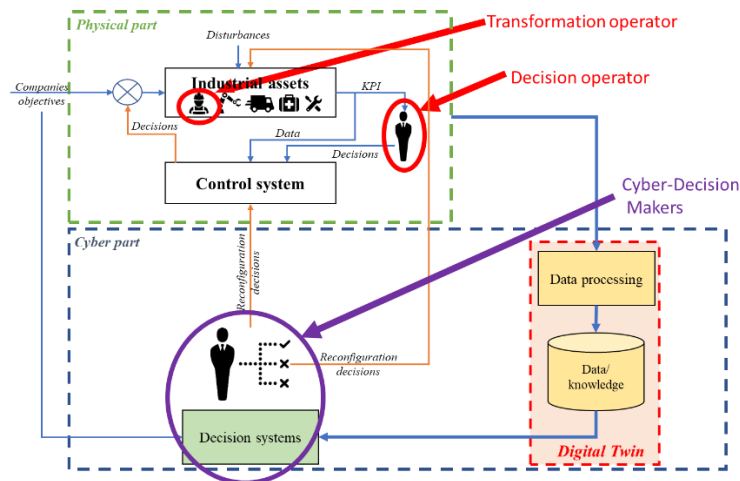


Fig 1. Operators in a generic ICPS (adapted from (Putnik et al., 2019))

3.2 Modelling human operators in a DT: what for?

The models integrated in a Digital Twin are strongly related to the usage that will be done in the decision systems of the cyber part (by Cyber-Decision Makers, denoted CDM in the following). The models of humans in Digital Twin are also subject to the same objectives.

A first matter of interest is obviously productivity. Transformation operators are mostly targeted by such models. Their interaction with the industrial systems implies delays and quality that is monitored and evaluated in order to optimize the current configuration of the system. The models are generally statistical, based on both historical observations and technical expectations. These models are necessary for the cyber decision systems to evaluate if the current configuration of the system performs as expected.

A second matter of interest is related to the pertinence of the decisions made by the decision operators. Based on retrospective what-if simulations of the possible behavior of the system considering various decisions, the cyber decision systems can evaluate the pertinence of the decisions previously made by the decision operators together with the control system. Without mentioning the skills of the decision operators, the objective is to evaluate if the available data and established decision process are suitable or need to be adjusted to optimize the decisions.

A last matter of interest of human modelling in Digital Twin relates to the estimation of non-detectable human-related parameters. The objective is to take advantage of the computing capabilities of the cyber part in order to evaluate for example some physiological parameters of the transformation operators and integrate these parameters in the decision-making process of the decision operators and control system.

4. ETHICAL RISKS AND STAKES OF HUMAN OPERATOR MODELLING IN A DIGITAL TWIN

Ethics is initially a philosophical concept. Several paradigms can be identified, namely utilitarianism (conceptualized by the philosopher Jeremy Bentham (Burns & Hart, 1996) and taken up and expended by JS Mills (Mills, 2012)) and deontology (a morale school of thinking proposed by Kant (Kant, 1965)). Ethics is now getting more and more studied in the context of future industrial systems (Trentesaux & Caillaud, 2020). Indeed, as discussed in the previous section, the advances in digital technologies fosters the merging of the cyber and physical worlds. Frontiers between the two worlds are getting more and more blurred and from our perspective, even if researchers and engineers do their best to design useful ICPS integrating human Digital Twins, ethical stakes are rising. This section intends to point out this aspect.

4.1 Ethical risks

Elaborating a list of ethical risks is a complicated task. Meanwhile, a way to elicit them is to use methods scanning the different systems concerned and for each, help the designer or the industrialist to imagine voluntary or involuntary bad usage or diversion of the initial design (Trentesaux, 2021). For

example, even RGD-compliant data from human operator Digital Twins can be used by human resources department of a company to identify who should be dismissed when a crisis occurs. Without intending to be exhaustive, the following items constitute a preliminary list of ethical risks that could be perceived in our past experience:

- A. *Intimate sphere violation*: the connection between physical and Digital Twins requires real-time data. The data acquisition risks to be intrusive in the intimate sphere of the operators (e.g. physical, physiological or cognitive sensors).
- B. *Managing human resources as machines*: Digital Twins of machines mixed with Digital Twins of humans in a global Digital Twin environment leads to a confusion between the constraints and objectives of each population. It is not intended to consider human as disposable resources.
- C. *Over usage*: Human models hardly capture a small percentage of the actual complexity of the physical twin. Specifically, the ability of operators to absorb temporary work overload shall not be standardized, as it might lead to a systematic over usage of operators.
- D. *Misuse of data*: data collected and treated along the process might be used for other purposes than the one accepted by the operators.
- E. *Loss of human initiatives*: by creating a cyber loop, based on the human Digital Twin, the operators are less encouraged to suggest enhancement initiatives, and more to rely on the cyber decision support.
- F. *Creativity restrictions*: standardization of methods, created by the cyber loop implementation, might tend to limit the potential of creativity of physical part operators, as it would generally go beyond the perimeter of the Digital Twin model.

4.2 Ethical stakes

The question is then how to help the management and the mitigation of such ethical risks. From our perspective and experience, several principles can be drawn beyond the compliance to regulations (e.g., EU GDPR and CSR). First, at the design stage of a human Digital Twin, three main principles have to be emphasized:

1. *Involvement*: the transformation operator subject to the Digital Twin and every actor involved in the management of his interest and wellbeing (medical staff, unions...) should be involved in the design process from the beginning to capture not only his expectations but also his fears that have to be counteracted.
2. *Durability*: production performance objectives should be considered in the design of the transformation operator Digital Twin not only for a short-term view, but also for long term, and the

longer, the better. Indeed, if a system lasts through time, it is a good indicator of its viability.

3. *Interfaces*: one should not forget about the pleasure the transformation operator may feel interacting with its digital counterpart. This notion of pleasure is seldom addressed or considered by industrialists and researchers. It is meanwhile a good way to ensure the long-term usability and ethics of the human Digital Twin.

Next, on the usage of the Digital Twin, some other principles require a specific attention:

4. *Intrusiveness*: accurately modelling a transformation operator requires to adapt to the specificities of each individual human beings. Two ways are currently studied: defining generic models of human beings (based on a classification made a priori and adjusted over time) or equipping them with sensors. Depending on the number of parameters needed, one should pay attention for example to the intrusion in the private sphere of the operators.
5. *Separation of concerns*: the Digital Twin is meant to help the decision-making process in the cyber part of

an ICPS. One should pay attention to only store and analyze the data from the transformation operator that are strictly necessary to the decision-making.

6. *Dampening*: by nature, the probability to obtain a Digital Twin of humans able to capture the actual essence of the physical counterpart is extremely low, due to the complexity and diversity of human beings. As a matter of fact, decisions in the cyber part should better consider the probability of mismatch between the twin and the actual behavior of the transformation operator before over reacting in case of problems.

4.3 Impact on operators

Table 1 presents a matrix aiming at indicating to whom the risks and stakes expressed before may concern: transformation operators (TOP), decision operators (DOP) and cyber decision-makers (CDM – might they be humans or AI-based). It indicates that the stake of intrusiveness is for example clearly related to the risk of intimate sphere violation for TOP and DOP (case A-4), and that the stake of dampening is related to CDM for any risk (cases A-6 to F-6).

The next section presents a case study to illustrate our discussion, focused on the usage phase.

Table 1. Matrix of implication of Digital Twin interactors with respect to ethical risks and stakes

	<i>Design of the human Digital Twin</i>			<i>Usage of the human Digital Twin</i>		
	<i>1. Involvement</i>	<i>2. Durability</i>	<i>3. Interfaces</i>	<i>4. Intrusiveness</i>	<i>5. Separation of concerns</i>	<i>6. Dampening</i>
A. Intimate sphere violation	TOP DOP	TOP DOP	TOP DOP	TOP DOP	CDM TOP DOP	CDM
B. Managing humans as machines	CDM TOP DOP	CDM TOP DOP	CDM	TOP	CDM TOP	CDM
C. Over usage of operators	CDM TOP DOP	CDM TOP DOP	CDM TOP DOP	TOP DOP	CDM TOP	CDM
D. Misuse of data	CDM TOP DOP	DOP CDM	TOP DOP	TOP DOP	CDM	CDM
E. Loss of initiatives	TOP DOP	TOP DOP	TOP DOP	TOP DOP	TOP DOP	CDM
F. Creativity restrictions	TOP DOP	TOP DOP	TOP DOP	TOP DOP	TOP DOP	CDM

5. CASE STUDY

The illustration provided in this section is based on an actual industrial study led by the authors. However, for confidentiality purposes, no indications are provided that could help the reader identify the corresponding industry. This example is based on a very large international group, specialist in the manufacturing and assembly of high value, high quality

and high technicity products, with an important matter of mass customization.

This study deals with the reduction of long-term risks and work-based diseases for the transformation operators. In opposition with short term effects (such as the human fatigue aware cyber-physical Production system developed by (Paredes-Astudillo et al., 2020)), the impact of the workload

on the operator is more dependent of the physiological characteristics of the operator than of the sole arduousness of the tasks. The main risks encountered by operators are MSD (MusculoSkeletal Disorders) (Kadir et al., 2019) and PSR (PsychoSocial Risks) (González-Muñoz & Chaurand, 2015). This study is focused on MSD. The objective is to illustrate the expected benefits of a decision support tool in a given industrial context, based on health-related parameters and human physiology modelling.

5.1 A beneficial approach

Initially, the industrial partner of this study observed an abnormal rate of MSD declarations among its operators, despite large efforts on workstations ergonomics. Prior to our study, they lead a medical survey, confirming that the felt pain was higher than expected for almost every operator on the manufacturing field. Their reaction was therefore to try and figure out a way to integrate arduousness in their scheduling. Considering the fact that operations are not repetitive, the traditional ergonomics approaches were not efficient enough, and some more tools needed to be defined. The suggested idea was to build a tool able to extrapolate the level of pain of operators considering the arduousness of the scheduled tasks. By doing so, the company shall obtain a lever enabling an efficient job rotation in this ever-changing environment.

The advantages are also medical. Indeed, in this very large company, medical services could obtain (with such models) real-time health alarms, triggering a contact with the operator to have an actual physical exam. By doing so, medical teams believe this could help enhancing preventive medicine and avoid MSD declarations.

5.2 A controversial approach

During this study, worldwide COVID-19 pandemics happened, and the world suddenly reconfigured. The industrial partner (economically) suffered as much as a lot of other companies all over the globe, but its size became a major drawback, and many operators were dismissed. Choices have been made to determine which operators had to be dismissed. What follows did not really happened, as the tool was not created yet. However, the considerations provided here were largely discussed with the partner in the following months.

These considerations are, at the time being, just questions, that highlight the need to carefully address the problem of data collection, treatment and storage, beyond regulations and industrial practices (GDPR compliance or CSR for example). Indeed, what if the data generated by this health-evaluation tool were used legally in a negative way (Risk D)? If an operator is more affected by arduousness of the tasks than another, can we consider that he is less productive on a long term (Risk D)? Why keeping operators that we estimate as being in pain, when other operators are assessed healthy (C)?

5.3 Risk mitigation measures

This short sample of questions illustrate the bias such a study could imply in the human resources decisions. For now, solutions have been found to mitigate the risks of negative usage of the data.

First, the tool is disconnected from the global ERP network from the company. It is only available on the station where the decisions are made, and data are manually imported from the ERP or inserted by a human operator. In such a large group, this single measure is efficient to limit the possibility for undesired services to collect and treat the data in an undesired manner. This corresponds to case D-4 of Table 1.

Second, the outputs of the tool, indicating the estimated risk of MSD development of each transformation operator, is not included in a fully automated scheduling tool. The scheduling algorithm run in the company is a classical tool, led by utilitarianism and deontology principles. Instead of providing a single solution, considered optimal on productivism criteria, it was modified in order to provide a set of more than one solution. By doing so, it enables the decision operator to integrate the data estimated by the tool in a more virtuous decision-making process (virtue being considered as stated by (Gibert, 2021)). This corresponds to case C-5 of Table 1.

Finally, no historical data are stored that could trace the reasons leading the operators to their current estimated physical state. The tool was designed to be able to estimate the evolution of potential pain with the only current state and arduousness of assigned tasks. This measure is intended to limit the possibility to mine data logs or learn from such evolutions. This corresponds to case D-5 of Table 1. For the record, it was also requested by the company, in order to limit the possibility for the lawyers of operators declaring an MSD to turn the tool against the company (but this question remains out of scope of this paper).

6. CONCLUSIONS

This paper intended to show how tangible are the ethical risks when designing human operator Digital Twin, and one can understand how our discussion could be easily generalized to other aspects relevant to Industry 4.0. For example, ICPS will not be comprised of a single human interacting with a single production system. Thus, information and decision architectures with various frontiers stating where and when one goes from one world (digital, real) to the other must be elaborated (Sparrow et al., 2021).

Despite what could be imagined, a growing set of industrialists are getting more and more concerned by ethics in the context of Industry 4.0, and not only because of societal or legal pressure (Berrah et al., 2021). But since there is still no operational tools helping them in managing and mitigating ethical risks, they feel unable to do this. It is an important and urgent need our research community should address.

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