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Procedia CIRP 40 (2016) 536 – 541

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13th Global Conference on Sustainable Manufacturing - Decoupling Growth from Resource Use

Opportunities of Sustainable Manufacturing in Industry 4.0

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Abstract

The current globalization is faced by the challenge to meet the continuously growing worldwide demand for capital and consumer goods by simultaneously ensuring a sustainable evolvement of human existence in its social, environmental and economic dimensions. In order to cope with this challenge, industrial value creation must be geared towards sustainability. Currently, the industrial value creation in the early industrialized countries is shaped by the development towards the fourth stage of industrialization, the so-called Industry 4.0. This development provides immense opportunities for the realization of sustainable manufacturing. This paper will present a state of the art review of Industry 4.0 based on recent developments in research and practice. Subsequently, an overview of different opportunities for sustainable manufacturing in Industry 4.0 will be presented. A use case for the retrofitting of manufacturing equipment as a specific opportunity for sustainable manufacturing in Industry 4.0 will be exemplarily outlined.

Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing

Keywords: Sustainable development; Factory; Industry 4.0

1. Introduction

The industrial value creation in the early industrialized countries is currently shaped by the development towards the fourth stage of industrialization, the so-called Industry 4.0. This development follows the third industrial revolution which started in the early 1970s and was based on electronics and information technologies for realizing a high level of automation in manufacturing [1].

The development towards Industry 4.0 has presently a substantial influence on the manufacturing industry. It is based on the establishment of smart factories, smart products and smart services embedded in an internet of things and of services also called industrial internet [2]. Additionally, new and disruptive business models are evolving around these Industry 4.0 elements [1,3].

This development towards an Industry 4.0 provides immense opportunities for realizing sustainable manufacturing using the ubiquitous information and communication technology (ICT) infrastructure. This paper will present a state of the art review of Industry 4.0 based on recent research and practice. Wherein, the macro and micro perspectives of Industry 4.0 will be visualized and analyzed. Subsequently, approaches to sustainable manufacturing are combined with the requirements of Industry 4.0 and an overview of opportunities for sustainable manufacturing in the macro and micro perspectives will be presented. Finally, a use case for retrofitting of equipment as a specific opportunity for sustainable manufacturing in Industry 4.0 will be exemplarily outlined.

2. State of the Art

The main ideas of Industry 4.0 have been firstly published by KAGERMANN in 2011 [4] and have built the foundation for the Industry 4.0 manifesto published in 2013 by the German National Academy of Science and Engineering (acatech) [1]. At European level, the Public-Private Partnership (PPP) for Factories of the Future (FoF) addresses and develops Industry 4.0-related topics [5]. The contents of Industry 4.0 in the US are promoted by the Industrial Internet Consortium (ICC) [6].

Peer-review under responsibility of the International Scientific Committee of the 13th Global Conference on Sustainable Manufacturing
doi:10.1016/j.procir.2016.01.129

The paradigm of Industry 4.0 is essentially outlined by three dimensions [3, 7, 8]: (1) horizontal integration across the entire value creation network, (2) end-to-end engineering across the entire product life cycle, as well as (3) vertical integration and networked manufacturing systems.

The horizontal integration across the entire value creation network describes the cross-company and company-internal intelligent cross-linking and digitalization of value creation modules throughout the value chain of a product life cycle and between value chains of adjoining product life cycles [7].

The end-to-end engineering across the entire product life cycle describes the intelligent cross-linking and digitalization throughout all phases of a product life cycle: from the raw material acquisition to manufacturing system, product use, and the product end of life [7].

Vertical integration and networked manufacturing systems describes the intelligent cross-linking and digitalization within the different aggregation and hierarchical levels of a value creation module from manufacturing stations via manufacturing cells, lines and factories, also integrating the associated value chain activities such as marketing and sales or technology development [7].

The intelligent cross-linking and digitalization covers the application of an end-to-end solution using information and communication technologies which are embedded in a cloud.

In a manufacturing system, the intelligent cross-linking is realized by the application of so-called Cyber-Physical Systems (CPS) which are operating in a self-organized and decentralized manner [7, 9, 10]. They are based on embedded mechatronic components i.e., applied sensor systems for collecting data as well as actuator systems for influencing physical processes [9]. CPS are intelligently linked with each other and are continuously interchanging data via virtual networks such as a cloud in real-time. The cloud itself is implemented in the internet of things and services [7]. Being part of a sociotechnical system, CPS are using human-machine-interfaces for interacting with the operators [11].

2.1. The Macro Perspective of Industry 4.0

The macro perspective of Industry 4.0 as shown in Figure 1 covers the horizontal integration as well as the end-to-end engineering dimension of Industry 4.0. This visualization is based on a strong product-life-cycle-related point of view by putting cross-linked product life cycles as central element of the value creation networks in Industry 4.0.

The horizontal integration from the macro perspective is characterized by a network of value creation modules. Value creation modules are defined as the interplay of different value creation factors i.e., equipment, human, organization, process and product [12]. The value creation modules, represented in their highest level of aggregation by factories, are cross-linked throughout the complete value chain of a product life cycle as well as with value creation modules in value chains of adjoining product life cycles. This linkage leads to an intelligent network of value creation modules covering the value chains of different product life cycles. This intelligent network provides an environment for new and innovative business models and is thus currently leading to a change in business models.

Displayed in Figure 1, the end-to-end engineering from the macro perspective is the cross-linking of stakeholders, products and equipment along the product life cycle, beginning with the raw material acquisition phase and ending with the end-of-life phase. The products, the different stakeholder such as customers, workers or suppliers, and the manufacturing equipment are embedded in a virtual network and are interchanging data in and between the different phases of a product life cycle. This life cycle consists of the raw material acquisition phase, the manufacturing phase - containing the product development, the engineering of the related manufacturing system and the manufacturing of the product - the use and service phase, the end-of-life phase - containing reuse, remanufacturing, recycling, recovery and disposal - as well as the transport between all phases.

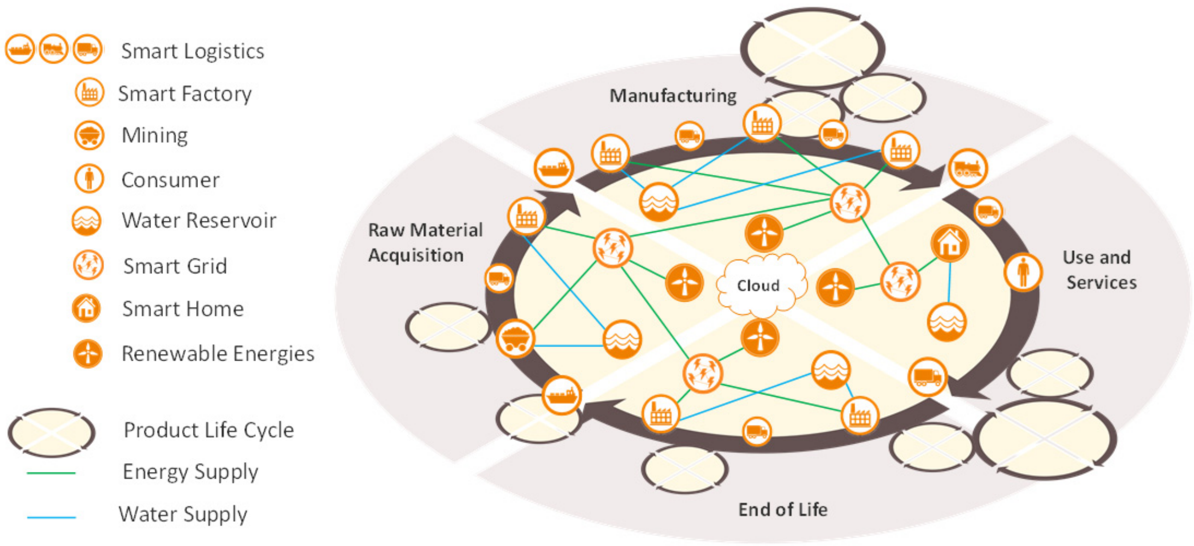

Fig. 1. Macro perspective of Industry 4.0

Those value creation modules i.e., factories which are embedded in this ubiquitous flow of smart data will evolve to so called smart factories. Smart factories are manufacturing smart products and are being supplied with energy from smart grids as well as supplied with water from fresh water reservoirs. The material flow along the product life cycle and between adjoining product life cycle will be accomplished by smart logistics. The stream of smart data between the different elements of the value creation networks in Industry 4.0 is interchanged via the cloud.

Smart data arises by expediently structuring information from big data which then can be used for knowledge advances and decision making throughout the product life cycle [13]. Smart factories are using embedded Cyber-Physical Systems for value creation. This enables the smart product to self-organize its required manufacturing processes and its flow throughout the factory in a decentralized manner by interchanging smart data with the CPS [14].

The smart product holds the information about its requirements for the manufacturing processes and manufacturing equipment. Smart logistics are using CPS for supporting the material flow within the factory and between factories, customers, and other stakeholders. They are also being controlled in a decentralized manner according to the requirements of the product. A smart grid dynamically matches the energy generation of suppliers using renewable energies with the energy demand of consumers, e.g. smart factories or smart homes, by using short-term energy storages for buffering. Within a smart grid, energy consumers and suppliers can be the same.

2.2. The Micro Perspective of Industry 4.0

The micro perspective of Industry 4.0 presented in Figure 2 mainly covers the horizontal integration as well as the vertical integration within smart factories but it also is part of the end-to-end engineering dimension.

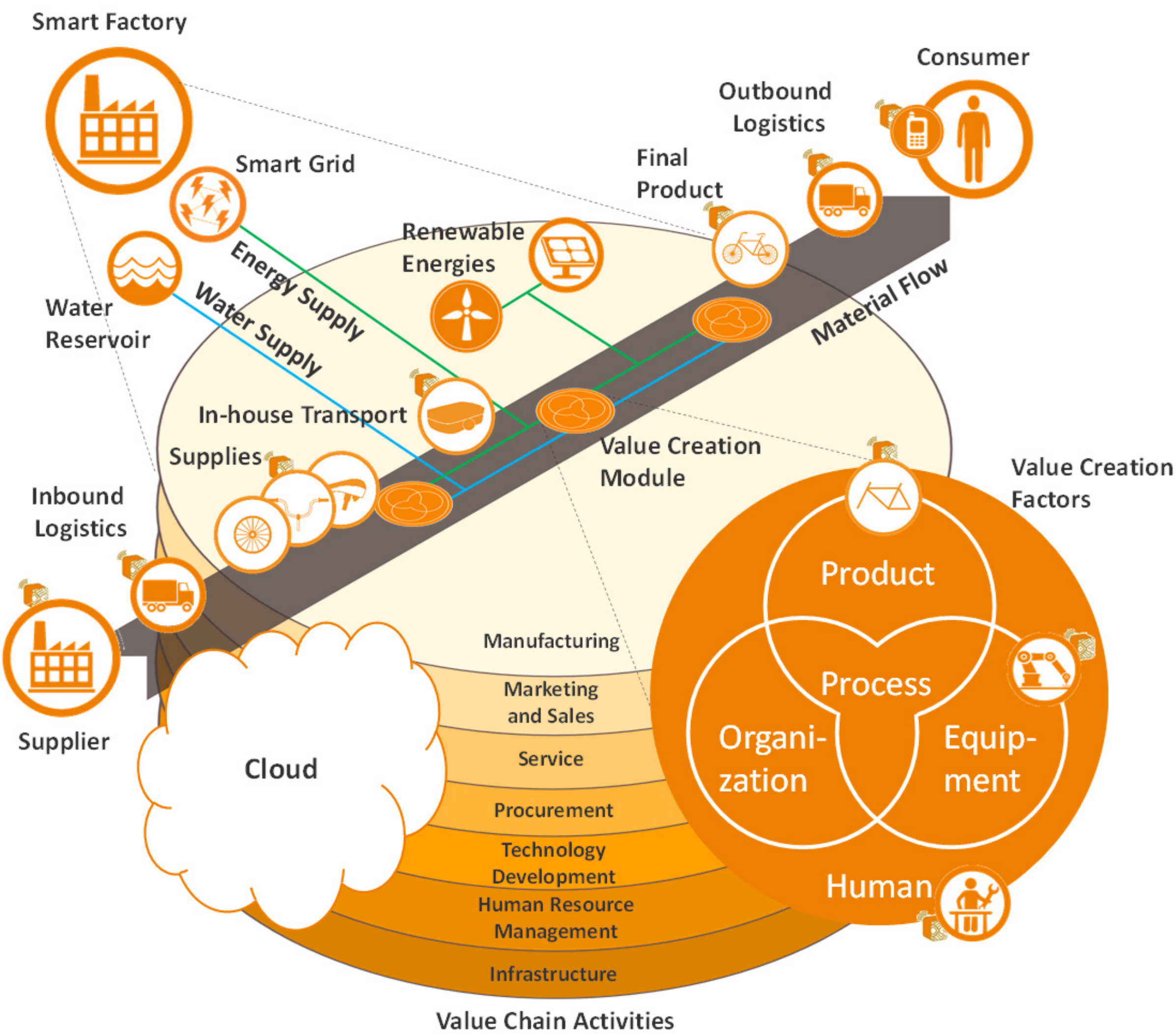

Fig. 2. Micro perspective of Industry 4.0

The smart factory as value creation module at the highest aggregation level contains different value creation modules on lower aggregation levels such as the manufacturing lines, manufacturing cells or manufacturing stations. Smart factories will increasingly use renewable energies as part of a self-sufficient supply in addition to the supply provided by the external smart grid [18]. The factory will thus become an energy supplier and consumer at the same time. The smart grid as well as the energy management system of the smart factory will have to be able to handle the dynamic requirements of energy supply and feedback. The supply of fresh water for the value creation modules within the smart factory is also another essential resource flow, requiring adequate and intact water reservoirs.

The horizontal integration from the micro perspective is characterized by the cross-linked value creation modules along the material flow of the smart factory also integrating the smart logistics. The in- and outbound logistics from and to the factories as part of the smart logistic will be characterized by transport equipment that is able to agilely react to unforeseen events such as a change in traffic or weather and which is able to autonomously operate between the starting point and the destination. Autonomously operating transport equipment such as Automated Guided Vehicles (AGVs) will be used for realizing the in-house transport along the material flow. All transport equipment is interchanging smart data with the value creation modules in order to realize a decentralized coordination of supplies and products with the transport systems. For this purpose, the supplies and products contain identification systems, e.g. RFID chips or QR codes. This enables a wireless identification and localization of all materials in the value chain.

Vertical integration and networked manufacturing systems from the micro perspective describes the intelligent cross-linking of the value creation factors: product, equipment and human, along the different aggregation levels of the value creation modules from manufacturing stations via manufacturing cells and manufacturing lines up to the smart factory. This networking throughout the different aggregation levels also includes the cross-linking of the value creation modules with the different value chain activities, e.g. marketing and sales, service, procurement, etc. [15].

The value creation module in a factory corresponds to an embedded Cyber-Physical-System. The manufacturing equipment, e.g. machine tools or assembly tools, are using sensor systems for identifying and localizing the value creation factors, such as the products or the humans, as well as for monitoring the manufacturing processes, e.g. the cutting, assembly, or transport processes. Depending on the monitored smart data, the applied actuators in the manufacturing equipment can react in real-time on specific changes of the product, humans or processes. The communication and exchange of the smart data between the value creation factors, between the value creation module and the transport equipment, as well as between the different levels of aggregation and the different value chain activities is being executed via the cloud.

Table 1 provides an overview of the main trends and expected development for the different value creation factors in Industry 4.0.

Table 1. Trends and expected developments for the value creation factors

Equipment	The manufacturing equipment will be characterized by the application of highly automated machine tools and robots. The equipment will be able to flexibly adapt to changes in the other value creation factors, e.g. the robots will be working together collaboratively with the workers on joint tasks [2].
Human	The current jobs in manufacturing are facing a high risk for being automated to a large extent [16]. The numbers of workers will thus decrease. The remaining manufacturing jobs will contain more knowledge work as well as more short-term and hard-to-plan tasks [10]. The workers increasingly have to monitor the automated equipment, are being integrated in decentralized decision-making, and are participating in engineering activities as part of the end-to-end engineering.
Organization	The increasing organizational complexity in the manufacturing system cannot be managed by a central instance from a certain point on. Decision making will thus be shifted away from a central instance towards decentralized instances. The decentralized instances will autonomously consider local information for the decision-making [14]. The decision itself will be taken by the workers or by the equipment using methods from the field of artificial intelligence.
Process	Additive manufacturing technologies also known as 3D printing will be increasingly deployed in value creation processes, since the costs of additive manufacturing have been rapidly dropping during the last years by simultaneously increasing in terms of speed and precision [17]. This allows designing more complex, stronger, and more lightweight geometries as well as the application of additive manufacturing to higher quantities and larger scales of the product [17].
Product	The products will be manufactured in batch size one according to the individual requirements of the customer [7]. This mass customization of the product integrates the customer as early as possible in the value chain. The physical product will be also combined with new services offering functionality and access rather than product ownership to the customer as part of new business models [17].

3. Sustainability in Industry 4.0

A paradigm Industry 4.0 will be a step forward towards more sustainable industrial value creation. In current literature, this step is mainly characterized as contribution to the environmental dimension of sustainability. The allocation of resources, i.e. products, materials, energy and water, can be realized in a more efficient way on the basis of intelligent cross-linked value creation modules [2].

Besides these environmental contributions, Industry 4.0 holds a great opportunity for realizing sustainable industrial value creation on all three sustainability dimensions: economic, social and environmental. Table 2 summarizes the opportunities of sustainable manufacturing for the macro perspective of Industry 4.0. Table 3 gives an overview of the opportunities for the micro perspective. The concepts presented in both tables merge the most important approaches of sustainable manufacturing in current literature with the trends and developments related to Industry 4.0.

Table 2. Opportunities of sustainable manufacturing for the macro perspective

Business Models	In Industry 4.0, new evolving business models are highly driven by the use of smart data for offering new services. This development has to be exploited for anchoring new sustainable business models. Sustainable business models significantly create positive or reduce negative impacts for the environment or society [19] or they can even fundamentally contribute to solving an environmental or social problem [20]. Additionally, sustainable business models are necessarily characterized by competitiveness on the long-run [20]. In this context, selling the functionality and accessibility of products instead of only selling the tangible products will be a leading concept.
Value Creation Networks	The cross-linking of value creation networks in Industry 4.0 offers new opportunities for realizing closed-loop product life cycles and industrial symbiosis. It allows the efficient coordination of the product, material, energy, and water flows throughout the product life cycles as well as between different factories. Closed-loop product life-cycles help keep products in life cycles of multiple use phases with remanufacturing or reuse in between. Industrial symbiosis describes the (cross-company) cooperation of different factories for realizing a competitive advantage by trading and exchanging products, materials, energy, water [21] and also smart data on a local level.

Table 3. Opportunities of sustainable manufacturing for the micro perspective

Equipment	The manufacturing equipment in factories often is a capital good with a long use phase of up to 20 or more years. Retrofitting enables an easy and cost-efficient way of upgrading existing manufacturing equipment with sensor and actuator systems as well as with the related control logics in order to overcome the heterogeneity of equipment in factories [10]. Retrofitting can thus be used as an approach for realizing a CPS throughout a value creation module, such as a factory, with already existing manufacturing equipment. It extends the use phase or facilitates the application in a new use phase for the manufacturing equipment and can essentially contribute to the economic and environmental dimensions of sustainability. It is particularly suitable for small and medium sized companies, being a low-cost alternative to the new procurement of manufacturing equipment.
Human	Humans will still be the organizers of value creation in Industry 4.0 [8]. Three different sustainable approaches can be used for coping with the social challenge in Industry 4.0. (1) Increasing the training efficiency of workers by combining new ICT technologies, e.g. virtual reality head-mounted displays with Learnstruments. (2) Increasing the intrinsic motivation and fostering creativity by establishing new CPS-based approaches of work organization and design, e.g. by implementing the concepts of flow theory [22] or using new ICT technologies for implementing concepts of gamification in order to support decentralized decision-making. (3) Increasing the extrinsic motivation by implementing individual incentive systems for the worker, e.g. by taking into account the smart data within the product life cycle for providing individual feedback mechanisms.
Organization	A sustainable-oriented decentralized organization in a smart factory focuses on the efficient allocation of products, materials, energy and water by taking into account the dynamic constraints of the CPS, e.g. of the smart logistics, the smart grid, the self-sufficient supply or the customer. This concept towards a holistic resource efficiency is being described as one of the essential advantages of Industry 4.0 [2,3].
Process	The sustainable design of processes addresses the holistic resource efficiency approach of Industry 4.0 by designing appropriate manufacturing process chains [23] or by using new technologies such as internally cooled tools [24].
Product	The approach for the sustainable design of products in Industry 4.0 focuses on the realization of closed-loop life cycles for products by enabling the reuse and remanufacturing of the specific product or by applying cradle-to-cradle principles. Different approaches also focus on designing for the well-being of the consumer. These concepts can be supported by the application of identification systems, e.g. for recovering the cores for remanufacturing, or by applying new additional services to the product for achieving a higher level of well-being for the customer [25].

4. Retrofitting Use Case

The objective of this use case has been the development of a retrofitting solution for a desktop machine tool within the laboratory of sustainable manufacturing of the Collaborative Research Centre 1026 at TU Berlin. The method for developing the retrofitting solution covers four sequential steps: (1) situation analysis, (2) definition of the monitoring strategy, (3) data processing and (4) implementation of the equipment in a CPS.

The situation analysis includes the definition of the list of requirements. In this case, the retrofitting solution is supposed to monitor the existing operational states of the equipment: shut on/off, idling, processing and fault. It also should be easy to install as well as cost effective.

Additionally, the situation analysis focuses on the selection of the sensor system according to the list of requirements.

In terms of the use case, an acceleration sensor has met the requirements appropriate.

The definition of the monitoring strategy contains the definition of the measuring parameters, the definition of the monitoring position and orientation of the sensor, the application of the sensor as well as the execution of the measurement. For the use case, a Beckhoff PLC has transformed the analog signals of the acceleration sensor into digital signals for the subsequent data processing.

The data processing evaluates the input data according to a predefined logic in order to identify the different operational states. The visualization of the data has been realized by a Human-Machine-Interface, which displays the current operational state as well as the measured vibration profile of the machine tool. Figure 3 shows the experimental setup of the milling machine, sensor and HMI.

This milling machine can now be implemented in a CPS. In connection with a smart product the retrofitted machine can decentrally schedule the material flow and is furthermore able to automatically react to any machine failures by e.g. informing the responsible worker.

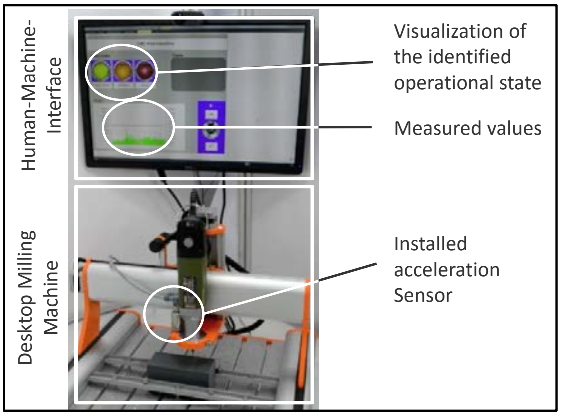

Fig. 3. Retrofitted desktop machine tool

5. Summary and conclusion

In this paper a state of the art review for the current industrial development know as Industry 4.0 has been presented. In order to give a comprehensive understanding of this development, the micro and macro perspective of Industry 4.0 have been described based on the current findings in research and practice. Subsequently, different opportunities for realizing a sustainable manufacturing in Industry 4.0 have been presented for the macro as well as for the micro perspectives. These opportunities are combining current research approaches in the field of sustainable manufacturing with the future requirements of Industry 4.0. Finally, a use case for retrofitting of a machine tool as a specific opportunity for sustainable manufacturing in Industry 4.0 has been outlined.

Acknowledgements

This research was supported the CRC 1026 "Sustainable Manufacturing – Shaping Global Value Creation" funded by the German Research Foundation (DFG).

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