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Transdisciplinary Evaluation of Simulation Software for Industry 4.0 Assembly Lines

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Abstract. Industry 4.0 is driving the revolution of manufacturing processes by combining innovative technologies and new interaction paradigms among systems and operators. In particular, the layout, tasks and work sequences of assembly lines are designed according to several transdisciplinary Design Principles (DPs), such as process efficiency, product quality, ergonomics, safety and operators' workload. A large variety of simulation software can be employed for evaluations. However, the related ability to assess multidisciplinary factors must be evaluated. The paper aims to provide a framework for guiding the assessment of simulation software in the context of Industry 4.0 assembly lines. Process requirements are first analyzed and mapped to select DPs, prioritized according to design goals by an analytical hierarchy process. Then, suitable simulation software is determined accordingly, and the virtual model is realized. Finally, the possibility of the software to provide meaningful elaborations for the selected DPs is assessed. The framework has been tested on a prototypal Industry 4.0 assembly line composed of automated logistic systems, cobots and systems to guide the execution of tasks. The line has been modeled in Siemens Process Simulate, analyzing the completeness and appropriateness of the functionalities of this software according to the defined DPs.

Keywords. Decision Support Tools, Interactive Simulation for Engineering, Industry 4.0, Design Principles, Transdisciplinary Engineering

Introduction

Industry 4.0 (I4.0) is a paradigm for companies that involves the socio-technological sphere [1]. The revolution of I4.0 includes the entire development chain, starting from the material suppliers until the use phase [2]. New technologies are implemented to increase the performances and efficiency of the industrial processes according to the I4.0 paradigm. Big data analytics, robotic manipulators, cyber-physical systems, augmented reality technologies, additive manufacturing, and simulation software enable the implementation of the I4.0 paradigm [3]. These technologies are interconnected and integrated into a network with an extensive exchange of data thanks to several types of sensors [4]. Also, technologies must communicate and interact with human workers [5], becoming Smart Operators [6]. Furthermore, I4.0 implementations are defined within transdisciplinary Design Principles (DPs) [7], guiding companies to develop the I4.0 paradigm in their processes.

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However, implementing I4.0 DPs and technologies needs to be carefully planned as they radically change the value chain. Also, cost assessment, analysis of risks, and analysis of potential benefits should be evaluated [1]. In this context, simulation software can support companies to analyze the several transdisciplinary factors of the I4.0 paradigm. Simulation software enables the modeling and the validation of products, processes, and systems [1]. Also, it can predict value chain performances, supporting decision-making [8].

Therefore, this paper provides a framework developed to guide a transdisciplinary evaluation of software in the context of I4.0 assembly lines. Process requirements are first analyzed and mapped to select DPs, prioritized by an Analytical Hierarchy Process according (AHP) to design goals. Then, suitable simulation software is determined accordingly, and the virtual model is realized. Finally, the software is evaluated based on the provided elaborations according to the selected DPs.

The remainder of the paper is organized as follows. A review of the DPs and types of technologies in the I4.0 context is reported in section 1. The proposed framework is then outlined in section 2. A practical test case is shown in section 3, and finally, conclusions are drawn in section 4.

1. State of the art

This paper provides an approach to evaluate simulation software in the I4.0 context. There are several types of simulations [1] and different simulation software. Many research works can be found in the literature focused on selecting simulation tools in this context. Cafasso et al. [10] proposed a framework based on two Multi-Criteria Decision Making (MCDM) to support the selection of simulation software in the I4.0 context. However, the authors do not perform the analysis according to the several DPs of I4.0. Also, the authors in [11] and [12] do not consider DPs. Grandi et al. [13] have evaluated simulation software based on subjective and objective evaluations. However, DPs have not been considered. Also, the evaluation is limited to the simulation of humans' postures during an assembly phase. Finally, other frameworks were proposed before the advent of I4.0 [14, 15].

1.1. Design Principles of Industry 4.0

First of all, the concept of DP is clarified. DPs are a set of definitions and guidelines to develop high-quality products or services in the context of the smart factory [7]. Table 1 summarizes the definitions of the I4.0 DPs drawn from an literature analysis.

Table 1. Summary of the DPs applicable in I4.0 scenarios

Name	Definition
DP1) Interoperability [16]	Two or more components to cooperate, communicate, and interact despite differences in language, interface, and execution platform.
DP2) Virtualization [17]	It refers to the development of a virtual environment that is a digital twin of all the components of a line or factory and a single component. Virtualization is enabled thanks to sensors and a significant exchange of data.
DP3) Decentralization [18]	It refers to the development process data that are not centrally gathered, elaborated or controlled. Indeed, data can be accessed from anywhere.

Name	Definition
DP4) Real-time capability [17]	The analysis of data in real-time, adapting the manufacturing according to data analysis. It can be described as the responsiveness and flexibility of the company.
DP5) Service orientation [19]	The company's focus is shifted from products to customers, providing services.
DP6) Modularity [20]	It refers to the capability of a system to be decomposed into modules. The modules can be changed and adapted to the specific product according to given requirements, increasing the manufacturing agility and flexibility.
DP7) Optimization [21]	It refers to the optimization of the entire supply chain. In particular, performances, productivity, and efficiency must be optimized. The problem can be described as functions that have to be minimized or maximized, considering certain constraints.
DP8) Vertical integration [1]	It refers to intra-company integration and interconnected manufacturing systems
DP9) Horizontal integration [22]	It refers to inter-company integration. So, it refers to a collaborative environment among companies, sharing data and resources.
DP10) Smart and customized product [23]	It means that companies are pushed to develop innovative products with a high level of personalization, increasing the level of business competitiveness.
DP11) Smart factory [24]	It refers to an integrated and collaborative value chain. It must adapt to changes according to the conditions of the supply chain. Also, smart factories include interconnected technologies.

1.2. Types of simulations

Simulation software has gained a primary role in the I4.0 paradigm [1]. Table 2 lists the major types of simulations in the context of I4.0. The reported categories represent the basis of the study and will be correlated to specific application contexts.

Table 2. Types of simulation categories in the context of I4.0

Name	Description/Main characteristics
Virtual commissioning	It represents the possibility to simulate a control strategy of a system in a virtual environment when actual implementations are not yet available
Virtual reality	It is an immersive and detailed environment. Users can interact with the virtual world making wide use of their senses
Discrete event	It is a simulation-based on the study of events. Events occur when the state of a system change at a particular time.
System dynamics	This approach studies the performance of a system during a specific time lapse.
Agent-based	This simulation uses agents that interact autonomously with each other. These agents are used to predict and analyze specific goals or events.
Augmented realty	This simulation connects the real world with virtual objects, and these objects coexist in the same place as the real world.
Artificial intelligent	It is the simulation of intelligent performances of technologies.
Petri net	It is possible to create the architecture of the manufacturing workflow operations. A similar approach is the discrete event simulation
Digital twins	A digital twin is a virtual representation of a real value chain, and the data flow between the real and the virtual environment is automatic.
Hybrid	It represents the combination of two or more different types of simulations.

2. Proposed framework

Software are used in various tasks, such as supporting the evaluations of the efficiency of processes, the ergonomics of assembly tasks, the physical behavior of designed products. However, most of the commercially available simulation software was conceived before I4.0 and the introduction of many interconnected and transdisciplinary environments. Over the years, updates have been provided to cope with the innovations of I4.0. Understanding when software is suitable for simulating I4.0 environments is demanding as the I4.0 panorama is vast and multidisciplinary. Therefore, the paper aims to develop a framework to support a systematic evaluation of simulation software in an I4.0 production context, as depicted in Figure 1. In particular, the goal of the framework is to verify the capabilities of the software in transdisciplinary evaluations of the simulated environment.

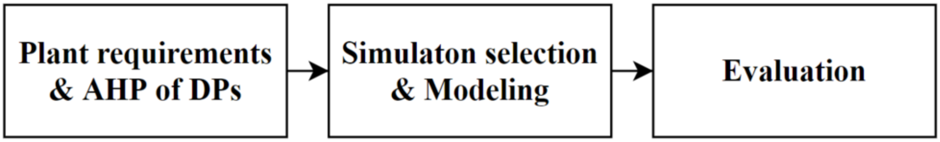

Figure 1. Framework for the evaluation of simulation software

The first step concerns the identification of initial requirements and design goals. After collecting the required data, functional requirements are defined according to the DPs of I4.0. Then, the most significant DPs are hierarchized via the AHP method. This method is based on a series of pairwise comparisons between a set of criteria, giving them a score of relative importance and assigning percentage weights [25]. AHP aims to support decision-makers while operating with several conflicting evaluations, obtaining an optimal compromise solution in a structured way [26].

The simulation software is then assessed according to the DPs, the systems to be simulated, and the type of simulation to be performed. After, the resources of the development chain are modeled, and these models are imported into the virtual environment of the simulation software. Then, the software is evaluated according to the DPs that can be satisfied. In particular, the possibility of the software to provide meaningful elaborations for the selected DPs is assessed.

A value from 0 to 5 is given to each DP based on how the software can capture the considered DP. The proposed approach provides an index (I) calculated through the weighted sum model [27] using Equation 1.

$$\mathrm{I} = \frac{\sum_{i=1}^{n} \omega i * DPi}{5} \tag{1}$$

Where ω_i is the hierarchized weight of the DP-ith calculated through AHP. DP_i is the given value of DP-ith and n are the selected DPs.

3. Case study

The proposed framework was tested on a prototypal assembly line composed of devices and facilities typical of I4.0 environments. The three main steps presented in Figure 1 have been performed in collaboration with a panel of three students, two professors, and two experts. All the participants were involved during the implementation of the virtual model of the assembly line in the software. The steps of the work are detailed in the following paragraphs.

3.1. Step 1: Assembly line requirement and AHP of DPs

The first step is to define the requirements and goals of the assembly line or plant. This phase was performed by asking the panel what requirements the assembly line should have. The authors have defined the goal of the assembly line as to be as efficient and effective as possible. After initial brainstorming, the identified requirements are:

R1. All the technologies of the line must communicate with each other;
R2. A virtual model of the line is mandatory to analyze and optimize performances;
R3. The assembly line must adapt to different scenarios and possible faults, increasing its inherent level of flexibility.

After that, requirements have been mapped to select DPs, as depicted in Table 3.

Table 3. Links among requirements and DPs (refer to Table 1 for DP numbering)

	DP1	DP2	DP3	DP4	DP5	DP6	DP7	DP8	DP9	DP10	DP11
R1	X										X
R2		X					X				X
R3				X		X					X

After identifying the DPs according to the requirements, these are hierarchized through AHP. This step was performed by asking the panel to apply the AHP method to D1, D2, D4, D6, D7, and D11. Table 4 summarizes the weights of each DP resulting from the second brainstorming.

Table 4. Weights (percentage) of DPs (refer to Table 1 for DP numbering)

DP1	DP2	DP4	DP6	DP7	DP11
16,98	22,63	23,61	17,13	16,46	3,19

According to Table 4, D2 and D4 result to be the most important DPs for the specific test case. Indeed, virtualization (D2) permits simulating the line, testing different configurations, and evaluating different options. Real-time capability is essential to increase the reliability of the assembly line. D1, D6, and D7 are considered equally important as they increase the line's performance. D11 has been considered less critical since smart manufacturing is a generic term. So, the panel members have considered the other DPs more critical for an assembly line.

3.2. Simulation selection and modeling of the line

The considered assembly line comprises several resources (see Figure 2). Robots, conveyors, warehouses, and humans interact along the assembly process. In this context, virtual commissioning, discrete events, and digital twins are systems providing the most significant insights. In particular, the authors have identified Tecnomatix-Process Simulate [28] as a suitable candidate platform to be assessed. Tecnomatix-Process Simulate is a comprehensive portfolio of digital manufacturing solutions for digitalizing automated manufacturing. In particular, Process Simulate allows the simulation of assembly line resources interaction and cooperation in a process.

Therefore, the demonstrative assembly line has been modeled in Process Simulate, as depicted in Figure 2. In particular, the assembly line has three main stations. The first one is the warehouse where the raw materials are stored. It comprises an operator and an automatic and vertical warehouse (1). This solution saves space on the plant, speeds up picking, and ensures spacing and safety for all operators. Then, the assembly station includes an operator and a vision system (3) to guide the user during the assembly phase.

The final station is the packaging station. It is composed of another operator and a vision system (4) that exchange data with a cobot (6). Also, a conveyor (5) is used to load and unload semi-finished products in the working zone of the cobot. Finally, an Automated Guided Vehicle (2) (AGV) was used to move the products and as an assembly base, increasing the safety of the process. AGV moves materials at the different stations of the assembly line. The details of the devices are reported in Table 5.

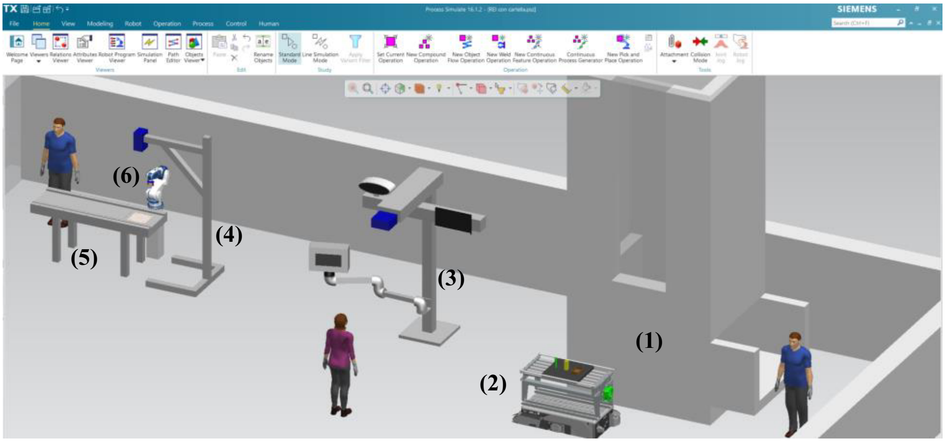

Figure 2. Demonstrative assembly line station modeled in Process Simulate. 1) Vertical and automatic warehouse; 2) AGV; 3) Vision system (assembly); 4) Robot vision system; 5) Conveyor; 6) Cobot.

Table 5. Resources of the assembly line

Name	Brand	Model	Activity
1) Modula	Modula	Lift	Storing industrial products, semi-finished products, spare parts, and any type of product in any industrial environment and department.
2) AGV+ roller conveyor	Comau	Agile 1500	Transporting the required materials to different stations.
3) Vision system (assembly)	Comau	Vir.GIL	Guiding the operator during the assembly phase.
4) Vision system (robot)	Ad hoc	Ad hoc	Guiding the cobot during the packaging phase.
5) Conveyor	Ad hoc	Ad hoc	Loading and unloading the materials from the robot working area.
6) Cobot	Comau	Racer5	Performing automatic operations, such as packaging of the final product.

The workflow of the assembly process is composed of the following phases. First, the required raw materials are provided to the operator by the automatic warehouse according to a requested product. The operator moves the raw materials onto the AGV. Then, the AGV transports the raw materials to the assembly station. Thanks to the vision system, the operator has been guided during the assembly phase. The AGV transports the semi-finished product to the packing station. Here, the operator loads the materials onto the conveyor, which moves the materials up to the working area of the cobot. The cobot performs the packaging operations. Finally, the operator loads the final product onto the AGV, which returns to the initial station.

3.3. Software evaluation

Process Simulate has been evaluated by developing the simulation of the entire assembly phases, as depicted in Figure 3. The operators' tasks have been simulated, providing an analysis of the postures and ergonomic metrics [13]. However, the mechanism of the Modula warehouse is approximate compared to the functionalities of the real one. Also, the movement of the AGV is simplified. The AGV is modeled as a generic device in the software, ignoring its actual kinematic behavior. The functionalities of the vision system to guide the operator in the assembly phase cannot be practically simulated. On the other hand, it is possible to implement sensors to convey signals among the different resources in the simulation. The packaging operations can be nicely simulated. Also, Process Simulate can develop the robot program file to be transferred to the controller according to the generated movements. However, the vision system that communicates with the robot cannot reflect the actual capabilities of the real one.

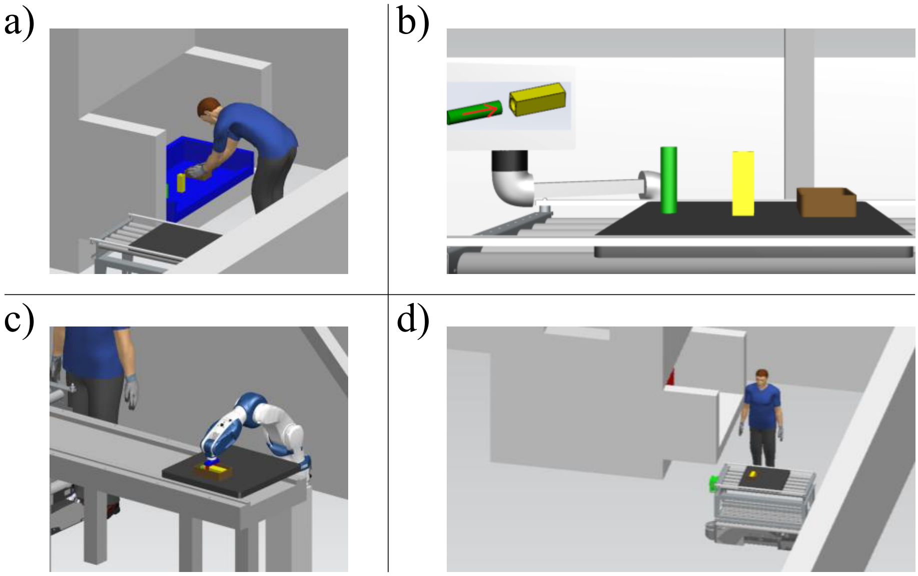

Figure 3. Simulation of the tasks. a) Loading the AGV with raw materials; b) Assembly phase; c) Packaging; d) Return to a home position

Then, the panel conducted the formal assessment of the software according to the characteristics of the simulation. In particular, a value from 0 to 5 is given for each DP by each participant. The value has been given based on how the software can capture each DP. Then, an average value was calculated for each DP, and it was rounded up to the nearest integer. Table 6 shows the results of this process.

Table 6. Evaluation of the simulation performed in Process Simulate

	D1	D2	D4	D6	D7	D11
w %	**16.98**	**22.63**	**23.61**	**17.13**	**16.46**	**3.19**
Student 1	3	5	3	5	5	3
Student 2	3	5	4	5	5	3
Student 3	2	3	4	5	5	2
Professor 1	1	3	3	4	3	2
Professor 2	1	4	2	5	4	1
Expert 1	2	3	2	4	4	1
Expert 2	1	4	2	4	3	2
Average	1.9	3.9	2.9	4.6	4.1	2.0
Value	**2**	**4**	**3**	**5**	**4**	**2**

Looking at the table, it emerges how the software marginally captures interoperability (D1). It is possible to simulate several devices exchanging signals. However, the communication among the resources is limited to predefined signals types. Process Simulate captures virtualization (D2). However, the panel has highlighted that some resources are identified as generic devices, losing the actual behavior. Real-time capability (D4) is partially captured. Thanks to the implementation of communication protocols, it is possible to connect to real external devices, such as PLC. However, the signal exchange mechanism has some latency. The software captures modularity (D6), since resources can be combined and integrated, allowing different configurations. The software captures optimization (D7) due to the possibility of exploring several alternative layouts and logic. Finally, it can be said that Process Simulate does not fully capture the Smart Factory concept (D11). This DP is quite vast and difficult to catch by a single software.

The index (I) is calculated according to Eq. 1. This value is used for a general evaluation of the software.

$$I = 70.6\%$$

To conclude, Tecnomatix-Process Simulate can be useful for simulating assembly lines in the I4.0 context. The panel of students, professors, and experts has agreed with the final output resulting from the framework's application. It can be concluded that the proposed analysis of the characteristics of a software can be beneficial to guide users in a systematic evaluation of simulation software in the context of I4.0 according to specific needs.

4. Conclusions and future works

This paper proposes a framework to evaluate the suitability of a certain simulation software in the I4.0 assembly line context. This framework was tested on a demonstrative assembly line composed of I4.0 resources and facilities. The three steps of the framework were performed in collaboration with a panel of students, professors, and experts. After defining the plants requirements and the related DPs, Tecnomatix-Process Simulate was selected as candidate simulation software. A digital twin of the demonstrative assembly line was developed in Process Simulate. After the simulation of the assembly phases, Process Simulate was evaluated according to the selected DPs.

The analysis has shown that the proposed framework is a valuable tool for performing a systematic and transdisciplinary evaluation of simulation software in the

I4.0 assembly line. Also, it can be adapted to different requirements and DPs, increasing flexibility and applicability. Also, implementing MCDM approaches and DPs of I4.0 is a promising direction during the software evaluation. Indeed, they proved to be valuable approaches during the decision-making phase.

As future directions, the framework should be tested on several test cases. Moreover, the framework could be extended to other manufacturing processes. Also, other software will be tested to evaluate the approach effectiveness. In this context, the analyses and comparisons of more software will be possible, in order to implement a MCDM approach. Finally, other steps of the framework will be validated to increase the completeness of the software assessment. In particular, evidences of the usefulness of software simulations will be gathered comparing simulated and real scenarios, and furthermore, extended evaluation indices will be developed.

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