Transformation of Conventional Manufacturing and Service Systems into a Cyber-Physical Environment: Review of Potential Solutions

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Abstract. The Fourth Industrial Revolution offers new potentials to increase the efficiency, availability, sustainability and transparency of manufacturing systems. The Industry 4.0 technologies are widely used in the field of purchasing, production, distribution and reverse processes to enhance the efficiency from a technological and logistics point of view. The application of these new technologies leads to the transformation of the conventional manufacturing and service systems into cyber-physical systems, where the design and operation of the new, globalised, interconnected and hyper-connected systems and supply chains require new optimisation approaches. Within the frame of this article, the author focuses on the potential of these mentioned Industry 4.0 technologies from a digitalisation point of view. After a systematic literature review, this paper introduces some potential ways to transform conventional manufacturing and related service systems into cyber-physical environment in the field of manufacturing processes in the automotive industry, hyper-connected collection and distribution systems in city logistics and switch pool packaging logistics in Industry 4.0 era, where smart sensors, intelligent tools, gentelligent products, digital twin solutions and edge computing support the transformation.

Keywords: Cyber-physical systems · Matrix production · Services · Hyper-connected networks · Digital twin technology · In-plant supply

1 Introduction

The new generation of intelligent manufacturing systems in the Industry 4.0 era can be characterised by an in-depth integration of new-generation technologies of Internet of Things solutions and advanced manufacturing technologies [1]. Digital twin solutions play an important role in the development and transformation of conventional systems into cyber-physical systems [2]. This transformation influences not only the operation but also the design of the manufacturing system because this mirroring can bridge the gap between the optimisation aspects of system design and the strategic and tactical aspects of the operation. The transformation of conventional manufacturing systems into a cyber-physical system can be performed in a wide range of manufacturing structures, and this

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transformation focuses on the physical layer, virtual layer, related service systems and digital twin data [3].

Today, the challenge for manufacturing and service companies is to meet increasingly dynamic and customised customer needs with mass production efficiency. Meeting these needs in an economical and sustainable way requires the implementation of new production and service paradigms, for which the digitalisation technologies emerging in the context of the fourth industrial revolution provide an excellent technological background. In the era of the fourth industrial revolution, so-called Industry 4.0 technologies are enabling the transformation of traditional production and service systems into cyber-physical systems. This transformation can result highly efficient, flexible, sustainable, cost-effective production and service systems that can exploit the opportunities offered by digitalisation to the mutual benefit of both manufacturers, service providers and customers. During the pandemic, these globalisation efforts have been somewhat overshadowed in the case of supply chains. This is because supply networks have undergone a major transformation, as manufacturing companies have sought to replace suppliers from the Far East with local suppliers to reduce supply risk. Nevertheless, it can be argued that the development of cyber-physical systems offers significant benefits not only for manufacturing but also for service systems. In this article, the main aspects of cyber-physical system design are presented and some Industry 4.0 technologies used are described through some examples.

This paper is organised as follows. Section 2 presents a systematic literature review, which summarises the research background of cyber-physical systems. Section 3 describes the model framework of the transformation of conventional manufacturing systems into a cyber-physical system focusing on matrix production. Section 4 presents the potential of a hyper-connected collection and distribution system in city logistics. Section 5 shows a potential solution for switching pool packaging logistics in Industry 4.0 era. Conclusions and future research directions are discussed in Sect. 6.

2 Systematic Literature Review

Within the frame of the systematic literature review (SLR), the main research directions and the main research gaps are identified. The systematic literature review includes the description of the methodology of SLR, the descriptive analysis focusing on the statistical and numerical analysis of research results published in articles, the content analysis of published articles focusing on the main research results and typical approaches, and the consequences focusing on main research directions and research gaps.

2.1 Methodology of the Systematic Literature Review

Within the frame of this systematic literature review, a 5 phase review process was used (Fig. 1), including the definition of research questions, performing the search in the Scopus database, include and exclude article, which are out of scope, descriptive analysis, content analysis, and conclusions [4].

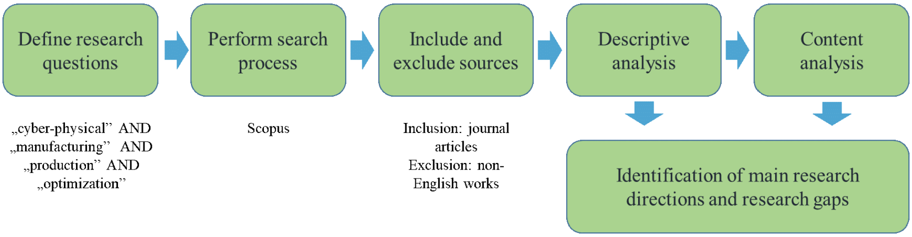


Fig. 1. Methodology of the systematic literature review

2.2 Descriptive Analysis

Firstly, the relevant search terms were defined, focusing on the research topic. It is a critical phase of the systematic literature review because there is a wide range of sophisticated review articles in the field of application of Industry 4.0 technologies and Internet of Things [5]. The following keywords were used in the Scopus database: (TITLE-ABS-KEY ("cyber-physical") AND TITLE-ABS-KEY (manufacturing) OR TITLE-ABS-KEY (production) AND TITLE-ABS-KEY (optimisation)). Initially, 519 articles were identified. This list was used for the descriptive analysis of the research field. The search was conducted in March 2022; therefore, new articles may have been published since then.

The transformation of conventional manufacturing processes has been researched in the past 10 years. The first articles in this field were published in 2011, focusing on the conceptual framework for dynamic manufacturing resource service composition and optimisation in service-oriented networked manufacturing. The number of published papers has increased in the last years; it shows the importance of this research field (Fig. 2).

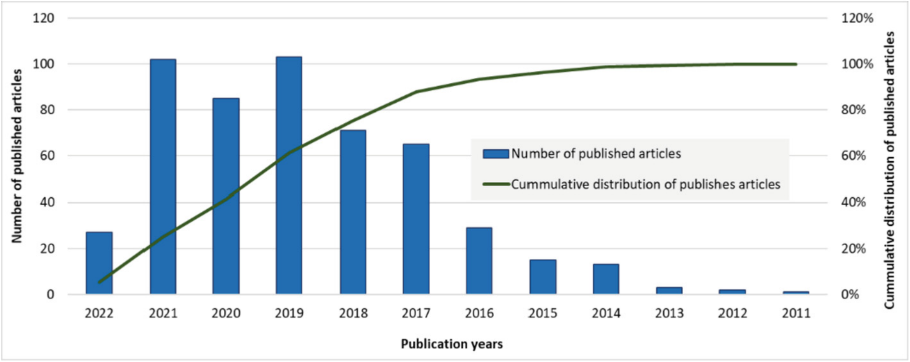


Fig. 2. Classification of articles by year of publication based on search in Scopus

The articles can be classified depending on the research area. Figure 3 shows the classification of these articles considering ten subject areas. This classification shows the majority of engineering and computer sciences, while mathematics and decision making show that cyber-physical systems offer new optimisation potentials for the design and operation of these complex systems and networks.

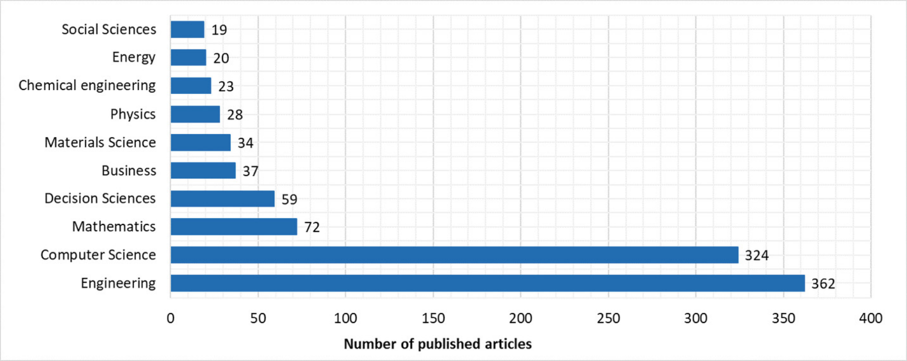


Fig. 3. Classification of articles considering subject areas based on a search in Scopus database

2.3 Content Analysis

The application of Industry 4.0 technologies is based on the solution of different scientific problems, which can be categorised as follows: (a) intelligent sensing and data acquisition from manufacturing and logistics, (b) collaborative decision making in the global value chain including purchasing, production, distribution and reverse processes, (c) life cycle assessment, security, maintenance and sustainability, (d) cooperative control and optimisation of human-machine interactions [6].

Data acquisition plays an important role in the efficiency of digital twin solutions, especially in the case of distributed production and service processes, therefore it is important to apply multi-modal data acquisition techniques and approaches to support the sophisticated design based on digital twin and discrete event simulation [7, 8].

However, the basic motivation of cyber-physical systems can be found in the expected technological and economic benefits, but social aspects should also be taken into consideration, focusing on the following problems: problem-solving efficiency of human stakeholders [9], efficiency improvement of human-based production tasks through the integration of sensor data from the technological and logistics resources and motion recognition of human operators [10], control of intuitive and efficient human-machine interactions between human operators and cyber-physical machine tools [11]. Cyber-physical systems have more favourable key performance indicators including availability, flexibility, efficiency, sustainability and transparency related parameters. The flexibility of cyber-physical manufacturing systems, including matrix production systems, is based on open-architecture machine tools, smart infrastructures [12] and other manufacturing and assembly resources, which make it possible to perform rapid changes through the application of individualised modules [13]. Other approaches focus on instruction-domain based solutions, where the work process of the cyber-physical system can be established on the basis of real-time status information of resources and processes [14].

Cyber-physical systems “create” new professions and lead to the birth of new methods and tools, because complex, global, interconnected systems generate new types of problems in the field of product design, process planning, inventory management, scheduling, and distribution [15]. The design and optimisation problems of cyber-physical systems can be solved using a wide range of algorithms and tools, including discrete event simulation [9], decision-making methods [16], special design architectures (i.e., configuration design – motion planning – control development – optimisation decoupling) [17], holistic matching approach [18], neural networks [19], swarming heuristics [20], evolutionary algorithms [21, 22], ontology-based resource reconfiguration [23], multi-layer decision making [24], clustering [25].

The transformation of conventional systems into cyber-physical systems lead to the transformation of objective functions and constraints of the design and operation problems, because previously isolated functions become integrated functions influencing the key performance indicators of the whole value chain [26]. The objective functions of CPSs are focused on the following aspects: costs, logistics performance, energy efficiency, sustainability [27], environmental impact, quality, availability, and efficiency. The efficiency of the transformation of conventional systems into cyber-physical systems is influenced by the architecture used; cloud-based self-organising architectures can support the improvement of key performance indicators through the reconfiguration options of agents in a collaborative way [28].

One of the key factors leading to the revolutionary new concept of cyber-physical supply chain solutions is the integration of digital technologies, blockchain and real-time data analytics. This integration has the potential to achieve a new quality in decision-making support by combining discrete event simulation, analytical and heuristic optimisation, and real-time data analytics supported by big data [29] and edge computing solutions [30, 31]. Lean management is also an unavoidable approach of cyber-physical systems because the lean paradigm supports the continuous value stream using a continuous optimisation and standardisation of resources and processes [32].

2.4 Conclusions of the Systematic Literature Review

More than 60% of the articles were published in the last five years. This result indicates the scientific potential of cyber-physical systems. The articles that addressed the transformation of conventional manufacturing systems into cyber-physical environment focus on a wide range of research topics, and based on the results of these researches, the following findings can be made:

- The in-depth integration of state-of-the-art technologies of IoT solutions and advanced, configurable, flexible manufacturing technologies is the key factor of cyber-physical systems.
- The transformation of conventional manufacturing and service systems influences not only operation but also the design of the manufacturing system through the integration of physical and digital layers of operations.
- The optimisation of human-machine cooperation is a key factor in manufacturing and assembly processes, where advanced design and planning architectures represent potential support.

- A wide range of optimisation methods and tools are used for the design and operation of cyber-physical systems, including simulation, heuristics, ontology and neural networks.

Only a few of the analysed articles focuses on the real-time data acquisition and digital twin-based transformation of conventional manufacturing systems into cyber-physical systems; therefore, this research topic still needs more attention and research. According to that, the main focus of this article is the demonstrate the main findings in this field, focusing on manufacturing processes in the automotive industry, collection and distribution systems in city logistics and packaging logistics.

3 Efficiency Improvement Through Matrix Production in Automotive Manufacturing Systems

In a conventional manufacturing environment, the static nature of material flow processes makes it difficult to achieve a level of flexibility in the manufacturing process that would allow for the increasingly dynamic and changing individual customer needs to be met with mass production efficiency. The matrix production concept of KUKA Robotics, where technological and logistics processes are separated from each other and autonomous material handling solutions perform in-plant supply between storage and matrix cells, can provide a solution (Fig. 4).

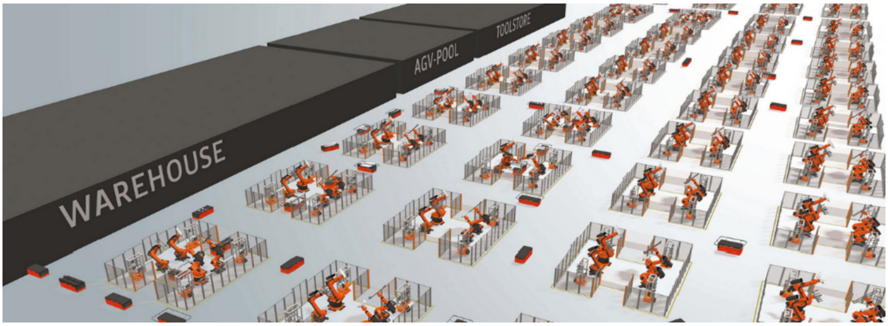


Fig. 4. The matrix production concept of KUKA [33]

Within the frame of this section, the basic concept of the transformation of conventional production systems into cyber-physical systems is described focusing on both the functional model of cyber-physical systems and the potential optimisation problems and solutions [34]. In the case of conventional production systems, the production planning and scheduling are based on ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System) data [35].

However, a wide range of computer-aided technologies are available from the ERP to support the digital simulation-based design and operation, including purchasing, manufacturing, inventory and order management, customer relationship management, human resource and workforce management and distribution, but in this case, the design and operation cannot take all real-time information into consideration. The application of Industry 4.0 technologies makes it possible to gather real-time data (failure data, status information, product information) and support the decision making process in the manufacturing system. While transforming conventional manufacturing system into cyber-physical system, smart sensors can be used to gather data from the physical processes (technological and logistics processes) of the manufacturing system. The data analysis is usually based on both edge and cloud of fog computing solutions. Edge computing focuses on the data analysis near the data source in order to increase the speed of communication. The data acquisition is especially efficient from intelligent tools and gentelligent sensors, where in-built smart microsensors are available. The analysed data is sent to digital twin aggregates, digital twin prototypes or digital twin instances, which represent the digital reflection of the physical system. Instances, prototypes and aggregates are integrated into a digital twin environment, where the real-time model of the physical production system exists. This real-time model is transferred to the discrete event simulation tool, where the assignment, routing, scheduling and facility location planning problems can be solved based on the real-time status of the physical system (Fig. 5).

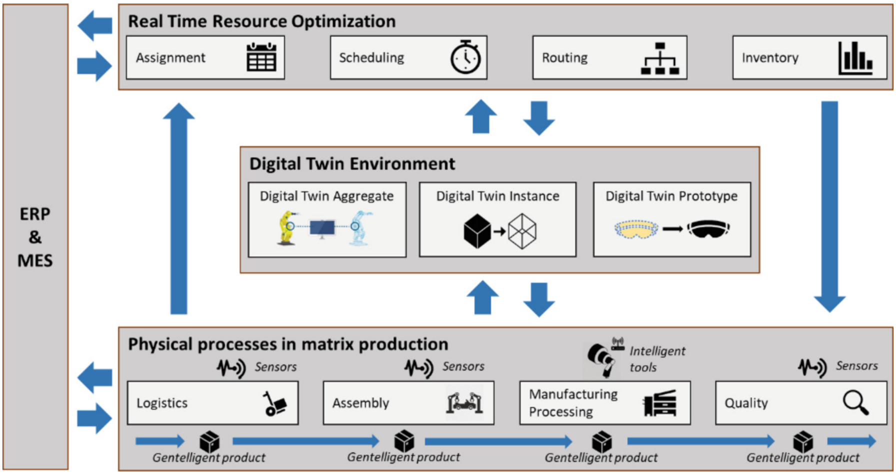


Fig. 5. Transformation of conventional manufacturing system into a cyber-physical system using Industry 4.0 technologies [33]

In a matrix production system, the application of green technological and logistics resources plays an important role, and it is especially important in the case of logistics resources, because the application of autonomous material handling solutions (autonomous guided vehicles -AGVs) can be realised by e-vehicles. In this case, not only the technological and logistics performance can be increased but also the costs and the environmental impact can be decreased.

The real-time optimisation model of a cyber-physical manufacturing system can be divided into two main phases. The first phase is the conventional planning, where the routing and scheduling of clustered in-plant supply demands are performed. The second phase is the real-time scheduling, where the parameters of the dynamically changing environment of the manufacturing system can be taken into consideration.

The optimisation of the cyber-physical system focuses on the minimisation of required time for the performance of in-plant supply processes. The logistics processes include the materials handling operations between raw material and component warehouses, tool storage, AGV pools and matrix grids. As constraints, we can take either time or capacity-based constraints into consideration, but also energy efficiency and emission-related parameters have a great impact on the optimal solution of the in-plant supply problems. In the literature, we can find different heuristic solutions for these kinds of integrated optimisation of logistics problems. One typical solution is based on the sequential metaheuristics integrating black hole heuristics and the discretised flower pollination-based routing, scheduling and real-time optimisation [33, 34].

4 Hyper-Connected Collection and Distribution Systems in City Logistics

Conventional city logistics solutions involve direct supply to pick-up and delivery points, which can be households, offices, shops, service providers or supermarkets. In the case of conventional city logistics solutions, the collection and distribution processes are carried out independently by each logistics service provider. This is partly due to the fact that the collection and distribution processes are so different that the logistics services provided by the different service providers cannot be combined due to the different resources and technological conditions required. It is therefore not possible to perform these collection and distribution processes in a cooperative manner. Another important reason for the lack of cooperative implementation is that logistics service providers have separate business management systems and do not use technologies that would allow coordination of previously separate and independent systems. This chapter will show how conventionally operated city logistics processes can be linked using Industry 4.0 technologies to create a hyper-connected service environment in which the service processes of previously independently operating service providers can be coordinated. This coordinated operation can result in a cost-effective operation that is also optimised in terms of environmental impact [35].

There are two main pillars for the design of a cyber-physical collection and distribution system:

- Transformation of the distributed, decentralised physical processes of collection and distribution into a centralised, integrated solution: The implementation of conventional collection and distribution processes in an urban environment allows conventional vehicles to travel almost unrestricted in inner-city areas, with significant environmental impacts. This environmental impact can be measured in terms of greenhouse gas emissions or calculated from consumption related to transport processes carried out by independent logistics service providers. The collection and distribution system could be adapted to include intermediate warehouses around the designated downtown zone, which could act as logistics service centers or cross-docking facilities to stop the material flow to the downtown area. At these cross-docking facilities, incoming goods can be transshipped from conventional delivery vehicles to vehicles serving locations in the downtown area, which can be predominantly electric vehicles or micro-mobility vehicles. In the case of collection processes, the process is reversed, with electric vehicles and micro-mobility vehicles performing the necessary collection tasks in the downtown area and the collected goods being transported to the cross-docking facility, from where the service providers will then use the conventional resources of transportation to transport the corresponding goods.

- Digital mirroring of the collection and distribution process: For conventional collection and distribution processes, integration is often not feasible because there is no solution to coordinate collection and distribution processes and operations performed by independent logistics service providers. The reasons for this are twofold. On the one hand, the service providers concerned may be competitors and therefore, most of the data relating to their processes are confidential. Secondly, they do not use technologies to retrieve the status of the processes of the individual service processes in real-time. Real-time data and the quasi-real-time information derived from them are of great importance since real-time status information of real physical processes and resources can be used to create an intelligent agent for design and optimisation, which can be used to consolidate and optimise in real-time the processes and operations of the individual service providers, which have been operating independently. This real-time optimisation can be achieved by using the digital twin technology, which allows replacing the independent logistic processes of the service providers operating in conventional city logistics systems with an integrated digital twin of the processes of these service providers based on the parameters describing the real-time status of these processes, which can be used to perform the necessary scheduling, assignment, routing, layout planning and controlling tasks in the cyber-physical collection and distribution process (Fig. 6).

The most important design parameters of the cyber-physical system are the followings: location of pick-up/delivery points within the urban area, volume, weight and required transportation and loading devices of pick-up/delivery tasks, preliminary or forecasted schedule of time frames available to perform collection and distribution operations. The potential mathematical model of the optimisation problem related to this transformed collection and distribution systems includes the objective function focusing on both costs and environmental impact. The constraints could be the followings: predefined service levels, available capacities of cross-docking facilities or transportation resources, predefined time windows to perform services, and predefined other key performance indicators, such as availability, flexibility or suitability.

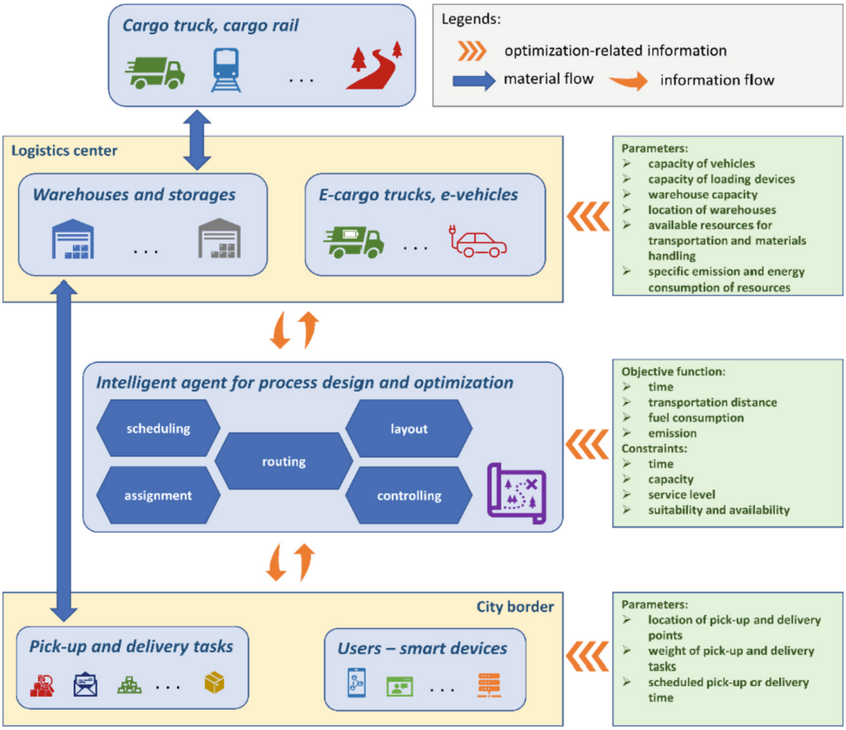


Fig. 6. Transformation of conventional city logistics operations into a cyber-physical collection and distribution environment through integration of independent logistics service providers using Industry 4.0 technologies [35]

5 Switch Pool Packaging Logistics in Industry 4.0 era

The industrial packaging market can be described as a dynamic and changing area of manufacturing-related services. The Allied Market Research reported that the size of the packaging market is expected to grow to about 70,000 million USD by the end of 2023. This growth can be characterised by annual growth of about 4%, and this fact validates the importance of continuous improvement of packaging solutions in the field of manufacturing and related services.

One typical solution of packaging systems is the switch-pool system, where each actor in the supply chain has its own returnable packaging and is responsible for its cleaning, maintenance [4, 36] and storage. Two typical variants of switch-pool systems are in use. In the first, only the sender and the receiver have their own returnable packaging. The return of the emptied returnable packaging means that transportation process is performed when the carrier delivers the packaged goods to the receiving party (manufacturer), so that the carrier can in this case, perform the following transportation: either transport the packaged goods from the supplier to the receiving party or return the empty returnable packages to the supplier. In the case of this option, there is no guarantee that the supplier will receive as many empty returnable packages from the manufacturer as the number of returnable packages sent with the packaged goods.

It is of course, possible to ensure, by means of an appropriate contract, that the receiving party (manufacturer) returns to the supplier the same amount of empty packaging as received with the packaged goods, but in this case, this may imply additional material handling operations from the manufacturer, for example by unloading goods to free returnable packages for reverse transportation in manufacturer supplier relation.

In another variant of the switch-pool solution, the carrier also has its own packaging pool. When the carrier receives the packaged goods from the supplier, it gives an appropriate amount of empty packaging, thus ensuring that the number of empty packaging that can be used at the supplier is kept at a constant and safe level. In this version of the switch-pool, the receiving party does not carry out any administrative activity in respect of empty means of transportation. The processes of the switch-pool packaging systems can be described as follows: (a) From the supplier, the carrier delivers the consigned packaged goods to the manufacturer. (b) The manufacturer receives the packaged goods from the carrier. (c) From the manufacturer, the carrier receives a quantity of empty returnable packaging corresponding to the quantity of packaged goods delivered. (d) If this quantity of packaging is not available at the supplier's demands, the carrier added the quantity of packaging from its own pool and delivers the resulting quantity of packaging to the supplier.

Based on the above reasoning, three typical processes can be formed within a cycle for a switch-pool. In the first case, the quantity of empty returnable packages to be returned is available at the manufacturer, and exactly the required quantity is shipped from the manufacturer to the supplier. In this case, the freight forwarder can carry out a direct transport between the two sites, as there is no need to unload or load empty packaging at a central depot (Fig. 7).

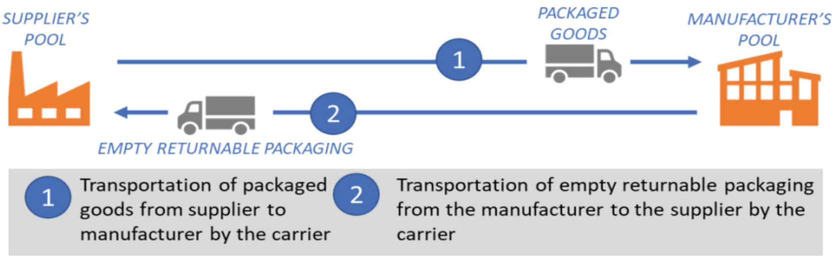
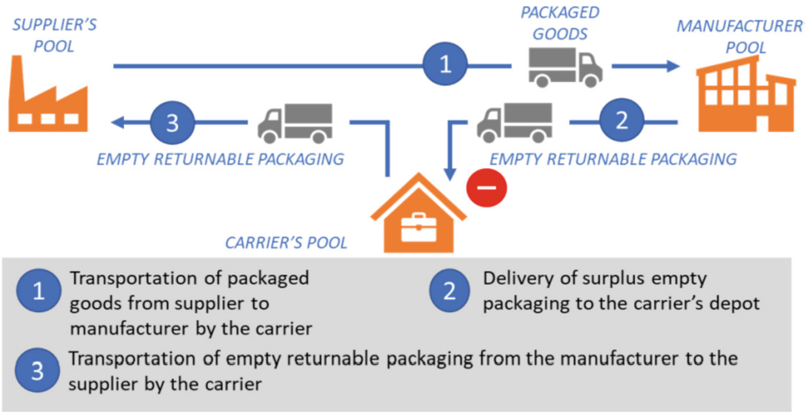


Fig. 7. One typical cycle of a switch-pool, if the quantity of empty packaging to be returned is available at the manufacturer and the carrier delivers exactly that quantity

In the second case, the quantity available at the manufacturer is greater than the quantity of empty returnable packages, so the carrier will ship the full quantity available. Since the supplier only needs to receive the quantities returned with the goods packed in that cycle, the excess quantity is deposited by the carrier in a central depot (Fig. 8).



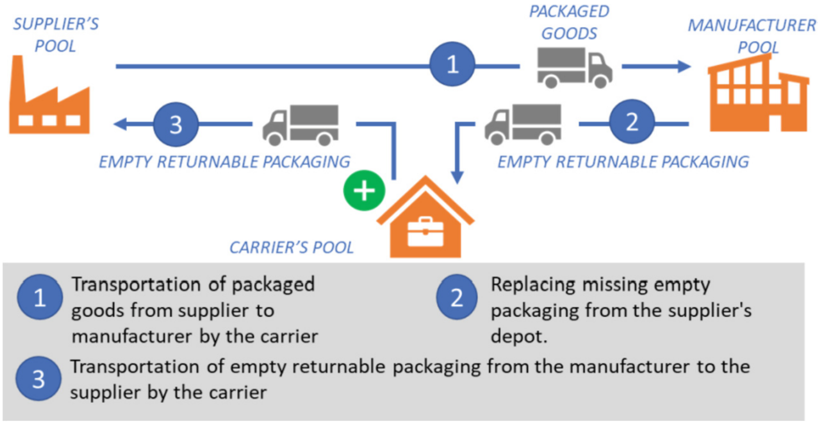
1 Transportation of packaged goods from supplier to manufacturer by the carrier

2 Delivery of surplus empty packaging to the carrier's depot

3 Transportation of empty returnable packaging from the manufacturer to the supplier by the carrier

Fig. 8. One typical cycle of Switch-pool, if the quantity available at the manufacturer exceeds the quantity of empty packaging to be returned and the carrier delivers the full quantity

In the third case, the quantity available at the manufacturer is less than the quantity of empty returnable packages, and the carrier shall therefore carry the available quantity. Since the supplier has to receive the exact quantity of the goods packed in the given cycle in return, the missing quantity of empty multi-package is replenished from a central depot (Fig. 9).



1 Transportation of packaged goods from supplier to manufacturer by the carrier

2 Replacing missing empty packaging from the supplier's depot.

3 Transportation of empty returnable packaging from the manufacturer to the supplier by the carrier

Fig. 9. One cycle of a switch-pool, if the quantity available at the manufacturer is less than the quantity of empty packaging to be returned, the carrier will replenish it from its own pool

There are a number of technological and logistical aspects of packaging processes that need to be taken into account in order to design and operate highly efficient, sustainable, flexible and environmentally friendly packaging systems. The characteristics of packaging systems has a great impact on almost all aspects of procurement, production, distribution and recycling. It is therefore important to develop packaging systems using advanced technologies that can transform conventional packaging systems into cyber-physical networks. In these cyber-physical networks, we can take advantage of the benefits of Industry 4.0 technologies to increase the availability, flexibility, efficiency, sustainability and transparency of technological and logistical processes.

Using Industry 4.0 technologies, including cloud computing, fog computing, edge computing, RFID technologies, simulation, augmented reality, big data analytics, cyber security solutions and smart devices, it is possible to make a transformation, as shown in Fig. 10.

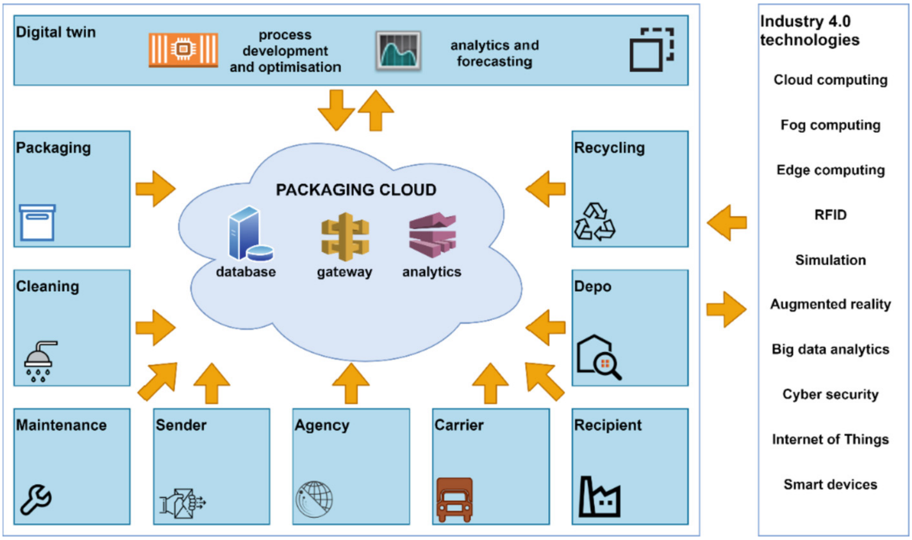


Fig. 10. Packaging logistics in Industry 4.0 era using Internet of Things technologies

The operation of the packaging system can be represented by a wide range of technological and logistics operations depending on the characteristics of the packaging (returnable or non-returnable, primary, secondary or tertiary). Typical packaging systems are working between suppliers of manufacturers and customers. Within the frame of this model, the focus is on the industrial part of the packaging systems, including the supplier-manufacturing relation. The supplier sends packaging from their warehouses to the warehouses of the manufacturer. Agencies take part in the coordination of the supply chain process and integrate the logistics processes of suppliers, manufacturers and carriers from a packaging logistics point of view. Carriers are responsible for the transportation of returnable and non-returnable packaging from the supplier to the manufacturer and return back from the manufacturer to the supplier. This material flow process can be interrupted by cleaning and maintenance operations because, depending on the quality (status) of the packaging, cleaning, maintenance or recycling operations can be added to the standard transportation, warehousing and loading operations. The supply chain of the packaging systems can be created in different ways, depending on the characteristics of the participants and required services.

6 Conclusions

Today, changing markets, increasing customer demands, shorter product lifecycles and the need for continuous availability are major challenges for companies. Companies that recognise and prepare for this process in time will be able to maintain their competitive position. In order to meet the dynamically changing customer needs, developing the Industry 4.0 capabilities of companies engaged in production and service activities is essential to increase their efficiency and expand their capacity. Every company needs flexible and reliable resources and processes to carry out production and service tasks efficiently. Production systems involve a wide range of resources, the effective management of which is essential for cost-efficient, reliable and sustainable operations. The management of resources is becoming increasingly important in a globalised, networked economy, as achieving optimal key performance indicators for cooperative production and logistics systems is a complex problem. Within the frame of this article, some potential ways for the transformation of conventional manufacturing or service systems are described. More generally, this paper focused on the potential of cyber-physical systems and demonstrated how IoT technologies could support this transformation. The main findings of this research work are the followings:

- The matrix production concept of KUKA Robotics is a suitable way to improve the flexibility and availability of manufacturing systems, especially in the field of the automotive industry. The separated technological and logistics processes can be controlled by a digital-twin enabled discrete event simulation, which makes it possible to optimise the processes using real-time status information and failure data.
- The separated and parallel conventional city logistics solutions can be linked using Industry 4.0 technologies to create a hyper-connected service environment for cost-efficient and sustainable first mile and last mile operation, where electromobility and micro mobility become more and more important.
- Packaging logistics plays an important role in the life of manufacturing companies. There are different types of packaging systems, but cyber-physical solutions can be used for both non-returnable and returnable primary, secondary and tertiary packaging.

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