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# Towards Human-Centric Digital Simulation: Guidelines to Simulate Operators Skills Acquisition and Health in Circular Manufacturing Systems

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**Abstract:** The ongoing environmental crisis motivates some businesses to shift towards a circular economy. This shift necessitates a comprehensive overhaul of their existing manufacturing processes to enhance their adaptability to circular principles. Amidst substantial uncertainty and a strong need for skilled human labour to handle intricate and variable tasks, operator training emerges as a pivotal element in guaranteeing the efficiency of the production system. Several solutions could be explored to improve operators' skills while integrating a strong social and environmental dimension. In this context, the use of simulation can carry out tests to optimize the acquisition of skills in circular manufacturing systems. However, the current simulation models rarely integrate knowledge from the human and social sciences to model operators in systems while they are crucial to the performance of circular workshops. This paper proposes a methodology to develop a digital simulation taking into account operators' health and skills acquisition in those systems.

**Keywords:** circular economy, industry 4.0, industry 5.0, discrete event simulation, manufacturing systems, operator skills modelling

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## 1. INTRODUCTION

The circular economy (CE) promotes the efficient use of resources and the reduction of environmental impact at every step of a product's lifecycle. To develop this concept at an industrial level, Circular Manufacturing Systems (CMS) , which are industrial production systems aiming to keep in use or restore some value of products, should be put in place (Denu et al., 2023). The complexity inherent to the reprocessing of products requires highly skilled operators with a range of specific skills that can take a long time to acquire (Arredondo-Soto et al., 2019). Moreover, some activities in CMS may involve increased health risks for operators (postures, carrying loads, etc.) (Caroly et al., 2019). These two aspects - health and learning - are particularly important in CMS, and can have a major impact on a workshop's performance.

In parallel, several articles have focused on the use of simulation in CMS, for their ability to test opportunities for improving systems before they are implemented, at lower cost and with greater ease. However, they neglect the social aspect despite its importance in measuring the performance of this type of workshop, as in most other articles on simulation. Only a few articles have focused on this subject, and a state-of-the-art has been proposed by Widok and Wohlgemuth (2015). They underline the difficulties of doing so but promote the importance of reintegrating humans in simulation. Indeed, without access to tools that can estimate the impact of operators' activities over the long term, they argue that it is much more difficult to move practices towards greater social sustainability (Widok and Wohlgemuth, 2016).

Then, there is also a lack of collaboration between disciplines in research on the themes of Industry 4.0 or CMS, leading many engineering papers not to include the human aspect, or to include elements that contradict the humanities and social sciences (H&SS). Moreover, several potential solutions with an impact on humans have been proposed to improve CMS performance, including the use of Industry 4.0 technology. However, the vast majority of these are merely unproven suppositions (Denu et al., 2023). In this context, the use of simulation could be valuable for gathering insights on these proposals from the literature given the difficulty and cost of obtaining concrete proof of these proposals. However, for these simulations to be relevant, they need to be carried out within multidisciplinary research teams to ensure the model's relevance on the human aspects, and to verify that the objectives of the simulation are relevant from both engineering and H&SS perspectives. As part of the development of CMS in the face of the current environmental emergency, it is important to find solutions to the problems associated with these systems and to integrate the social dimension into the search for solutions consistent with sustainable development. Moreover, the use of simulation - one of the technologies of industry 4.0 - with a primary focus on the well-being of operators in the context of promoting a sustainable paradigm like CE makes this approach a perfect example to illustrate in the concept of industry 5.0. Thus, this paper proposes a methodology for the development of a simulation model for CMS that takes into account H&SS aspects and workshop performance. Particular emphasis is placed on skill acquisition and operator health, as those are particularly critical in CMS.

The research question proposed is: How can the skills acquisition and operator health be modelled in digital simulations to represent CMS, to improve their performance from a sustainable perspective? Following a literature review on simulation and H&SS in Section 2, a methodology for a simulation including human aspects is given in Section 3. An application is proposed in Section 4, and the model limitations and perspectives are discussed in Section 5.

## 2. LITERATURE REVIEW

This section introduces the main concepts related to simulation and human modelling, with a focus on CMS and taking into account engineering and H&SS literature.

### 2.1 *Simulation and modelling for CMS*

Several researchers deploy simulation models for CMS. Goodall et al. (2019) and Charnley et al. (2019) propose simulation models based on real-time data acquisition from sensors. Okorie et al. (2020) compare Discrete Events Simulation (DES), System Dynamics and Agent-Based Modelling of remanufacturing systems to assess the most suitable method to reflect the circular processes complexity. DES, which is based on the simulation of events that occur at discontinuous time intervals, is particularly suitable for simulating processes at the tactical and operational decision-making levels. Reviewing the literature on simulation also brings to the fore that social aspect is generally not taken into account and the modelling done is seldom compared with H&SS knowledge. Although this area has received little research attention, Widok and Wohlgemuth (2015) tried to define social criteria to integrate into the assessment of manufacturing systems (covering physical, organizational and psychological aspects). Then, Widok and Wohlgemuth (2016) present the challenges for integrating social influences into DES software and present a prototype integrating ergonomic aspects. Using controversial models of human behaviour, they conclude that progress needs to be made in modelling social aspects, and to have extensive data collection on these themes to find models that best represent human behaviour. Thus, several scientific hurdles need to be overcome in the simulation of operators involved in CMS, by incorporating a multi-disciplinary vision (e.g., ergonomics, psychology, sociology) toward more sustainable practices. Dode et al. (2016) also proposed a DES integrating fatigue (mainly muscular), recovery and learning to assess the impact on productivity and production quality, as well as the impact on risks for operators. Other work introduce the impact of social aspects into the performance of workshops, such as Sobhani et al. (2016), which proposes modelling to optimise the operations performance by integrating ergonomics indicators, and quantifying the impact of operators' health on operations.

### 2.2 *Operators' skills and knowledge acquisition in CMS*

The challenge of CMS is to put used products back into service with processes generally including inspection, disassembly, repair, reassembly and testing. The unpredictable quantity of operations to perform creates many uncertainties in the processes, and difficulties in standardizing and automating processes of CMS. The tasks complexity perform entails a

high need for manual work, creating high costs (Kurilova-Palisaitiene et al., 2018) and the need to manage customs process flows for each product (Klein et al., 2021). To overcome the challenges of CMS (such as part availability or lack of technical data), operators need to develop extensive and unique competence to recreate products (Guelle et al., 2023). These skills evolve and depend on the situation in which they are built (Jonnaert, 2017), through experience acquired by the operator on the parts. In CMS, this gain in experience translates into an improvement in quality (Kurilova-Palisaitiene et al., 2018), thus the need of an extensive training to enable a rapid increase in operators skills. Proposals to increase the skills acquisition have been proposed by researchers, such as job rotation - allowing employees to perform different tasks within a company (Bocewicz et al., 2023). Digital technologies (DTs) have also been used for training, such as Digital Twins and Virtual Reality (VR) in linear activities (Martínez-Gutiérrez et al., 2023).

Several learning and forgetting mathematical models have been proposed by research, and some even applied it to CMS (Jaber and El Saadany, 2011). However, those models often concentrate only on economic indicators and does not include the particularities of individual differences between operators. Moreover, some indicators of those models could be difficult to determine, such as learning rates. Indeed, competence cannot be directly observed, but it can be seen through the operators' behaviour and performance (Rabardel et al., 1998).

### 2.3 *Operator health*

In ergonomics, health has been defined as "a dynamic balance between physical, psychological and social well-being, throughout life", by Rabardel et al. (1998). It also underlines that training is a positive aspect of an operator's health at work, as the link between skills and health is very close, especially in the way in which they act in unpredictable situations at work (Delgoulet and Vidal-Gomel, 2013). Moreover, acquiring skills not only preserves the employees' health and safety but also contributes to the CMS's performance. Several solutions for improving health have been proposed by researchers on both practices (e.g. job rotation) and DTs. Nevertheless, there is a significant gap in evidence of the usefulness of these solutions. Indeed, the costs associated with the technological implementation, as well as the difficulty of providing empirical evidence on these new possibilities, thwart their implementation in manufacturing systems. As mentioned above, the lack of a reliable model to represent operator health and the absence of a link with learning is a major gap in the literature to test those assumptions with a simulation model.

To conclude, the development of digital simulation could be beneficial to try possibilities to improve training and protect operator health with fewer costs and reduced time before testing implementation in a real case. The main barrier to the use of such a simulation stem from the fact that current simulations do not sufficiently take into account the human aspects in production systems due to the difficulty of modelling human behaviour. Given their importance, a proposal is therefore made to create the essential foundation of a simulation and describe methods for computerising models that better represent the human element in the system.

### 3. METHODOLOGY FOR DYNAMIC OPERATORS' HEALTH AND SKILLS MODELLING

In this section, the aim is to identify methods for modelling an operator in a CMS based on real data. The following questions are therefore addressed: what characteristics for a DES taking humans into account? What parameters and modelling patterns to use to integrate humans into a CMS simulation? What methods to build a model based on real data?

#### 3.1 Digital simulation to take human into account

One of the main challenges of an operator-centred simulation is twofold: to study the impact of the process on the operator and to study the impact of the operator on this process. These two elements are closely linked: reproducing the actions of a process several times enables the operator to gain experience, and the operator's experience reduces the time needed to execute a process. At the same time, a process can affect an operator's health, which in turn can have an impact on process time. When a system is highly dependent on humans, as is the case in CMS, its performance is largely linked to the operators and their specific characteristics. Indeed, as each operator is unique, it is necessary to take individual characteristics into account in the simulation to be as close as possible to the real situation and to find relevant solutions according to the different individuals interacting in the production system. The first question for including humans in the simulation is therefore: what impact do operators have on process times, and what impact do processes have on operators? In the context of a CMS, three main elements interact with each other: the products, the operators and the processes.

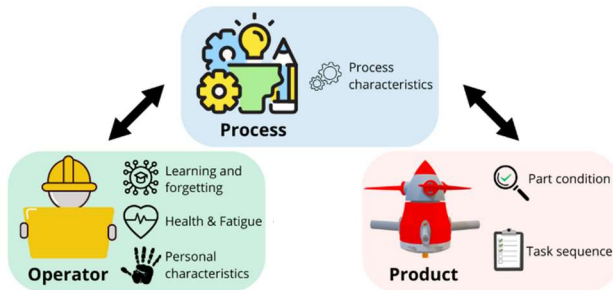


Figure 1. Simulation components

The product may have several characteristics which influence the performance of the CMS, such as its type or initial quality, which impacts the task sequence, the time taken for product recovery, or the health impact on operators.

The operators' characteristics to take into account in a CMS are linked to learning, health (physical and psycho-social), fatigue and every data relevant to the study objectives (e.g. apprehension in the use of DTs if the aim is to test the impact of the implementation of one of these DTs in the system).

Finally, the processes provide the link between the operators and the products, as shown in Fig. 1. It is during this process that the operator has an impact on the product and vice versa, hence the absence of a direct connection between the product and the operator. The simulation has therefore to take into account the process characteristics (operation type, minimum skills required, etc.). For each process, the impact of initial product quality is estimated based on field data. Thus, a first mathematical model should calculate the processing time (PT),

taking into account operator (experience, health, etc.) and the part characteristics (quality), as shown in Fig.2.

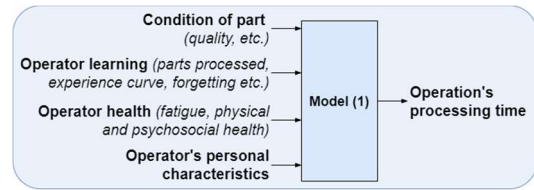


Figure 2. Model (A) for processing time computing

In parallel, as learning, health and fatigue evolve as the parts are processed, they need to evolve throughout the simulation to study their impact on the processes. A second mathematical model (B) is needed to calculate the impact on the operator of the processing, depending on the process and the part quality as shown in Fig. 3. To the authors' knowledge, no existing model takes these elements into account. As indicated in the literature, models of learning, forgetting and fatigue exist independently, but are not combined. Section 3.3 explains how these phenomena can be modelled based on real field data.

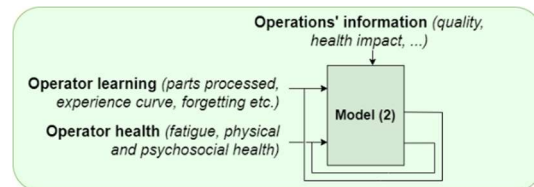


Figure 3. Model (B) for updating operator health conditions

Furthermore, the indicators proposed are not exhaustive and a study of the interactions in the system must be carried out to list the relevant indicators. Some elements linked to the working environment may be important to get closer to the real system (for example, the temperature of the workshop, etc.). Now that the components and models needed for simulation have been explained, their integration into a DES is detailed in section 3.2, along with a proposed modelling model.

#### 3.2 Proposed patterns for simulation

The simulation aims to represent a workshop with several processes, flows and resources (such as operator), to study the interaction between several processes. Thus, DES tools seem particularly adapted to this objective, to help in the decision-making to improve and optimize the operation of complex production systems. The first step is therefore to define the operation of a single process independently of the others, taking operators and parts into account. The second step is to create the other processes, by adapting the modelling pattern proposed to reproduce its operation. The final stage involves creating the right links between the processes to enable the operation of the system to be simulated in its entirety, and so study the interactions between the different processes that make up the CMS, and de facto define its performance.

A modelling pattern is therefore proposed to implement the operation of a process in a DES (see Fig. 4). As the models utilized to handle operators' dynamics contain feedback loops, the DES pattern must precise the sequencing of the computations. Therefore, Fig. 4 only shows the chronological execution but not the data exchanged between subprocesses. The proposed operation for a manufacturing process step consists of 3 main stages. 1) The operator selection according

to the process requirements and the parts to be processed, 2) the part processing and 3) the computation of the process impact on the operator.

### 3.2.1 Operator selection

The first step is to find a qualified operator for the process, as represented in yellow in Fig. 4. To do so, upon arrival of a part and before starting its processing, a first check is made whether an operator is present, to call one if not. At this point, the operator's qualification is checked for the operation (by verifying that his current experience is higher than that needed for the task), as his level of health, must not fall below a threshold to preserve the operator's health. If the operator doesn't match the requirements for the task, another operator is called and the same process is repeated until a qualified operator for this task is available. The assignment rules can be modified to test different work organisations in the workshop.

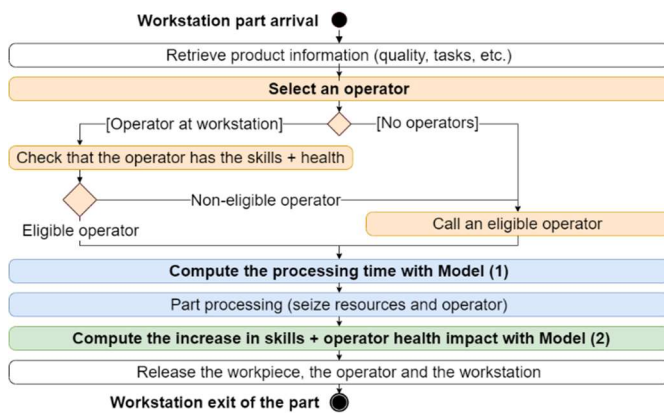


Figure 4. Activity diagram for part processing

### 3.2.2 Part processing

Once the operator is at the workstation (blue section in Fig. 4), the PT is calculated based on three data: the time needed by an operator to perform the process based on its experience with the given processes, its health, its fatigue, the quality of the part processed. The poorer the quality of the part, the longer the PT due to the additional operations required on the part. Operator fatigue takes into account fatigue linked to the working time since the start of the day, as well as the operator's physical and psychosocial state of health.

### 3.2.3 Updating of operator's health and learning

At the end of part processing (green section in Fig. 4), the operator's skill and health levels are updated. Concretely, the number of parts produced by the operator in the process is increased, reflecting its increased experience and the increase in skills. Then, each component of the operator's health is updated with a model to find with real data. The operator and the part are then released to start processing a new part. To study the interaction of operations in the workshop, this pattern must be duplicated for each operation in the DES.

### 3.3 Collecting data to feed human and processes model

As seen above, and given the difficulties associated with the use of generic models in the literature, the methodology proposes to establish models to represent PT (model (A)) and to represent changes in the health and skills of operators

(model (B)). The various values required to feed these models have been detailed in the Fig. 2 and Fig. 3.

Data for processes, such as job execution speeds, the occurrence of parts quality and the time spent to retrieve poor-quality parts, could be retrieved thanks to data acquisition of processes and observation of the real situation. At the same time, to include the human component, an ergonomic analysis of workstations must be carried out to quantify the impact of the tasks performed on fatigue, and physical and psychosocial health. This ergonomic analysis is based not only on observation of the evolution of postures and operator behaviour over several cycles but also on questionnaires proposed to operators to gather data on the impact of tasks on them. The questionnaire should be designed according to the situation under consideration, using, for example, physical and psychosocial indicators from existing questionnaires, such as those compiled by the French National Research and Safety Institute for the Prevention of Occupational Accidents and Diseases (INRS, 2022). The initial health condition could also be calculated with such a questionnaire to initialize operators' initial health. Relevant data gathered from that step could be the perceived mental workload, cognitive engagement, etc. Following those data, the impact for physical and psychosocial impact could be calculated for each workstation, and a health capital is given to each operator. To better understand the operators' actions, feelings and limit bias, methodologies such as self-confrontations could be carried out. It consists of questioning individuals about their actions, based on video recordings of their activities. A key point to consider in this method is ethics, given that the process involves processing personal data and records of individuals. It is therefore important to establish a protocol that takes this into account, while minimising data collection and ethical conflicts.

As this approach aims to create a model from field data, it is difficult to propose a generic model that is suitable for all situations, hence the need to create an appropriate protocol to collect data in an appropriate format for a statistical analysis enabling to model the given scenario. Several useful elements in the creation of the mathematical models proposed above could be denoted. Concerning skills topics, the literature on learning identifies two important elements in the mathematical modelling of Model (A): the learning curve generally takes as its variable the number of operations performed on a process, while the forgetting curve takes as its variable the time that has elapsed since the last operation was performed on a process. Concerning health topics, existing models of operator fatigue, or physical wear and tear are controversial, thus the proposition made in Section 4 for this topic.

## 4. APPLICATION

To carry out a test of the methodology, a physical simulation was carried out with 30 participants aged between 19 and 45 on a technological platform, for a two hours experiments including training, disassembling small tidal turbines for one hour under similar experimental conditions, and answering questionnaires. The average number of processes completed by participant is around 5. A tablet application was given to each participant to compile PT and a video was recorded to analyse the learning phase, the first potential effects of fatigue

and posture. The long-term effects on health could not be studied and would require a large volume of data over a wide period. Analysis of the data enabled us to determine an initial model (A) in the form of (1).

$$\text{processingTime} = \frac{\text{operatorTaskTime} \times (1 + \text{qualityImpact})}{\text{operatorHealth}} \quad (1)$$

Each component of (1) is now detailed. *OperatorTaskTime* was inspired by Wright (1936) learning model, with the inclusion of a minimum time for operations as shown in (2), with  $T_1$  the theoretical time for producing the first unit,  $T_{inf}$  the minimal time for the operation,  $i$  the number of parts already processed by the operator (i.e. its experience) and  $\ell$  its learning rate. The value of  $T_1$  and  $\ell$  are determined for each operator based on real value with a power regression.

$$\text{OperatorTaskTime} = (T_1 - T_{inf}) \times i^{-\ell} + T_{inf} \quad (2)$$

Concerning *qualityImpact*, it represents the random part of the process, both for the variability of the process related to the operator and to the part quality. In the example, the parts are sorted into three quality levels: good (no additional operation), medium (minor corrective actions) or poor (major corrective actions). Then, the quality component is modelled as a triangular distribution for each type from the field data.

Concerning *operatorHealth*, the H&SS literature indicates that the onset of physical or psychosocial disorders is multifactorial, individual and difficult to predict with accuracy. Trying to predict with certainty the onset of pain at a given body part seems utopian, so it is proposed instead to model health as a global capital that evolves according to two characteristics: physical and psychosocial. Thus, it could be assumed that the capital varies between 0% and 100%. An operator at his best starts at 100% whether it is in good health on all the health aspects taken into account in the model, and this percentage decreases as the parts are processed and depending on the operation on which the operator works. Indeed, the impact scores calculated should correspond to a risk factor for musculoskeletal disorders or psychosocial risk, and not an exact score reflecting the systematic appearance of disorders at a given level. The aim is, therefore, to minimize this risk factor as much as possible, rather than trying to avoid exceeding certain levels. Each operation is thus assessed ergonomically, and a physical and psychosocial impact score is calculated for each operation. The fatigue linked to the daily operation is also assumed to be modelled in the same way, with the difference that the capital can increase once the fatigue has been recovered. Model (B) is thus signified as a series of equations, which are updated each time an operation is completed according to (3). The components could be either fatigue (short-term) or physical or psychosocial health.

$$\text{HealthComponent} = \text{previousHealthComponent} \times \text{operationHealthImpactComponent} \quad (3)$$

This proposal is intended to illustrate the methodology, and how it can be applied. Further experiments to collect a larger number of data sets are required to determine the relevance of this model or to test others, as presented in Section 5.

## 5. DISCUSSION AND RESEARCH PLANNING

As highlighted by the literature review, the inclusion of human aspects in digital simulation has not been the subject of much

research due to its complexity or lack of interest. Thus, the proposed methodology has several original features. Based on joint work between researchers in engineering and H&SS, this work has provided an opportunity to take a step back from the work carried out in engineering to take better account of human aspects with the most recent research in H&SS. It also leaves a great deal of opportunity for multidisciplinary collaboration, given that the proposed methodology integrates the work of ergonomists in the model development, which can already have a critical look at the processes studied and a sharing of knowledge that brings benefits to both parties. Finally, this methodology has been successfully used in the laboratory to develop the proposed simulation model.

Several limitations could be denoted. The first lies in the hypothesis taken. The case study on which the simulation is built is based on several simplifications to demonstrate the technical feasibility of taking a plurality of indicators on human operators linked to skills learning. Indeed, the system studied was a simulation on a technological platform with simplified processes and a few volunteer students on a short-time simulation. There are limits to the mathematical modelling proposed in the application section. A wave of experimentation with a larger batch of data is thus required to test the current and other models (such as with a design of experiment, for example).

Another limitation concerns the potential complexity of the model depending on the number of data items taken into account. It may be tempting to include a very large number of variables to represent humans as accurately as possible, but it is necessary to discard as soon as possible any variables that have a minor impact on performance in real cases. In addition, the difficulty of determining some parameters experimentally - such as the learning rate - should not be underestimated. Finally, it should be borne in mind that model validation also becomes more complex as the complexity of the model increases. Including human beings in the simulation is therefore like treading a tightrope: the model must be sufficiently complex to be able to reproduce the process characteristics, without becoming too complex to compute in real industrial scenarios.

Finally, several elements are currently being explored to bring the simulation closer to real-life situations and enable to testing of various hypotheses relating to the improvement of skills acquisition in a manufacturing context. First of all, the aim is to represent a greater diversity of operators, by collecting the data on more participants confronted to various situations to bring the model closer to reality and to implement other key elements (forgetting during learning, breakdown of skills into sub-skills, etc.). The second objective is to experiment with the model with the inclusion of emerging DTs in the process (such as VR, Cobot or artificial intelligence) to model their impact on learning and health in several scenarios. The third objective is to extend the reasoning to other existing CMS stations, such as those used by Charnley et al. (2019) in their simulation. The fourth objective is to include environmental aspects in the CMS, by calculating the different environmental impacts during the process based on values from a Life-Cycle Assessment. Finally, the fifth objective is to test the simulation model on a real industrial case study.



## 6. CONCLUSION AND PERSPECTIVES

This research has several practical implications for manufacturers. The aim of this article is to propose a guideline for simulating a production workshop carrying out CE operations using DES. As operators are at the heart of these CMS and their performance, this methodology lists key aspects needed to model human aspects in simulation, suggests modelling patterns to implement H&SS aspects in DES and proposes a method for data collection and treatment. The aim of this methodology, co-constructed with H&SS knowledge, is to propose an easy-to-apply method in an industrial setting (based on activity observations and easy-to-use questionnaires). The benefits of this approach could be numerous for manufacturers who are as dependent on human labour as they are on CMS. During the creation of the simulation, the study of the process with a human-centred vision enables knowledge to be transferred to the company concerning the activity of the operators. Once the simulation has been created, the manufacturer will be able to test scenarios or opportunities for improvement easily, and quantify the economic and human impact of the decision on its process, before eventually implementing the solution. This solution can be both organisational and technological, with the aim of increasing system performance while preserving the health and well-being of operators at work.

For researchers' implications, the main contribution lies in the inclusion of H&SS knowledge in the modelling of a production system and it explores an alternative way of simulating humans than those already existing, which had several limitations in its ability to faithfully represent humans. The article differs from others in the field in that it uses ergonomic and work psychology diagnosis as a basis for calculating an impact score for the activity on the operators, without attempting to calculate precisely the elements of the operators' health (WMSDs, fatigue, etc.), and with the aim of being easier for manufacturers and ergonomists to apply.

At the dawn of Industry 5.0, taking better account of individual human aspects and the preservation of their health in the development of simulation models becomes essential, given that simulation is generally used for decision-making in the creation or evolution of industrial systems. It is, therefore, more urgent than ever to take greater account of the human factor, and adopt sustainability in engineering research, and speed up multidisciplinary projects involving the H&SS.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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