# Conceptual Framework of a Digital Twin Fostering Sustainable Manufacturing in a Brownfield Approach of Small Volume Production for SMEs

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**Abstract.** SMEs are increasingly forced to shift to more sustainable manufacturing. Industry 4.0 can support the transformation and foster innovation. But, SMEs need solutions with a low barrier to entry in terms of investment, IT knowledge and capacities. A framework based on value and material flow analysis, low investments and user-oriented IT skills is proposed. As an example, it is implemented in the furniture industry and shows a digital twin in terms of monitoring the energy and material flows. In addition, a product-specific allocation of energy consumption, energy peak shaving and other applications are possible.

**Keywords:** Industry 4.0 technology · Green transformation of manufacturing

## 1 Introduction

For decades, growing economic, environmental and social challenges have reinforced the need for a "green transformation" in production. The increasing demand for resources by industry leads to environmental problems. As small and medium-sized enterprises (SMEs) are responsible for 60–70% of industrial pollution in Europe, they need solutions to address sustainability [1, 2]. Combined with resource scarcity which entails supply risks and price volatilities, this poses major challenges, but also offers opportunities in terms of reduced environmental impact and lower supply risks. All companies, including SMEs, must develop their business models into sustainable ones.

Sustainable manufacturing (SM) can be seen a part of sustainable development (SD): Based on the UN Brundtland Commission, which has defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs", the approach is applied to the concept of SM [3]. In addition, the UN agreed on the 17 SD Goals (SDGs) in 2015. Three of them relate to SM and cover different aspects, namely SDG 7, 9 and 12. While SDG 7 and 12 consider energy intensity or material consumption, that can be achieved with SM approaches and technologies, SDG 9 emphasizes building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation. Target 9.4 explicitly calls for upgrading infrastructure and retrofitting industries to make them sustainable, with increased resource-use


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efficiency and greater adoption of clean and environmentally sound technologies and industrial processes [4].

## 2 Sustainable Manufacturing in the Context of Industry 4.0

### 2.1 Sustainable Manufacturing and Industry 4.0

There has been no uniform definition of SM among scientists for years, and even today different approaches are associated with SM [5, 6]. A general definition is given by Chen and Zhang, who describe SM as “the science and technology of manufacturing based on the idea of SD” [7]. Loglisci et al. go further, seeing SM as a key component of SD [8]. Following Moldavska and Welo, most definitions agree that SM is the creation of a product or service taking into account the environmental, economic and social dimensions. However, the literature distinguishes between whether it is a strategy or concept on the one hand, or a paradigm or system on the other. Further, while it can be assumed that the entire life cycle is considered, only a few deal with the end-of-life in the context of SM. Almost all definitions reflect the goal of reducing impacts or improving the relevant factors of production [5].

For this paper, SM is defined as “the integration of systems and processes capable to produce high-quality products and services by utilizing less and more sustainable resources such as energy and material, being safer for societies, employees, consumers, stakeholders and being able to mitigate social and environmental impacts throughout its whole life cycle” [9]. Bonvoisin et al. present four overlapping and complementary layers that considers the objects addressed and disciplines concerned to achieve SM [10]: According to these layers, the framework looks at the first layer, manufacturing technologies, which addresses the two factors of value creation process and equipment. The aim is to increase energy, resource and economic efficiency and reduce environmental impact through a digital twin by applying I4.0 technologies.

### 2.2 Industry 4.0 Enabling Technologies for Sustainable Manufacturing

I4.0 describes the transformation of the industry through Internet of Things (IoT), data and services. The term integrates different perspectives, sectors, industries, corporate functions, technologies and subject areas [11]. Its technologies have a huge scope of application and cover a broad spectrum. Suleiman et al. 2022 list 24 concepts that also include concepts beyond production: With regard to sustainability, the concepts of circular economy, remanufacturing, sustainability and Recycling 4.0 are mentioned. Accordingly, the sustainability concept of I4.0 “enables and supports sustainability by deploying digital technologies and business models with a focus on energy efficiency, pollution control, and value chain optimization” [12].

Ching et al. identify eight I4.0 technologies that are relevant for the economic, ecological and social dimension of SM [13]: Artificial Intelligence, Blockchain, Big Data Analytics, Cyber-Physical (Production) Systems (CP(P)S), Industrial Internet of Things (IIoT), Digital Twins (DT), mixed reality and robotics. Others mention fog and cloud computing, actuators and sensors, 3 D print (additive manufacturing), cognitive computing, simulation and modelling related to sustainable or energy efficient manufacturing, to name but a few technologies [14–17].

For the purpose of this framework, technologies such as CPPS, IIoT, DT and sensors as well as methods such as data analytics and machine learning are relevant (Table 1). The technologies collect, transfer, store and process real time data via the infrastructure of the network (IIoT), while data analytics and machine learning methods analyse them for decision-making. These technologies and methods drive the digital transformation of production systems, which offer a variety of opportunities to use real-time data to increase sustainability in manufacturing [17–20]. Based on this, metrics are often used for SM assessment that prepare the real-time data for further use, e.g. key performance indicators, process maps, forecasts. Several metrics are available taking into account the three dimensions of sustainability [21–24].

**Table 1.** Terms, definitions and application of I4.0 technologies and methods

| | Term | Defintions | Application in the context of the conceptional framework |
|---|---|---|---|
| Technologies | CPPS | A cyber-physical (production) system (CP(P)S) is comprising a set of interacting physical and digital components, which may be centralised or distributed, that provides a combination of sensing, control, computation and networking functions, to influence outcomes in the real world through physical processes [25]. In a production context, it is referred to as a CPPS. | Based on the IIoT, machines, IoT connectors and sensors on the shopfloor level, ERP and MES systems, data bank and analytic software form a CPPS. |
| | DT | A digital twin (DT) is a digital representation of a physical unit (real device, object, machine, service, or intangible asset) or product-service system that comprises its selected characteristics, properties, conditions, and behaviors by means of models, information, and data within a single or even across multiple life cycle phases [26]. | Real-time data from machines and sensors, enriched with ERP and MES data, create a digital twin from the processing data, machine data, value and material flow data of the process chain. |
| | IIoT | The Internet of Things (IoT) form the infrastructure for the networking of cyber-physical systems and enables people and CPS to have controlling, coordinating and location-independent access to the integrated CPS [27]. The application of the IoT in an industrial context is referred to as Industrial Internet of Things (IIoT) [18]. | The IIoT enables the conmuication of the Industry 4.0 components and provides the network for digital data collection and the CPPS. |
| | Sensor | A sensor is a device that detects the input stimulus, which can be any quantity, property or condition from the physical environment, and responds to a measurable digital signal. For instance, the input stimulus can be pressure, force, flow, light, heat, motion, humidity or many other environmental phenomena. The output signal is usually an electrical form of a signal (voltage, current, capacitance, resistance, frequency, etc.), which is converted into a readable display or transmitted electronically over a network [28]. | Sensors are collecting data (power, compressed air, waste, exhaust, etc.) and transmit them digitally via IIoT to a data bank or cloud. |
| Methods | Artificial Intelli-gence | A subtopic of artificial intelligence (AI) is machine learning, in which algorithms are used to recognise patterns and regularities. Solutions can then be developed based on the empirical data sets. | Machine learning is used to detect anomalies in manufacturing, e.g. processing characteristics. |
| | (Big) Data Analytics | Data analysis can be divided into the categories system infrastructure and analysis methods. While system infrastructure focuses on preparing the data for analysis, analysis methods focus on how to gain insights from the data. The latter are divided into descriptive, predictive and prescriptive analyses [29]. | Data analysis methods are used to monitore efficiency or to predict power performance for demand side management or peak shaving. |

Therefore, I4.0 technologies are recognised as a key facilitator in SM [6, 30]. Kumar et al. take a different perspective, noting that SMEs are under enormous pressure to produce more sustainable. Stakeholders ask SMEs to implement sustainability and request, for example, information on resource, material and energy consumption or their carbon footprint. The application of I4.0 may support SME in these efforts [31]. However, due to their economic footprint, SMEs are one of the most important pillars for the sustainable growth of national economies [30].

### 2.3 Industry 4.0 Challenges for SME and Small Volume Production

Large manufacturers are often taking a leading role in the adoption of technologies as they have greater opportunities to embrace and transform them, while many SMEs are reluctant to adopt [32]. The main barriers for adopting I4.0 are a lack of expertise and a short-term strategy mindset [33, 34]. In addition, limited IT skills, capacities and investment costs are a common concern [35]. SMEs' production is often characterised by heterogeneous machines of different ages, from different manufacturers and with a variety of protocols and sometimes missing processing information (brownfield) [36]. Or it is a production that not infrequently also has a batch size of up to 1.

Studies tend to focus on global companies. Consequently, SMEs are often treated similarly in their transformation towards SM and I4.0, although they have different requirements. Thus, research is needed to support SMEs that help smaller players to continue or implement I4.0 innovations. Due to limited capacities, technologies need to prove their benefits quickly in order to be pursued further in SMEs. I4.0 applications for SMEs therefore require solutions that have low barriers to entry [35].

## 3 Framework for a Digital Twin for Sustainable Manufacturing

### 3.1 Method of Value and Material Flow Analysis in the Context of I4.0

Increasing sustainability in manufacturing is related to inputs and outputs, internal and external process parameters and characteristics, machining time, quality and the condition of machines and tools. Therefore, a combined value and material flow analysis was developed as a methodological basis in the context of I4.0 [37]. Depending on the aim of SM, the availability of (digital) data from different sources, ranging from ERP and MES systems to product data and machine and sensor data, is analysed and missing data must be collected with the help of I4.0 technologies (Fig. 1).

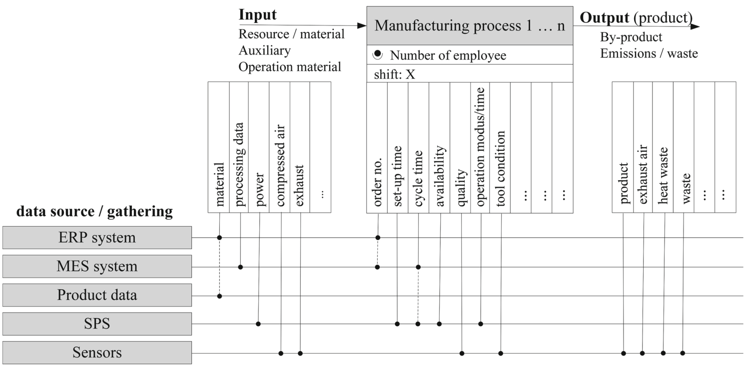


**Fig. 1.** Value and material flow analysis in the context of I4.0 for SM

Thus, I4.0 technologies offer a real-time, consistent and continuous collection of relevant data from the machines, sensors and operational information systems to implement a digital twin for the value and material flow of a process chain. In combination with data analytic methods and user-related process knowledge, the data-based value and material flow model can be used for various issues of SM.

### 3.2 Framework for a Digital Twin in the Context of Sustainable Manufacturing

The framework links the methodology of value and material flow analysis with the architecture of I4.0 real-time based information, communication and data processing technologies. The stored data are then used to provide real-time data for operations profitability, energy and resource efficiency towards digital twins. The framework is developed for a brownfield approach that allows SMEs to retrofit their existing machines with I4.0 technologies regardless of heterogenous machine types, age, data format. Aim is to provide an I4.0 based solution for SM with a low entry threshold (Fig. 2).

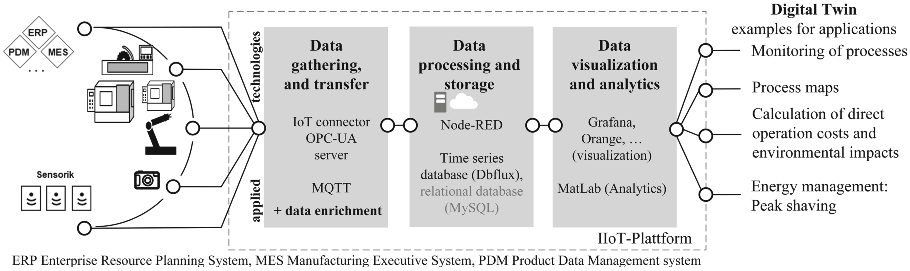


**Fig. 2.** Architecture of the conceptional framework for SM

Data from ERP, MES and PDM systems as well as machine data are collected with an OPC-UA server that converts them. While the machine data is real-time data from operations, the others are static data for process or product-specific analyses. Sensor data is collected by IoT connectors located at the machine site and transmitted using the messaging protocol MQTT (Message Queuing Telemetry Transport). In a next step, the data is processed with the object-based programming Node-RED and written to a database. Since the data is collected in small time steps, a time series database is recommended to process the flood of data appropriately in terms of time and storage capacity. The processed data serves as a digital backbone for visualization and analytics. Simple applications such as the monitoring of value and material flows as well as the utilization of machines are already possible with open source graphics programs. For data analytics, MatLab is recommended as a common tool for engineers. Descriptive analytics such as process maps for improved start-up of a process at the beginning of a shift to prescriptive analytics dealing with the energy peak shaving based on production planning and process data in order to reduce energy demand from the power grid.

### 3.3 Application of the Conceptional Framework for SM

The framework is applied in a small volume production in the furniture industry. It reflects typical processes from the panel sawing, edge banding and drilling and milling (Fig. 3). At shop floor level, the machines are equipped with IoT connectors, sensor technology for power, compressed air, exhaust air and waste, with data being collected every 250 ms. In the periphery system, the compressor and exhaust air system are equipped with sensors (power). In addition, data is extracted from the CAD product configurator, ERP and MES systems. This data characterises the material, density and size of the material and the parts to be produced, machining data per process step, e.g. type of edge band, number of sides to be edged, number of drillings per part. The data collected by the IoT connectors is transmitted via the MQTT protocol and processed with Node-RED. The material and product data are provided via an OPC UA server. All data is written to a DBflux database; all data analytics are carried out with MatLab.

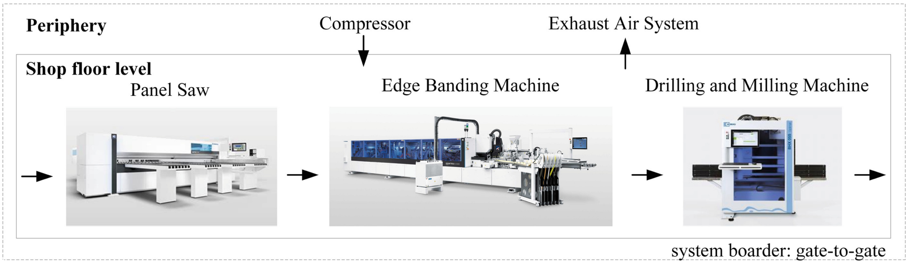


**Fig. 3.** Process chain in the furniture industry

The digital backbone of real-time data, enriched with product and process data, enables diverse applications in terms of SM. In the field, a real time monitoring of energy and material consumption for a small volume production with a parameterized process model was developed based on real-time data (Fig. 4). This allocates the consumption and power demand to specific components. Further applications develops a parameterized process (chain) model for forecasting energy and material consumption or machine occupancy, assessment of the total power demand to shave energy peaks, and direct offsetting of energy and processing costs at component and product level; or calculation of cumulative energy demand or $CO_2$ footprint of a product.


**Fig. 4.** Small volume production of a sideboard: Power demand monitoring by defined bandwidth with/without heater of a banding edge machine for glueing the edge

Depending on the impacts and potentials of the manufacturing processes, SMEs need to derive strategies on how I4.0 can support sustainability efforts.

## 4 Conclusions

Based on a combined value and material flow analysis, the conceptional framework presents an approach that can be applied to implement SM applications in the context of I4.0. The methodology of material flow analysis is mainly known among environmentally oriented economists and engineers, but qualifies as a suitable approach for SMEs by combining it with the well-known method of value flow analysis. To address the SME situation, the framework avoids proprietary solutions to create a digital twin. Furthermore, it focuses on a brownfield environment with machines from different manufacturers and different levels of digitalisation, as is often the case in SMEs. The I4.0 hardware and software have a low barrier to entry in terms of costs and required skills. SMEs can apply it to a single process and then gradually extend it to others. Successes in real-time process monitoring and process maps encourage SMEs to take further steps. Various application as direct cost calculation or accounting of environmental impacts of products in small batch production are possible. However, there is a need for further research into solutions for a horizontal process integration.

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