Integrating Life-Cycle Assessment into Automotive Manufacturing—A Review-Based Framework to Measure the Ecological Performance of Production Technologies

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Abstract The transition of automotive manufacturing towards sustainability becomes more relevant when new product technologies as lightweight and electric powertrains shift environmental impacts from the use phase to the production phase. Therefore, a systemic assessment and an ecological optimization of novel production processes is necessary before implementation in factories. Furthermore, product design choices pre-determine the environmental performance of production processes. Based on a brief literature analysis of sustainable manufacturing, a framework is developed that integrates production processes with product development processes in an ecological context. The identification of ecologically-relevant core processes represents the basis for the framework development and explains, why the integration of life-cycle considerations in product development processes is decisive. Aim of the framework is to contribute to a holistic understanding of drivers that generate environmental impacts in automotive production. Furthermore, it establishes a life-cycle approach for production, which is crucial to evaluate the ecological relevance of individual resource flows to, within and from the system. The applicability of the framework is critically discussed concerning scope of the assessment, data requirements, functional unit and potential allocations problems.

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1 Introduction

Since early the industrialization in the 19th century, industrial production has significantly accelerated the accumulation of societal welfare, but as well caused an increasing damage to the environment. The transformation of natural resources in industry to goods and services generates by-products and emissions, which impact locally and globally on the environment (Herrmann et al. 2015). Climate change, water and air pollution, resource depletion and biodiversity loss represent the main environmental impacts, which are associated with industrial activities. Recent scientific findings show that anthropogenic interference has exceeded some of the planetary boundaries (Rockström et al. 2009). Global production and consumption systems need to be "re-tuned" to avoid a strong impact on human livelihoods described as "sustainable development" by the Brundlandt Commission (WCED 1987).

In automotive production, the variety of applied processes, used materials and required to produce a conventional car is great (Schmidt et al. 2004; Rivera and Reyes-Carrillo 2016). Current developments in automotive engineering imply a shift towards electric powertrains and lightweight car bodies (Tagliaferri et al. 2016; Schmidt et al. 2004). These transformations will induce new production technologies and processes to the factories and potentially change the ecological performance of car manufacturing as especially battery production is associated with high energy demands (Romare and Dahlöf 2017; Notter et al. 2010). However, transformative processes in manufacturing are multi-dimensional, dynamic, complex and are often not comprehensively designed due to lack of understanding (Moldavska 2016). The aim of this article is to provide a systemic approach, how vehicle manufacturing processes can be systematically described and ecologically assessed. For this purpose, a framework is developed and critically discussed concerning its applicability.

2 Methodological Approach for Framework Development

The development of the framework merely focuses on the understanding of the ecological dimension of automotive manufacturing. This is due to the fact that—-following an advanced understanding of sustainability by Rockström (2015)—the environmental dimension of sustainability represents the foundation for social and economic activity. The development of a framework is based on a brief literature analysis and divided into four steps (see Table 1): (1) a summary of the current state of sustainable manufacturing categories; (2) the adaptation of these categories on automotive production to identify core processes of the framework; (3) the determination of relevant elements (factors, determinants) of the core processes that determine

Table 1 Methodological approach for framework development

Step	Step 1	Step 2	Step 3	Step 4
Content	Literature analysis and identification of sustainable manufacturing categories	Identification of ecologically-relevant core processes of automotive production	Subdivision of core processes into system components	Identification of relationships among system components and framework development

system components; (4) the identification of (inter-)relationships of these system components as well as system boundaries to establish a framework.

Literature analysis to identify categories and principles of sustainable manufacturing

First, of existing approaches to and relevant aspects of sustainable manufacturing are analyzed: automotive production, sustainable manufacturing, industrial ecology, Life Cycle Engineering (LCE) and Life-Cycle Assessment (LCA). Aim of the analysis is to evaluate definitions, concepts, frameworks and methods that represent a foundation for the first purpose of this study to identify "categories" of sustainable manufacturing.

Adaptation of sustainable manufacturing on automotive production to identify core processes

Hence, the identified categories and principles of sustainable manufacturing are related to automotive production to identify "core processes" of the framework. These determine key relationships of relevant elements and layers of manufacturing for the development of a systemic understanding and for the definition of system boundaries.

Determination of system components and framework development

The previously defined core processes are divided into their relevant "system components". These represent steps, parts or evolutionary phases and can be described as information or resource flows. Finally, the logical relationships of the individual system components are identified to establish the framework. Therefore, it is crucial to understand, how individual system components are (inter-)related.

3 Results

3.1 Categories of Sustainable Manufacturing

Sustainable manufacturing represents an urgent but as well a very broad research field. As of 2017, various approaches concerning sustainable manufacturing exist.

The definition by the U.S. Department of Commerce is commonly applied (Moldavska and Welo 2017):

> [Sustainable manufacturing is the] creation of discrete manufactured products that in fulfilling their functionality over their entire life-cycle cause a manageable amount of impacts on the environment (nature and society) while delivering economic and societal value.

Despite ongoing research for decades, most scientific contributions have been identified being published since 2010 (Hartini and Ciptomulyono 2015; Moldavska and Welo 2017). Current research highlights various definitions, frameworks, measurability, metrics and methods to grasp the multi-dimensional and inter-disciplinary challenge (Haapala et al. 2013). Moldavska and Welo (2017) have conducted an extensive literature review and point out relevant categories (see Table 3) , which define sustainable manufacturing in its complexity. According to their analysis, sustainable manufacturing approaches the production of products/services from both a triple-bottom-line and life-cycle perspective. Sustainability in manufacturing should be integrated in business models (not vice versa) and is understood in a two-fold-manner—to produce in a sustainable manner and to produce sustainable products.

3.2 Core Processes of Automotive Production in the Context of Sustainable Manufacturing

The application of a life-cycle perspective on automotive manufacturing leads to the production life-cycle, which enables a description of relevant resource flows during each life-cycle phase. Applied reduction strategies as cleaner production (UNEP 2001), symbiotic use and closed loop, resource re-utilization/recovery (Chertow 2007) can be systematically assessed concerning their influence on the environmental impact. The categories "integrating perspective" as well as the "relationship between sustainability and manufacturing" can be understood as the biosphere-technosphere relationship of automotive production. Sustainability should be integrated in production processes to produce in a sustainable manner (Moldavska and Welo 2017). This relationship has been conceptually described through the concept of Industrial Ecology (IE) which aims to provide tools and methods to understand their complex relationship (Ehrenfeld 1997). The categories "domain", "potentials to enhance" and "potentials to decrease" can be related to the product-production relationship. Product design decisions have an impact on the ecological performance of production processes as a specific product design implies discrete manufacturing processes (Götze et al. 2014). The Integrated Framework for Life-Cycle Assessment (Hauschild et al. 2017) has been developed to relate product/production engineering activities to an absolute sustainability context. This implies the recognition of planetary boundaries as defined in by Rockström et al. (2009). The framework is considered useful, as it enables assessments, from both the technology level (bottom-up) and the global sustainability level (top-down).

3.3 System Components

The previously identified core processes are subdivided into system components, which are relevant for the framework development. The system components represent sub-processes and can be considered as variables that influence the ecological performance of production.

Product-production relationships

The integrated LCE-framework (Hauschild et al. 2017) is considered valid to describe the (inter-)relationship between product design and production in a factory context as it differentiates between different engineering life-cycle phases. Kaluza et al. (2016) present and apply this framework and highlight four relevant stages of automotive product development. Their distinction in “product specification”, “concept development”, “detailed development” and “production preparation” (Kaluza et al. 2016) will be used to describe the product/production-relationship.

Production life-cycle

Applying life-cycle thinking on production, the understanding of each life-cycle phase differs when comparing it to products (see Table 2). The first phase “raw materials” represents the material/energy requirements. The “production” phase represents the production of process material (pre-chains). The “use phase” of a product comprehends energy and material requirements for the production process in the factory. Finally, “end-of-life” represents the disposal/recycling phase, which describes the impacts of by-products such as airborne emissions, wastewater, waste or other by-products.

Biosphere-technosphere relationship

The biosphere-technosphere relationship of manufacturing is conceptually evaluated by concepts as Industrial Ecology (Ehrenfeld 1997) and Industrial Symbiosis (Chertow 2007) which describes the exchange of material and energy flows from ecosystems to industries and back. The biosphere represents a mandatory precondition for the technosphere, as it provides natural resources and represents the

Table 2 Distinction between product and production life-cycles

Life-cycle	Raw materials	Production	Use phase	End-of-life	Functional unit
Product	Product materials and energy	Manufacturing process	Energy and material requirements for utilization	Product recycling/disposal	A discrete good/service
Production	Energetic, organic and abiotic resources	Pre-chain process of process materials	Manufacturing process	Emissions Waste Waste water	A discrete manufacturing result

sink for undesired production outputs (emission, wastewater, waste). The relationship of both spheres can be described as a system boundary with "natural resources" (input) and "emissions, waste, wastewater" (output) on the biospheric side, while the transformation of these resources to pollution occurs within the technosphere.

Resource flows (input-transformation-output)

The transformation of natural resources in industrial processes to (undesired) emissions or pollutions requires a clear distinction for. Raw materials are transformed into pre-products, which are hence transformed in the production processes to by-products and might finally become an emission, a waste or concentrations in wastewater. IS enables the consideration of recovery/secondary utilization or closed loop of these flows among partners in industries to enable a secondary use of by-products (Chertow 2007). Six system components concerning natural-industrial material flows are identified as "natural resource demands", "production pre-chain (process inputs)", "production", "by-products (process outputs)", "energy/material recovery" and "emissions, waste, wastewater" (Table 3).

3.4 Identification of Relationships and Framework Development

Product development-production preparation

The product-production relationship describes an engineering process that connects product development with subsequent production planning (Kaluza et al. 2016). Product design choices pre-determine ecological impacts of the production as the product design defines the planned production machinery and process (e.g. the number of welding points). Relevant product information is therefore necessary to describe the subsequent production process comprehensively. Approaching the product development from an LCE perspective, the relationship between product and production is represented through evaluating future (ecological) impacts of the production process (Hauschild et al. 2017) (Fig. 1).

Production life-cycle, resource flows and biosphere-technosphere relationship

The production life-cycle is characterized through a transformation of natural resources into finished goods and undesired by-products. To ensure transparency within the factory, the production is divided into "unit process", "process chain" and "facility/technical building services" according to the multi-level factory perspective of Duflou et al. (2012). To supply the production with the necessary resources, resource flows from production pre-chains represent the necessary inputs. Downstream, the process generates by-products (excess energy or undesired process outputs) which represent either input flows back to the production (recovery)/to other industries (secondary use) or leave the technosphere. as airborne emissions, waste

Table 3 Categories of sustainable manufacturing and their adaptation on automotive production

Sustainable manufacturing category	Content	Automotive production	Core process	System components
Life-Cycle perspective	Total life-cycle as perspective for product assessment	Total life-cycle as perspective for production assessment	Production life-cycle	Natural resources Production pre-chain Production Emissions, waste, waste water
Time perspective	Not extensively discussed, but both short- and long-term thinking is mentioned in some publications	Short- and long-term	*Depending on case or scope*	
Integrating perspective	TPL as a concept to combine economic, environmental and social dimensions of manufacturing	Integration of sustainability in production processes (not vice versa)	Biosphere-technosphere relationship	Natural resources (input) emissions, waste, wastewater (output)
Relation between sustainability and manufacturing	Description in a two-fold manner: 1. Manufacturing for sustainability (of sustainable products) 2. Sustainability of manufacturing (produce in a sustainable manner	Sustainability of automotive production (produce in a sustainable manner)		
Domains	Product, process, community, customers, employees	Product and process (product design and production planning processes)	Product-process relationship (as information process)	Product specification Concept development Detailed development production preparation Production preparation
Potentials to enhance	Economic benefits, natural environment, safety	Integrated engineering and planning processes		
Potentials to decrease	Resources (non-specified), energy, materials, pollution (non-specified), wastes, toxic materials, pollution to air	Cleaner production, recovery/recycling, closed loop, symbiotic use	Resource flows (input-transformation-output)	Natural resource demands Pre-chain (process inputs) Production By-products (process outputs) Energy/material recovery Emissions, waste, wastewater
Moldavska and Welo (2017)		*Own adaptation*		

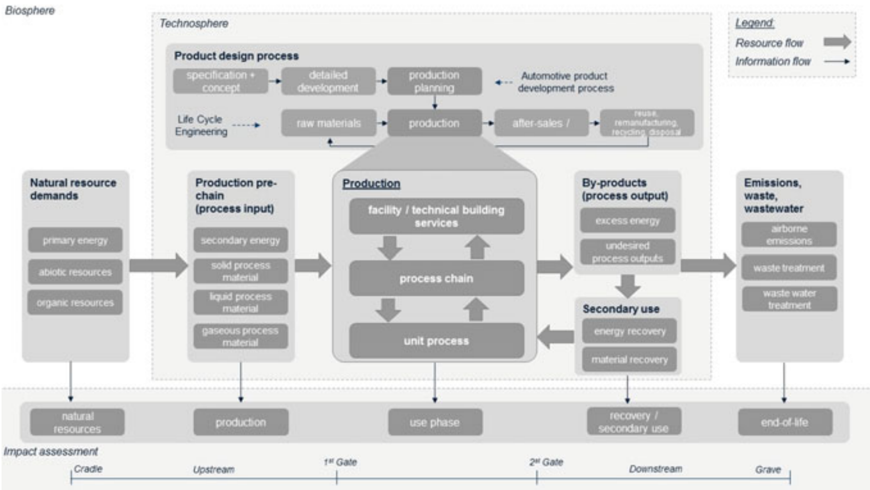

Fig. 1 Framework to measure the ecological performance of production technologies

or waste water. Therefore, the technosphere-biosphere relationship is characterized through a system boundary, whereas natural resource demands and emissions, waste and wastewater are on the biosphere side while their utilization in the production process occurs in the technosphere.

4 Discussion

The framework enables an iterative engineering process, which evaluates future ecological impacts of the manufacturing life-cycle due to a specific automotive product design. Once conducted, the derived information can be used to optimize the product life-cycle until an optimum has been reached. A detailed impact analysis of each input or output flow concerning their ecological relevance and type of impact (human health, ecosystem, resources) is possible. Depending on the scope, the production can be evaluated concerning upstream (Cradle-to-Gate), in-factory (Gate-to-Gate), downstream (Gate-to-Grave) or the entire life-cycle (Cradle-to-Grave) impacts. In Gate-to-Gate assessments, a distinction of impacts between unit process, process chain and facility/technical building services is possible. Furthermore, the frameworks enables a holistic comparative assessment of different production process variants through applying it to different process designs. Problem-shifting, as a common engineering phenomenon, can be excluded as the framework is based on life-cycle considerations.

This implies a careful and distinct definition of the scope and the functional unit as well as a thorough process understanding including up- and downstream processes. The framework enables a narrow (unit process) or a wide scope (entire factory).

Therefore, cut-offs need to be carefully selected der to avoid double counting or excluding relevant resource flows. This implies the availability of data or profound assumption, which might lead to greater uncertainties in the results. The choice and definition of the functional unit, which should relate to the desired outcome of the production, represents a critical process. Depending on the time perspective, the functional unit could represent a single process result (short-term) or the accumulation of process results of an annual production (long-term). The results might differ due to the allocation of indirect resource flows as e.g. the factory heating. Furthermore, allocation problems need to be solved, when different products are produced on one production line. Therefore, multi-functionality of production systems has to be taken into account when applying the framework on entire factories or in a long-term time perspective. The allocation of impacts could be solved through averaging (per produced item/product) or specification: per production output (produced number of specific product/total number of produced product), per required production space (area per specific product/total area), per economic considerations (revenue per specific product/total revenue) or per produced time (production time per specific product/total production time).

5 Conclusion

Automotive manufacturing represents a complex process as it requires complex process chains and applies a variety of processes to produce cars of a certain quality within a set time frame. A transformation towards ecological sustainability represents therefore a multi-dimensional process, which requires a holistic and systemic frame to include all relevant aspects that influence the ecological performance. This work focuses on the ecological dimension as it represents the basis for a sustainable socio-economic development. Based on a literature analysis of sustainable manufacturing and its categories, this paper identifies core processes of automotive production that impact on the environment. These core processes are evaluated concerning their relationships to establish a framework that enables a systematic and holistic impact assessment of automotive production processes. It furthermore enables the estimation of production impacts due to product design processes and is therefore useful to support LCE approaches in automotive engineering. Current changes in car technologies (e.g. lightweight, electric powertrains) induce changes in production processes and therewith the ecological performance of factories, too. Therefore, a thorough and holistic evaluation of these new production technologies is necessary and urgent. We propose the aim to generate an early and thorough ecological understanding of new manufacturing process before they are integrated into automotive factories.

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