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Impact of Industrial Cyber-Physical Systems on Reconfigurable Manufacturing Systems

Catherine DA CUNHA[1] **and Nathalie KLEMENT**[2]
[1] *LS2N UMR CNRS 6004, Ecole Centrale de Nantes, France*
[2] *Arts et Métiers Institute of Technology, LISPEN, HESAM University, Lille, France*

11.1. Context

A production system allows for the realization of a product so that a customer order can be fulfilled. Physical flows such as supply of raw materials or components, finished products, movement of personnel and information flows (to track production) are necessary for the successful completion of the finished product. All of these flows must interact with each other. Industrial cyber-physical systems (ICPS) can be used particularly in the context of production systems, hence the appearance of a new term: CPPS (cyber-physical production system). We can thus specify the general definition of ICPS, as illustrated in Figure 1.3. In the context of production systems, the industrial system is the production system, made up of resources (see section 11.1.2). A digital control system allows for a certain number of decisions to be made regarding production. Today, all of these elements are connected, thanks to intelligent sensors and the Internet of Things, which makes

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For a color version of all figures in this book, see www.iste.co.uk/cardin/digitalization.zip.

it possible to define the CPPS and the addition of the cyber layer. The rise of CPPS has led to better management of production systems because of the data processing of physical flows and information flows. The CPPS architecture, historically based on a holonic or multi-agent version defining the physical and cyber parts, is described in more detail in Chapters 7 and 8. This chapter focuses more specifically on the potential impact of the ICPS approach in the context of goods production.

11.1.1. *Developments*

The term production system refers to a set of activities and operations that enable the manufacture of a product (Blackstone 2010). The typology of production systems has evolved considerably during the 20th century. They have adapted to market developments and have also been able to integrate technical and social progress (see Table 11.1). Thus, the technical progress of the First and Second Industrial Revolutions (especially mechanization and electrification), as well as the availability of a large workforce, made it possible to respond to the constraints of mass production via the development of dedicated production systems. The third industrial revolution relied on advances in robotization to introduce variety into the product offering via flexible production systems.

CPPS correspond to the introduction of the technical advances of the fourth industrial revolution.

Constraints	Levers	Type of production system	Specificities
– High production volume – Reduced costs	– Mechanization – Electrification – Large workforce	**Dedicated manufacturing system**	– Low product variety – Dedicated hardware – Specialized operators
– Frequent renewal of the offer	– Robotization – Skilled labor	**Flexible manufacturing system**	– Wide variety of products – Adaptive hardware – Multi-skilled operators
– Changing markets	– Digitalization – Expert and adaptive workforce	**Reconfigurable manufacturing system**	– Customization – Reconfigurable hardware – Continuing education

Table 11.1. *Evolution of production systems*

11.1.2. *Issues*

The manufacturing sector is central to Europe's sustainability, be it economic, societal or environmental. In 2018, manufacturing production accounted for 14.2% of EU GDP[1]. A total of 33 million employees work in the 2 million European manufacturing companies. The sector is responsible for 25% of waste, 23% of greenhouse gas emissions and 26% of NOx[2] emissions. Chapter 3 describes in detail the sustainability issues that are of primary importance in the context of production. It is therefore necessary to consider production as an important link in the overall value chain, which has a strong impact on sustainability. As a result, modern production issues such as energy management, control of pollutant emissions, and efficient use of resources are emerging.

11.1.3. *Resources*

According to de Pablos and Miltiadis (2008), the production system can only implement a strategy (determining the mission and objectives of the organization) if the resources are mobilized to obtain a competitive advantage. However, this advantage, which was initially economic, must now be positioned in the more global context of sustainable development (see Chapter 3).

A resource is a means necessary to carry out a task. There are several types of resources: human and material. Human resources are by definition the most capable of reacting to the unknown and the most flexible in terms of the tasks to be carried out. Human capital is made up of the knowledge and skills of employees as well as of relational capital (reputation, customer portfolio, etc.) and structural capital (processes and governance) (Edvinsson 1997).

In order to carry out an operation, one or more resources are needed, human or material, for a certain period of time. Historically, the material resources considered were essentially the production machines, fixed, dedicated to a particular activity, or a limited number of operations in order to carry out a manufacturing order established according to different operating ranges. This concept has also evolved to take into account all the technical means necessary to carry out an operation: tools, energy, raw materials, information and so on. Some resources are fixed, others are mobile (mobile robots, etc.). There are also resources that can be reconfigured and reorganized according to the production to be carried out. The ability to reconfigure

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[1] Manufacturing, value added (% of GDP) – European Union. From The World Bank: Data, 2018.

[2] EIT, SIA thematic factsheet on Added-Value Manufacturing, 2017.

is a major evolution of production systems, supported by the development of CPPS, and this chapter sits within this context.

11.2. Reconfiguration

To respond to the fluctuating nature of markets, both in terms of volume and diversity of desired products, the concept of a reconfigurable manufacturing system was defined by Koren *et al*. (1999). This type of organization relies on six characteristics to guarantee cost-controlled production that is capable of responding quickly to radical market changes:

1) Scalability: adaptability to a change in production volume.

2) Convertibility: adaptability to changes in product specifications.

3) Diagnosis: identification of problems.

4) Customization: adaptability to the company's uses and processes.

5) Modularity: possibility of adding, removing or modifying functionalities.

6) Integrability: simple connection and interaction.

This concept remained utopian for a long time, but the technical and scientific advances of the Fourth Industrial Revolution have made it possible for this concept to be implemented in reality (Koren *et al.* 2018).

11.2.1. *Implementation and decision levels*

To implement reconfigurable manufacturing systems (RMS), different issues need to be addressed.

– When investment decisions are made:

  - How can we imagine scenarios of market evolution?
  - How can we evaluate *ex ante* the reconfigurability potential of different resources?

– When markets change:

  - When should we reconfigure?
  - How can we evaluate alternative reconfigurations?

The decisions that need to be made in order to manage a production system properly are classified by levels, as shown in Table 11.2.

Decision level	Time horizon	Decision
Strategic	Years to come	Sizing the system according to future demand (reconfigurable?)
Tactical	Weeks – months	Allocating resources to operations, balancing resources, planning operations
Operational	Hours – days	Scheduling operations, reacting to hazards Supply?

Table 11.2. *Decision levels*

11.2.2. *Information systems*

A CPPS is by definition connected. Taking the model historically defined by the ISA 95 standard, through the CIM (computer-integrated manufacturing) pyramid, the information flows circulate in the following way, layer after layer.

The customer order arrives via ERP (enterprise resource planning). ERP processes the demand: Can the production system meet the demand from its stocks? Does it need to launch a new production order? Does it have the components in stock and the resources available? Once the decision to start production has been made, APS (advanced planning and scheduling) can be used here to plan and schedule production in an optimized way.

This production order will be transmitted via the MES (manufacturing execution system) and the different intermediate layers (SCADA and PLC) to the workshops through the different sensors and actuators. This model can be considered as an traditional version of the information system of production systems. It represents a system where the decision is centralized. Each actor must refer to a single database to know the necessary information, which wastes time during information processing. In version 4.0 of information systems, information is decentralized, in a star configuration. Each actor is able to communicate with any other actor. Each actor knows only the information they need (see Figure 11.1). The product is an integral part of the network. The adoption of a CPPS design approach enables the implementation of version 4.0.

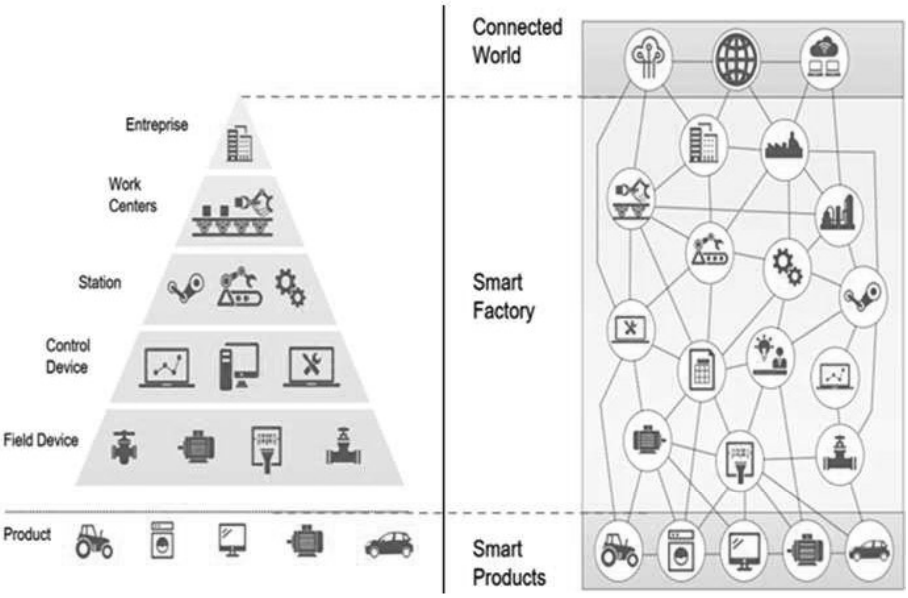

Figure 11.1. *Centralized versus decentralized information system (Deutsches Institut fuer Normung (DIN SPEC 91345) 2016)*

A decentralized information system makes it possible for the production system to be flexible. Several means are used in this new information system: intelligent sensors, RFID (radio-frequency identification) technology and the Internet of Things. Connected to the physical part of the CPPS, they feed the cyber part where data analysis is carried out to optimize production performance more globally. These analyses, coupled with predictive techniques (sales, etc.), also allow for the optimization of stocks, energy consumption, maintenance processes and status monitoring of production resources.

11.2.3. *Adaptation in the context of CPPS/RMS*

All categories of resources must be taken into account to ensure the reconfigurability of production systems. If the six characteristics (see section 11.2.1) have been defined for machine-tool type material resources, they can be adapted to evaluate the other types. A proposal of adaptation for software is as follows:

1) **Scale**: capacity of the software to follow the evolution of a load according to the structuring factors of the company (number of employees, turnover, etc.).

2) **Convertibility**: ability to transform existing software functionality to meet new production requirements.

3) **Diagnosis**: self-diagnosis and identification of possible software problems.

4) **Customization**: ability to adapt the software to the company's uses and processes.

5) **Modularity**: ability to add, remove, replace and/or upgrade tools on the software to fit the production.

6) **Integrability**: connection and interaction with the business environment (other mechanical, information and control interfaces).

We can even add a seventh characteristic specific to this type of resource.

7) **Connectivity/IoT/mobility**: information access management (access via mobile, smartphone, tablet, from home, etc.).

New hardware resources have recently emerged, which are flexible, mobile and easily programmable. They are therefore ideal resources for reconfigurable manufacturing systems. These resources can use mobile collaborative robotics.

11.2.4. *Where and when to reconfigure?*

An example is illustrated in Beauville dit Eynaud *et al.* (2019): consider a site assembling two large product families. There are a number of variants per family. This site has two assembly lines, one line per product family. Each line is capable of processing all the variants in its family. Due to market fluctuations, the quantity of products to be produced in each of the two families is uncertain. Staying with the same configuration would be a risky bet: one line could be undersized and the other line oversized if the future market favors one family over the other. One reconfiguration strategy envisaged is to have a new line, capable of reconfiguring itself in real time to manufacture all the products of the two families: a fixed line using the same structure as the two previous ones with dedicated machines capable of carrying out the operations common to both families, to which mobile collaborative robots would be added. Thanks to the CPPS, these robots would move autonomously to the appropriate station to perform the operation required for the product.

11.3. Modeling

A digital shadow is a real-time representation of the state of a real system (product or production system; Schluse *et al.* 2018). This "monitoring" is possible via instrumentation that collects data through various sensors or the Internet of Things. A digital twin is a digital simulation model connected to the digital shadow of a real production system, (see Chapter 6). This digital twin can be deployed either at the physical or the cyber level of the CPPS, depending on the physical twin considered (from the equipment to the complete production system).

11.3.1. *Data collection*

Good management of production systems requires a certain number of key performance indicators (KPIs). These KPIs make it possible to monitor the proper functioning of the system in question: the overall equipment effectiveness (OEE) is traditionally the most closely monitored indicator. As introduced, these indicators are evolving in the context of sustainability and are being augmented by societal and environmental requirements beyond the usual requirements (cost, time and quality).

The CPPS allows for real-time monitoring of data; however, the amount of data in a production system is potentially huge. One problem is managing data overload (Woods *et al.* 2002) and building indicators that enable monitoring and decision-making. Leveraging and synthesis of these KPIs makes it possible to create an intelligent dashboard. Ritou *et al.* (2019) propose a multi-level aggregation approach based on business knowledge (Figure 11.2). This approach is applied to connected machine tools but can be generalized to other material resources of CPPS.

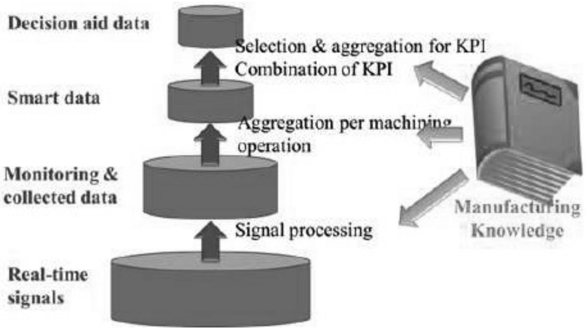

Figure 11.2. *Multi-level aggregation system (Ritou* et al. *2019)*

Aggregation operations are particularly important when KPIs are built from multiple data sources; for example, the OEE depends on the opening time (time in seconds, measured on the resources) and the quality (a number of parts or a rate from the quality department). Typically, within the workshops, interactive screens are used to show staff if the production system is working properly or, on the contrary, if corrective action is needed. For example, Beauville dit Eynaud *et al*. (2021) redefined the KPIs used for reconfigurable assembly lines.

11.3.2. *Simulation platforms*

Cyber-physical systems can be interesting levers for improving both economic performance (productivity gains and agility) and working conditions. However, the complexity of these systems makes decision-making difficult. It must therefore be based on effective feedback of actual performance as well as on simulation tools that enable the impacts of change to be anticipated. These tools, which replicate the behavior of the real system, can be digital (see the previous section) as well as take the form of physical simulation platforms.

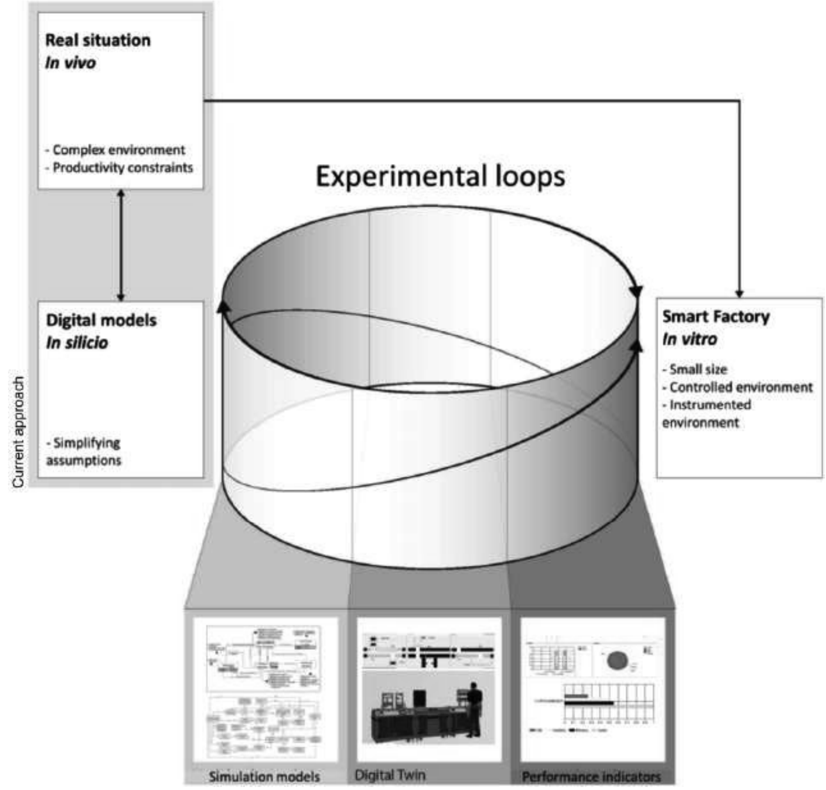

Figure 11.3. *Experimental loops (Puviyarasu and da Cunha 2021)*

These platforms are controlled and highly instrumented environments. Composed of modular elements, they meet the characteristics of reconfigurability and can replicate real production situations. Experimental loops between the industrial situation (in vivo), their digital modeling (in silico) and experimentation in a controlled environment (in vitro) can thus take place (Figure 11.3).

Solutions identified as performing well in digital models can be implemented in these platforms at low cost (time and relocation of platforms) and without any impact on real production. Deviations between the performances predicted by the digital models and those observed on the platforms make it possible to improve the digital models by identifying new parameters that were not previously taken into account. Only solutions validated in silico and in vitro will be deployed in real production systems.

11.4. Ergonomics/cognitive aspects

Collaborative robotics, by definition, is used so that humans work in direct contact with the robot. Thanks to a certain number of sensors with which it is equipped, the robot is able to detect the presence of the operator, and thus to slow down when they approach or even to stop activity. The workstation composed of a collaborative robot helps the human from an ergonomic point of view. This new resource can be used as a third hand to flexibly position the product on which the operator will have to perform their operations.

Other uses are under development (Quenehen *et al.* 2020). A given product is composed of a task list with tasks that can be performed in three modes: a 100% human mode (the operator does the entire task), a 100% robotic mode or a collaborative mode (the human and the robot work together to perform the task). Each task is defined by a different process time depending on the mode used. Quite often, the human mode is the fastest mode. However, it is also the most tiring for the operator. Hence, each task is also weighted with a cognitive factor depending on the mode used. A task performed by a human will be affected from an ergonomic point of view. If it is performed by the robot, its process time will be the longest but the ergonomic factor will be the best. The compromise is therefore the collaborative mode: similar process time but considerable ergonomic gain. However, not all operations are feasible using all modes. Current work is therefore focused on the assignment of operations between a human and a robot, with economic (related to process time) and ergonomic considerations.

The second issue addressed in the context of the integration of Human 4.0 is the cognitive aspect: how to improve the working conditions of the human. Let us first look at human as an operator. The operator must be versatile if they want to continue to be considered the most reconfigurable resource possible. This requires the human to increase their range of skills: to perform a greater diversity of tasks on a greater diversity of products. The CPPS can help people to increase their versatility. Let us imagine an assembly line composed of several manual assembly stations. This line is capable of assembling a multitude of products. If the operator wants to remain the most reconfigurable resource, they should know all the operations that can be performed on all of the products at all the stations – mission impossible. A cognitive system can help the operator in this task. Upstream, at the strategic decision level, the balancing of operations between the different stations, as well as the assignment of operators to the stations, has been decided. The scheduling of the different products has also been decided. Thanks to the information system and our connected product, we are able to display live at each workstation via a screen the operations that each operator has to perform on the product they have in their hands (determined by the given product identification, balancing, assignment and scheduling). This is the contextualized display at the workstation. We can also imagine going further thanks to a pick-to-light system that would make it possible for the components that must be assembled to be displayed to the human, or even through the use of augmented reality.

The part considering the decision-maker is dealt with in the following section.

11.5. Operation of the information system

The information system governing a production system has been described previously. Here, we will detail some situations illustrating the contributions induced by the definition of a CPPS, in particular in the management of hazards.

11.5.1. *Operational level: procurement*

Using the terminologies defined in Table 11.2, the problems classically addressed at the tactical level concern planning or resource allocation. What are the advantages of CPPS in our daily production system, at the operational level? Procurement is a good example of a decision to be made at the operational level. Components or raw materials are needed to make a product (which will be component assembly or transformation of raw materials). To improve the working conditions of the operator, these components are made available at the workstation or at the edge of the line. The connected system indicates when the line-side stock has been depleted in order to trigger a replenishment order.

An e-Kanban system can also be used. This is an adjustment tool that is based on the production carried out over a time window. By making the link with the bill of materials of the various products, it deduces the sub-components consumed over this window with a view to their replenishment (internal and external). Compared to the traditional or dematerialized Kanban, it saves having to process information on the consumption of each line-side sub-component. Combined with the knowledge of future production orders, the system is able to calculate future supply needs. This replenishment can be done autonomously by using mobile collaborative robots which would pick up the right components from the main stock at the right time and move them to the right stock on the line.

11.5.2. *Responding to disruptions*

Sensors are present in the system under consideration: on human or material resources, products or stocks, for example. A sensor in the field signals a failure at a given moment: a material resource that breaks down, a human resource that is absent and a lack of supply. Let us take these three cases in order:

– Broken-down material resource in breakdown: the information will be transmitted to the maintenance department, who carry out the necessary intervention as soon as possible. If a component needs to be changed on the faulty resource, the maintenance operator can check if it is in stock and plan an order if necessary. The time during which the resource is unavailable will be indicated. Thus, the planning and scheduling can be recalculated by considering this missing resource.

– Absent human resource: in a similar way as before, it will be necessary to recalculate the planning and scheduling considering that this resource is missing. Extrapolation: connection with a temping company to replace this person as soon as possible.

– Lack of supply: reaction in the emergency by quickly supplying the workstation so that production is not negatively affected. However, it will be necessary to correct this perturbation in the long term: Why was the supply not made, information not transmitted, resource dedicated to supply unavailable, stock in shortage?

The cases treated above illustrate the bottom-up case. The information (the perturbation) is noticed in the field; this information is processed by the decision-maker via the CPPS (replan, reschedule, resupply, with the least possible impact on the order book) and then goes back down to the workshops to continue production. There may also be a case of a downward perturbation: for example, a loyal customer places an urgent order. This order will have to be integrated (planned, allocated and scheduled with its impact on the scheduling) on the planned production, to satisfy this loyal customer, with the least possible impact on the initially planned production.

11.5.3. *Decision support*

Decision support methods have been proposed for decades to offer solutions to decision-makers. These tools do not aim to replace human beings but to help them in their decision-making. Klement and Silva (2020) propose a generic decision support tool that can be used for planning, allocation or scheduling problems. This tool could be extended to help the human make the best decision to manage the manufacturing system. The connectivity of the systems provided by the CPPS now allows for a better description of the real systems, thus a better parameterization of the tools of assistance to the decision and especially a transfer of the decision from the decision-maker towards the field.

The use of the information system makes it possible to create a dashboard to monitor production. This dashboard includes the indicators presented in section 11.3.1. Amzil *et al.* (2021) propose a virtual Obeya: a multi-view real-time dashboard so that each user has access only to the information pertinent to them in real time. In addition to simply monitoring production, this virtual Obeya is also a decision support tool. Thanks to the connectivity of the systems, all the available data is continuously fed into an IoT hub. Data conversion allows interoperability. The causal analysis of all of this data by a tool using neural networks and genetic algorithms not only makes it possible to detect perturbations, but also to anticipate them in order to prevent future disruption to the real system. The CPPS now makes it possible to predict the future through better data analysis to improve the management of manufacturing systems.

11.6. Illustrative example

Let us take an example of an assembly line consisting of six manual stations, arranged in a line. This line is used to assemble cylinders. A wide variety of cylinders can be assembled, depending on the different options (about a hundred configurations, total assembly times vary between one and three minutes). Thanks to preliminary load balancing studies, for each cylinder, the operations to be performed at each station are known. A visual example of this production system is shown in Figure 11.4.

Figure 11.4. *Manual assembly line developed at the Arts et Métiers Campus in Lille, with educational and industrial transfer objectives*

Taking up various concepts detailed in this chapter, transforming this line to a CPPS has several advantages:

– Quality: thanks to the contextualized display at the workstation, the operator knows in real time which assembly operations they have to perform on the product they have in their hands, without having to learn by heart the planned schedule for the day or all the possible ranges. With the pick-to-light system, this also makes it possible to illuminate the correct component to be picked up and assembled.

– Supplies: thanks to automatic line-side replenishment via AGV, coupled with the e-Kanban system, line-side stocks are always supplied in the right quantity and with the right type of components.

– Production monitoring: thanks to the interactive dashboard, production problems can be easily visualized and corrected as soon as possible. With a virtual Obeya, the causes can also be anticipated.

Figure 11.5 shows a close-up of the line with the integration of the technologies mentioned. This line is used at the Arts et Métiers campus in Lille in an educational context to teach industrial management to engineering students. It is also a support for the research activities of the LISPEN (*Laboratoire d'Ingénierie des Systèmes Physiques et Numériques*, Physical and Digital Systems Engineering Laboratory) teachers-researchers as well as for the activities of demonstrators or industrial transfer.

Figure 11.5. *Line equipped with 4.0 technologies (collaborative robot, RFID, interactive dashboard)*

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