Combining Life Cycle Assessment and Manufacturing System Simulation: Evaluating Dynamic Impacts from Renewable Energy Supply on Product-Specific Environmental Footprints

Jan-Markus Rödger\textsuperscript{4} · Jan Beier\textsuperscript{2} · Malte Schönemann\textsuperscript{3} · Christine Schulze\textsuperscript{3} · Sebastian Thiede\textsuperscript{3,5} · Niki Bey\textsuperscript{4} · Christoph Herrmann\textsuperscript{3} · Michael Z. Hauschild\textsuperscript{1}

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Abstract
The eco-efficiency of actual production processes is still one dominating research area in engineering. However, neglecting the environmental impacts of production equipment, technical building services and energy supply might lead to sub-optimization or burden-shifting and thus reduced effectiveness. As an established method used in sustainability management, Life Cycle Assessment aims at calculating the environmental impacts from all life cycle stages of a product or system. In order to cope with shortcomings of the static character of life cycle models and data gaps this approach combines Life Cycle Assessment with manufacturing system simulation. Therefore, the two life cycles of product and production system are merged to assess environmental sustainability on product level. Manufacturing simulation covers the production system and Life Cycle Assessment is needed to relate the results to the final product. This combined approach highlights the influences from dynamic effects in manufacturing systems on resulting life cycle impact from both product and production system. Furthermore, the importance of considering indirect peripheral equipment and its effects on the manufacturing system operation in terms of output and energy demands is underlined. The environmental flows are converted into impacts for the five recommended environmental impact categories. Thus, it can be demonstrate that Life Cycle Assessment can enhance the process simulation and help identify hot-spots along the life cycle. The combined methodology is applied for analysing a case study in fourteen scenarios for the integration of volatile energy sources into energy flexible manufacturing control.

Keywords Life cycle manufacturing system simulation · Manufacturing system simulation · Life cycle assessment · Product-specific environmental footprints · Energy flexible manufacturing systems · Energy flexibility

\textsuperscript{1} Division of Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark (DTU), Produktionstorvet, Building 424, 2800 Kgs. Lyngby, Denmark
\textsuperscript{2} The Boston Consulting Group GmbH, Im Mediapark 8, 50667 Cologne, Germany
\textsuperscript{3} Sustainable Manufacturing and Life Cycle Engineering, Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig, Langer Kamp 19B, 38106 Brunswick, Germany
\textsuperscript{4} Ramboll Management Consulting GmbH, Chilehaus C – Burchardstraße 13, Hamburg 20095, Germany
\textsuperscript{5} Manufacturing Systems, Faculty of Engineering Technology, Department of Design, Production & Management, University of Twente, De Horst 2, Building 20, Enschede 7522 LW, The Netherlands
Abbreviations

- ABS: Agent based simulation
- ADP: Abiotic resource depletion potential
- AP: Acidification potential
- CA: Compressed air
- CA. dem. Wait: Compressed air demand during “waiting” process state
- CA. dem. prod.: Compressed air demand during “production” process state
- Cont.: Continuous process type
- DES: Discrete-event simulation
- El. dem. Wait: Electrical energy demand during “waiting” process state
- El. dem. prod.: Electrical energy demand during “production” process state
- EoL: End-of-life
- FU: Functional unit
- HTP: Human toxicity potential
- HVAC: Heating, ventilating and air-conditioning
- GWP: Global warming potential
- LCA: Life cycle assessment
- LCD: Life cycle design
- NMVOC: Non-methane volatile organic compounds
- NOx: Nitrogen oxides
- PEF: Product environmental footprint
- POCP: Photochemical ozone creation potential
- TBS: Technical building services
- VRE: Volatile renewable electricity

Latin Symbols

- \( CA_n(t) \): Process-specific compressed air demand
- \( CA_{sys} \): Total compressed air system volume
- \( CAP_n \): Capacity of product buffer
- \( C_{tn} \): Process cycle time
- \( EL_n(t) \): Process-specific electricity demand
- \( R_n(t) \): Compressed air demand similarly modelled
- \( p_{max} \): Maximum system air pressure level
- \( p_{min} \): Minimum system air pressure level
- \( p_{sys}(t) \): System air pressure

1 Introduction and Motivation

Manufacturing plays an important role in the global economic development but it also contributes to a large share of environmental pollution and affects the human health. In particular, air pollution (e.g. NOx, SO2 and CO2 emissions) caused directly or indirectly by manufacturing are major drivers of increasing environmental impacts [1]. For some types of products (e.g. electronics), the manufacturing stage already dominates the environmental impact from the whole life cycle and combined with increased affluence of the growing population this will lead to higher total impacts of manufacturing [2]. Thus, adjusted manufacturing strategies are required to unburden the environment while maintaining the important contribution of manufacturing to economic wealth.

Consequently, producing companies are subject to increasing pressure from legislation and customers to improve their own activities towards more sustainable manufacturing. This requires production engineers, factory planners and product designers to identify improvement measures for existing manufacturing systems as well as innovative concepts for new facilities. Suitable methods and tools for the evaluation of different measures and concepts are required in order to identify feasible measures reducing the energy and resource consumption in manufacturing systems. These methods and tools have to consider the entire life cycle of a manufacturing system including environmental impacts related to production (e.g. construction of a factory building and production of machines) and end-of-life.

An established method used in environmental or sustainability management is life cycle assessment (LCA) which aims at calculating all environmental impacts from all life cycle stages of a product or system [3]. Existing standards (e.g. ISO 14040/44), data sources and software tools (e.g. EcoInvent, GaBi) support the conduction of an LCA. However, there are some shortcomings of LCA (e.g. [3–5]) which reduce the usability of LCA results. For example, due to the static character of LCA data and prevalent data gaps, often only average values from data bases are used in combination with generic black-box models to determine environmental impacts of upstream processes and materials. Consequently, processes and materials are not described with actual values but only with generic average values. Furthermore, it is not possible in traditional LCAs to consider dynamic effects of time dependent variables. As an example, if volatile renewable energy sources are used to meet a certain demand (e.g. 500 kWh/day), it does not mean that a manufacturing system with a demand of the same amount during the same period could be supplied by solely this energy source. If the electrical power demand of a production facility at a specific point in time exceeds the current power supply from available renewable sources, the remaining power demand must be supplied by the electricity grid. The demand profile does not match the supply profile, although the total amounts of energy may be identical. This situation is illustrated in Fig. 1.

Consequently, the environmental impacts related to energy generation are not constant but time-dependent based on the availability of renewable energy sources [6]. For this reason, it is necessary to evaluate the timing of power demand and supply in combination with the timing of the
production activity. There may be situations in which electricity from renewable sources is available but no production activity is scheduled. In contrast, there may be situations in which production activity has to take place and no electricity from renewable sources is available. This aspect is important for the evaluation of the overall environmental impacts. However, this aspect cannot be included in a traditional LCA, which is based on a balance sheet type of calculation.

In order to overcome the static character of LCA, it is suggested to combine LCA with simulation. Simulation is an established method for planning and optimization of manufacturing systems. It allows to imitate and evaluate the operation of a modelled system over time including interactions between different system elements along with inherent amplifying or damping effects. An approach for combining LCA with simulation is proposed, enabling a holistic evaluation of environmental impacts of a manufacturing system over its life cycle. Manufacturing simulation is dealing with the production facility as shown in Fig. 1 and LCA is covering the related upstream and downstream processes. This approach allows a combined assessment of both the life cycles of products and of manufacturing systems related to the final product, as shown in Fig. 2.

The proposed approach highlights the relevance of the influences from dynamic effects in manufacturing systems on resulting life cycle impacts from both product and production system. Furthermore, the importance of considering indirect peripheral equipment and its effects on the manufacturing system operation in terms of output and energy demands is underlined. As results, this paper derives a concept for the combination of LCA and manufacturing system simulation explaining the model types for each methodology, and it presents a case study applying the combined methodology for analysing the case of the integration of volatile energy sources into manufacturing control.

2 Life Cycle Assessment and Manufacturing System Simulation

In order to develop a novel approach, which is able to combine the previously mentioned two different life cycles while retaining benefits of manufacturing system simulation, an explanation of both approaches and a review of available methods is provided first. As a starting point, LCA is briefly described with a special focus on manufacturing systems. The second subsection details the current state of

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1 Time steps for the simulation depend on the dynamic production system behavior (high or low dynamic) and data availability (e.g. energy supply data) and must be adjusted according to the defined goal, production system and computational resources. In discrete event production simulation, simulation time steps < 1 s are possible. However, available data resolution can be a limiting factor for total reasonable model time resolution.
manufacturing system simulation, followed by an overview
of manufacturing system simulation in the context of LCA. Finally, a gap analysis reflects the motivation of the new
holistic approach to assess manufacturing.

2.1 Life Cycle Assessment of Manufacturing Systems

Alting introduced the idea of life cycle design (LCD) and
formulated basic ideas of product life cycle concept [7].
The definition from Alting and Jørgensen of sustainable
production is still widely used and describes sustainable
production as products which are designed, produced,
distributed, used and disposed of with minimal (or none)
environmental and occupational health damages, and with
minimal use of resources (materials and energy) [8]. Man-
ufacturing systems consist of thousands of compo-
nents, which can fulfill their purpose, producing products,
through their interconnection. Assessing those systems in
a consistent and systematic way is rather challenging. Diff-
ferent methods have approached that problem to quantify
the environmental performance of companies (e.g. [9–11])
or manufacturing plants [12] or at more detailed levels in
the manufacturing system [13–16], but no model exists
which quantifies all relevant environmental impacts holis-
tically, taking a life cycle perspective. Thus, LCA [17] is
a valuable tool to gain insight into these complex systems
to predict their environmental performance and be able to
compare different systems and configurations in a consist-
et and transparent way. LCAs compromises four phases,
which provide the framework of a consistent assessment
of manufacturing systems:

1. Goal and scope definition (e.g. intended application,
   functional unit, system boundaries)
2. Inventory analysis (e.g. data collection and input output
   analysis)
3. Impact assessment (evaluating the significance of poten-
   tial environmental impacts using inventory results)
4. Interpretation (critical reflection of results from inven-
   tory analysis and from impact assessment in order to
   conclude and reach to recommendations)

Manufacturing inventory analysis requires collecting
emission and resource consumption data of the reference
system within its delimitations defined in goal and scope
[18]. It is advisable to collect primary data at the great-
est level of detail (e.g. elementary flow level) to provide
as much information (e.g. location, time period, emis-
sion to air and water) as possible for a temporal and spa-
tial impact assessment [19]. Ideally, life cycle inventory
accounts for all material and energy flows used in the sys-
tem but realistically not all data can be provided. Those
exemptions (cut-off criteria) are allowed but potential
individual impacts must be analyzed on their significance
beforehand, because small amounts can have tremendous
impacts. The impact assessment should be as concise as
possible to provide e.g. production planers with the most
valuable information without compromising the overall
assessment. Thus, selecting environmental impact catego-
ries should encompass today’s main issues (e.g. energy
and material consumption) in the production systems and
should reflect common best practice [11, 20] to ensure
comparability. Each LCA should be concluded with an
interpretation phase, where impact assessment results are
interpreted against the goal of the study and their uncer-
tainties assessed to qualify the robustness of the decision
to be supported with the LCA.

2.2 Manufacturing System Simulation

Simulation is a widely used methodology for planning and
analyzing of manufacturing systems. Its general principle
is to use a model of a real world system in order to replicate
the system and to study the system behavior over time [21–23].
A model describes the internal structure of a system (e.g. states
and state transitions of the system) and consequently defines
the relations between inputs and outputs of the system. Models
can be used in different simulation runs, i.e. utilizing different
input parameters, in order to study the dynamics and interac-
tions of systems or system elements, which is a benefit com-
pared to static methods such as mathematical optimization.
Furthermore, simulation can provide transparency regarding
a system’s cause and effect relations and thus improve under-
standing of a system’s behaviour and internal mechanics. Dur-
ing the planning of manufacturing systems, simulation is often
used to determine (virtual) performance indicators of current
or prospective manufacturing configurations. This allows
testing of manufacturing strategies and system alternatives
without interrupting the current manufacturing operation or
without real-life (prototypical) testing for the case of newly
designed systems [21, 24, 25]. Negahban and Smith provide an
overview about simulation approaches for the design, planning
and operation of manufacturing systems [26].

Different kinds of models are used for different purposes.
For example, machines and processes are often simulated
based on a mixed discrete and continuous dynamic system
approach, which allows representing discrete objects and
variables and continuous flow (e.g. energy) variables in a
single combined model. The operation of process chains is
usually described with a discrete event model structure in
which actions are triggered by events at discrete points in
time [27, 28]. Agent based simulation (ABS) is an extension
to discrete simulation which allows a decentralized mod-
elling of single object’s individual behavior in a defined
system environment. Each object has a specific inherent
logic and interacts with other objects dynamically during model runtime. The concept of agents is also used for shop floor control and scheduling [29, 30]. In ABS, products are not considered as simple generic events, which trigger certain actions such as machine operation tasks. Instead, each product instance is an agent with individual characteristics. This allows simulating the product specific behaviour and the manufacturing progress as well as the directly related resource demands depending on the state of the manufacturing system such as availability of renewable energy sources.

### 2.3 Manufacturing System Simulation for Life Cycle Assessment

The combination of environmental assessment or even full LCA with simulation was already proposed by different authors (see Table 1). These concepts and tools facilitate an in-depth modelling of manufacturing activities (e.g. duration of machine states) as well as energy and material flows. Some of them use simulation to determine the cumulative amounts of inputs (e.g. energy, materials, supporting media) and outputs (e.g. waste or finished goods) of processes, for example to assess lean and green strategies in manufacturing systems [31, 32]. Newest developments address the implementation of computational Life Cycle Assessment approaches, that supports the modelling of complex systems and their interactions [33, 34].

However, the holistic assessment of interactions between different manufacturing system elements has rarely been done [i.e. process, production equipment and technical building services (TBS)] based on manufacturing simulation. An increase of product variants leads to additional process steps and even additional equipment. Additional equipment (e.g. industrial robot incl. a spot-welding gun) with its own environmental impacts (see vertical life cycle in Fig. 2) has not been considered holistically so far in manufacturing simulation, besides the process-related material and energy consumption. This gets more important since the introduction of the new ISO 14001 [35], which entails the life cycle approach. Specific impacts of scheduling and control strategies cannot be assessed and allocated to individual products during a defined period, which might get important due to the plans of the European Commission to support customers with Product Environmental Footprint (PEF) (e.g. [36]).

Nevertheless, some publications show valuable approaches, which are described below. Andersson et al. describe the problem of combining dynamic aspects in production processes with LCA. Discrete event simulation could enhance the environmental assessments of Type III ecolabels of products and a new tool (EcoProIT) was developed. The focus is on the production stage as well, but data for machinery could be added in the software [37]. Brondi and Carpanzano as well as Harun and Cheng focus on processes considering several material and energy flows combined with associated environmental impacts [3, 38]. Sproedt describes different simulation tools in detail and analyses them regarding their level of detail, applicability and evaluation incl. environmental impact categories [39]. Based on this extensive state of the art research, a new approach has been developed, which focuses on the production process including upstream processes and impacts, but the machinery and equipment has not been considered. Sproedt specifies the method in a subsequent publication, but still lacking the consideration of end-of-life (EoL), capital goods, and TBS [40]. Löffgren and Tillmann propose a method that combines life cycle perspective and discrete-event simulation (DES) to use for decision-making. Upstream activities, material, machinery, overhead and energy related environmental impacts are considered [41]. However, the EoL of machinery or other residues were not accounted for. Table 1 shows the evaluation of identified combinations of LCA with simulation.

According to Kiefer et al., production itself gets more complex, and a higher degree of automation and more product variants are expected [42]. This leads most likely to additional environmental impacts of manufacturing due to additional material inputs, and this should be assessed to avoid potential sub-optimization within the manufacturing process (production process vs. equipment vs. TBS). Specific production strategies, like increase of renewable energy usage might lead to additional equipment (i.e. energy storage). Eco-efficiency of actual production processes is still the dominating research area but neglecting impacts of...
production equipment, heating, ventilation, air conditioning (HVAC) and lighting might lead to sub-optimization or burden-shifting and thus reduced effectiveness. None of the valuable approaches is able to combine two life cycles and relates the results to a common functional unit (i.e. product).

To cope with these research gaps, this paper merges two life cycles of product and production system to assess environmental sustainability on product level. Manufacturing simulation covers the production system and Life Cycle Assessment is needed to relate the results to the final product. This combined approach highlights the relevance of the influences from dynamic effects in manufacturing systems on resulting life cycle impacts from both product and production system. Furthermore, the approach considers indirect peripheral equipment and its effects on the manufacturing system operation in terms of output and energy demands.

3 Combined Holistic Approach: Life Cycle Manufacturing System Simulation

It is proposed to address the shortcomings of LCA (being static, relying on assumptions and black box models, etc.) by combining it with manufacturing simulation. LCA often refers to static inventory data during the production stage and not reflecting time-dependent impacts of the manufacturing processes. Machine operations often imply dynamic indirect demands (like heating and ventilation) and processes will be adjusted due to e.g. higher demand which leads to additional interactions between manufacturing system elements. To be able to assess these interdependencies in terms of environmental impacts it is suggested to use data which has been generated by a manufacturing simulation model [43]. Such approach enables to imitate the dynamic manufacturing system behaviour and to determine the timing of production operations, energy and material demands. This detailed knowledge about the use of resources during manufacturing further improves the inventory analysis for raw material production and energy generation.

This chapter presents a generic framework for the interaction of LCA and manufacturing simulation (Sect. 3.1) and explains how LCA (Sect. 3.2) and simulation models (Sect. 3.3) could be built to provide the desired functionalities. Finally, the chapter ends with the description of a concept for combining LCA and simulation (Sect. 3.4).

3.1 Framework

Utilizing simulation of manufacturing systems has the advantage to study system behaviour and evaluate different scenarios, e.g. options to integrate volatile renewable
electricity (VRE) supply and manufacturing system configurations. Results from simulation runs can be used in an LCA model to quantify the environmental impact of a given scenario. Subsequently, different scenarios can be compared and strategies formulated to enable environmental impact improvement of the given system, considering inherent material- and energy flow dynamics, combined with a life cycle perspective under multiple environmental impact indicators. Figure 3 illustrates the input and output structure of the proposed combined manufacturing system simulation and LCA concept. Different scenarios can be tested, such as integrating VRE supply, different battery storage options or different manufacturing system capacities. A set of input parameters according to scenario definitions is derived. Being a combined approach, manufacturing system specific (e.g. state-based behaviour of processes) and LCA specific (e.g. environmental impact of energy supply) parameters are included, as well as combined parameters (e.g. target production levels). These input parameters are then used in the manufacturing system model to calculate further input for the LCA model, based on dynamic behaviour of the system. As such, the manufacturing system model and evaluation provides dynamically calculated inventory data for the production stage to the LCA model. The LCA model is then used to determine the environmental performance of a given functional unit, e.g. one product, and considers dynamic dependencies between life cycle stages (e.g. manufacturing and use phase). In summary, the manufacturing system model has the task of considering manufacturing system material flow and energy demand dynamics during production of a product (which is the use phase of the manufacturing system), while the LCA model considers the broader life cycle dynamics of the manufacturing system. Further, both models supply a set of indicators, which can be used for combined interpretation of results regarding environmental and operational impact. The goal and scope definition of the LCA specifies both parameters solely used in the manufacturing system modelling, jointly used parameters and parameters used in life cycle inventory analysis. Additionally, it defines the system boundary as well as the functional unit of the manufacturing system (e.g. produced product units per time). The simulation results will be used in the LCA of the manufacturing system. The advantage is that already during the simulation phase of a production environmental hot-spots can be identified and sub-optimization be avoided. Followed by an interpretation and discussion the analysis is concluded and further actions can be taken.

Fig. 4  System boundaries of the life cycle assessment of manufacturing (VRE = volatile renewable electricity, HVAC = heating, ventilation, air conditioning)
3.2 Life Cycle Model

The LCA of manufacturing system has the main target to analyse the system holistically—this requires the inclusion of machinery, infrastructure and (in-) direct energy demand to be able to determine a realistic environmental impact and to avoid burden shifting between different elements of the factory. Figure 4 illustrates the proposed system boundary, including energy and product flows, environmental impact accounting and parameter dependence between system elements. In essence, all relevant manufacturing system elements and their (dynamic) energy demand from either the public grid or on-site VRE supply sources are included. The related environmental impact from both energy supply and the production of required equipment (e.g. raw materials to manufacture a machine) is accounted for, as well as a potential positive impact from material recovery. Parameters are changed according to different scenarios, resulting in a different dynamic energy demand and environmental impact values. Industry processes require machine tools and equipment that leads to inherent environmental impacts although the production line has not produced anything yet. Therefore, the inventory data of machine tools must be enhanced and should rather not be based on generic datasets. The factory building itself is a material intensive product system and should be included as soon as it will be newly built (greenfield) for the production. Otherwise, if the production takes place in an existing building (brownfield) a specific share (based on i.e. economic, depreciation or mass-based allocation) should be accounted. Sometimes the factory is rather old and no data is available. This must be clearly stated. The utilization phase of the manufacturing system is increasingly complex due to the changing energy market and nowadays several sources (e.g. wind, solar etc.) provide energy. These sources have very different environmental impact profiles, which leads to a necessary higher level of detail in the energy modelling. The TBS consumption (e.g. HVAC or lighting) should also be considered. Furthermore, maintenance needs attention due the increasing numbers of machineries installed. As soon as different production technologies with the same output are assessed, the material consumption has to be analysed as well. As mentioned beforehand, the production system is very material intensive, and the EoL-phase becomes very relevant due to the possibility of reusing or recycling the machinery hence avoiding environmental impacts from virgin production.

To assess the whole manufacturing system critical performance parameters in industry such as annual output, cycle time and shift work should be used. They define the layout and configuration of the manufacturing line. The inventory of infrastructure and the resulting overhead consumption are dependent variables of the process layout. LCA has introduced the functional unit (FU) to compare different layouts, quantifying the provided service (e.g. number of products) by the studied system. For the case of manufacturing, a low aggregation level is required to analyse individual impacts of production following a process simulation approach (see Sect. 3.3). Considering above factors, the FU has to at least consist of

(i) the output of the production system (specified as a rate, e.g. units per time)
(ii) in a specific month
(iii) and reference year
(iv) at a defined location

in order to predict individual environmental impacts in a relevant form and to ensure comparability of manufacturing systems. To identify the hot-spots and identify burden shifting within the manufacturing system the assessment model should focus on three main constituents of the system:

• Process: Direct electricity demand of the whole process (e.g. machine tools and transport belt) as well as other energy carriers like gas, compressed air and thermal energy per FU. All process related material consumption per product as well as process specific emissions should be accounted for as well.
• Infrastructure: All machinery (e.g. robots, welding guns, installations for compressed air and centralized lubricant system) including their material use and impacts from their manufacturing, maintenance and replacement during the lifetime of the production line, allocated by total estimated production volume of the line over its lifetime
• HVAC and lighting: All indirect energy demand to keep production running, based on the occupied area of all components including needed space for supply of intermediate products. For ventilation and heating, the height of the factory has to be considered.

In many production processes, more than one product variant is produced with the same equipment and therefore an allocation is needed, which is based on a combination of the number of products and the specific weight and cycle times of the products. There is no consensus so far about which impact assessment method (endpoint or midpoint) should be used. The endpoint impact assessment is still rather immature [44] and it hides the sources of damage and makes it more difficult to see improvements in midpoint scores like climate change from specific design choices. Therefore, midpoint assessment was chosen as it allows to compare different system design the impact categories (like global warming) are known in industry [45] analysed the correlation between different impact categories and global warming potential. They found for infrastructure-related products (e.g. machine tools) a strong correlation between
global warming potential (GWP) and all other environmental impact categories. Weaker correlation can be expected when specific products (e.g. electronic components) are assessed, due to their material composition. Manufacturing itself is an energy-intensive process thus impact categories have to be chosen which reflect the difference between different energy supplies. According to Laurent et al. resource depletion (ADP) and human toxicity (HTP) should be considered as well [45]. Thus, in environmental assessment of manufacturing system, it is proposed to use the following five midpoint categories (for further information [18]):

1. Acidification potential (AP) [kg SO₂-Equiv.]: Terrestrial and aquatic acidification from air emissions of acidifying gases. Impact: High importance for infrastructure.
2. Human toxicity potential (HTP)[kg DCB-Equiv.]: Quantifies the human exposure and toxic effects through inhalation, indirectly by ingestion of chemicals emitted to the environment. Impact: High importance for infrastructure and production.
3. Global warming potential (GWP100) [kg CO₂-Equiv.]: Increase in radiative forcing of the atmosphere due to human activities. Relatively high importance for the impact of the process, if the energy carriers are based on fossil sources. Impact: Equally important for the process, HVAC and lighting as well as infrastructure.
4. Abiotic Resource Depletion Potential (ADP elements) [kg Sb-Equiv.]: Extractable resources (metals and ores) for human use and that have a functional value for society and are non-fossil. Impact: High importance if solar energy or batteries will be used in the manufacturing system.
5. Photochemical Ozone Creation Potential (POCP) [kg ethene-Equiv.]: Damages to vegetation and human health from reactive compounds like ozone formed through reactions in the atmosphere between OH-radicals, the anthropogenic air pollutants nitrogen oxides (NOx) and different non-methane volatile organic compounds (NMVOC). Impact: Relatively high importance for infrastructure.

The distinction between the three main parts of manufacturing systems—infrastructure, overhead and process related environmental impacts opens the opportunity to integrate manufacturing process simulation into LCA. Manufacturing system modelling usually covers only the use phase, but how the manufacturing and EoL-phase is linked will be explained in detail in the following paragraph.

### 3.3 Manufacturing System Model

A manufacturing system model is required to determine time-dependent energy and material flows for further environmental impact assessment. Based on the manufacturing system presented in [43, 46], a unidirectional process flow structure with intermediate buffers is applied (Fig. 5). In total, the manufacturing system consists of \( N \) processes (index \( n = 1, \ldots, N \)) with \( N + 1 \) buffers. Each process has an incoming and an outgoing buffer with capacity \( \text{CAP}_n \) (in number of storable products). The first and the last buffer are never empty or full, i.e. the first buffer always offers enough (raw material) input for the first process while the last buffer, which holds final products, is always capable of storing an additional product. Products are removed if the buffer fill level surpasses a given threshold. Processes transform input to output (i.e. change characteristics of input products), which requires a given cycle time \( C_{t_n} \) (e.g. in seconds) and energy input. Two different process classes are introduced, binary and continuous processes. A continuous process (e.g. a conveyor belt) can change its processing rate and thus time to complete a product transformation within a minimum \( (C_{t_{n,\text{min}}}) \) and maximum \( (C_{t_{n,\text{max}}}) \) boundary. A binary process can either transform a product at a defined rate and required cycle time \( C_{t_n} \) or perform no transformation, i.e. is switched-off or is waiting. Processes can be starved (no input material) or blocked (unavailable outgoing buffer space).

Energy demand of processes is modelled using a state-based approach. Considered process states are off, switching-on, switching-off, waiting and processing. Depending on process state, the process requires a fixed or variable amount of energy. For simplicity, only electricity and compressed air (CA) demand is modelled within this approach. Each process state corresponds to a process-specific electricity demand \( EL_{n}(t) \) (e.g. in kW) and compressed air demand \( CA_{n}(t) \) (e.g. in \( \text{Nm}^3/\text{h} \)). All states are assumed to result in a state-fixed energy demand except processing of continuous processes, which has a rate dependent energy demand

\[
EL_{n,\text{processing}}(t) = EL_{n,\text{processing,fixed}} + EL_{n,\text{processing,variable}} \ast R_{n}(t)
\]

(1)

with \( R_{n}(t) = 1/C_{t_n}(t) \) (compressed air demand similarly modelled) (c.f. [27, 47]).
A compressor park is attached to the manufacturing system and supplies CA. Total CA system volume \( CA_{sys} \) (e.g. in m\(^3\)) is the sum of the attached storage tank volume and additional system volume from pipes and intermediate tanks. System air pressure \( p_{min}(t) \) (e.g. in bar) must not drop below a minimum pressure level \( p_{min} \) and cannot exceed a maximum pressure level \( p_{max} \). The compressor electricity demand is also state dependent and similar to a binary process. Compressors are switched-off if a given idle waiting time has passed without the requirement of additional CA production to save energy. Further, CA losses (e.g. due to leaks) are modelled as a continuous outflow from the system.

VRE supply is integrated into the overall model by considering time-dependent power output of on-site generation facilities, differentiated by energy source (e.g. wind- and solar-based supply). Further, grid electricity supply is available if own supply is insufficient (i.e. own supply is lower than own demand). Further, own generation exceeding system electricity demand is fed into the grid with assumed substitution of the average grid mix. Specific values for electricity generation by source and time (i.e. full supply profiles) can either be modelled using physical and/or stochastic approaches (see e.g. [48]) for an overview of energy models) or measured supply profiles can be used. Within this work, the latter approach is followed to limit modelling complexity.

A battery can be integrated in the system to store electricity from renewable sources. The modelled battery is characterized by a charge and discharge time (e.g. in hours), its capacity (e.g. in kWh), its cycle efficiency (in percent), its self-discharging rate (e.g. in percent per day) and its cycle life time (e.g. how many complete charge and discharge cycles can be completed before the battery reaches a given (e.g. 80\%) remaining capacity). The battery is only charged if the VRE generation is higher than the system electricity demand, and discharged when the system demand is higher than the generation (subject to the battery’s capacity, state of charge and energy flow constraints).

Finally, a central electricity control enabling energy flexibility is introduced to reduce the difference between the manufacturing system electricity demand and the VRE supply in order to achieve energy self-sufficiency (see e.g. [49]). First, processes are determined for which the activity can be regulated without compromising the total system’s throughput (they must not be bottleneck processes). To determine bottleneck processes, a customer cycle time is introduced (e.g. in seconds), denoting the rate at which products are withdrawn from the last buffer. The process with the lowest remaining production capacity (assuming a known planning horizon) is determined. If the withdrawing rate of the last process is lower than any processing rate within the process chain, the withdrawing process is the initial bottleneck. However, if processes accumulate idling time, their remaining production capacity is reduced and, depending on other processes’ remaining production capacity, a process might become the (new) bottleneck of the system. In order to avoid starving or blocking of bottleneck processes, adjacent processes are also excluded from electricity control if buffer fill levels (buffer remaining capacity) fall below (is higher than) a given threshold for upstream (downstream) processes. Bottleneck processes are always scheduled to process a part at the speed needed to avoid throughput losses.

Compressors are assumed to be controllable by the central electricity control if the current system pressure is within given boundaries. If system pressure has been equal to minimum or maximum pressure and is still closer to minimum/maximum pressure than a defined security factor, compressors are switched-on (minimum pressure) or to idle (maximum pressure) without allowing central electricity control to adjust production.

If the central electricity control detects an on-site mismatch between generated electricity and electricity demand, all binary processes (manufacturing processes and compressors) which can be adjusted are determined. The combination of processes on/off states, which yield the closest fit to energy supply, is determined and processes scheduled accordingly. If scheduled electricity demand is not equal to supply, continuous processes are adjusted to improve supply and demand matching. Utilizing this two-step control aims at increasing supply–demand fit as a combination of energy flexible binary processes is unlikely to be perfectly equal to VRE supply.

### 3.4 Merging Manufacturing System Simulation and Life Cycle Assessment

As outlined above, merging manufacturing system simulation and life cycle is important to avoid sub-optimization and burden-shifting. The combined analysis has to reflect the production process parameters and is thus the starting point in the merged process simulation. The framework encompasses the three consecutive phases—defining goal and scope, life cycle inventory and impact assessment (see Fig. 6).

The life cycle model, which is developed according to the goal and scope, consists of the three parts—machine tools and equipment (infrastructure), process and HVAC and lighting. Based on the results of a combined discrete-event and continuous time manufacturing system simulation, a process model is established in a LCA software. The process model uses output data like energy flows, material flows, and characteristic system parameters like system throughput from the manufacturing system simulation and thus acts as an interface (cf. Fig. 4). The process model converts input data from the simulation to supply additional calculation steps with required input data.
The machine tools and equipment model consists of product LCAs of all infrastructure needed and creates input flows which calculates the demand of the process and supplies the information (material data) about the infrastructure. These values are dependent on several manufacturing system parameters, e.g. overall production volume and thus number of products to be assessed, use of renewable energy, product storage and energy storage. This dependency is used to parameterize the allocation of inventory data to specific products in a consistent way. For example some infrastructure is only used if the throughput is increased or if more energy is needed. It is an inevitable step for more realistic product and production specific inventory data and reflects more real production circumstances. The HVAC and lighting model is based on specific requirements (e.g. [50–52]) for manufacturing facilities (e.g. light intensity, air quality and temperature) and these process parameters provide the information to calculate the input per FU. This approach allows determining the demand of heating, ventilation and lighting for each machine tool and transport belt as well as for the area where the intermediate products are supplied. This above describe procedure is able to determine realistic production data and result in an inventory list which is combined with environmental unit process databases (e.g. EcoInvent). These databases can provide default emission factors for several components, materials and energy carriers to avoid additional primary data collection. Environmental flows are generated which will be converted into impacts for the five recommended environmental impact categories in the following phase. The dynamic nature of the manufacturing simulation ensures that adjustments of production parameters like system throughput can be immediately reflected in the environmental impact profile of the system in a comparable analysis to support the production planners in their decision making.

4 Application of New Approach

In order to demonstrate the applicability of the proposed concept, an example of a manufacturing system process chain has been modelled. A simple six-step sequential manufacturing process line is chosen for this purpose. Figure 7 illustrates the process chain structure, example machines, work piece and corresponding model parameters. The six process steps consist of three manufacturing processes and three transport processes, e.g. conveyor belts. Product buffer storage is available between each transport to decouple processes. The considered work piece is a hollow cylinder, which first passes through a turning process, is transported via an automated system to a milling process and then, again via automated transport, to a grinding process. All manufacturing processes are modelled as binary controllable processes, i.e. with a fixed energy demand during processing and fixed (non-interruptible) duration. Rates of transport processes/conveyors and the associated energy demand are assumed to be controllable variables.

4.1 Scenarios and Experiments

In total, fourteen different scenarios are modelled and results evaluated. Table 2 provides an overview of essential parameters and their changes between scenarios.

The scenarios in the table are:
Fig. 7 Example process chain structure and parameters

Table 2 Relevant scenario parameters

| Description               | Control (on/off) | Battery capacity (kWh) | CA-tank volume (Nm³) | Buffer capacity (no) | Cycle time (s) | Products (no) |
|---------------------------|------------------|------------------------|----------------------|----------------------|---------------|---------------|
| Grid Mix (GER)            | off              | 0                      | 5                    | 200                  | 600           | 4031          |
| Base case I               | on               | 0                      | 5                    | 200                  | 600           | 4031          |
| Base case II              | on               | 0                      | 5                    | 200                  | 600           | 4031          |
| Battery storage I         | on               | 10                     | 5                    | 200                  | 600           | 4031          |
| Battery storage II        | on               | 20                     | 5                    | 200                  | 600           | 4031          |
| Battery storage III       | on               | 30                     | 5                    | 200                  | 600           | 4031          |
| Intermediate product storage I | on      | 0                      | 5                    | 50                   | 600           | 4031          |
| Intermediate product storage II | on     | 0                      | 5                    | 100                  | 600           | 4031          |
| Different production levels I | on   | 0                      | 5                    | 200                  | 400           | 6047          |
| Different production levels II | on  | 0                      | 5                    | 200                  | 500           | 4838          |
| Different production levels III | on | 0                      | 5                    | 200                  | 700           | 3455          |
| Different production levels IV | on   | 0                      | 5                    | 200                  | 800           | 3023          |
| Base Case I (Balanced)    | off              | 0                      | 5                    | 200                  | 600           | 4031          |

Bold indicates the parameter variations that are made in each specific scenario parameter set compared to the previous parameter set.

Buffer capacity refers to capacity values for all buffers, denoted as value for a single buffer.
Based on Base Case I Scenario parameters, but the German grid provides all electricity.

**Base case I**
The initial base case as with parameters according to Table 2, without energy flexible electricity control. This scenario is set as reference for a one-piece flow strategy, i.e. without influencing energy demand of the system towards matching on-site supply.

**Base case II**
Similar to Base Case I except with energy flexible electricity control.

**Battery storage**
Inclusion of a battery storage system with varying capacity (10, 20, 30 kWh). Charge and discharge time is 3 h for each case.

**CA storage**
Varying total system CA storage capacity (10 m³), i.e. altering the amount of energy which can be stored in the system’s compressed air.

**Intermediate product storage**
Varying buffer capacity of intermediate product storage (50 and 100 pieces for each intermediate buffer). The amount of storable products influences the system’s energy flexibility if processes are starved or blocked more frequently.

**Different production levels**
Adjusting the withdrawing rate from the final buffer (one product every 400, 500, 700, 800 s), which corresponds to a changing target production output.

**Balanced (Base Case I)**
Assumes that the manufacturing system only demands electricity from on-site VRE generation, i.e. the system is fully self-sufficient, neglecting time discrepancies between energy demand and supply.

To outline the complexity of the different scenarios the Base Case I Scenario will be described rather detailed. To supply CA, four compressors are installed in the compressor park. Two compressors of two different types are modelled: the first (second) type produces 15 Nm³/h (30 Nm³/h) CA requiring 1.75 kW (3.5 kW) of electricity, idle waiting requires 10% of production electrical energy without any compressed air output. Total CA system volume is set to 5 m³, pmin to 7 bar, pmax to 9 bar, idle waiting time is 60 s and losses are assumed to be 20% of average CA demand for a production rate of six pieces per hour, and are therefore 9.775 Nm³/h. The initial buffer capacity of the transport lines connecting the machines is set to 200 pieces, with an initial content of 50 pieces in each buffer. Customer cycle time (last buffer’s withdraw rate) is 600 s, i.e. one product gets withdrawn from the last buffer every 10 min. The base case includes no battery storage. VRE supply is modelled utilizing collected data from experimental generation facilities located in the city of Braunschweig, Germany. A solar and wind time series from 3rd September 2013 to 31st September with a 1 s sample rate, which has been averaged over 1 min intervals, is used. Magnitude of both time series was adjusted to match the total electricity demand from the system over mentioned 28-day time horizon for the no-control strategy, with an equal total supply from wind and solar sources. Aside from total energy demand values (e.g. in kWh), the indicator self-sufficiency is used to describe an increase in on-site VRE demand. Self-sufficiency is the ratio between on-site demand of VRE and total system demand over time (e.g. in percent). The remaining system demand is supplied by a connected power grid, in which also surplus generated electricity is fed-in. The process results were was integrated into a life cycle model in GaBi from thinkstep©. This entails all infrastructure, which are needed to fulfil the FU of producing one product under predefined circumstances. Thereby LCA of machineries, conveyor belts, batteries and CA storage systems were conducted and their impact allocated based on the total intended production volume of the production line. Reliability and maintenance of the individual components are considered and are linked to the process parameters. As an example, if the battery is used quite frequently the limit of loading cycles might be reached, which leads to an additional battery along the lifespan of the production line. For the use phase, upstream processes of energy provision were considered e.g. the production of solar cells or the average environmental impact of the German grid mix. Thereby a more realistic comparison of the impacts along the use phase was achieved. The EoL was modelled by using generic datasets from GaBi as well.
4.2 Results

Each of the fourteen scenario results entails all machinery, transportation in between those, HVAC and lighting as well as process related consumption. All scenarios are normalized based on the Grid Mix (GER) scenario—either in absolute terms (first vertical axis) or per product (second vertical axis). To demonstrate that LCA can enhance the process simulation and to identify hot-spots as well as to avoid sub-optimization, a relative approach was chosen, normalising all scenario results against the results for the Grid Mix scenario. In Fig. 8 the bars represent the relative absolute amount and the data points per product. The blue bars and points indicate process related impacts whereas HVAC and lighting consumption (TBS) is indicated by grey bars. The remaining bars reflect impact caused by the machine tools and equipment (infrastructure) of the process chain.

Global Warming Potential (GWP) is a popular impact category in industry and thus a detailed assessment has been performed. The Grid Mix Scenario (German Grid Mix from 2010) shows a typical distribution—roughly 65% are caused by the process and the rest by the TBS and infrastructure. Usually the process impacts are smaller but due to the dense layout of the process chain and very efficient lighting, the TBS consumption is rather small. Following the process related impacts per product (blue dots), a clear trend of less impact can be identified for the other scenarios due to their increasing share of renewable energy. Starting from 65% in the Grid Mix Scenario the process only accounts for roughly 22% of the GWP in the Battery Storage III Scenario. In the Intermediate Storage I Scenario a higher impact can be observed due to the not fully utilized storage system. The reduction of the cycle time in the Production Levels Scenarios I–IV shows that the energy consumption per product increases if the machinery is not utilized efficiently. The TBS consumption impacts indicate no change except for the Production Levels Scenarios I–IV where the cycle time per product has been increased. The production equipment impacts change as soon as additional storage systems for VRE are required (Battery Storage I–III). Overall, it can be

Fig. 8 Global warming potential [kg CO₂eq for 4031 products] of the studied scenarios normalized against the Grid Mix Scenario. EoL is not displayed as there is no added value for the comparison between scenarios
concluded that the integration of VRE in the energy supply has a positive effect on the GWP. The share of process related impacts are lower and the other categories are getting more important for future improvements. By using the life cycle approach it could be clearly shown, that the positive impacts of more self-sufficiency are partly neutralized by additional impacts from the production equipment. If the LCA approach would not have been used an increased potential for sub-optimization is inherent, as a scenario with more self-sufficiency has less environmental impacts in the use phase. Increasing production volume and thus distributing fixed (non-throughput related) impacts to a higher number of products intuitively results in less impact per product. However, this strategy’s feasibility is subject to market conditions, i.e. if the demand for the product is not sufficient, a volume increase is not rational. In a worst case scenario, additional products causing higher total impact, cannot be used and need to be abandoned, causing an increased relative impact for utilizing remaining products. The TBS consumption is still a major contributor due to the occupied area and volume. Especially if the manufacturing lines need to get more flexible, due to more product variants or by reacting on VRE supply or different demands of the market. Applying the other environmental impact categories (AP, HTP, ADP, POCP) a less detailed overview seems to be evident enough to draw conclusion (see Fig. 9). All results are internally normalized against the results for the Grid Mix Scenario and the number of products produced.

The impact of infrastructure is shown in light orange, the HVAC and lighting in grey and the process in light blue. All five impacts are shown for each scenario separately. The ADP (elements) is a very interesting impact category because it indicates that in many respects the integration of VRE is not beneficial. Due to the installation of solar panels rare earth elements are extracted and this is reflected in the high impact for the process energy where the production of the solar cells is included. Additional batteries (see orange bar in Battery Storage I–III) for storage of VRE contributes significantly to an increase. Compared to the Grid Mix Scenario none of the others is beneficial for the ADP impact category compared which leads to an interesting optimization and trade-off problem between impact categories. It can be clearly seen that as a result of implementing (additional) batteries a higher AP for the infrastructure can

Fig. 9 Impact results for global warming potential (GWP), acidification (AP), human toxicity (HTP), abiotic resource depletion (elements, ADP) and photochemical ozone creation potential (POCP) for 13 scenarios, normalized against the grid mix (GER) scenario. No weighting between impact categories was applied.
might not have a significant impact on GWP, independent of storage options indicate that including battery storage for example, small GWP changes incurred by different battery elements and altering system set-up. Small differences between scenarios can also lead to additional conclusions. Therefore, the Production Level I Scenario where the throughput has been increased seems to have the least environmental impacts whereas the Battery Storage III Scenario has overall even more impact than the Grid Mix Scenario for all impact categories except GWP. Looking at the HTP a similar overall pattern can be seen. However, for this impact category the infrastructure has the highest value of the three parts of a manufacturing system followed by process impacts. The additional battery is worsening the environmental performance and the Battery Storage III Scenario has the highest HTP impact. In contrast, the Production Level I Scenario where the throughput has been increased seems to have the least HTP impacts among all scenarios. The impact category POCP shows a similar pattern. Process and infrastructure has almost the same share with roughly 40% in the Grid Mix Scenario. Implementing renewable energy can lower the process impact, whereas the battery Storage Scenarios show an increase in infrastructure impacts and are in total less beneficial. Again, the Production Level I scenario shows the lowest impact per product. Consequently, it is most beneficial to produce more. Nevertheless, this obviously does not lead to less environmental impacts in absolute terms and is subject to market conditions.

4.3 Discussion of Results

Depending on the chosen impact category for LCA, significantly different outcomes are obtained (e.g. GWP vs. ADP). Further, differences between scenarios can be marginal for some indicators, for example GWP. As a result, drawing a definite conclusion on which scenario/system set-up outperforms another scenario is ambiguous, as a weighting of input categories would be required. For the case of marginal differences in outcomes, including or excluding system elements (i.e. shifting system boundaries, e.g. including or excluding HVAC) can affect outcomes and interpretation. Therefore, choosing adequate system boundaries is of essence to obtain a sound solution. Sensitivity analyses have to be carried out to estimate impact of including or excluding elements and altering system set-up. Small differences between scenarios can also lead to additional conclusions. For example, small GWP changes incurred by different battery storage options indicate that including battery storage might not have a significant impact on GWP, independent of the battery size (within small to medium changes). However, changes due to different production levels are much more significant, indicating that a focus should be set to increase production levels (if feasible) before including (additional) battery storage, if GWP is considered as indicator. CA storage or intermediate product storage seems to be more favourable in terms of GWP. In general, results indicate that environmental impact estimation considering manufacturing system dependencies and life cycle impacts of production equipment can improve traditional (static) estimations and thus allows a more realistic evaluation of different system design and operating set-ups.

5 Conclusion and Outlook

A concept for integrating dynamic manufacturing system simulation and LCA has been proposed. A general framework has been established and the concept’s applicability demonstrated in a case study. As such, the common approach improves the information value compared to stand-alone manufacturing system simulation and LCA. As the proposed method is based on the combination of modelling approaches, a careful balancing between increased accuracy and added complexity needs to be done. Setting-up two complex models requires substantial knowledge, resources and data availability, which might be, depending on the specific use case, not available in a company. Further, increasing accuracy is only beneficial if conclusions can be refined or changed. For a case where increased accuracy leads to no additional conclusions, added modelling and data collecting efforts are not substantiated. This leads to the conclusion that an upfront basic test (e.g. if energy data show a high dynamic difference between grid mix and energy mix of on-site VRE supply and demand) might be beneficial to indicate if more detailed modelling is required. For instance if more dynamic production leads to additional peripherals (e.g. batteries), additional assessments should be carried out. The selected five impact categories cover a broad aspect of environmental impacts in manufacturing and secure that a sub-optimization between them are prevented. Choosing ADP (elements) as an impact category covers the additional rare earth consumption of VRE technologies as well as from battery storage systems. Applying the integrated LCA/manufacturing system simulation method to a wider range of different product types and production systems (e.g. continuous or batch production processes, dividing and converging material flows) would be beneficial to allow more generalized conclusions on a methodological level. Additionally it would be great if efficiency improvements of individual machinery would be analysed in conjunction with up- or downstream process steps or life cycle phases. Sometimes efficiency improvements at one point in the chain leads to sub-optimal solution at another point—therefore rather
effectiveness should be a measurement instead of efficiency. Further, widening system boundaries under VRE integration is of special interest. For example, including grid transportation requirements and stability measures (e.g. backup generation, power quality facilities and energy storage such as pumped hydro) within the LCA would allow for more detailed conclusions on the impact of direct demand of decentralized generation and enabling measures. From an energy flexibility perspective, including LCA into a structured target search for improving energy flexibility of manufacturing systems (e.g. comparing embodied energy storage, battery storage, wind/solar/CHP supply options) under ecological indicators obtained by LCA is of interest. Considering agent-based modelling of manufacturing systems and products, assigning environmental impacts to single product units, depending on system dynamics (i.e. which machine has processed which product utilizing a specific share of renewable energy), would allow a more specific allocation of manufacturing impacts to products. This becomes especially important in a multi-product environment with different possible ways a product can take through a manufacturing process. Further, additional indicators (e.g. economic) can be included to improve decision making under multiple objectives. From a conceptual perspective, the proposed approach can be extended by including additional methods, such as optimization approaches from operations research. The current concept focuses on obtaining a structured overview of different (environmental) indicators for different scenarios. Including optimization methods would allow for searching a system set-up/strategy which is (quasi-)optimal under a given set of target parameters (environmental, economic, operational). However, this approach would require a specific target function, which would most likely include several objectives. As such, weighting/prioritizing objectives would be required (unless a pareto-optimum can be found). In addition, the inherent dynamic complexity of manufacturing systems provides additional challenges with regards to computational complexity and required time/resources to solve (optimize) a problem.

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References

1. Gutowski, T. G., Allwood, J. M., Herrmann, C., & Sahni, S. (2013). A global assessment of manufacturing: Economic development, energy use, carbon emissions, and the potential for energy efficiency and materials recycling. Annual Review of Environment and Resources, 38(1), 81–106. https://doi.org/10.1146/annurev-environ-041112-110510.

2. Kim, S. J., & Kara, S. (2014). Predicting the total environmental impact of product technologies. CIRP Annals Manufacturing Technology, 63(1), 25–28. https://doi.org/10.1016/j.cirp.2013.07.007.

3. Brondi, C., & Carpanzano, E. (2011). A modular framework for the LCA-based simulation of production systems. CIRP Journal of Manufacturing Science and Technology, 4(3), 305–312. https://doi.org/10.1016/j.cirp.2011.06.006.

4. Andersson, J., Skoogh, A., & Johansson, B. (2012). Evaluation of methods used for life-cycle assessments in discrete event simulation. In C. Larosque, J. Himmelspach, R. Pasupathy, O. Rose, & A. M. Uhrmacher (Eds.), In Proceedings of the 2012 winter simulation conference. Berlin.

5. Andersson, J. (2013). Life cycle assessment in production flow simulation for production engineers. In Proceedings of the 22nd international conference on production research. Iguassu falls: international foundation for production research (IFPR).

6. Raichur, V., Callaway, D. S., & Skerlos, S. J. (2015). Estimating emissions from electricity generation using electricity dispatch models: The importance of system operating constraints. Journal of Industrial Ecology, 20(1), 42–53. https://doi.org/10.1111/jiec.12276.

7. Alting, L. (1991). Life-cycle design of industrial products: a new opportunity/challenge for manufacturing enterprises. In Concurrent Engineering I. Berlin.

8. Alting, L., & Jørgensen, J. (1993). The life cycle concept as a basis for sustainable industrial production. CIRP Annals Manufacturing Technology, 42(1), 163–167.

9. CDP, UN Global Compact, WRI, & WWF (2015). Science Based Targets.

10. Martinez-Blanco, J., Finkbeiner, M., & Inaba, A. (2015). Guidance on Organizational Life Cycle Assessment. UNEP/SETAC Life Cycle Initiative.

11. Neugebauer, S., Martinez-Blanco, J., Scheumann, R., & Finkbeiner, M. (2015). Enhancing the practical implementation of life cycle sustainability assessment: Proposal of a Tiered approach. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2015.04.053.

12. Favi, C., Germani, M., Mandolini, M., & Marconi, M. (2016). Plantica: A lifecycle approach to map and characterize resource consumptions and environmental impacts of manufacturing plants. Procedia CIRP, 48, 146–151. https://doi.org/10.1016/j.procir.2016.03.102.

13. Duflou, J. R., Sutherland, J. W., Dorndorf, D., Herrmann, C., Jeswiet, J., Kara, S., et al. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals Manufacturing Technology, 61(2), 587–609. https://doi.org/10.1016/j.cirp.2012.05.002.

14. Veleva, V., & Ellenbecker, M. (2001). Indicators of sustainable production: framework and methodology. Journal of Cleaner Production, 9, 519–549.

15. Jayal, A. D., Badurdeen, F., Dillon, O. W., & Jawahir, I. S. (2010). Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology, 2(3), 144–152. https://doi.org/10.1016/j.cirp.2010.03.006.
16. Kellens, B., Dewulf, W., Overcash, M., Hauschild, M. Z., & Duflou, J. R. (2012). Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLC-Co2P2E) initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. *International Journal of Life Cycle Assessment*, 17(1), 69–78. https://doi.org/10.1007/s11367-011-0340-4.

17. ISO 14040. (2006). Environmental management: Life Cycle assessment—Principles and framework. Geneva: ISO.

18. Hauschild, M. Z., Huijbregts, M. A. J., Alvarenga, R. A. F., de Baan, L., Dewulf, J., Fantke, P., & van Zelm, R. (2015). Life cycle impact assessment. In M. Z. Hauschild & M. A. J. Huijbregts (Eds.) (1st ed.). Dordrecht: Springer.

19. Sauer, B. (2012). Life cycle inventory modeling in practice. In M. A. Curran (Ed.). Life cycle assessment handbook: A guide for environmentally sustainable products. Beverly: Scrivener Publishing LLC. https://doi.org/10.1002/9781118528372.ch3.

20. ISO 14044. (2006). Environmental management—life cycle assessment requirements and guidelines. Geneva: ISO.

21. Banks, J., Carson, J. S., Nelson, B. L., & Nicol, D. M. (2010). *Discrete-event system simulation* (5th ed.). Upper Saddle River: Prentice Hall.

22. Verein Deutscher Ingenieure (VDI). (2014). VDI 3633, Sheet 1: Simulation von Logistik-, Materialfluss- und Produktionsystemen: Grundlagen (engl.: Simulation of systems in materials handling, logistics and production—Fundamentals).

23. Ghadimi, P., Kara, S., & Kornfeld, B. (2015). Renewable energy integration into factories: Real-time control of on-site energy systems. *CIRP Annals Manufacturing Technology*, 64(1), 443–446. https://doi.org/10.1016/j.cirp.2015.04.114.

24. Law, A. M. (2007). *Simulation modeling and analysis* (4th ed.). Boston: McGraw-Hill.

25. Chung, C. A. (2004). *Simulation modeling handbook: A practical approach*. Boca Raton: CRC Press.

26. Negabban, A., & Smith, J. S. (2014). Simulation for manufacturing system design and operation: Literature review and analysis. *Journal of Manufacturing Systems*, 33(2), 241–261. https://doi.org/10.1016/j.jmsy.2013.12.007.

27. Thiede, S. (2012). Energy efficiency in manufacturing systems. In C. Herrmann & S. Kara (Eds.). *Sustainable production, life cycle engineering and management (Sustainabl)*. Berlin: Springer. https://doi.org/10.1007/978-3-642-28084-7.

28. Thiede, S., Seow, Y., Andersson, J., & Johansson, B. (2013). Environmental aspects in manufacturing system modelling and simulation-State of the art and research perspectives. *CIRP Journal of Manufacturing Science and Technology*, 6(1), 78–87. https://doi.org/10.1016/j.cirp.2012.10.004.

29. Monostori, L., Váncza, J., & Kumara, S. R. T. (2006). Agent-based systems for manufacturing. *CIRP Annals - Manufacturing Technology*, 55(1), 697–720.

30. Barbosa, J., & Leitao, P. (2011). Simulation of multi-agent manufacturing systems using Agent-Based Modelling platforms. IN 9th IEEE international conference on industrial informatics, IEEE, pp. 477–482. https://doi.org/10.1109/indin.2011.6034926.

31. Greinacher, S., Moser, E., Herrmann, H., & Lanza, G. (2015). Simulation based assessment of lean and green strategies in manufacturing systems. *Procedia CIRP*, 29, 86–91. https://doi.org/10.1016/j.procir.2015.02.053.

32. Diaz-Elsayed, N., Jondral, A., Greinacher, S., Dornfeld, D., & Lanza, G. (2013). Assessment of lean and green strategies by simulation of manufacturing systems in discrete production environments. *CIRP Annals Manufacturing Technology*, 62(1), 475–478. https://doi.org/10.1016/j.cirp.2013.03.066.

33. Cerdas, F., Thiede, S., & Herrmann, C. (2018). Integrated computational life engineering: Application to the case of electric vehicles. *CIRP Annals*, 67(1), 25–28. https://doi.org/10.1016/j.cirp.2018.04.052.

34. Cerdas, F., Thiede, S., Jurasek, M., Turetskyy, A., & Herrmann, C. (2017). Shop-floor life cycle assessment. *Procedia CIRP*, 61, 393–398. https://doi.org/10.1016/j.procir.2016.11.178.

35. ISO 14001. (2015). *ISO 14001 Environmental Management Systems Revision*.

36. EC. (2016). Product Environmental Footprint Pilot Guidance: Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase Version 5.2—February 2016. Brussels.

37. Andersson, J., Johansson, B., Berglund, J., & Skoogh, A. (2012). Framework for ecolabeling using discrete event simulation. In *Emerging M and S applications in industry and academy symposium 2012, EAIA 2012: 2012 Spring simulation multiconference* (pp. 77–84).

38. Harun, K., & Cheng, K. (2011). Life Cycle Simulation (LCS) approach to the manufacturing process design for sustainable manufacturing. In 2011 IEEE international symposium on assembly and manufacturing (ISAM) (pp. 1–8). https://doi.org/10.1109/isam.2011.5942370.

39. Sproedt, A. (2013). Decision-support for eco-efficiency improvements in production systems based on discrete-event simulation. Zurich: ETH Zürich.

40. Sproedt, A., Plehn, J., Schönleslen, P., & Herrmann, C. (2015). A simulation-based decision support for eco-efficiency improvements in production systems. *Journal of Cleaner Production*, 105(2015), 389–405. https://doi.org/10.1016/j.jclepro.2014.12.082.

41. Lögren, B., & Tillman, A. M. (2011). Relating manufacturing system configuration to life-cycle environmental performance: Discrete-event simulation supplemented with LCA. *Journal of Cleaner Production*, 19(17–18), 2015–2024. https://doi.org/10.1016/j.jclepro.2011.07.014.

42. Kiefer, J., Baer, T., & Bley, H. (2006). Mechatronic-oriented Engineering of Manufacturing Systems Taking the Example of the Body Shop. In *13th CIRP international conference on life cycle engineering* (pp. 681–686). Leuven: CIRP.

43. Beier, J., Thiede, S., & Herrmann, C. (2015). Increasing energy flexibility of manufacturing systems through flexible compressed air generation. *Procedia CIRP*, 37, 18–23. https://doi.org/10.1016/j.procir.2015.08.063.

44. Hauschild, M. Z., Goedkoop, M., Guinée, J., Huijbregts, M., Jolliet, O., et al. (2013). Identifying best existing practice for characterization modeling in life cycle impact assessment. *International Journal of Life Cycle Assessment*, 18(3), 683–697. https://doi.org/10.1007/s11367-012-0489-5.

45. Laurent, A., Olsen, S. I., & Hauschild, M. Z. (2012). Limitations of carbon footprint as indicator of environmental sustainability. *Environmental Science and Technology*, 46(7), 4100–4108. https://doi.org/10.1021/es204163f.

46. Beier, J. (2017). Simulation approach towards energy flexible manufacturing systems. In C. Herrmann & S. Kara (Eds.). *Sustainable production, life cycle engineering and management (Sustainabl)*. Berlin: Springer. https://doi.org/10.1007/978-3-662-46639-2.

47. Gutowski, T. G., Dahmus, J., & Thiriez, A. (2006). Electrical energy requirements for manufacturing processes. *13th CIRP international conference on life cycle engineering*. Luven.

48. Jебaraj, S., & Iniyan, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews*, 10(4), 281–311. https://doi.org/10.1016/j.rser.2004.09.004.

49. Schulze, C., Blume, S., Siemon, L., Herrmann, C., & Thiede, S. (2019). Towards energy flexible and energy self-sufficient manufacturing systems. In *Procedia CIRP* (Vol. 81, pp. 683–688). Elsevier B.V. https://doi.org/10.1016/j.procir.2019.03.176.
50. DIN EN ISO 7730:2006-05, Ergonomics of the thermal environment – analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005).
51. DIN EN 12464-1:2011-08, Light and lighting – Lighting of work places. Part 1: Indoor work places (EN 12464-1:2011).
52. DIN 33403-5:1997-01, Climate at workplaces and their environments. Part 5: Ergonomic design of cold workplaces.

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Jan-Markus Rödger Dr. Jan-Markus Rödger is Manager for Strategy & Sustainability Advisory at Ramboll Management Consulting. Ramboll is a world-wide leading sustainability consultancy with more than 16,000 employees around the globe. The focus is to implement sustainable solutions in product and production development as well as establishing management system to track the performance. He conducted research in the field of Life Cycle Engineering at the University of Edinburgh, Technical University of Denmark as well as at the University of California Berkeley.

Jan Beier is currently a Principal at Boston Consulting Group, and is a former research fellow in the team for Sustainable Manufacturing & Life Cycle Engineering at the Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig. His research field has focused on renewable energy integration into manufacturing systems, where he authored and co-authored several publications.

Sebastian Thiede is a full professor of Manufacturing Systems at the University of Twente within the Department of Design, Production and Management. Before he was heading the Sustainable Manufacturing research group at the Institute of Machine Tools and Production Technology (IWF) of Technische Universität Braunschweig, Professor Thiede conducted various projects in context of sustainability and digitalisation in manufacturing and published over 180 publications in scientific journals.

Niki Bey is Senior Manager for Strategy & Sustainability Advisory at Ramboll Management Consulting. Ramboll is a world-wide leading sustainability consultancy with more than 16,000 employees around the globe. The focus is to implement sustainable solutions in product and production development as well as establishing management system to track the performance. Before he was Associate Professor in Life Cycle Management at the Department of Technology, Management and Economics, Technical University of Denmark (DTU).

Malte Schönemann was a research fellow in the team for Sustainable Manufacturing & Life Cycle Engineering at the Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig. He was leading the team for eco-efficient battery cell manufacturing. His main fields of research were material flow and value stream analysis, multi scale simulation as well as data driven methods with the majority of use cases from the manufacturing of lightweight hybrid components and battery cells. Currently, Dr. Schönemann is working in the automotive industry on enabling a sustainable electric mobility.

Christine Schulze is a research fellow in the team for Sustainable Manufacturing & Life Cycle Engineering at the Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig. Her research fields are energy flexibility with focus on technical building services and renewable energy integration in production systems, where she authored and co-authored several publications.

Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig. His research field has focused on renewable energy integration into manufacturing systems, where he authored and co-authored several publications.

Technical University of Denmark (DTU).
Christoph Herrmann is university professor for Sustainable Manufacturing & Life Cycle Engineering and co-director of the Institute of Machine Tools and Production Technology (IWF), Technische Universität Braunschweig as well as member of the institute management at the Fraunhofer Institute for Surface Engineering and Thin Films (IST). Professor Herrmann has conducted various industry and research projects in the context of life cycle engineering and sustainable manufacturing on national and international level. He has published more than 300 papers and book publications as author, co-author and editor. Professor Herrmann is member of the International Academy for Production Engineering (CIRP).

Michael Z. Hauschild is university professor in Quantitative Sustainability Assessment of products and systems and head of Division of Quantitative Sustainability Assessment at DTU Management Engineering, Technical University of Denmark (DTU). His research focus on life-cycle assessment methodology particularly environmental life-cycle impact assessment, but also social impacts in a life cycle assessment perspective. He has published more than 400 papers and book publications as author, co-author and editor. Professor Hauschild is fellow of the International Academy for Production Engineering (CIRP).