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Operator-centred Lean 4.0 framework for flexible assembly lines

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Abstract

This article provides a starting point for developing a methodology to successfully implement Industry 4.0 technology for assembly operations. It presents a novel multi-layer human-centred conceptual model in line with Lean philosophy which identifies the assembly operator functions and relates them to other production departments, identifying how they would be affected by incorporating new digital technologies. The model shows that assembly operators would only be directly supported by hardware digital technologies, while the production support departments would mainly employ Industry 4.0 software technologies. The work presented here paves the way for developing a methodology for implementing Lean Assembly 4.0.

Keywords: Assembly; Lean; Industry 4.0; Human-centred, Operator.

1. Introduction

The term Industry 4.0, initially adopted by a German strategic program [1], is used nowadays to express the relationship between different elements of the current manufacturing sector and the new digital technologies. Recent research on Industry 4.0 tends to focus on the possibilities brought by a certain new digital technology or develops a framework to understand what the effect of would be incorporating such new technologies.

Scarcely explored is the development of implementation methodologies that bridge Industry 4.0 conceptual frameworks with the current state of industrial environments, and the process to successfully deploy new digital technologies that bring the expected returns of investment [2]. Additionally, if the Lean production approach and its techniques are also related to this implementation, the concept of Lean 4.0 could be used as shown in the literature [3].

This article aims to provide a starting point for developing a methodology for successfully implementing Industry 4.0 technology for assembly operations, in line with Lean production principles. To do so, the model presented here links assembly elements and ancillary departments to Industry 4.0 Key Enabling Technologies for assembly operations, considering the operator as the centre of the model, which is coherent with Industry 4.0 principles [4,5], Lean manufacturing [6] and the EU prospects for Industry 5.0 [7].

In section 1.1 changes in demand trends are presented, introducing a particular issue resulting from mass-customisation: high-mix low-volume. Section 1.2 describes the focus shift towards people in both Lean production and Industry 4.0. Section 1.3 introduces the role of new technology to support humans in assembly: Operator 4.0. Section 2 introduces an operator-centred Assembly 4.0 model which identifies which digital technologies have a place in supporting operator functions and interactions in the Industry 4.0 factory. Finally, Section 3 presents the conclusions of the article.

1.1. Demand trends: mass customisation requires flexibility

Although a clear segmentation traditionally existed between mass-produced goods and made-to-order products, the market

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trends have been shifting towards the customisation of mass-produced items [8]. Despite this not being economically sustainable in the past; technological advances have made it possible. Managing the complexity associated with mass customisation remains one of the main challenges for global production networks [9]. In the near future, mass customisation could not only become desirable, but expected of any company wanting to remain competitive. In this context, adaptable, changeable, and decentralised manufacturing networks will possess key competitive advantages [9,10].

Mass customisation leads to a particular production demand problem, high-mix low-volume: a large number of items being demanded, in small amounts each one, and with a variation not depending on seasonal trends, making its forecast difficult and inefficient. To stay competitive in such a context, manufacturing companies will need to become more flexible without compromising their productivity.

Fortunately, several Industry 4.0 digital technologies are expected to prove useful in achieving this as already shown in the literature [11–13].

1.2. Production evolution: Lean 4.0 and focusing on people

New digital technologies have set the landscape for a fourth industrial revolution, conceptualised as Industry 4.0, which describes a vision of increased flexibility and automation; data and information flow across processes, functions, and companies; enhanced quality achieving zero-defect production; leveraging big data, neural networks, machine learning and Artificial Intelligence, among other digital technologies, to maximise efficiency [4].

Lean manufacturing, a generalization of world-leading Toyota Production System, has proven its efficiency in high demand variability, shorter new product development cycles and customer-focused, highly competitive environments [14, 15]. It is therefore a solid starting ground for any manufacturing system evolution seeking to improve productivity and flexibility at the same time. One of the key characteristics that set apart Lean production systems is its respect for people and people's key role in their company's continuous improvement journey [16, 17].

Hence, Lean production needs to be the cornerstone on which Industry 4.0 technologies rely to enhance production. Lean automation is then the synergy between the Lean approach and the new digital technologies – Lean 4.0 [12]. According to Kolberg and Zühlke [18], Computer Integrated Manufacturing (CIM) failed due to the complexity required for the automation technology, while the Lean approach was successful because of its high effectiveness, achieved by reducing complexity and avoiding non-value-added processes.

Although Industry 4.0 solutions to specific Lean production issues may prove useful, either replacing or enhancing existing Lean tools, it is looking at the production system from a holistic perspective where the maximum benefits of disruptive digital technologies could be achieved [3,12].

1.3. Assembly and Operator 4.0

The goal of flexible assembly systems in the Industry 4.0 era, named 'Assembly 4.0' by Cohen and Faccio in [19] –a term that will be used in the present article– is to address the mass customisation demand paradigm. The most relevant key enabling technologies for assembly are –according to [20]– the Internet of Things, Big Data, Real-time optimisation, Cloud computing, Cyber-Physical Systems, Machine Learning, Augmented Reality, Cobots and Additive Manufacturing.

Considering the critical role of assembly line level operators on Lean production systems performance, it is only natural to consider how new digital technologies would enhance the human operator best traits, and help to cover their weaknesses, aiming for a 'human-automation symbiosis' [5]. To analyse this human-technology interaction, it would be useful to start from the operator's perspective to ensure that the implementation of changes does not negatively affect people but supports them [21].

As proposed in this novel work, keeping the operator at the centre is the focus of the methodology approach proposed and described in the following section, where all the interactions between an assembly operator and production activities and its environment have been established and analysed.

2. Operator-centred assembly 4.0 model

Due to the success of Lean production systems and because respecting people is one of its key features, human operators need to be at the centre of any methodology seeking to integrate Industry 4.0 digital technologies for assembly operations.

This model aims to explain, from the point of view of the assembly operator, which of its productive functions would be affected by Industry 4.0 technologies, and how. It also explains how new digital technologies would affect the material and information flow between the operator and the main Departments which support assembly operations, such as Logistics & Planning, Maintenance and Quality Control.

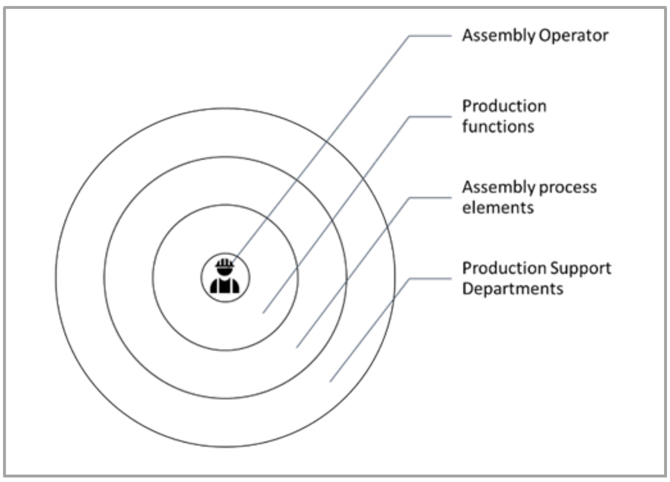

Fig. 1. First stage of the human-centred model of assembly systems

The model proposed consists of two stages. The first stage (see Figure 1) develops three concentric layers: the productive functions carried out by the operator, the elements used to do so, and the Production Support Departments involved with the operator; along with how they interact with the operator (Sections 3.1 – 3.4, respectively). The second stage relates Industry 4.0 digital technologies with its specific point of application from the first stage (Figure 4, Section 2.5).

2.1. Production functions

The first layer considered in the model presented in Figure 1 –the most closely related to the operator– consists of the production functions. Manual assembly operators carry out four main productive functions:

- Assembly (AS): attachment of parts together or to the previously processed unit, including manipulation of the units into and out of the workstation
- Quality Control (QC): building quality in each process step, along with the required tests performed by the operator
- Changeover (CO): adjustments to the workstation, tools, parts, and fixtures to assemble a different product model
- Communication (CM): recording, sending, and receiving data or information.

2.2. Assembly process elements

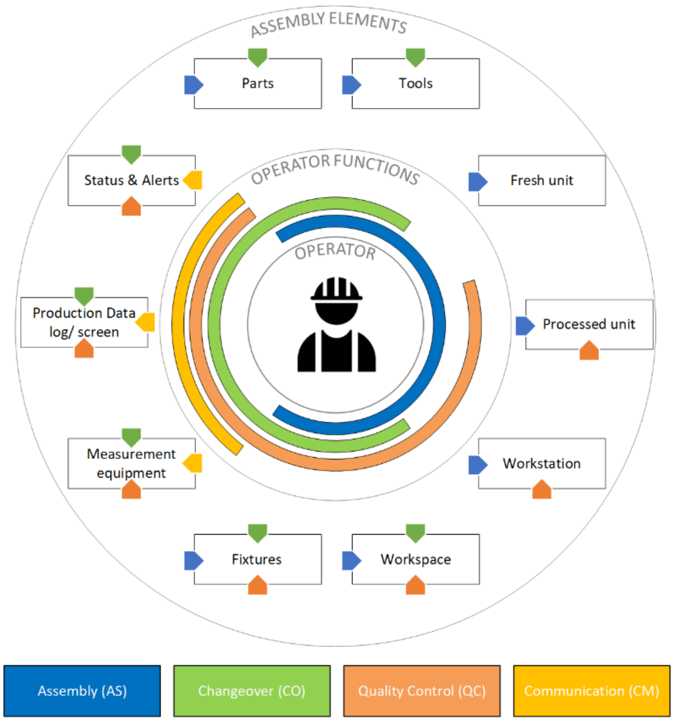

Fig. 2. Assembly operator functions and process elements utilised to perform them

To develop these production functions in 2.1, several assembly process elements are used, which constitute the second layer, as shown in Figure 2:

- Workspace: the actual space in which the assembly task is carried out. Involved in AS, QC and CO.
- Workstation: the physical space where the in-process unit is held while parts are assembled. Involved in AS and QC
- Fresh unit: the next upcoming unit to be processed. Involved in AS
- Processed unit: the previously assembled unit. Involved in AS and QC
- Tools: devices employed to attach parts to the unit. Involved in AS and CO
- Parts: components to be assembled to the in-process unit. Involved in AS and CO
- Status & alert display: devices which function is to inform of the production status and visually or audibly alert of any anomalous situation. Involved in AS, CO and CM
- Production data log/ screen: physical or digital means of tracking the production schedule, recording data, and displaying supporting information. Involved in AS, CO and CM
- Measurement equipment: devices utilised to gauge or test relevant characteristics of the in-process unit. Involved in QC, CO, and CM
- Fixtures: devices employed to hold the unit while performing assembly or QC operations. Involved in AS, QC and CO

2.3. Production Support Departments

Assembly operators are supported by five key departments of the organisation: (i) Assembly: other operators, situated upstream, in parallel or downstream in the process stream; (ii) Production Management: including team leaders and assembly managers, they typically deal with non-conforming situations; (iii) Maintenance: they ensure the tools, fixtures and machines; (iv) Quality: they establish Quality Control policies, calibrate and validate testing equipment; (v) Logistics & Planning: they provide the correct materials and parts at the right time, retrieve empty packaging and schedule production.

2.4. Operator – Supporting Departments interaction

As Figure 3 depicts, operators interact with the supporting departments using a combination of process elements. White arrows indicate material flow, while black arrows indicate data flow.

As shown in Figure 3.a, operators receive fresh units from upstream process steps; and send processed units towards downstream process steps. Information relating non-conformities or upcoming changeovers in shared typically verbally in an informal manner. Formal information about the production status is shared using Status & Alerts process elements, such as Andon lights or display screens. Operators also exchange information formally with Production Management using Production Data logs and screens. Measurement equipment often sends test data to an IT system that stores it and provides Data Analytics.

Operators and Maintenance exchange information via Status & Alerts and Measurement Equipment (see Figure 3.b). Also, Maintenance provides and maintains Tools and Fixtures, in response to the operator’s information regarding its state.

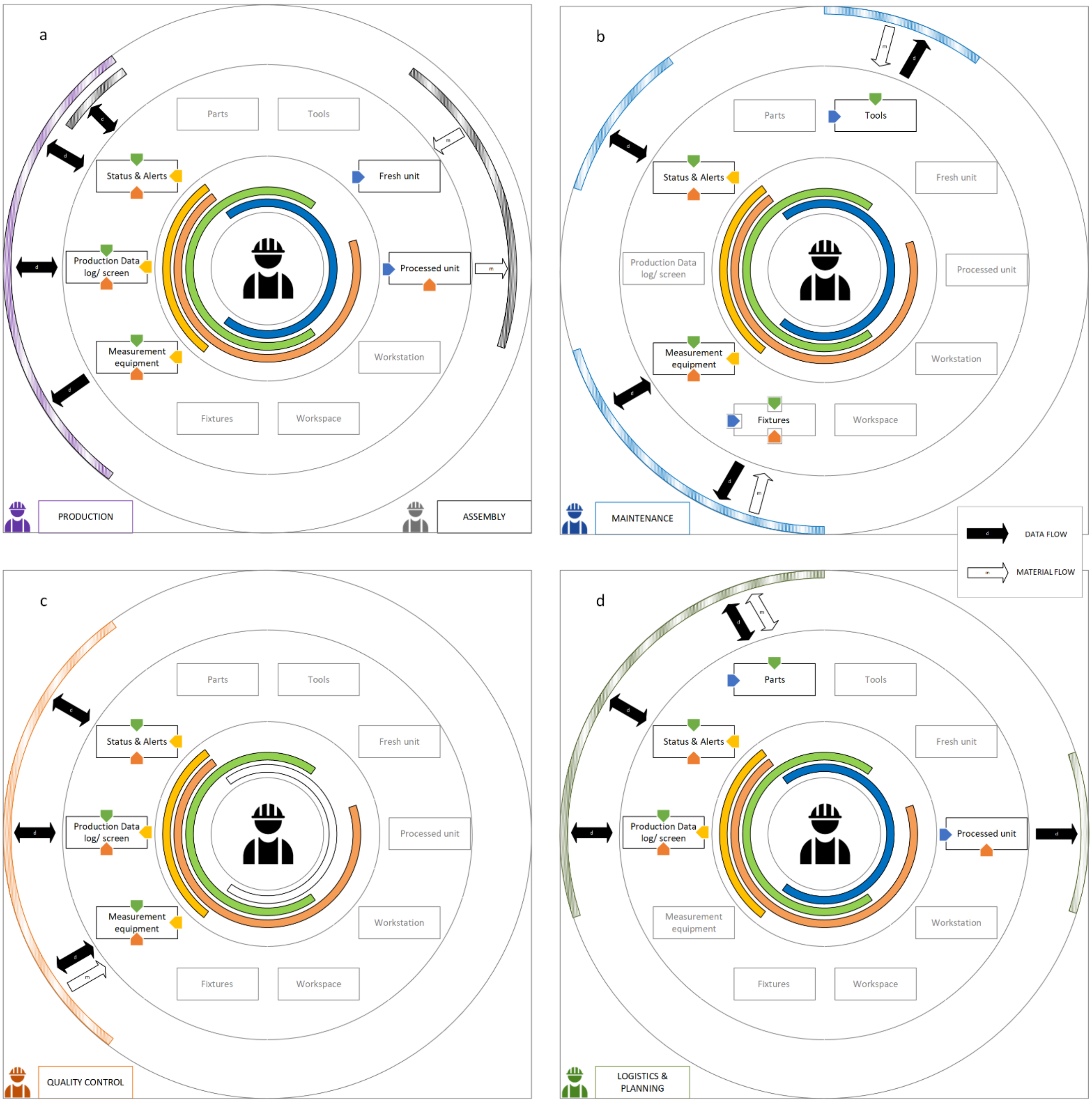

Fig. 3. Operator – Supporting Departments interaction: (a) Production Management & Assembly; (b) Maintenance; (c) Quality Control; (d) Logistics & Planning.

Operators and Quality exchange information via Status & Alerts, Production Data log/screens and Measurement Equipment. Additionally, Quality provides and maintains the Measurement Equipment (see Figure 3.c) that Operators use to perform QC.

Figure 3.d shows that Logistics & Planning provide the operator with parts to be assembled onto the unit, and they retrieve empty packing (material flow) Along with parts or empty boxes, information is transmitted, e.g., when using a Kanban or a twin-bin system. Operators also provide implicit information through successfully processed units, which are a measure of production output. They also exchange information via Status & Alerts, Production Data log/screens. A key piece of information provided by Logistics & Planning is the production schedule, specifying batch sizes and changeovers, which can impact the operator's productivity.

2.5. Industry 4.0 enabling technologies for Assembly

To connect the proposed model with Industry 4.0, nine enabling technologies have been considered as particularly relevant for Assembly Systems [20]. Six of them are software technologies (Internet of Things, Big Data, Real-time optimisation, Cloud computing, Cyber-Physical Systems, Machine Learning), and three are hardware technologies (Augmented Reality, Cobots, Additive Manufacturing).

While the assembly operator's main functions are not expected to change due to the availability of new digital technologies, the way these functions are developed will need to evolve to enjoy its benefits. The relationship with Supporting Departments also shows potential for improvement. Lastly, Supporting Departments are expected to integrate new digital technologies to obtain increased benefits. Although the latter technologies will not be employed directly by the assembly operator, they will affect his work. Therefore, the implementation of new digital technologies at all levels needs to consider the impact on assembly workers to be successful. Figure 4 depicts which Industry 4.0 digital technologies would be beneficial at each layer of the model.

Three key technologies could be used by operators to carry out its functions, as shown in Figure 4: Augmented Reality or Mixed Reality (AR/ MR) [22], collaborative robots (cobots) [23] and Cyber-Physical Systems (CPS) [24].

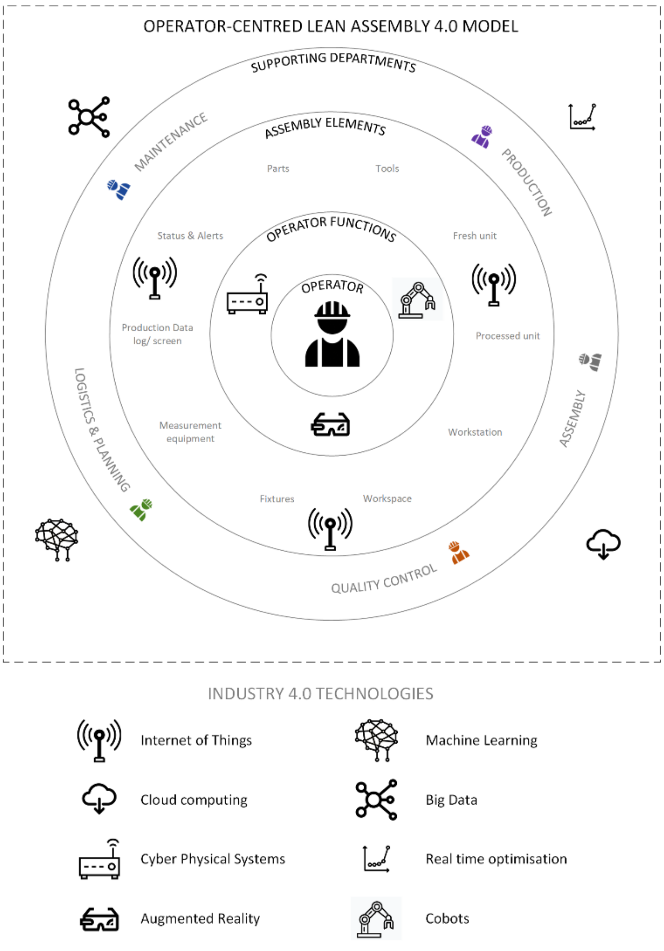

Fig. 4. Industry 4.0 technologies to be employed at each layer of the Human-Centred Assembly 4.0 model.

Aiming to support the assembly operator main functions (see section 2.1), Augmented Reality/Mixed Reality could be widely used: enhancing the operator cognitive ability while performing a changeover –which would need to be streamlined and mastered to achieve mass customisation, and supporting a zero-defect assembly and Quality Control, as introduced in [25]. Cobots are to be used not only for assembly tasks, but also to flexibly present the unit-in-process in the best orientation and position for an ergonomic human operation or inspection; even contributing to quick changeovers. Finally, CPS would gather and receive data, reducing the cognitive load of the operator while ensuring the quality and reliability of the data captured and sent in the workstation.

Regarding the Operator's interaction with the Supporting Departments, the Internet of Things could be employed to communicate the vast amount of data required to and from them. Industrial IoT can be combined with Augmented Reality technology to provide real-time maintenance assistance remotely to assembly operators, reducing the equipment downtime in the event of a breakdown, in a similar fashion to systems used to facilitate engineering knowledge to maintenance technicians [26]. Augmented Reality can also provide enhanced tools for communication between Operators and the Supporting Departments, enabling collaborative assembly process design, analogously to the product process design presented in [27].

Finally, Supporting Departments could benefit from using Cloud computing, Big Data, Machine Learning and Real-Time optimisation, which would affect assembly operations positively in the long term. These software technologies would influence greatly the bottom-line results, but these will not be directly perceived by assembly operators since they will not be in close contact with such technologies. For example, Big Data and Digital Twins for Logistics & Planning would help optimise in-factory stock levels while ensuring reliable feeding of components to assembly cells, but this optimisation is hardly seen from the operator point of view.

2.6. Discussion

The multi-layer model presented previously explains an Assembly operator functions, the tools utilised for such end, and its interactions with the Production Support Departments, from a human-centric perspective. It then establishes which of the previous layers could be affected by Industry 4.0 digital technologies, and which technologies would enhance each particular function or relationship.

As Figure 4 shows, there is a clear differentiation between the technologies used by the operator to perform its functions (hardware technologies), and the technologies used by the Production Support Departments – not directly by the operators (software technologies).

Although this model does not reveal how to successfully implement Industry 4.0, its necessary prerequisites, or the expected order of magnitude of the benefits it would bring; it does identify which technologies could be used to support each one of the operator's duties, making it a solid starting point for future research.

This model is builds on top of the foundations laid by solid previous research: the central role of people for Industry 4.0 [4, 5] and for Lean assembly systems [6], as well as the EU prospects for Industry 5.0 [7]. However, it has not been validated experimentally to date.

To determine the prerequisites and the potential benefits of implementing Industry 4.0 technologies according to the framework presented here, validation in an industrial real study case is deemed necessary.

3. Conclusion

Aiming to achieve mass customisation, production systems in the Industry 4.0 era will need to support the Assembly operators when and as needed. The importance of people in Manufacturing systems was already a key point in successful Lean production systems, and Industry 4.0 technologies need to embrace this perception.

A human-centred model was presented, explaining, from the point of view of the assembly operator, which of its productive functions would be affected by Industry 4.0 technologies, and how so. One clear differentiation appears between the technologies used by the operator to perform its functions (hardware technologies), and the technologies used by the Production Support Departments – not directly by the operators (software technologies).

This model does not aim to be exhaustive for all kinds of manual assembly process, but it does include everything related to most manual high-mix low-volume processes, and it is open enough to allow additions from specific processes to adapt it where necessary.

Future lines of work would employ this model to develop an explicit methodology for implementing Industry 4.0 digital technologies aiming to support the human Assembly operator and evaluating the potential gains in industrial contexts, thus providing empirical validation in real industrial study cases. This would correlate Assembly 4.0 implementation to key operational KPIs (e.g., productivity, on-time delivery, first time yield) when analysing a particular case study, whose boundary conditions and approach could be properly established by the model.

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