




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

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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 demonstrated 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

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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
NM VOC	Non-methane volatile organic compounds
NO _x	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
Ct_n	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. NO_x, 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

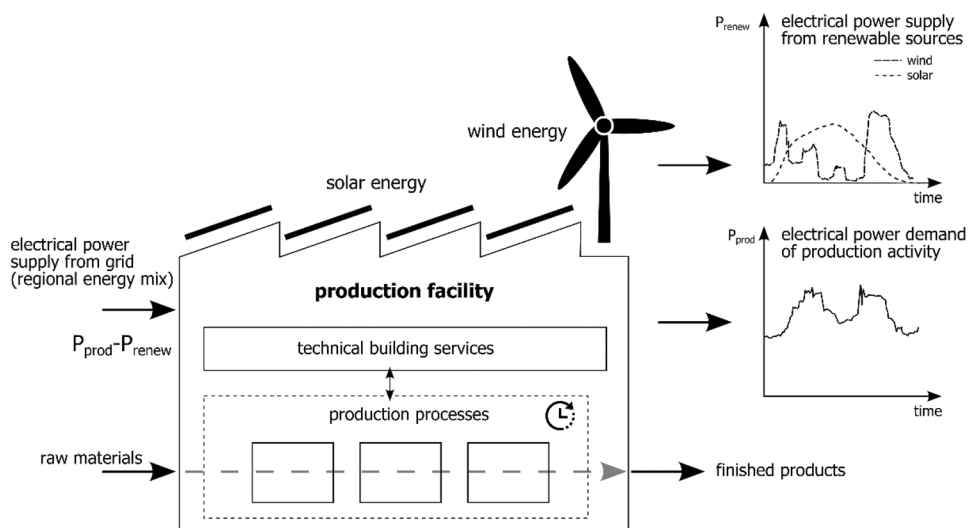
the whole life cycle and combined with increased affluence of the growing population this will lead to higher total impacts of manufacturing [2]. Thus, adjusted manufacturing strategies are required to unburden the environment while maintaining the important contribution of manufacturing to economic 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

Fig. 1 Reference production facility which is used in manufacturing simulation. Electrical power demand is often not matched with power supply from renewable sources and needs additional effort for real integration



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.¹ 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

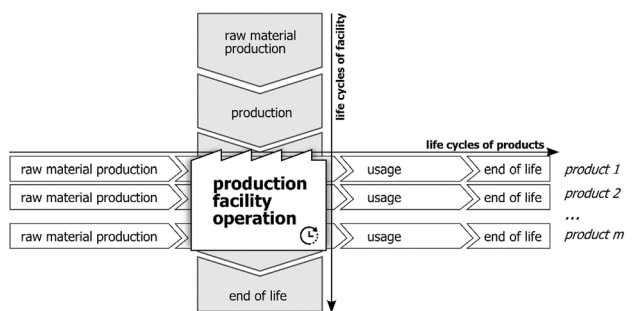


Fig. 2 Merging two life cycles to assess environmental sustainability on product level. Manufacturing simulation (see Sect. 2.1) can only cover a part and life cycle assessment (LCA) is needed to relate this to the final product

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]. Manufacturing systems can consist of thousands of components, which can fulfil their purpose, producing products, through their interconnection. Assessing those systems in a consistent and systematic way is rather challenging. Different 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 holistically, 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 consistent and transparent way. LCAs comprises 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 potential environmental impacts using inventory results)
4. Interpretation (critical reflection of results from inventory 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 greatest level of detail (e.g. elementary flow level) to provide as much information (e.g. location, time period, emission to air and water) as possible for a temporal and spatial impact assessment [19]. Ideally, life cycle inventory accounts for all material and energy flows used in the system but realistically not all data can be provided. Those

exemptions (cut-off criteria) are allowed but potential individual impacts must be analysed 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 planners with the most valuable information without compromising the overall assessment. Thus, selecting environmental impact categories 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 uncertainties 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 analysing 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 behaviour 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 interactions of systems or system elements, which is a benefit compared to static methods such as mathematical optimization. Furthermore, simulation can provide transparency regarding a system's cause and effect relations and thus improve understanding of a system's behaviour and internal mechanics. During 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 modelling of single object's individual behaviour in a defined system environment. Each object has a specific inherent

Table 1 Overview of literature reviewed about production process simulation and life cycle assessment

Publication	Priority		Approach			Simulation		System		Life-Cycle		
	DES	LCA	Framework	Method	Applied	static	dynamic	Production	Product	Capital goods	Process	TBS
Brondi & Carpanzano, 2011	☉	☉	✓	✓	✓	✓	x	✓	x	0	1,3,4	0
Harun & Cheng, 2011	☉	☉	x	✓	✓	✓	x	✓	x	1*	1*,3,4*	0
Löfgren & Tillman, 2011	☉	☉	x	✓	✓	x	✓	x	✓	1,3	1,3,4	0
Andersson, J. et al., 2012a	☉	☉	✓	x	x	x	✓	x	✓	0	1*,3*,4*	0
Andersson, J., 2013	☉	☉	x	✓	✓	✓	x	x	✓	1*,3*,4*	1*,3*,4*	0
Sproedt, A., 2013	☉	☉	✓	✓	✓	x	✓	✓	x	0	1,3	0
Sproedt et al., 2015	☉	☉	x	✓	✓	x	✓	✓	x	0	1,3	0

0 None
3 Use stage including upstream and downstream process
1 Raw Material extraction and production
2 Use stage excluding upstream and downstream process
4 End-of-Life
* mentioned, but not applied

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 process 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]. Löfgren 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

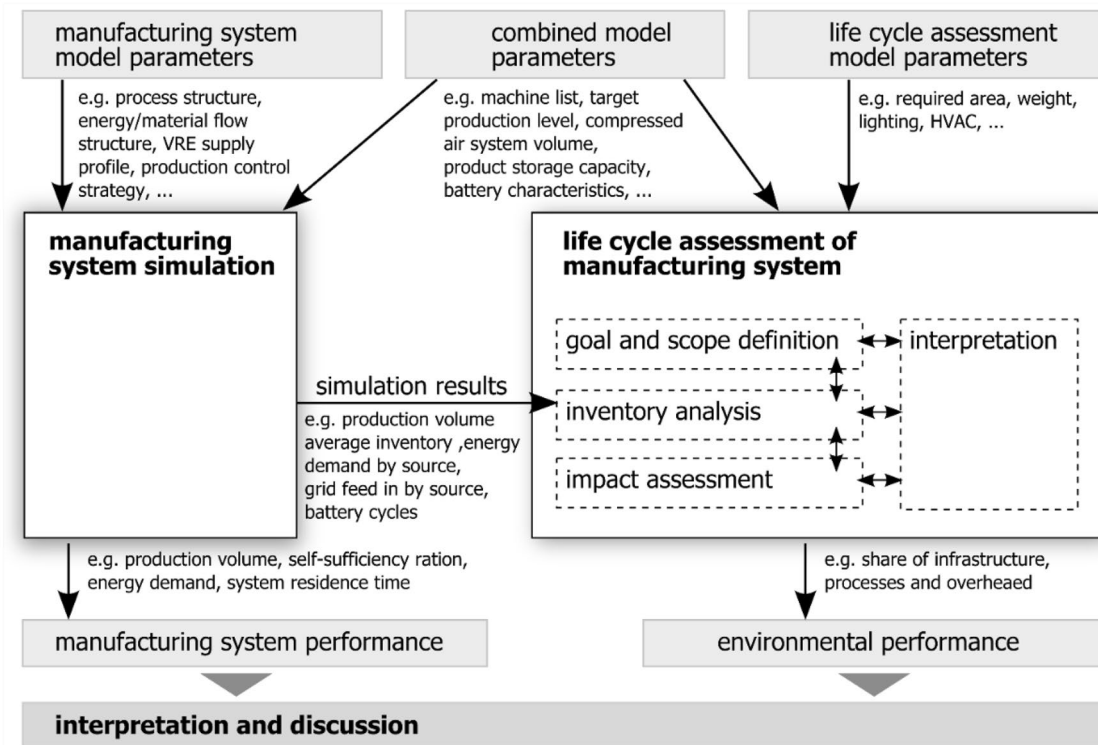


Fig. 3 Input and output parameter structure and interaction between manufacturing system model and LCA model

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

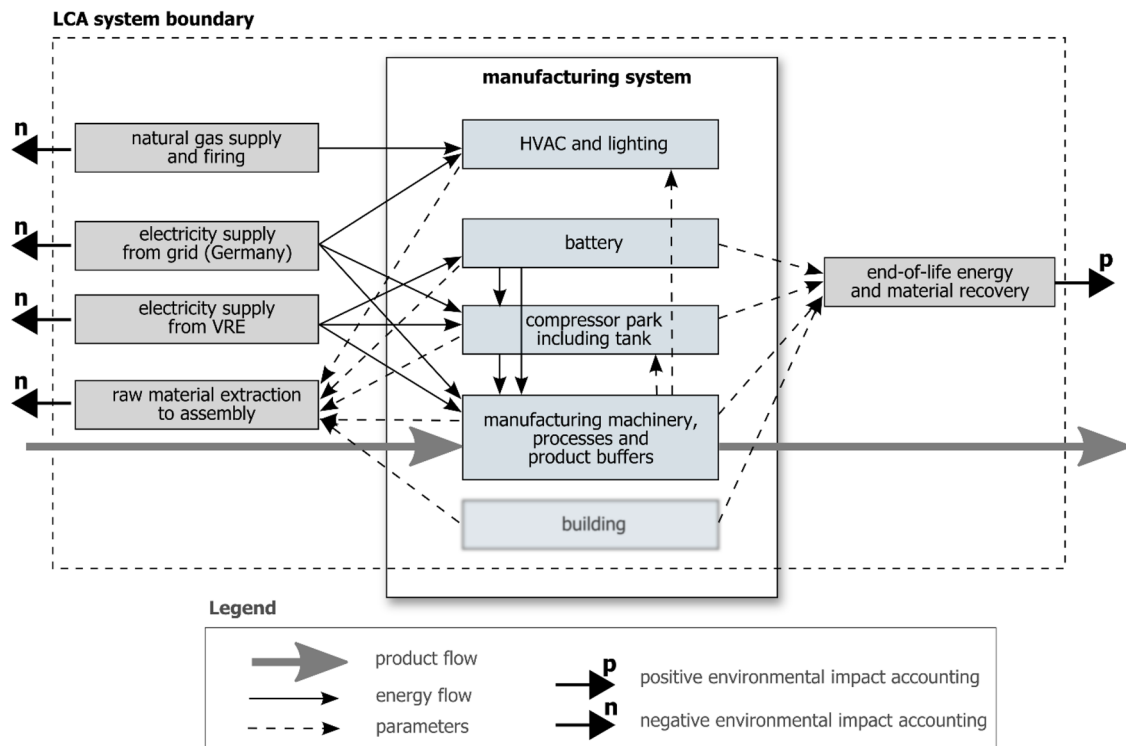


Fig. 4 System boundaries of the life cycle assessment of manufacturing (VRE = volatile renewable electricity, HVAC = heating, ventilation, air conditioning)

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.

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,

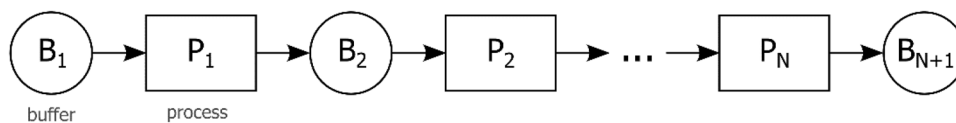
quantifying the provided service (e.g. number of products) by the studied system. For the case of manufacturing, a low aggregation level is required to analyse individual impacts of production following a process simulation approach (see Sect. 3.3). Considering above factors, the FU has to at least consist 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

Fig. 5 Manufacturing process chain

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 the 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 SO_2 -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 CO_2 -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 $n = 1, \dots, N$) with $N + 1$ buffers. Each process has an incoming and an outgoing buffer with capacity 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 Ct_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 ($Ct_{n,min}$) and maximum ($Ct_{n,max}$) boundary. A binary process can either transform a product at a defined rate and required cycle time Ct_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 Nm^3/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

$$EL_{n,processing}(t) = EL_{n,processing,fixed} + EL_{n,processing,variable} * R_n(t) \quad (1)$$

with $R_n(t) = 1/Ct_n(t)$ (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 $p_{sys}(t)$ (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.

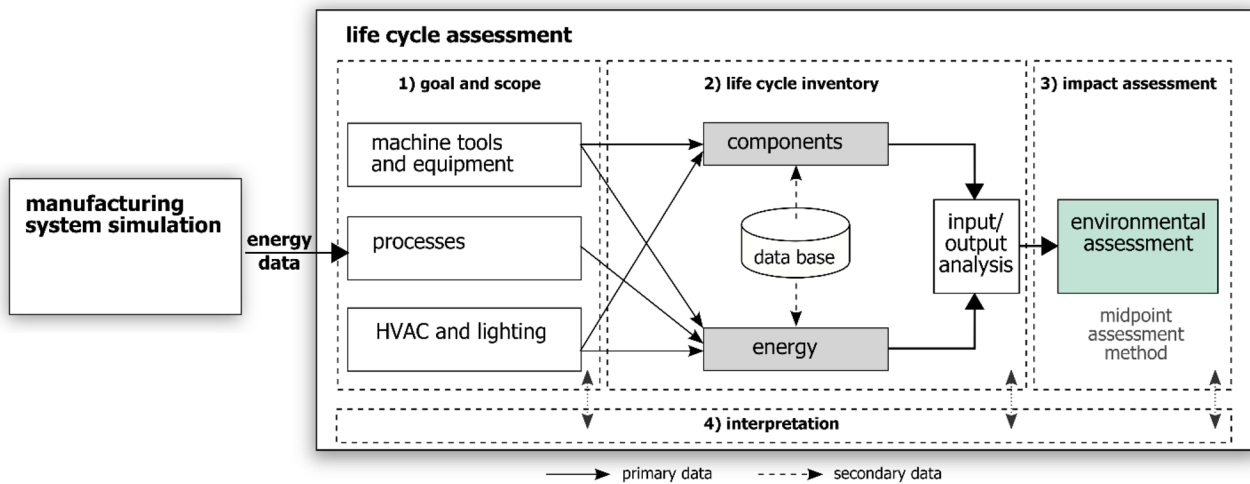


Fig. 6 Consecutive approach of merging process simulation and life cycle assessment

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:

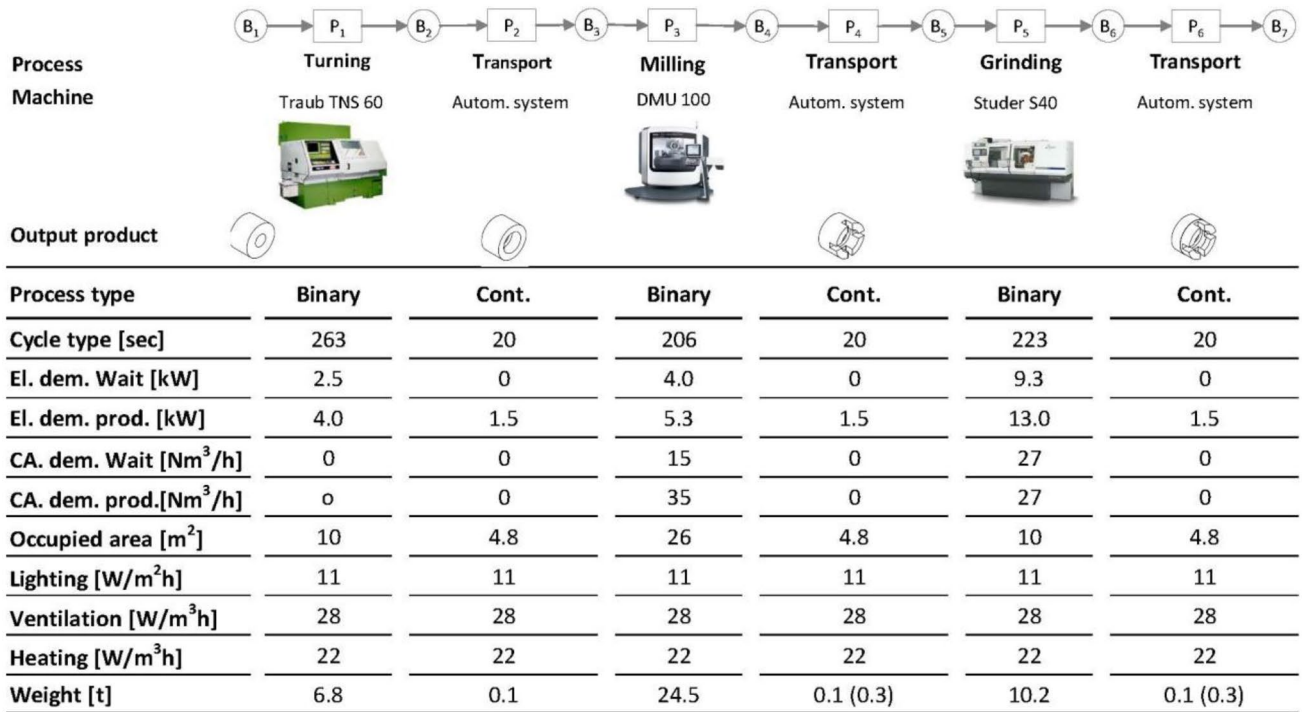


Fig. 7 Example process chain structure and parameters

Table 2 Relevant scenario parameters

Description	Control (on/off)	Battery capacity (kWh)	CA-tank volume (Nm ³)	Buffer capacity (no)	Cycle time (s)	Products (no)
Grid Mix (GER)	off	0	5	200	600	4031
Base case I	off	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
CA storage I	on	0	10	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

Grid Mix (GER)	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 m ³), 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, p_{\min} to 7 bar, p_{\max} 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 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.

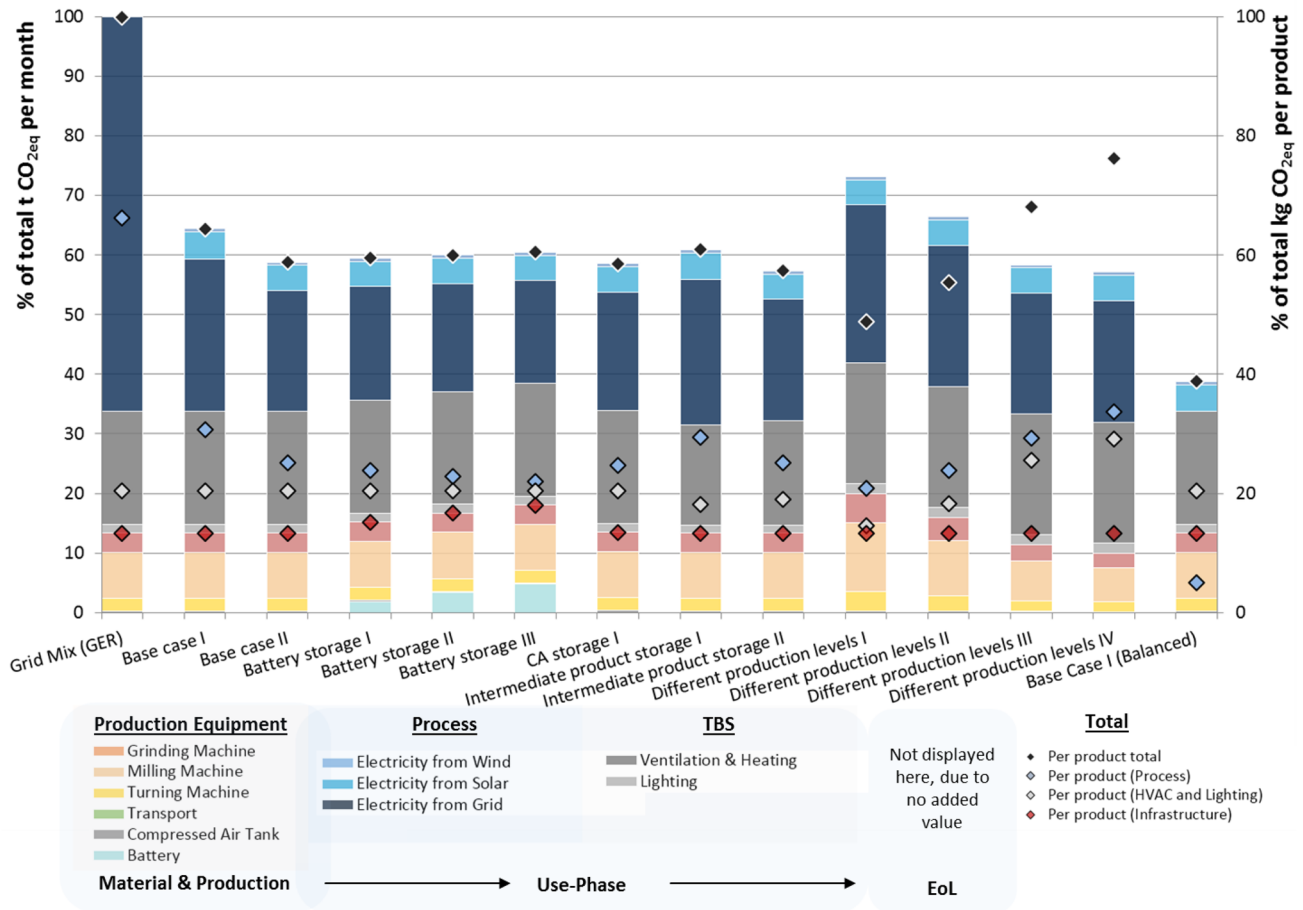


Fig. 8 Global warming potential [kg CO₂eq for 4031 products] of the studied scenarios normalized against the Grid Mix Scenario. EoL is not displayed as there is no added value for the comparison between scenarios

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

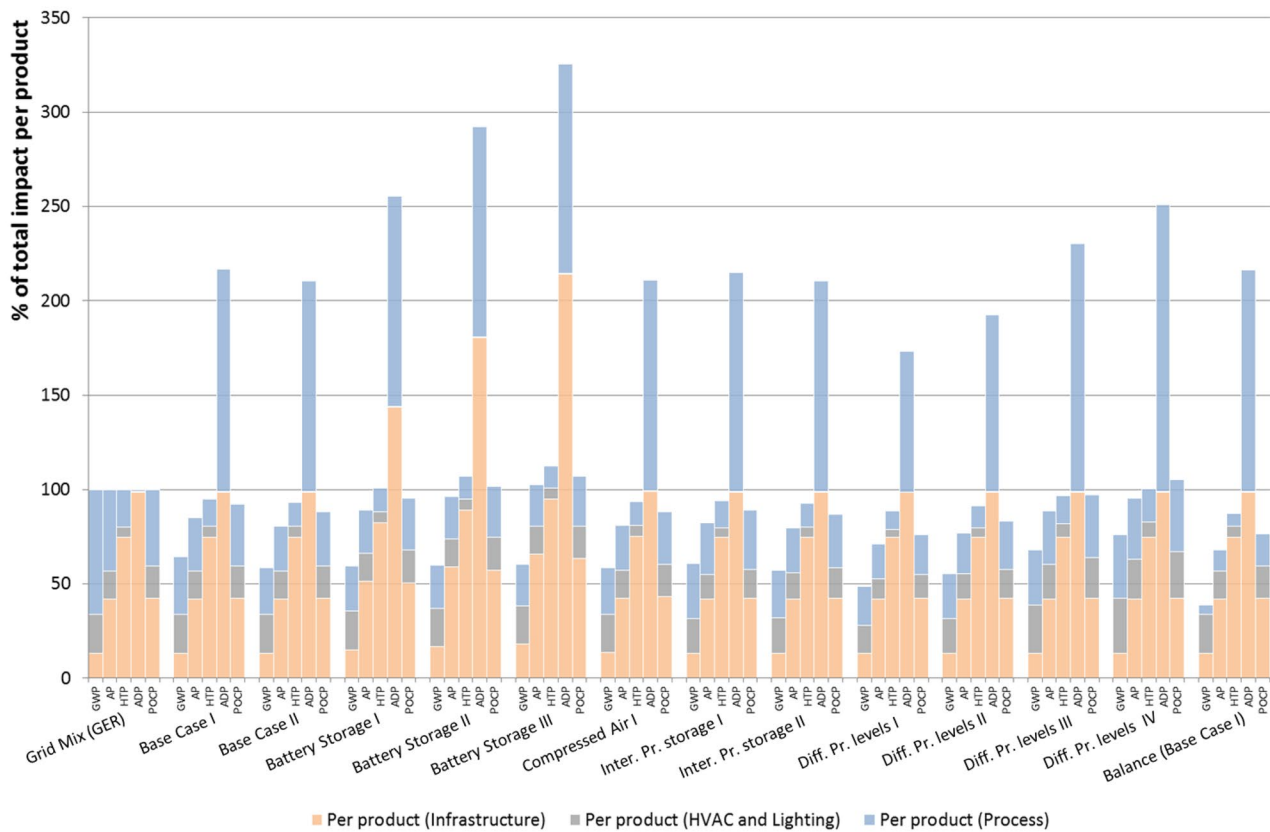


Fig. 9 Impact results for global warming potential (GWP), acidification (AP), human toxicity (HTP), abiotic resource depletion (elements, ADP) and photochemical ozone creation potential (POCP) for

13 scenarios, normalized against the grid mix (GER) scenario. No weighting between impact categories was applied

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

be expected. Meanwhile due to additional use of VRE the process impacts (blue bar) can be reduced. The reduction clearly correlates with the amount of power supplied by the grid mix plus some additional impacts of solar energy. Overall the lowest impacts can be expected if the production line is fully supplied by renewable energy (Balanced (Base Case I)). However, this is not realistic due to the mentioned demand/supply mismatches. 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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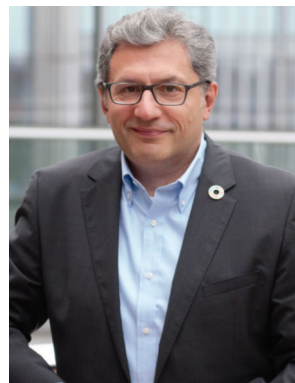


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