Symbiotic Integration of Human Activities in Cyber-Physical Systems

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Abstract: Human integration in cyber-physical systems (CPS) is playing a crucial role in the era of the digital transformation, notably because humans are seen as the most flexible driver in an automated system. Two main reference models for human activities in production systems are usually considered, namely Human-in-the-Loop (HitL) and Human-in-the-Mesh (HitM), which present different requirements and challenges. This paper aims to overview the different activities related to the human integration in CPS, particularly discussing the requirements that can be found in HitL and HitM models for the different phases of the decision-making process, namely detect, determine, develop and describe; and analyzing the technologies and computational tools to support these human activities. The human integration in CPS is illustrated through three examples, where humans playing the operator and manager roles are integrated in the PERFoRM and FAR-EDGE ecosystems, covering different phases of the decision-making process.

Keywords: Cyber-physical systems, human integration, Human-in-the-Loop, Human-in-the-Mesh.

1. INTRODUCTION

The Manufacturing sector has experienced several relevant transformations in the past centuries due to a diversity of technological innovations; latterly the Fourth Industrial Revolution has been boosted by Cyber-physical systems (CPSs) (Kagermann et al., 2013). The possibility to connect powerful autonomous devices with computational, sensorial, actuating and communication capabilities has opened up the way towards the integration of the material and human world of the shop-floor with the digital world of the information systems.

Humans are in fact a unique enabler for flexibility in an advanced automated CPS, and is one of the pillars of Industry 4.0. It is important to highlight that some decades after the disillusion from the idea of the unmanned factory, there is large consensus among the stakeholders, that the fourth industrial revolution leads to social-cyber-physical systems, in which the role of human is core (Kagermann et al., 2013). Humans are required to steer the transformation, to intervene for updating production plans and reconfiguring the systems (Pacaux-Lemoine et al., 2017). However, to fully exploit the potential of humans in manufacturing environments characterized by CPS, specific human-centric design approaches are required, together with methodologies and technologies for the symbiotic integration of the human activities in CPS (Boy, 2011; Romero et al., 2015).

The objective of this paper is to provide an analysis of the human activities needs when integrating in CPS systems, by analyzing the available technologies and required computational tools to support this human integration. Three examples of the implementation of such human integration in flexible and reconfigurable factory architectures, based on CPS, Internet of Things (IoT), cloud and edge technologies, are described.

The remaining paper is organized as follows: Section II summarizes the human activities needs in cyber-physical systems according to the decision-making process and the role of the human, and Section III discusses some available technologies to support the human activities. Section IV presents an analysis of the required functionalities of computational tools to support the human activities and Sections V and VI provide three examples of implementing the integration of human activities in the PERFoRM and FAR-EDGE CPS ecosystems. Finally, Section VII rounds up the paper with the conclusions.

2. HUMAN ACTIVITIES IN CYBER-PHYSICAL SYSTEMS

In production systems, we can refer to two main reference models for human activities: Human-in-the-Loop (HitL) and Human-in-the-Mesh (HitM) (Fantini et al., 2016). The first refers to situations in which the worker is directly participating in the process of products fabrication or assembling and its loop of control; it is usually enacted by the role of the Operator. The second model refers to situations in which the worker is participating to the process of production planning and its loop of control, and it is usually enacted by the role of the Manager. The activities of HitM require relentless focus on the execution of the manufacturing processes and have an immediate impact on the quality of part processing and assembling; the activities of HitM allow for intermittent attention but need sophisticated methods.

Human activities for both models can be described with reference to the decision making process, summarized in four main phases (Fantini et al., 2018):

i. Detect, phase in which awareness about the situation requiring decisions is achieved;
ii. Determine, phase in which the alternative options with their potential consequences are identified, analysed and selected to make the decision;
iii. Develop, phase in which actions are executed in order to implement the decision;
iv. Describe, phase in which the relevant information about the performed decision making process and its results are reported.

In order to integrate the human activities in CPS, with the final goal of achieving symbiotic behaviours leading to improve overall performances, it is necessary to analyze the needs of both HitL and HitM in each phase, which are summarized in Table 1.

In this paper we first address the needs of the HitL with reference to the fabrication process, to the typical situation of an Operator attending a machining workstation. In such a situation, the Operator typically has to take a part, fix it in the workstation, launch the machining program, supervise the machine and finally remove the part from the workstation. This simplified description does not convey the complexity of the task. A more comprehensive, although not exhaustive, analysis of this activity, taking into account the variety of parts, the events that can occur, and consequent decisions to be made, encompasses several issues that the HitL has to handle. On this basis it is possible to identify the requirements of the HitL with reference to each of the four phases of the decision-making process:

i. When starting a new processing cycle, in order to prepare the part and start the machining, the HitL needs to know what specific part has to be processed next in the workstation and what part program has to be applied. During the execution of the part program, the HitL needs to detect any possible problem depending on the machine or the part.
ii. In order to start machining, the HitL needs guidance about how to position the fixtures and the part, and to identify the correct part program. When a problem has been detected, the HitL needs to identify and select the most appropriate actions to fix it, such as replacing the worn or broken tool or how to fix a part's defeat. In particular, the HitL needs support in relating the identified situation to its causal chain, to consider the alternative actions to remove the root cause and to remedy the damage, which may imply interactions with and authorization by HitM for reworking.
iii. In order to execute the decided actions, the HitL needs support on how to find and fix the part and the tools, adapt the part program or do the reworking.
iv. For several reasons, including quality assurance and the request to accumulate, share organizational learning, the HitL needs to record the whole process of decision-making and related results with a minimum effort.

The needs of the HitL in the assembly process differ from those in the fabrication processes:

i. The HitL requires to be alerted when it is time to start a novel assembling cycle.
ii. The HitL needs to be supported in deciding which product to start assembling next. This decision is particularly critical in case the variety is particularly high as it is the case for customized products.
iii. During the assembling operations, the HitL needs to receive spatial information and guidance about which components are to be assembled and how.
iv. The HitL needs to confirm that the assembly has been executed according to the product-specific bill of material and assembly instructions.

The needs of the HitM analyzed in this paper refer to the Manager that is responsible for the production, whose main task typically consists of managing the production schedules to guarantee efficiency and delivery times. Also in this case, the complexity of the task is related to the number and variety of the products, processes, machines, and to the events and cases that can occur. On this basis, in analogy with the HitL, it is possible to analyse the main needs of the HitM in each phase:

i. In managing the production schedule, the HitM needs to anticipate and detect any issue that affect the regular execution of the production scheduling. In particular, the HitM needs to know if a workstation is having a breakdown or if a problem prevents a part to be ready as an input to the production, because it was not delivered by the supplier or an upstream department. Furthermore, the HitM needs to quickly detect when performances are deteriorating.
ii. Once detected an issue, the problem has to be analyzed and a decision has to be made. Therefore the HitM needs support to identify the causes, and to formulate and select the most appropriate course of action. This course of actions may concern planning maintenance interventions and modifications of the dispatching and scheduling plans. Decision-making may hence require the involvement of other roles, e.g., the Maintenance Technician, which may lead to the need for coordinated decision-making.
iii. In the execution of the decision made, the HitM needs to implement the decided action, by launching new activities and/or modifying the plans. Furthermore the HitM has to ensure that these activities and changes are communicated to all the involved persons and systems.
iv. In analogy with the HitL, the HitM needs to capture and record all the elements of the decision making process followed, together with the outcomes.

Table 1. Human activities according to decision-making and role.

Decision-making process phase	Human-in-the-Loop Needs	Human-in-the-Mesh Needs
Detect (situation awareness)	• Know short-term scheduling and associated information • Know local/process/product-specific anomalies	• Know overall system behaviour and performances • Know system anomalies
Determine (analysis and decision making)	• Identify events/causes • Select the most appropriate local operation	• Identify causes, formulate and select courses of action, coordinate and decide
Develop (task execution)	• Perform the selected local operation	• Launch activities, deploy and communicate scheduling and dispatching plans
Describe (reporting, explaining)	• Record decisions and actions made • Record comments	• Record decisions made and reason behind them • Record comments

Even with reference to the limited scenario addressed in this paper, the critical role of the workers clearly emerges. In fact, both the Operator, in the loop of control of the manufacturing process, and the Manager, in the mesh of the interconnected systems, handle complex tasks and need various and relevant support.

3. ANALYSIS OF TECHNOLOGIES TO SUPPORT THE HUMAN ACTIVITIES

The human integration benefits of the use of several hardware and software technologies, namely technological devices to support the interface, IoT technologies to support the connectivity and data storage, and computational applications to support the decision-support processes. This section analyses the first two issues and the next section details the third one. This analysis considers that the needs of the operator role are different compared to those of the manager role.

3.1 Technologies to Support the Interface

Technologies such as such as augmented and virtual reality, wearable tracker, intelligent personal assistant, collaborative robot, social network, big data analytics, have been identified for supporting humans in the context of Industry 4.0 (Romero et al., 2016). Particular emphasis has been given to the role of the Operator for the specific requirements and constraints implied by its tight interaction with the physical world. However, also the Manager can benefit from a set of supporting technologies (Moeuf et al., 2018).

For the purpose of this paper, first we have to analyze the physical devices and the technologies supporting the Human Machine Interface (HMI) for both the HitL and HitM approaches. As a second step, we need to consider the type of service. The HitL is usually close to the workstation and requires to have his/her hands free only for executing few operations such as loading and unloading the parts and the fixtures, in fabrication; and positioning and assembling the parts, in the assembly. Therefore, fixed devices on the workstation, such as touch screens, could easily fit. Alerts could be provided through buzzers and flashing lights. However, spatial information about the actual localization of parts and tools, or about how these objects could be more effectively displayed through other types of mobile devices, such as smart glasses or watches. Finally, for describing and explaining activities, in addition to completing pre-defined forms, the possibility to record comments and photographs has to be provided through voice recorders and cameras associated with the smart devices. The HitM could be sitting at his/her desk part of the time, but also be moving on the shopfloor. Therefore a computer or a tablet could be considered adequate.

3.2 Technologies to support Connectivity and Storage

The integration of the human in the performance of the several identified activities requires the proper use of technologies to support the data acquisition, transmission and storage. For this purpose, IoT technologies are used to transparently support the connectivity among distributed heterogeneous hardware devices and software applications. OPC-UA (Open Platform Communications - Unified Architecture) technology is becoming a de-facto standard in industrial environments, where a vast number of vendors are increasingly offering their components to natively communicate using it.

The use of publish/subscribe approaches allows the development of loosed coupled solutions facing the interoperability and scabality issues, decoupling the communication among several components that compose the system architecture. In this domain, MQTT (Message Queuing Telemetry Transport) and OPC-UA, in its publish-subscribe approach, are becoming emergent technologies.

Cloud based systems also play an important role in such area to support the storage of the huge amount of data that is being generated at the shop floor and to host the execution of complex machine learning algorithms to perform data analysis supporting monitoring, diagnosis, optimization and planning. In case of the huge amounts of generated data, non-relation data bases are more suitable.

4. ANALYSIS OF FUNCTIONALITY TOOLS TO SUPPORT THE HUMAN ACTIVITIES

As previously referred, computational applications play also a crucial role to support the human integration in CPS. The analysis of Table 1 allows to identify several functionalities that these computational tools should provide to face the human activities needs, namely communication, monitoring and analytics. The degree of use of these functionalities by the human strongly depends on the decision-making process being performed and on the role of the human, as illustrated in Table 2.

Table 2. Funcionalities that computational apps should provide for the human integration.

Role	Decision-making phase	Communica-tion	Monitor-ing	Analytics
Operator	Detect	High	Low	
	Determine	Medium		
	Develop	High		
	Describe	High		
Manager	Detect	High	High	High
	Determine	High		High
	Develop	High		
	Describe	Medium		High

The communication cluster comprises functionalities related to the visualization and communication of information to the human, e.g., information regarding to the procedure of how to process a part or to execute a maintenance intervention, or the evolution of operational parameters of a machine/system along the time. At this stage, bilateral communication is also supported, i.e. from the humans to the systems for reporting activities.

The monitoring related functionalities comprise the capability to detect anomalies in performance indicators, erroneous processing conditions and warnings about the machine health. At last, the distributed data analysis functionalities are related to the use of machine learning and simulation techniques to analyze data to detect patterns and trends in data regarding diagnosis, prediction, optimization and planning, supporting also the formulation and selection of alternative options. Amongst others, data analytics, deep learning, what-if simulation techniques and root-cause-analysis methods can be properly used.

These functionalities address the needs of the Operator and the Manager with various degrees of support, depending on the role and on the different phases of the decision making process, as illustrated in Table 2. Visualization is very useful for the Operator in all the phases to provide this role with information easily connected to the physical world in which it operates. Monitoring is relevant in the detecting decision-making phase supporting the Operator to identify local anomalies, and it is of the utmost importance for the Manager to support the identification of undesirable behaviours of the production system, early detection of upcoming failures or other problems. Data analysis is particularly important to support the detection and determine phases for the Manager, to enhance capabilities for the recognition of undesirable situations and the prediction of possible the consequences under different hypothesis. In the future, it is reasonable to expect that these analytics functionalities will become more and more important to support human decision-making, at each level of the organizations, including operators.

5. EXAMPLES OF HUMAN INTEGRATION IN THE PERFORM ECOSYSTEM

This section describes two examples of how some human activities are integrated in the PERFoRM CPS, supported by the KPI Visualization and Monitoring tool. These examples address the manager role for the detect and determine decision-making processes.

5.1 PERFoRM Architecture

The human integration is a crucial issue in the PERFoRM ecosystem, which aims at the seamless reconfiguration of machinery and robots, aligned with the Industry 4.0 principles, allowing to integrate data from different data sources in a transparent manner to support the data analysis for system reconfiguration.

The PERFoRM system architecture (Angione et al., 2017) is based on a network of distributed HW devices (e.g., robotic cells and Programmable Logic Controllers (PLCs)), SW applications (e.g., SCADA (Supervisory Control and Data Acquisition), and data analysis apps) that expose their functionalities as services following the SOA (Service-oriented Architecture) principles. These devices and applications are interconnected in a seamless, transparent, secure and reliable manner by using an industrial middleware (see Figure 1), enabled by the use of standard interfaces that allow to reach pluggability and interoperability. The connection to legacy production systems, e.g., databases or production devices, use adapters that translate their own data model into the standard interfaces defined in PERFoRM.

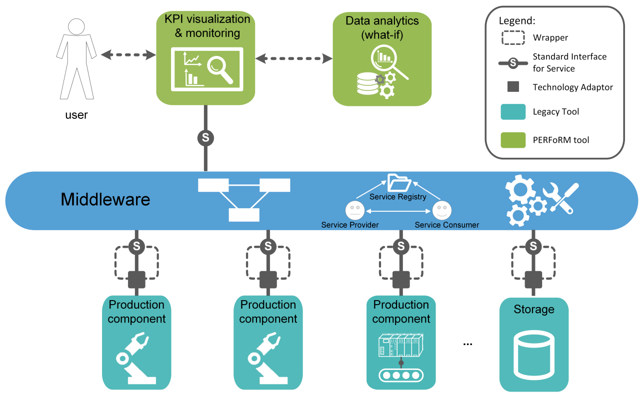

Figure 1. PERFoRM system architecture.

PERFoRM also comprises a set of tools particularly designed with advanced algorithms and technologies to support the visualization, monitoring, reconfiguration and optimization of CPSs. One of developed SW tools is the KPI (Key Performance Indicator) Visualization and Monitoring tool (Pereira et al., 2017) that provides a set of functionalities to support the tactical and strategical decision-making to mitigate the occurrence of condition changes and to optimize the system operation to face business opportunities. Particularly, it allows to detect deviations and trends in the evolution of factory's KPIs, and to perform what-if game simulation based on the analysis of the effect that the variation of KBFs (Key Business Factors) will provoke in the associated KPIs.

5.2 Detect and Determine Decision-Making Processes at HitM

This tool provides a mean for the human integration in CPS, particularly addressing the HitM layer (manager role) running the data visualization, monitoring and analysis to support detect and determine decision-making.

The production manager is able to visualize the main KPIs of the production process through the user interface (UI) provided by this tool, as represented in Figure 2, which shows in real time the KPIs of the several production stations. The UI provides the target and the actual KPIs values, as well as their evolution trend (positive or negative), using a colour schema, for a simple, intuitive and comprehensive understanding, and a quick detection of problematic situations.

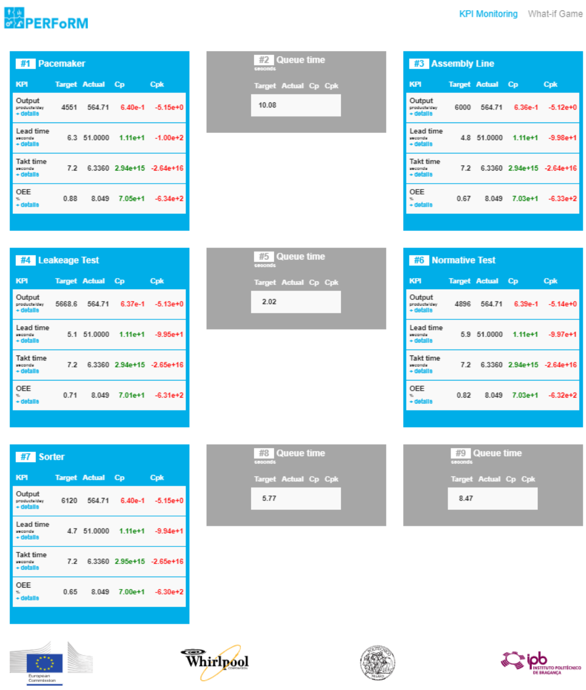

Figure 2. Visualization of KPIs to support the detect decision-making process

The visualization of the several KPIs requires the collection of data from the machinery disposed along the production line, that is performed through the use of the industrial middleware and technological adapters, which provides seamless interoperability among distributed and heterogeneous HW and SW applications.

This tool also supports the human activity related to the determine decision-making phase, particularly the formulation and selection of options. In fact, the production manager is able to perform a what-if game analysis by simulating the change in critical KBFs and assessing in real-time the impacts of the KPIs for a given station. For this purpose, the production manager can play with several DoFs (Degrees of Freedom) related to KBFs, namely the setup time and performance boundaries, and the tool runs several simulations and calculates the alternatives for the specified set of defined KBFs. The results are shown in a spider diagram, illustrating their impact in the operational production indicators. An important feature of the tool is the capability to learn from the human profile and past experience to sort the available alternatives and present only the most promising ones.

6. EXAMPLES OF HUMAN INTEGRATION IN THE FAR-EDGE ECOSYSTEM

This section describes one example of how some human activities are integrated in FAR-EDGE, supported by the simulation functionality. This example address the operator role for the determine decision-making process.

6.1 FAR-EDGE Architecture

The FAR-EDGE architecture (Isaja and Soldatos, 2018) represents the conceptual framework for factory operating systems, based on the principles of Cloud, Edge Computing and IoT technologies. The virtualization of the factory automation pyramid entailed by this solution enables flexible integration of new technologies and devices, easy configurability, and scalability. Through its seven layers of components, and the four cross-cutting functionalities of Management, Security, Digital Models, Field Abstraction & Data Routing, the FAR-EDGE solution allows decentralized control and services to support the three key domain functionalities of Automation, Analytics and Simulation (see Figure 3).

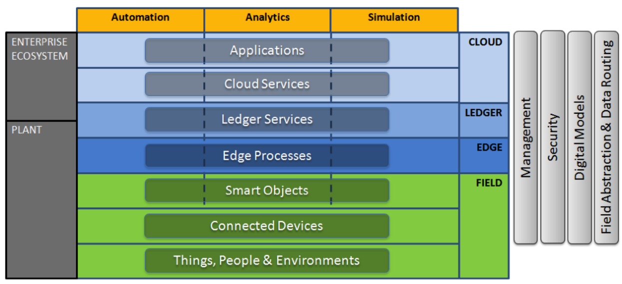

Figure 3. FAR-EDGE reference architecture

The FAR-EDGE open platform is conceived to lower the barriers for manufacturing enterprises to move towards Industry 4.0, by migrating from conventional ISA-95 based control architectures to CPS based systems. In particular, concepts to support this transformation have been developed based on a step-wise approach that progressively incorporates the new components within the existing infrastructures (Soldatos et al., 2019). Therefore, industrial companies can continue to leverage legacy systems, such as Manufacturing Execution Systems (MES) or Finite Capacity Scheduling (FCS), and at the same time benefit from cloud, edge nodes, and edge gateways, so that novel services and applications can be made available prior to the full deployment of the whole FAR-EDGE architecture. This is particularly relevant for enabling ways of supporting and integrating human workers within CPS, that are not possible with conventional production control systems. Real time data and computation capabilities provide the operators with real time simulations that anticipate the effect of alternative options on production performances.

6.2 Determine Decision-Making Process at HitL

The FAR-EDGE simulation tool, based on quasi real time data, provides the assembly line operator great support to perform sequencing operations. The decision about what item is to be assembled next is in fact critical in case of "assembled to order" products, in order to ensure delivery time, to optimize the flow and the overall utilization of resources. Wrong sequencing decisions, may lead to production breaks due to unavailability of components or equipment. The tool can display, based on real time data from the shop floor and from the warehouses, the anticipated consequences of different sequencing options on delivery time, productivity and other KPIs for the Operator to decide. Furthermore, the tool can recommend the best option, in accordance with pre-defined criteria. In both cases, the human is well integrated in the loop of production control production systems and well supported in the determine phase of the decision making process (Tavola et al., 2018).

7. CONCLUSIONS

This paper overviews the different activities related to the human integration in CPS, particularly discussing the needs that can be found in HitL and HitM models for the different phases of the decision-making.

The integration of human in CPSs is illustrated through three examples, where operators and managers are integrated in PERFoRM and FAR-EDGE systems, covering different phases of the decision-making process. In particular, it was showed two examples in PERFoRM focused in the HitM role and addressing the detect and determine phases of the decision-making process, and another example in FAR-EDGE focused in the HitL role and addressing the detect phases of the decision-making process.

The diffusion of these integration models in the manufacturing sector, as for other projects affecting socio-technical systems, requires to take into account human and organizational aspects, included the acceptability from the perspective of the workers.

Future work is devoted to examine in more depth the state of the art of the available technologies to support human activities, and to extend the analysis of exemplary implementations to the human activities, HitL and HitM models, in different phases of the decision-making process. Furthermore, future research may address the relationships between humans and CPS from the perspective of other stakeholders, such as the consumers of manufacturing goods.

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REFERENCES

Angione, G., Barbosa, J., Gosewehr, F., Leitão, P., Massa, D., Matos, J., Peres, R.S., Rocha, A.D., and Wermann, J. (2017). Integration and deployment of an industrial architecture for the perform project. *Procedia Manufacturing, Proc. of 27th Int'l Conf. on Flexible Automation and Intelligent Manufacturing (FAIM'17)*, 896–904.

Boy, G.A. (2011). *The Handbook Of Human-Machine Interaction: A Human-Centered Design Approach*. Ashgate Publishing Limited.

Fantini, P., Pinzone, M., and Taisch, M. (2018). Placing the operator at the centre of industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. *Comput. Ind. Eng.*

Fantini, P., Tavola, G., Taisch, M., Barbosa, J., Leitão, P., Liu, Y., Sayed, M., and Lohse, N. (2016). Exploring the integration of the human as a flexibility factor in CPS enabled manufacturing environments: Methodology and results. In *Proc. of 42nd Annual Conference of the IEEE Industrial Electronics Society (IECON'16)*, 5711–5716.

Isaja, M. and Soldatos, J.K. (2018). Distributed ledger architecture for automation, analytics and simulation in industrial environments. *IFAC-PapersOnLine*, 51(11), 370–375.

Kagermann, H., Wahlster, W., and Helbig, J. (2013). Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Technical report, German National Academy of Science and Engineering.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., and Barbaray, R. (2018). The industrial management of smes in the era of industry 4.0. *International Journal of Production Research*, 56(3), 1118–1136.

Pacaux-Lemoine, M.P., Trentesaux, D., Rey, G.Z., and Millot, P. (2017). Designing intelligent manufacturing systems through human-machine cooperation principles: A human-centered approach. *Computers & Industrial Engineering*, 111, 581 – 595.

Pereira, A., Petrali, P., Pagani, A., Barbosa, J., and Leitão, P. (2017). Dynamic monitoring of key-performance indicators in industrial environment. In *Proceedings of the 15th IEEE International Conference on Industrial Informatics (INDIN'17)*, 1129–1134.

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, A., and Gorecky, D. (2016). Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. In *Proceedings of the International Conference on Computers & Industrial Engineering (CIE46)*, 1–11.

Romero, D., Noran, O., Stahre, J., Bernus, P., and Fast-Berglund, Å. (2015). Towards a human-centred reference architecture for next generation balanced automation systems: Human-automation symbiosis. In *Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth*, 556–566. Springer International Publishing, Cham.

Soldatos, J.K., Cavadini, F., and Lazaro, O. (eds.) (2019). *The Digital Shopfloor: Industrial Automation in the Industry 4.0 Era*. River Publishers.

Tavola, G., Rocca, R., and Spaggiari, G.M. (2018). Business Cases Analysis. Technical report, Deliverable 8.7, FAR-EDGE.