Chapter 1
Towards Eco-Factories of the Future

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Abstract One-third of the global greenhouse gas emissions is caused by combusting fossil fuels to manufacture products and goods. Contemporary initiatives to lower the emissions chiefly focus on eco-efficiency, seeking for minimized energy demand and to a smaller extend also for minimized resource consumption. In addition to that, new technologies, a demographically changing workforce and the desire for new individualized products put further pressure on manufacturing companies. To encounter all those new trends and challenges successfully, various perspectives of a factory have been proposed to improve the understanding of all involved interdependencies between the factory elements. However, most of those perspectives lack to take all contemporary challenges and trends into account. Therefore, this chapter provides an extended perspective on the elements of a future factory.

1.1 Introduction

Various examples from history substantiate the important role of manufacturing for the development and prosperity of nations and hence also the growing wealth of the population (Gutowski et al. 2013; Reinert 2007). A key part for that development plays the machinery industry. Since the manufacturing of goods needs adequate production machinery including different components made for specific machine tools to produce in turn parts for diverse goods, manufacturing has strongly contributed to the vast economic growth of the last two hundred years (Rynn 2011). The importance of manufacturing can be also derived by comparing, for example, the world trades allocated to merchandise export (US$ 18.3 trillion) with the amount of commercial services (US$ 4.3 trillion) (World Trade Organization 2013). Based on that, a country's trade balance often reveals information about its wealth in two ways since

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services often depend on manufactured goods and cannot be offered independently (Aurich and Clement 2010; Kuntzky 2013).

In the light of the outlined importance of manufacturing related to a country's development and wealth, it is a country's objective to sustain or re-establish a strong manufacturing industry. However, to achieve this factories have to adapt to new and evolving challenges in manufacturing to remain competitive. This requires a responsible dealing with those challenges, which primarily involve among others:

- **Digitalization** as an industrial and societal challenge affects many areas of work and private life. From a manufacturing perspective, particularly more mature and economically feasible technologies in conjunction with evolving technologies and approaches from the Industry 4.0 umbrella offer significant potentials for improvements (Kagermann et al. 2013).
- The advancing **urbanization** process poses a challenge for industrial societies, since 66% of all people are expected to live in cities in 2050 (acatech 2016). This means that urbanization is of particular importance in industrialized countries, while cities are also drivers for the depletion of new knowledge and therefore offer the best prerequisites for disruptive innovations in industry as well as society.
- This comes along with a people's increasing desire for **individualization**. As a result, higher product varieties with lower specific lot sizes follow, which implies a rethinking of current manufacturing practices for instance based on economies of scale.
- As a consequence of the aforementioned challenges, a **change of work** towards an increasingly digitized working World 4.0 requiring new skills, qualifications and knowledge will follow. Although many effects of the digitized working World 4.0 are not regarded as determinable, they are often considered to be designable due to its often interdisciplinary context (Bundesministerium für Arbeit und Soziales 2016; Bundesministerium für Bildung und Forschung 2016; Hirsch-Kreinse 2014; United Nations 2014). This challenge of qualifying employees is further reinforced by the demographic change in societies.
- Another challenge relates to **sustainability** aspects in manufacturing, which is associated to a lack of natural resources and therefore prices and legislative regulations to comply with in terms of greenhouse gas or volatile organic compounds emissions as well as many others. As a result, energy and resource efficiency improvements have been and still are high on the agenda of manufacturing companies. In that context, the matching of factory internal energy and media demands with external volatile renewable energy sources grows in importance for manufacturing companies and is summarized as energy flexibility (Duflou et al. 2012).

The complex influence of those challenges on manufacturing companies implies that many of them cannot be viewed in isolation from each other to meet customer needs on the one hand and comply with emerging market situations on the other hand (e.g. in product volume per variant). As a result, the contemporary situation for the manufacturing industry is on a verge of change, which can be best understood by looking at its evolution over the last two centuries. This evolution involves several paradigm changes from Craft Production over Mass Production to Lean Manufactur-

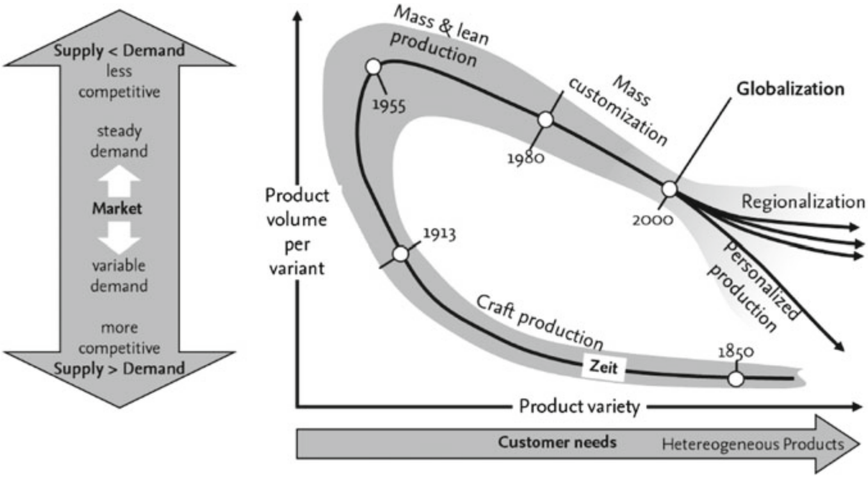

Fig. 1.1 Relationship between volume and variety in manufacturing paradigms (reproduced from reference Koren 2010 with permission)

ing, Mass Customization, while it is still ongoing as manufacturing companies are in the process of adopting to new challenges and trends (Hu et al. 2011). Figure 1.1 illustrates the evolution of the aforementioned manufacturing paradigms, which are described in more detail in the following.

The first paradigm is known as *craft production* since it responded to a specific customer order. The manufactured products were unique, which implies a high product variety through a high flexibility. However, since all products were created manually, they incurred relatively high costs as no automated manufacturing systems were in place for this paradigm (Hu 2013).

Mass production denotes the second paradigm, which fosters the production of products at lower cost through large-scale manufacturing. However, there was only a limited variety of products applied. Typical characteristics of this paradigm were Henry Ford's moving assembly line and his statement: "Any customer can have a car painted any color that he wants so long as it is black" (Ford and Crowther 1922). The peak of the mass production paradigm was reached after World War II, since demands for products increased rapidly. In general, mass production comprises three different principles. The first one regards interchangeability to improve the assembly selection of parts. The second principle denotes the concept of a moving assembly line, which transports the products, e.g. cars, to the workers. Since the workers executed the same tasks repeatedly, the products could be manufactured with lower tolerances, quicker and therefore at lower assembly costs (EyeWitness to History 2005). The third principle describes what is commonly known as Taylorism. With the help of Taylorism, work is subdivided into several specialized but repetitive tasks.

Lean manufacturing also emerged as a result from World War II in Japan due to the country's limited resources and is often referred to as the "Toyota Production

System" as its major developer. From a manufacturing perspective, this paradigm aims at minimizing all sorts of waste—also known as *Muda*—through maximizing customer value along the product's value chain. The widespread application of this paradigm in contemporary production systems underlines the importance of the Lean Management Philosophy (Womack et al. 1990).

Mass customization originated from the customer demand for increased product variety at the end of the 1980s. Particularly, the automotive industry adopted that principle quickly, leading, for example, to 1017 different possible combinations for the BMW 7 series alone (BMW Group 2014). Again, three principles constitute this paradigm (Hu 2013). At first, different family architectures are introduced which differentiate between product modules that are shared among each product while others are only provided individually upon customization request (Tseng et al. 1996). This helps to manifest the second principle, which describes the distinction of the manufacturing process into a rather push- and pull-oriented production and assembly part. This implies a delayed differentiation of products, which is typically known as a customer decoupling point to customize the final product while saving costs and increasing the responsiveness of the assembly system (Lee and Tang 1997; Ko and Hu 2008). The reconfigurability of a manufacturing system states the third principle and denotes the prerequisite for changing product mixes and demands to improve the overall system's performance (Koren et al. 1999; Koren et al. 1998). This, however, comes at the expense of handling a manufacturing system with an increased complexity (Hu et al. 2008).

As a result from smaller product volumes and a rising variety (see Fig. 1.1), it emerges a trend towards more *personalized products* (Hu 2013) Thus, various different work steps and cycle times are involved which are often independent from typical manufacturing KPIs, such as tact times of typical assembly lines. Ultimately, this may lead to the economically feasible manufacturing of very small lot sizes as a gain from improved production system flexibility.

Another arising trend is the need for environmentally benign manufacturing due to higher living standards, a growing demand of consumers for products and consequently more resources for energy production, which lead to rising energy and resource prices (Herrmann 2010). Stricter legislative regulations to comply with emission boundaries follow, which is why a *sustainable production* is more important than ever for manufacturing companies.

Furthermore, *information and communication technology (ICT)* will play an important role in the future manufacturing sector. This is already reflected by the past progression: Starting with first NC machines in the 1950s (Pease 1952) over computer-controlled production cells in the late 1960s (Talavage and Hannam 1987) to the idea of computer-integrated manufacturing (CIM) in the late 1970s (Mitchell 1991) a constant advancement is notable. Since the costs of ICT components have dropped significantly while the technology becomes more versatile and powerful, there will be multiple new ways how these components will change future production systems, as indicated by the present research trends towards cyber-physical systems (CPS) (European Commission 2014).

The aforementioned trends bear also a *social influence* on future manufacturing companies in multiple ways. At first, professionals will have to learn how to cope with the new trends through *production-related learning environments* to familiarize themselves with the new technologies and circumstances (DIHK 2011; VDI Nachrichten 2014; Damodaran 2001). Secondly, personal desires gain in importance so that living circumstances, for example in the light of a progressing urbanization, will further reinforce the wish for short commuting distances (The World Bank 2013). Hence, it remains questionable whether factories and therefore production systems might be integrated into residential areas as good neighbours (Chertow 2007). Thinking and taking this idea one step further, *future production ecosystems*, may be considered as a place which is not only ecological efficient in itself but also enables benefits for its environment from a holistic perspective. In that context, factories may be in a symbiosis with their surroundings in terms of their role in smart grids, local (climate) constraints or sharing conditioning and treatment units e.g. for fresh, process or wastewater with and from residential areas (Chertow 2007; Greenpeace 2012).

1.2 Factories of the Future Framework

To respond to the outlined trends such as urbanization or digitalization in form of cyber-physical production system (CPPS), Herrmann and colleagues propose a renewed holistic understanding of a factory of the future (Herrmann et al. 2014). This understanding seeks to address more than ever all three dimensions of sustainability—economy, ecology and society. While aiming at higher profitability from an economic perspective, the factory should also be associated as a place with a positive impact on its surrounding area by improving the quality of air and water, exploiting local waste flows, providing renewable energies or by acting as storage for surplus. From a social perspective, future factories should be perceived as a people's place, where they can focus on collaborative learning and developing new skills. Figure 1.2 shows this new perspective and differentiates between four main aspects worth considering in the planning of future factories which will be further explained in the following:

- Symbiotic flows and urban integration of the factory
- Adaptable factory elements: adaptive building shell, modular and scalable TBS, and flexible production system
- Production cloud and cyber-physical systems
- Learning and training environments.

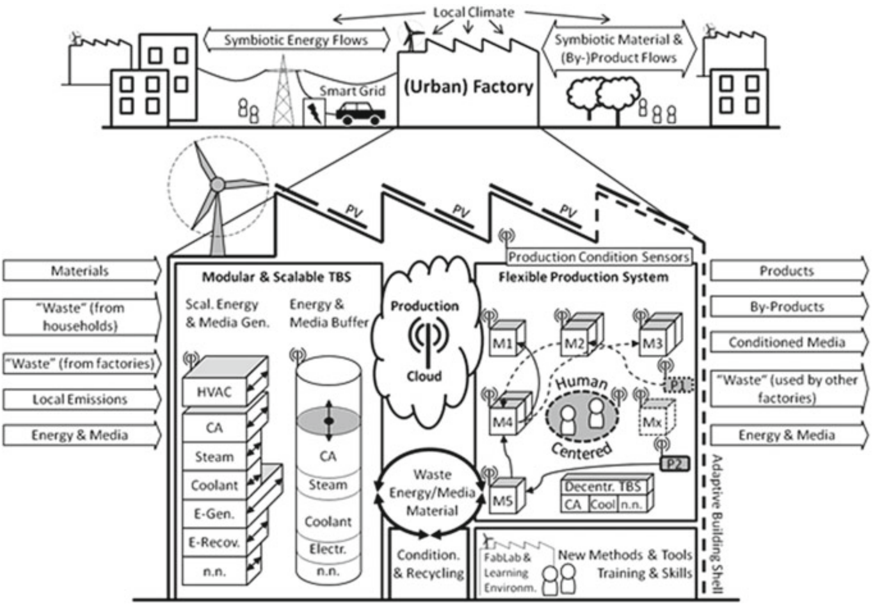

Fig. 1.2 Holistic understanding of a factory of the future and its flows (Herrmann et al. 2014)

1.2.1 Symbiotic Flows and Urban Integration of the Factory

While many contemporary approaches of sustainable production are chiefly concerned about minimizing resource and energy input flows as an efficiency effort (Despeisse et al. 2012; Braungart et al. 2007), this may not be a remedy for an adequate long-term solution. This is because efficiency efforts describe strategies for damage management as opposed to strategies that rather focus on new shifts in strategy. Such a shift could imply for future factories to cease opportunities for a potential upcycling of material or media quality over time. Consequently, factories will be capable of generating a positive recoupling between the two sustainability dimensions of economy and ecology, which is known as eco-effectiveness. Thus, eco-effectiveness helps to close loops between material and energy flows within the factory itself but also in collaboration with the factory's external environment (Braungart et al. 2007). Positive effects may entail that solid waste will be used for new products while wastewater will be treated and renewable energies will be produced or stored helping to neutralize local emissions.

An eco-effective production resembles strong similarities to a biological system, where material flows serve as biological nutrients for living systems while "waste" does not exist, as it is an input for another living system (Ayres and Simonis 1994). This idea is also adopted by the concept of a factory of the future as it incorporates a symbiotically sharing of material and energy flows with its (urban) infrastructure and/or with other factories to foster the integration of smart grid technologies. Some examples of this idea have already been rudimentarily implemented in form of so-called industrial symbioses within eco-industrial parks, such as Kalundborg or the Haven in Rotterdam. Chertow gives an overview of further realized projects in the context of industrial symbioses (Chertow 2000).

1.2.2 Adaptable Factory Elements

The literature presents a variety of perspectives and slightly different terms regarding the structure, composition and elements of a factory (Wiendahl et al. 2007; Müller et al. 2009). However, among those perspectives there is a consensus to group the elements of a factory into the building shell, the technical building services (TBS) and the production equipment, which include single machines or process chains (Hesselbach 2012; Thiede 2012). This categorization helps to emphasize the manifold connections (e.g. regarding production system utilization, machine states, media demands, weather) between all involved factory elements and its entities with each other. This connection is realized through different material, energy, media and information flows, which have to be maintained and controlled subject to induced internal or external changes on the production system (Westkämper and Zahn 2009). Thus, a factory and its production system can also be perceived as a complex control system with internal and external influencing variables (Thiede 2012). To transform factories, it is important to bear the following five principles in mind while designing future factory elements: *modularity, scalability, universality, compatibility and mobility* (Wiendahl et al. 2007).

1.2.2.1 Adaptive Building Shell

The building shell mainly insulates the factory and separates the other factory elements from the outer conditions and the local climate, respectively. Future requirements concerning the building shell regard their potential of flexibility in terms of changeability. As the whole factory is chiefly determined by its primary structure, e.g. the distance between the supporting columns of the building, it seems beneficial to use larger distances of 30–40 m between two pillars instead of 20 m, which is state of the art at the moment. This helps to gain spatial flexibility and therefore higher degrees of freedom regarding utilization for only little increased invests by approximately five per cent (Wiendahl et al. 2005). Since the structure of a factory is commonly planned upfront, the building shell and its pillars are hardly changeable afterwards. Thus, flexibility limits can be extended by adopting those new principles in the early planning stage or by thinking about completely new building concepts, which are more flexible to changing requirements. Examples of such new building concepts and structures are factories comprising modular containers, factories within transportation systems such as ships or trains as well as air-inflated factory structures (Wiendahl et al. 2005).

From an ecological perspective, the building shell can contribute to either being made of appropriate building materials, such as cement, or by incorporating useful functions, e.g. for cleaning the air by absorbing and photocatalytically decomposing various pollutants from the air (Chen and Poon 2009). The roof of a factory is predestined for the installation of renewable power plants to acquire and save energy from solar and wind. To support the power generation new materials with integrated energy generation capabilities like building-integrated photovoltaics (BIPV) and superseding retrofit solar power systems can be employed (Eiffert and Kiss 2000). Provided that enough energy can be stored within the factory, this could enable energy-self-sufficient factories, which can act independently from the grid and may be a favourable solution for rural areas of developing countries.

1.2.2.2 Modular and Scalable TBS

In production systems exist diverse media flows which are directly linked to the manufacturing operations. Many of those media flows are provided by TBS, which pre-process energy and media flows including compressed air, heating, cooling, water and coolants subject to the required production conditions (Thiede 2012). In future factories, TBS will be linked both physically and virtually to the production systems. This will enable to go beyond mere production monitoring purposes through an automated optimization production condition concerning controlling variables such as temperature, lighting, humidity.

Apart from factory internal energy and media provision, the TBS technologies may also be used to integrate factory external energy and media demands and supplies to interact symbiotically with the factory surroundings. As a positive effect from this potential collaboration, future factories may be used as energy and media buffers to level fluctuating inputs and outputs in certain areas and thus help stabilizing, for instance, the electric grid as a backup for power blackouts (Eyer and Corey 2010; Masaud et al. 2010). With respect to the realization of factory internal storage options, central battery systems or compressed air energy storages as well as decentralized systems such as electric vehicles or even products, which imply an increased production in times of energy availability, appear to be reasonable.

To be able to incorporate such changes resulting from the integration of surrounding energy and media flows as well as renewable energy technologies, future TBS must be designed and controlled to react quickly on fluctuating demands and supplies. In addition to that, fluctuating customer orders and a high degree of product individualization leading to more fragmented process chains with unequal energy and media demands further emphasize this need of quick TBS responsiveness. Because of decreasing product life cycles, more frequent changes of the production system can be expected, which will also entail an impact on the TBS. Therefore, a modular, expandable and partly decentralized TBS structure could be more suitable than traditional centralized systems, although it may come at the expense of lower a degree of efficiency of small or decentralized systems compared to larger, monolithic TBS structures. The design of decentralized TBS modules may be similar to the idea of plug-and-produce, which has been derived from the plug-and-play principle of computing (Hildebrand et al. 2005). In that sense, the high degree of hardware and software standardization facilitates the integration of additional elements and devices by simply plugging them to machines, transport systems or TBS and start working instantly, similar to an USB device connected to a PC. Consequently, increased demands of, for example, compressed air could be handled with a plug-and-produce extension for the existing compressor, which therefore owns standardized interfaces. This could help to avoid an over-dimensioning of systems as upgrading and downgrading would be possible at all times with minor efforts.

1.2.2.3 Flexible Production System

A flexible production system of a future factory is capable of responding to an increased variety and complexity of future products. To operate such a system profitably while using minimal resources, a high degree of machine utilization is required. However, particularly for assembly operations, traditional concepts are not able to maintain an optimal utilization of machines while producing components with a high variance in processing times on the same production line (Krajewski et al. 2010) Since all product variants require a different work content, varying processing times and hence cycle times for all products and processes follow. Thus, traditional production and assembly lines seem to be not suitable to respond to future requirements in terms of flexible production and assembly. A promising approach to alleviate this issue could be an increased versatility of the production machines. This allows every machine to assemble a big variety of different product variants. As a consequence, products may choose different paths through the production system subject to their preferred objective, which could be a time, priority or energy optimized path for each individual product variant. The preferred paths for each product further depend on the properties of the other product variants currently in the system as well as the individual states of the machines in the multi-machine production environment. To implement such a flexible production system, an appropriate flexible transport system, allowing an individual distribution of material to the production resources, is needed as well.

Similar to the TBS, a flexible production system may also follow the plug-and-produce philosophy (Hildebrand et al. 2005) to provide a high degree of scalability to respond to changing market demands. Such a system can be well represented by multi-agent system (MAS) approaches, which base upon a set of distributed autonomous but cooperative entities such as products and machines (Wooldridge 2002). In that sense, many decisions then can be made decentralized and collaboratively by the agents, based on their individual logic, resulting in an optimized performance of the whole production system. This approach also facilitates a quick reconfigurability of the system, because no fixed central systems for production planning and control have to be changed. As appropriate information flows are essential for operation, most elements of the system will be equipped with sensors and empowered to communicate with each other about their current states and potential orders or product queues waiting in suitable buffers.

Apart from all technical aspects, it is important for future production systems to be designed around human employees as they will be needed in all phases of factory operations, from the planning through operation to maintenance and repair (Zuehlke 2010). Furthermore, technologies should be designed and developed in such a way so that human cognitive and sensomotor abilities can be used and/or systematically developed, e.g. using learning and training environments (see Sect. 1.2.4). Thus, technology has to be adopted to human needs instead of a conversely adaption of human action to technological constraints.

1.2.3 Production Cloud and Cyber-Physical Systems

Since information technology (IT) will further increase overall factory layers, including a wide application of sensors on shop floor level, the collection, consolidation and processing of those information will be very important. As monolithic IT architectures will fade, there will be space for new, agile platforms, which can gather data and use them to provide different services and/or make decentralized decisions. Independent entities or agents can then perform those services or decisions. For example, CPS can support human workers on shop floor level by providing context-specific live information gathered by the sensors from the production system, which will be pre-processed for the specific task.

The vast amount of gathered data in the factory of the future requires the setup of a decentralized data pool, the "production cloud", which collects and allocates all information from the production system as well as TBS entities. Typical data include productivity (e.g. processing and cycle times), energy and resources data (e.g. energy demands per process/machine/part), product-related information (e.g. product quality indicators) or data concerning the production conditions (temperature, humidity, lighting etc.) as well as the current status and state of all factory elements and its entities. Having all those data stored and accessible in a production cloud entails several benefits, such as a high degree of transparency through embedded monitoring and control functions, which provides useful information for future improvement measures. The production cloud could also serve as a link to cloud manufacturing services (Tao et al. 2011), which appears to be an adequate approach for the manufacturing of individualized products within virtual manufacturing networks. Every factory of the network can offer its services with regard to free capacity, deliverable quality or achievable delivery times, causing individual supply chains for every product or variant. This idea is very similar to the concept of an Internet of things (IoT), which was presented in the 1990s (Weiser 1991; Ashton 2009). According to the IoT, all physical elements also have a virtual representation in an Internet resembling structure. To achieve such a virtual representation, a broad installation of sensors, actuators and processors including distinct identifiers of all objects, e.g. realized by integration of RFID tags, are required to duplicate the physical system and its behaviour. Such a vision of a Factory of Things, composed of self-organizing smart objects without a traditional hierarchy, is also known as Smart Factory (Zuehlke 2010).

1.2.4 Learning and Training Environments

Regardless of all technological progress, human abilities will still be a significant success factor of future factories. Therefore, highly educated employees are required which undergo continuous training to keep pace with changing external requirements and technological improvements. To facilitate this learning and training process, "Learning Factories" (also referred to as Teaching Factories) could play an important role in educating the employees since they can experiment and research new topics at realistic production processes (Chryssolouris et al. 2013). Those processes can typically be adjusted for case-specific teaching purposes of different target groups. Furthermore, such learning environments also allow for the communication and testing of theoretical knowledge in practical application and learning results can be transferred to real factory applications. A Learning Factory can comprise both physical and digital environments. Physical environments contain real system components such as machines, assembly, logistics, information and energy flow modules, while the digital environments include planning, modelling, visualization and simulation tools to experience different effects and measures virtually. Physical and digital environments can also work together, where some improvements scenarios can be first modelled and evaluated virtually and subsequently be tested and assessed in the physical learning environment (Wagner et al. 2012). The concept of Learning Factories is an established concept in academic research, but also an increasing implementation of Learning Factories and scenarios can be observed in industry.

Future factories may involve fabrication laboratories or "FabLabs", which contain a collection of tools for design and modelling, prototyping and fabrication, instrumentation, testing, debugging and documentation for a wide range of production relevant applications (Gershenfeld 2012; Mikhak et al. 2002). This will empower people to design, physically realize and test their own personalized product creations in the FabLab by using the provided infrastructure and machines. Since this enables an easy entrance to new technologies, this approach may be especially beneficial for regions with lower education or prosperity, as they support regional development by catering specific individual needs of the people. In addition to that, FabLabs also state a platform for knowledge transfer to broad parts of the society in industrial countries (The International Fab Lab Association 2012).

1.3 Conclusion and Outlook

Manufacturing constitutes an important factor for the prosperity of nations and a vital source of innovation and development. To guarantee the competitiveness of the manufacturing industry, factories had and always have been under pressure to adapt to new challenges and trends. This resulted in several changes of manufacturing paradigms over the last two centuries. Today and future factories face various evolving trends. Those trends involve highly customized products manufactured by an eco-friendly production system with significantly lower environmental impacts. This is often realized using new ICT technologies while providing social options for production-related learning and an integration of the factories into its spatial (urban) surrounding.

To face those trends, this chapter presents a holistic factory perspective of the future, which addresses the contemporary trends in manufacturing. The presented vision contains four main aspects: first, a symbiotic integration of the factory into its surroundings and in particular to urban or domestic areas as well as an orientation towards eco-effectiveness, heading for a positive recoupling between economy and ecology. Second, since a high degree of flexibility of the factory infrastructure is needed, adaptable and modular main factory elements, namely building shell, TBS and a flexible production system, are needed. Third, as the operation of such a system is only feasible through a decentralized gathering and use of information, the integration of a production cloud concept is proposed. Furthermore, a widespread application of ICT is indispensable, which will help to link the physical and digital factory representations with each other. The fourth and last aspect addresses the necessity to provide learning and training to hone human skills and abilities as future production system will be still human-centred. To achieve that, the implementation of specific learning environments such as Learning Factories seems promising.

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