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Life cycle targets applied in highly automated car body manufacturing – method and algorithm

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Abstract

Automotive companies are striving for higher productivity, flexibility and more sustainable products to meet demands of central stakeholders (e.g. regulation, customers, investors). New drive systems or lightweight-design of cars often imply an environmental *burden shifting* from one life cycle stage to another, e.g. from the use-stage to the manufacturing stage. More products will be manufactured for an increasing population and higher efficiency effort may lead to increased consumption (*rebound effect*). An optimization of the manufacturing stage is thus increasingly important but it has to be done from the perspective of bringing the product's life cycle performance in accordance with sustainability requirements. In order to support the companies in finding effective solutions, the framework "Sustainability Cone" was applied and an algorithm developed guiding the definition of economic and environmental target states (TS) in automotive manufacturing. Especially during the early phase of planning, largest improvements can be achieved, however target states are not yet integrated in production simulation software (e.g. PLM tools). This paper describes the approach and its application in the planning of a body shop, being one of the most relevant and complex steps of car production. The approach addresses all relevant levels, e.g. a robot, a production cell and the entire production line. So-called life cycle targets (LCT) are introduced, which represent a specific share of the target state, reflecting the importance (i.e. activity-based) of each level. Using this approach, a product and production system can be planned holistically and any rebound effect factored in and sub-optimization can be avoided.

Keywords: Manufacturing, Sustainability, Life Cycle Assessment, Production Planning, Automation, Target Setting

1. Introduction / Problem

Automotive companies are striving for higher productivity and flexibility and more sustainable products to meet demands of central stakeholders (regulation, customers, investors). In terms of more sustainable products companies have different approaches e.g. introducing new drive systems or lightweight-design in their cars. However such new concepts often imply an environmental burden shifting along the life cycle of the car from the use-stage to the manufacturing stage. Additional impacts can be expected due to the introduction of new materials and due to higher complexity of the production system to achieve more flexibility, (e.g. Volkswagen AG (2014) or Krinke (2014)). The question arises, whether efficiency improvements during the use stage of product systems also lead to the most effective solution overall. Hauschild (2015) even argues that more products will be manufactured for an increasing population with concurrent rising affluence and amended user behavior, and efficiency may induce increased consumption (rebound-effect). Thus the leverage of more efficient product systems often does not result in lower total environmental impact. Thus a different approach may be needed to ensure that consumption and production become sustainable by staying with certainty within the limits of environmental sustainability (e.g. 2° Celsius Scenario of the IPCC (2014) means a remaining budget of 390 - 940 Gt CO_{2eq} emissions). Although the concept of environmental sustainability limits (e.g. Planetary Boundaries from Rockström et al. (2009)) is not new, it attracts increasing attention as the limits draw nearer. The idea of target states for different sectors and industries is already practiced in various ways by authorities (e.g. the European emission trading scheme (European Commission, 2012)), Science (e.g. absolute sustainability (Bjørn et al., 2016)), by companies (e.g. investment) or non-governmental organizations (e.g. Science Based Targets(2015)). Today it is more likely that environmental conscious companies remain profitable on the long term (e.g. Dow Jones Sustainability Index Value increased by 45 % within the last 5 years). However there is no consensus how to allocate the emission budgets between countries or even sectors (Hauschild et al., 2017). Targets are often implemented top-down according to confidential production white papers, but in fact, two life cycles “meet” in car production – the life cycle of the product and the life cycle of the production system, and the two need to be considered together to derive targets for manufacturing in order to ensure eco-effective solutions. Based on a literature study in Section 2, existing approaches are analyzed and the following questions identified as essential to answer before targets on the product level can be integrated in manufacturing and to stay within the desired target state of the environment:

i) How can a target state for a car be implemented in the early phase of production planning? (This is addressed in Sections 3 & 4)

ii) How can targets be assigned to all individual process steps (incl. infrastructure, machinery, auxiliaries, utilization and end-of-life) of a Body-in-White production in a consistent and applicable manner? (Section 5)

After those theoretical sections, the approach is applied in a real case study (cf. Section 6) and a target for a car body is allocated to the individual process steps. The new approach is discussed in Section 7 and the paper is concluded with an outlook in Section 8.

2. Literature

The mentioned topics in the introduction leads to several research areas (e.g. manufacturing, sustainability assessment, production planning, macro economy, energy management, environmental management) which have been affected and have to be reviewed for potential frameworks, methodologies and algorithms. The aim of the literature review was to identify frameworks, methods and approaches to implement targets for product systems in the different levels in manufacturing companies. Publications were identified in four consecutive steps to cover the quite open research area with a growing number of synonyms. Manufacturing system can be clustered in different groups, namely company, product, factory, process, which reflect the different levels in manufacturing. To get a more comprehensive overview each publication was assigned to the levels it deals with (cf. Tab. 1).

Tab. 1 Focus of the 21 investigated frameworks and approaches within the field of sustainable manufacturing (●=covered, ○=not covered) sorted by year

		Company					Product					Factory					Process				
Author	Year	Econ.	Environ.	Social	LCA	Applied	Econ.	Environ.	Social	LCA	Applied	Econ.	Environ.	Social	LCA	Applied	Econ.	Environ.	Social	LCA	Applied
Alting, L. & Jørgensen, J.	1993	○	○	○	○	○	○	●	●	●	○	○	○	○	○	○	○	○	○	○	○
Veleva, V. & Ellenbecker, M	2001	●	●	●	○	○	●	●	●	●	○	●	●	●	○	○	●	●	●	○	○
Herrmann, C. et al.	2008	●	●	●	○	○	○	○	○	○	○	●	●	●	○	○	●	●	●	○	●
Rockström, J. et al.	2009	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Silva, N. De et al.	2009	○	○	○	○	○	●	●	●	●	●	●	○	○	○	○	○	○	○	○	○
Jayal, A.D. et al.	2010	○	○	○	○	○	●	●	●	●	●	●	●	●	○	○	○	●	●	○	●
Mittelstadt, J.	2010	○	○	○	○	○	○	○	○	○	○	●	●	○	●	○	●	●	○	●	○
OECD	2011	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Duflou, J.R. et al.	2012	○	●	○	○	○	○	○	○	○	○	○	●	○	○	○	○	●	○	○	○
Garetti, M. & Taisch, M.	2012	●	●	●	○	○	●	●	●	●	○	●	●	●	○	○	●	●	●	○	○
Umeda, Y. et al.	2012	●	●	○	○	○	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○
Haapala, K.R. et al.	2013	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	●	●	○	○
Kampker, A. et al.	2014	○	○	○	○	○	○	○	○	○	○	○	●	○	●	○	○	○	○	●	
Mousavi, S. et al.	2014	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	○	○	●
Shuaib, M. et al.	2014	○	○	○	○	○	●	●	●	●	●	○	○	○	○	○	○	○	○	○	○
Bjørn, A. & Hauschild, M.Z.	2015	○	○	○	○	○	○	●	○	○	●	○	○	○	○	○	○	○	○	○	○
Martinez-Blanco, J., Finkbeiner, M. & Inaba, A.	2015	○	●	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Neugebauer, S. et al.	2015	●	●	●	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Russell-Smith, S. V. & Lepech, M.D.	2015	○	●	○	○	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○
Science Based Targets	2015	○	●	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Bähre, D. et al.	2016	○	○	○	○	○	○	○	○	○	○	○	●	○	○	○	○	●	○	○	○

Bearing in mind that target states of functionalities should be implemented, most of the reviewed frameworks lack the top-down approach from the global perspective to subordinated levels, like individual machine tools. Applicability, as one of the main demands from industry, is rarely given as none of the suggested frameworks is aligned to the stage-gate model of industry planning. The term s*ustainability* has been mentioned several times by describing all three dimensions, but the majority of frameworks is only dealing with the environmental perspective and neglecting the same level of detail for the economic and social dimensions. Manufacturing is understood in most of the frameworks as a combination of several levels – from factory and/or product down to production system and process. This kind of thinking should be improved by even more levels with respect to the stage-gate model in automotive manufacturing and to specific circumstances of products and production lines in industry. This level of detail reflects the actual situation in terms of decision-making in most of the companies. In regards to the life cycle perspective, the product level is in focus, but neglecting mostly the factory level (e.g. more product variants) and process level (e.g. more automation, more machinery). Another important observation from the review is that most of the frameworks are intended to be used for *reporting* purposes (i.e. bottom-up). Some frameworks are most likely capable of being implemented in *planning/design* stage (i.e. top-down), namely (e.g. Kampker et al., 2014; Silva et al., 2009). However none of the suggested frameworks has actually been integrated into industrial planning tools (e.g. PLM - Software) and further plans were not described. The following Fig. 1 describes the identified gaps (red bars) of the literature review in terms of economic, environment, social and LCA.

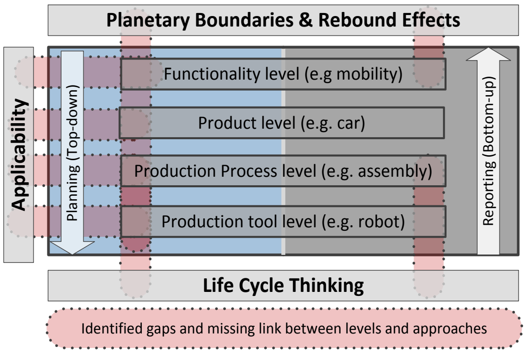


Fig. 1 Result of the Gap Analysis summarizes the different levels analyzed in the frameworks and their missing links (red bars) to the main requirements of a sustainable manufacturing framework for planning und reporting

None of the approaches set up the link between planetary boundaries (i.e. absolute targets) and the product. However according to Rödger et al. (2016) the functional unit of the life cycle approach (ISO 14040, 2006) could be used to set up the missing link in a new framework, because

- the demand of functionality is inherently linked to the functional unit of products,
- it can be used as a reference point for absolute targets to avoid burden shifting and
- thereby integrating planetary boundaries to the Product development process (PDP) and Production planning process (PPP) to avoid rebound effects.

These points are not considered yet in sustainable manufacturing frameworks and should be inherent in order to achieve the integration of absolute targets in production planning. In the following Section 3 the Sustainability Cone as a new framework is presented, which entails the above-mentioned points and establishes these missing links.

3. The Sustainability Cone – a consistent and applicable way to integrate target states

The competitive environment in automotive manufacturing leads to a cost-optimized system, which might favor environmental sub-optimization (i.e. rather obtain a quantity discount through using the same type of robot for all applications instead of using process-specific robots with different and overall lower environmental footprints). It has been shown by Rödger et al. (2016) that it is possible to avoid this through a sustainability assessment framework, which is adapted to the existing decision-making processes and thus ensure manufacturability. Doing this in alignment with the existing product development processes (PDP) and production planning processes (PPP) (i.e. stage-gate models) leads to greater awareness within the company. These processes are top-down approaches and potentially conflict with classic life cycle assessment, which is a bottom-up approach. Life cycle Assessment (ISO 14040, 2006) usually analyzes existing products or systems in retrospect. Recently, authors have suggested even more approaches, such as target state (Ellen MacArthur Foundation, 2016), planetary boundaries (Rockström et al., 2009), carrying capacity (Steffen et al., 2015)) trying to quantify global environmental impacts, and Bjørn et al., (2016) have incorporated the boundary perspective into LCA to support absolute environmental sustainability assessment, in order to push forward environmental benign product and systems development. Applying and aligning these different approaches is quite challenging, but the recently published framework – The Sustainability Cone – attempts to combine all different views on the manufacturing systems (see Fig. 2).

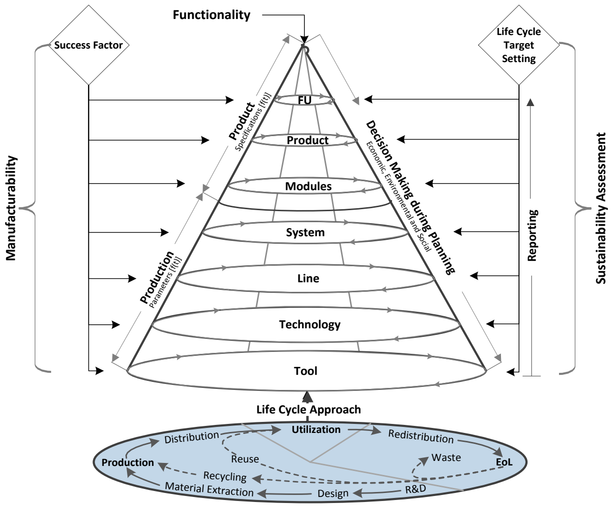


Fig. 2 Sustainability Cone: Conceptual framework of merging life cycle perspective, product and production to derive life cycle targets (LCT) thus optimizing product and production in an early planning phase (Rödger et al., 2016)

Using this framework allows to apply the concept of target states towards which a product or system as a whole could strive. Those target states (i.e. "40 t CO_{2e}“or “30.000 €”) can be used for functionalities (i.e. individual transportation) which are inherently connected to the functional unit (e.g. 150.000 km/10 years) of products (e.g. car or bicycle).The desired target states of functionalities can be used to avoid burden shifting between life cycle stages of product or systems and at the same time be integrated in existing PDPs and PPPs. Manufacturing is undergoing constant changes (i.e. more automation (IFR, 2016), shorter product life cycles (Montalvo et al., 2016)) on the competitive globalized market. According to Kiefer et al. (2006) automotive manufacturing in particular is affected by those changes and dealing with additional challenges (i.e. shorter ramp-up times, increase number of variants and ramp-ups, more mechatronic components as well as complexity). Implications for how target states can be used in highly automated manufacturing and in specific production processes as well as for machineries have not been investigated yet (cf. Section 2).

The following sections describe a concrete procedure of allocating target states to the different levels in highly automated manufacturing based on the Sustainability Cone framework. In this course, also the decision-making process and the identification of success factors and of available data sources will be described in order to explain the new approach of life cycle-target setting holistically.

4. Life Cycle Target Setting in highly automated car manufacturing – Goal and Scope

To avoid any burden-shifting target states can be used to describe products or systems holistically, i.e. applying a life cycle perspective. Therefore Life Cycle Targets (LCT) are introduced, which reflect financial as well as environmental impacts. Companies and production planners still consider the life cycle of a production from a financial perspective – planning, realization, operating and redistribution. The life cycle used in this approach is actually based on ISO 14040 – which covers the stages raw material extraction, the production, the use- and the EoL (End-of-Life). This section will provide the methodological background of integrating the life cycle targets in highly automated car manufacturing. A detailed mathematical description follows in Section 5. To be able to integrate and determine LCT for each subsequent level in BIW (Body-in-White) production, a detailed understanding of industrial planning is needed. Therefore, within this section some side aspects in PPP are covered such as how, and when which decisions are made, which data is already available and which key performance indicators need to be measured.

The approach of backcasting has been used as an inspiration, as it is a decision and planning method to develop pathways to reach a certain future state, by using interim goals during the process (Byrd, 2001). This entails planning backwards, making assumptions and adjust product, resources and processes to achieve the future state. Future states are in this example the target states for highly automated car manufacturing. Applying this thinking in manufacturing (cf. Fig. 3) starts with a projection of environmental and financial impacts ((i),①),depending on the production volume (or rather number of functional units (x)), by the OEMs (Original Equipment Manufacturer) is needed. A typical car production is designed for about 250.000 units per year over a period of 6-7 years. Overall 1.5 mio units (x´) should be sold, a reduction of investment and environmental impact is necessary (②) in order to comply with the desired target state (i´). Dividing i´ by the number of units (x´) leads to the specific impact per unit (p´,③). This is the life cycle target (④) which is the marginal impact at a specific production volume that may not be exceeded. As the demand may change, the production volume may change as well to x´´ (⑤). This leads to a higher cumulative impact (i´´, ⑥) and must be compensated by improvements in the production in order to be able to comply with the target state i´. These new circumstances lead to a new life cycle target (p´´,⑦).

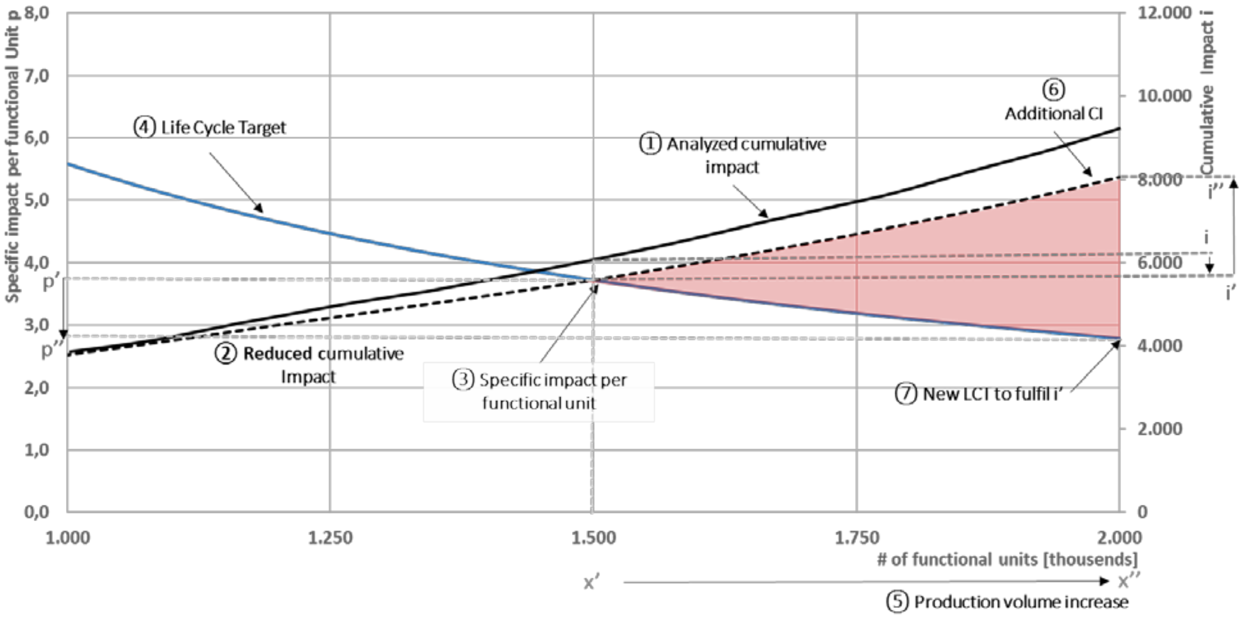
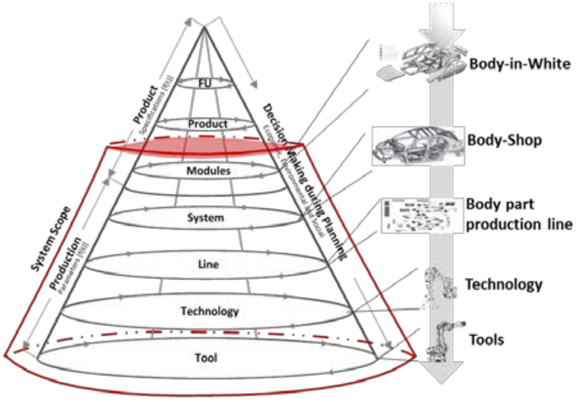


Fig. 3 Methodological approach and use of Life cycle targets exemplified by production volume increase

To integrate life cycle targets in production systems, a functional unit according to ISO 14040 (ISO 14040, 2006) must be defined for each product or systems at each level (see Fig. 4). Those functional units inherently cover the whole life cycle, which is essential to be able to compare financial Life Cycle Targets (fLCT) and environmental Life Cycle Targets (eLCT). For conducting fLCT it is recommended to use the environmental Life Cycle Costing approach (e.g. Swarr et al. (2011)), as it uses similar system boundaries as Life Cycle Assessment. Elaborating further on the system level approach, the first functional unit should be an assembled BIW which is ready to be used in the superior level or process step (i.e. the paint shop). Additionally, type of variant and destination market must be defined, as safety-related mechanical properties depend on such information and directly influence the subordinate level. The functional units of each level in the product system are defined exemplarily in Fig. 4. As the production gets more branched on each subordinated level, each functional unit gets more detailed as well. Therefore it is beneficial to know production- and product-specific planning parameters. Additionally, the functional unit should consist of financial and planning-related parameters already used in the organization, since otherwise, determining those parameters becomes an obstacle for the practitioner, putting applicability of the approach at stake.



Functional Unit (examples)	Description
One fully assembled BiW for the German market ready for further use in paint shop, availability > 85 %	One specific type (e.g. variant) of BIW depending of pull strategy from superior level (e.g. market, left- or right-hand drive), production location (statutory holidays), shift-system (2 or 3 shifts and statutory break times)
Assembly of BIW-parts for BIW according superior level at a given time in a specific cycle time (62 sec) with an overall availability > 95 %	Production of one BiW (i.e. assembly of underbody, side frames & roof, doors, fenders, tailgate, hood) under predefined circumstances (e.g. station wagon, left-hand drive, country-specific, cycle time, availability, redundancy)
Three underbody parts (steel alloy) joined first by adhesive bonding (200 mm, 1-Component), supported by spot-welding (8 spots), process time (36 s), passing on to next station (3 s) availability > 98,7 %	Production of one BiW-part (e.g. Underbody) by joining three parts with regards to cycle time, availability, joining sequence, flexibility and redundancy. New part conveyed to next production line (cell).
4 Spot-welds, process time of max. 3 sec between spots, maximum geometrical freedom, availability (> 99,8 %), accuracy of ±0.05 mm	Handling or joining (e.g. spot welding, riveting etc.) of two parts with specific technology with respect to cycle time, accuracy, geometrical freedom and redundancy
Degree of freedom (min. 6 axes), reach of 3.000 mm, payload of 180 kg, cycle time of 15 secs, availability (>99,95 %), accuracy (±0.05 mm) and high reproducibility	Flexible or stationary (robot or mount), depending on required geometrical freedom, cycle-time, availability, accuracy and redundancy

Fig. 4 Scope of life cycle target setting in highly automated body-in-white (BIW) manufacturing. For each level, an example is given of a generalized functional unit and a description.

Production planning in the automotive sector begins at the end of the product development, around four years before start of production (SOP). The production line must be capable of several variants (i.e. versions of a car model), flexible enough to produce BIW adjusted to different regulations, providing a high availability and meet the local challenges (e.g. shift-system, climate conditions). Due to the increasing complexity in production planning the digital factory is necessary (VDI, 2008). To avoid any far-reaching mistakes the production planning is based on a fixed procedure , which can be described as stage-gate process (Cooper, 2008). Along this process, critical success factors (Go/Kill-decisions) have to be met to pass the gates and reach the next stage. Specific indicators and parameters like shift-system, working-hours, accuracy and joining sequence and so forth are used to back up critical success factors like cycle time, annual output and investment. These factors are important to determine LCT, as they inherently describe the activity taking place at each level and even in subordinated levels in very detail. Thus an activity-based top-down allocation of target states to determine fLCT and eLCT is recommended which is described in very detail in Section 5. Along the planning process of highly automated BIW production there are three potential gates where the use of LCTs can be beneficial. Tab. 1 shows the procedure as it is done today (left column), how it would be complemented with LCT (middle column) and how it can be applied (right column).

Along production planning a lot of data is not easily accessible and prepared for sustainability assessment. Data (e.g. layouts of cells and number of components) can be collected automatically from standard spreadsheets such as MS Excel© and from pdf-documents (e.g. mathematical approach of calculating machine running times) even before the first gate. Additional specific data can be manually extracted from production simulation software (i.e. PLM), which is already clustered in product, resource and process related data. Life Cycle data bases (e.g. EcoInvent (ecoinvent, 2014), ELCD (EPLCA, 2015) or GaBi (Thinkstep, 2015)) have to be linked to the inventory data as well in order to cover the product or system holistically. All this data can be used to derive sufficient activity-based allocation factors. The associated algorithm in Section 5 combines all these data pools which can be tapped into to determine activity-based LCTs during the first stage. Assumptions are inevitable in such a complex system, especially the life-time of machinery, changes in specific emissions from energy systems over time and the EoL of the infrastructure need to be mentioned and taken into account during the critical review. It is highly recommended to make a sensitivity analysis based on predefined uncertainty factors for above mentioned clusters. Those are included already in the algorithm, to be able to deliver accurate and correctly specified LCT-ranges to prevent any failure (incl. its potentially far-reaching consequences).

Tab. 2 Production planning procedure today, adjusted process with LCT and an example of its application

<table>
<tr><th></th><th>Today</th><th>Life – Cycle Targets</th><th>Example</th></tr>
<tr><td>1</td><td>The OEM creates a factory and production layout including a resource list of machinery and auxiliaries. This information is send to a contractor, which elaborates a functioning model of the production line including investment costs.</td><td>OEM determines target states for the production line and conducting life - cycle targets based on the internal data and algorithm in Section 5. Those will be integral part of the tender.</td><td>OEM calculation: Impact of 11 based on predecessor line → 9 % reduction required in actual production → Target state of 10 → Actitiy-based allocation leads to eLCTs of → 5.9 Line 1 & 3.2 Line 2 & 0.9 Line 3</td></tr>
<tr><td>2</td><td>The second iteration is affected by the final product adjustments and subsequent production changes (like joining sequences) have to be integrated. The contractor assures a full functional line in terms of annual output and cycle time.</td><td>Contractors adjust, upload latest data and calculate life - cycle targets for their proposal. OEM calculates potential exceedance or savings, which can be used in other cost centers to comply with target states of demanded functionality.</td><td><table>
<tr><th></th><th>Line 1</th><th>Line 2</th><th>Line 3</th><th>Total</th></tr>
<tr><td>eLCT</td><td>5.9</td><td>3.9</td><td>0.9</td><td>10.0</td></tr>
<tr><td>Contractor 1</td><td>[5.2]</td><td>4.2</td><td>[1.3]</td><td>10.7</td></tr>
<tr><td>Contractor 2</td><td>5.6</td><td>[3.3]</td><td>1.4</td><td>10.1</td></tr>
<tr><td>Savings</td><td>0.7</td><td>0.6</td><td>-0.4</td><td>9.1</td></tr>
</table></td></tr>
<tr><td>3</td><td>An additional option exists for contractors. They can provide an offer with their individual ideas, but the OEM Standard of machine operating and non-productive times must be followed. A new resource list, layout and cycle time diagram must be prepared incl. adjusted investment.</td><td>A LCT-optimized production line can be an additional option to achieve competitive edge. This part is another additional option for the OEMs to comply with target states. Other cost centers might have serious problems to fulfill their targets due to e.g. technical reasons thus other parts can contribute more significant to the overall goal.</td><td><table>
<tr><th></th><th>Press Shop</th><th>BIW</th><th>Paint shop</th><th>Total</th></tr>
<tr><td>eLCT</td><td>3.5</td><td>10</td><td>22</td><td>35.5</td></tr>
<tr><td>Press shop[1]</td><td>3.8</td><td>-</td><td>-</td><td>3.8</td></tr>
<tr><td>Paint shop[1]</td><td>-</td><td>-</td><td>22.6</td><td>22.6</td></tr>
<tr><td>eLCT optimized</td><td>-</td><td>9.1</td><td>-</td><td>9.1</td></tr>
<tr><td>Savings</td><td>-0.3</td><td>0.9</td><td>-0.6</td><td>35.5</td></tr>
</table>[1] best available technology</td></tr>
</table>

Another critical point in LCT setting is the selection of impact categories. The spectrum of potential impacts to be assessed is broad, but to avoid numerous assessments (Rödger et al., submitted) suggest the following five environmental impact categories as giving an adequate coverage for most manufacturing systems:

- Acidification Potential (AP),
- Human Toxicity Potential (HTP),
- Global Warming Potential (GWP100),
- Abiotic Resource Depletion Potential (ADP elements),
- Photochemical Ozone Creation Potential (POCP) plus
- Primary energy demand (PED).

These selected categories show a low internal correlation and cover the most important environmental topics in manufacturing (Laurent et al., 2012). In support of easy implementation, it is suggested to use mid-point characterization factors according to the Institute of Environmental Science at University of Leiden (Guinee, 2002), as this is well-established practice among car manufacturers (e.g. (Audi AG, 2011; Mercedes-Benz AG, 2010; Volkswagen AG, 2014). Using this set of five impact categories, potential burden-shifting between impact categories can be identified. Preferably, any aggregation of the five to a combined single-score should be avoided in order to (i) be able to identify main contributing impact categories and (ii) avoid introduction of additional uncertainty which would result from for aggregated single-scores necessary normalization and weighting steps. For the economic dimension, environmental life cycle costing is recommended (Hunkeler et al., 2008). This limited number of parameters (i.e. additional six environmental parameters as well as the slightly adjusted financial parameter) should enhance the planning process and allow practitioners applying LCTs (i.e. production planners and production managers) to simulate and plan environmentally and economically more sustainable manufacturing solutions.

5. Algorithm to determine Life Cycle Targets

Automated production lines in automotive manufacturing are often very branched, and setting life cycle targets (LCTs) for each individual level (System, Line, Technology and Tool) and sub-systems can be quite challenging. Therefore to support the understanding of the whole approach of determining LCTs Tab. 3 lists several abbreviations which are used in the following description.

Tab. 3 Abbreviations and symbols used in the algorithm

Abbreviation & Symbol	Description	Unit
AS	Assembly (Part of car body production)	[-]
co	Number of auxiliary components (e.g. fences and conveyors)	[#]
CP	Country of production	[-]
ct	Cycle time in seconds	[s]
de	Direct secondary energy consumption (power) per joining equivalent	[kWh]
di	Dimension of the intermediate product	[dm^3]
em	Number of employees	[#]
ex	Share of externally produced parts on level n	[%]
FI	Finish (Final step in car body production)	[-]
ic	Installed capacity of the ressource	[kW]
ie	Indirect secondary energy consumption (e.g. HVAC)	[kWh]
in	Share of in-house production on level n	[%]
IV	Intended production volume	[#]
Je	Number of joining equivalents	[#]
js	Number of process steps within a joining sequence	[#]
k	Index for the first zone	[-]
lct	Specific life cycle target for a level in the sustainability cone	[kg CO2eq, GJ or €]
LCT	Overall Life Cycle Target for a car body	[kg CO2eq, GJ or €]
m	Index for the last zone	[-]
M	Material used in car body	[-]
ma	Mass	[kg]
n	Level in production according to the sustainability cone	[-]
no	Number of intermediate product within the process step	[#]
pp_n	Process relateded allocation factor for zone n	[-]
pr_n	Product relataded allocation factor for zone n	[-]
re_n	Resources related allocation factor for zone n	[-]
ro	Number of robots	[#]
st	Number of stationary installed technologies	[#]
ST	Structure Production Line (Part of the whole car body line)	[-]
Te	Number of technologies (e.g. Joining or Handling)	[#]
ti	Actual utilization of the technology	[s]
TRL	Technology Readiness Level (1-9)	[-]
TS	Target State	[kg CO2eq, GJ or €]
UB	Underbody line (Part of the whole car body line)	[-]
uf	Uncertainty factor (dimensionless)	[-]
vo	Occupied volume of the ressource	[dm^3]
$vr_{vt,pr,z,in}$	Specific share of in-house production	[%]
VT	Variant type of car body	[-]
α_n	Uncertainity factor for product related production planning parameters	[-]
β_n	Uncertainty factor for process related production planning parameters	[-]
γ_n	Uncertainty factor for resource related production planning parameters	[-]
δn	Overall allocation factor for all production planning clusters	[-]
ε	Factor for allocation within a cell (dimensionless)	[-]
λ	Allocation factor for technology and components	[-]
σ_i	Allocation factor for indirect secondary energy consumption	[-]
τ_i	Direct secondary energy consumption per joining equivalent	[kWh]

To be able to determine LCTs, first of all target states (TS) and life cycle targets of BIW have to be defined. Target states could be identified by using the functional unit(s) and by additional information like type (VT) and shares (VS) of variants to be produced, total intended production volume (IV) and country of production (CP) as well as targeted market (TM). The individual LCT depends on the material composition (M), as well as on the mass (ma) and the impacts from the EoL. As a result, variant-specific life cycle targets (lct_{vt}) and the share for material and production $lct_{vt,mpr}$ can be determined. In order to use those individual LCTs in production correctly, a general understanding of the production layout is needed to be able to follow subsequent steps in the algorithm. Starting from the highest level in BIW production (cf. System level in the Sustainability Cone) the production process is usually separated into three main zones (Underbody (UB), Structure (ST), Assembly & Finish (AS&FI)) which together represent the main production line (cf. Fig. 5).

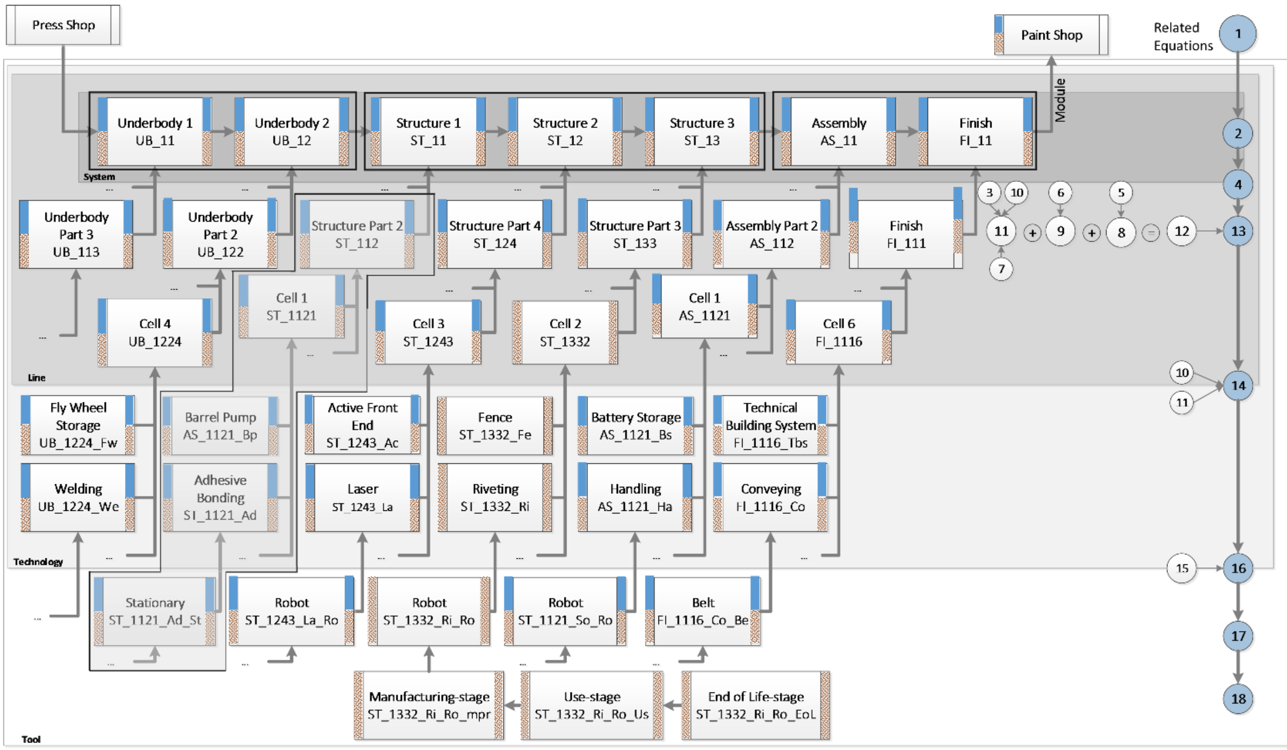


Fig. 5 Typical pattern of production line including nomenclature of all components within the different levels of the Sustainability Cone. Two different variants are produced (blue and brown rectangles), only brown variant need additional infrastructure (i.e. ST_1332) for further production steps to comply with additional static requirements. Some intermediate parts might be produced externally (blue shadowed, ST_112), which can be excluded from more detailed life cycle target setting and used in tendering.

Before starting with specific lcts, the factor material can be excluded (see Eq. 1), as no particularly relevant material waste can be expected, as intermediate stamped parts are joined in highly automated production. According to Heil et al. (2014) up to 75 % of the primary energy demand of a BIW is due to its material. For the financial demand, expert opinions are necessary, and the environmental impacts can be determined by using existing LCAs or emission factors based on databases, such as EcoInvent (ecoinvent, 2014), ELCD (EPLCA, 2015) or GaBi (Thinkstep, 2015).

$$\mathbf{lct}_{vt,pr} = \mathbf{lct}_{vt,mpr} - \mathbf{lct}_{vt,m}$$

Eq. 1

The production line is organized in different zones, where within the core line only large, fixed and highly automated equipment should be installed, rather large parts are joined to limit logistic efforts. At each branch the production gets more complex, thus a consistent and applicable allocation between these different areas (UB, ST, AS & FI) is needed. As mentioned before (cf. Section 4) production planning software clusters production parameters into ‘Product, Resource and Process’. Within these clusters some valuable parameters (see Tab. 2) were identified as they describe the activity taking place quite well. Entailed information can be used to determine individual life cycle targets for each production zone (z). First aim is to allocate production related $\mathrm{lct}_{vt,pr}$ of a BIW to one of the three main zones (UB;ST, AS&FI) by using the total number of installed

- technologies (te), e.g. joining and handling
- auxiliary components (co), e.g. fences and conveyors

Tab. 4 The three clusters Product, Process and Resource from digital production planning software (i.e. PLM Systems) populated here with parameters used to determine activity-based allocation factors for determining individual life cycle targets

Product (PR)	Process (PP)	Resource (RE)
Number of parts (no): Usually in each production step at least one intermediate product is treated or joined with another part. The number is an indicator of complexity and importance of the particular production step.	**Cycle-time (ct):** Is the driving force in BIW production. Based on the shift-system, idle and non-productive periods, and annual output a specific time per BIW is defined. The main line usually has the same cycle time, but subordinated levels might differ. The ones closest to the main cycle time is more important.	**Technology (te):** Two different kinds are used - joining and handling. Each technology has its own specifications (e.g. weight, area and volume). Based on this information each technology a weighting factor is assigned to. Especially the upstream processes are quite relevant, thus detailed information regarding the type material is needed.
Weight (ma) : Each part has its own weight, it is an indicator for the direct energy consumption during handling, as well as for the detailed assessment of upstream processes.	**Joining Sequence (js):** Small to medium to large parts under the consideration of location specific circumstances. Some entail several joining steps which leads to bottlenecks (close or equal to maximum of e.g. spot welds or length of welding seam per station). The ones with highest number of joining steps is more important.	**Component (co):** Additional components (e.g. fence, Low Cost Automation, social and service rooms) are measured based on their weight, area and volume. Especially the upstream processes are quite relevant.
Dimension (di): Each part has its own dimension, it is an indicator for the *indirect* energy consumption during handling, as more area and volume is needed.	**Joining Equivalent (je):** Each choice of technology depends on the material composition, the required product properties and individual process times, which is summarized in the joining equivalent. The ones with highest number of joining equivalents gets a higher lct.	**Employee (em):** Some of the work is done by actual workers and they are treated equally to technologies. Required area and volume are used to derive weighting factor.

Additionally, the total number of joining equivalents (je) for each joining technology has to be determined. Joining equivalents are a means to compare different joining technologies. All technologies are related to one spot weld of steel alloy, which e.g. equals 10 -20 mm of laser weld of the same alloy (cf. Table S3, Supplementary Information). All OEM typically calculate their individual equivalents, which usually can be found in their production standards. These equivalents combine the specific process time as well as the joining characteristics (e.g. stiffness). Data (i.e. number of joining / handling technology, components and employees) can be extracted from early listing of Resources. By putting the data of each zone in relation an activity based allocation of each individual zone (z) can be achieved (cf. Eq. 2).

$$\mathbf{lct}_{\mathbf{vt},\boldsymbol{pr},\boldsymbol{z}} = \left. te_i * je_i + co_i \middle/ \sum_{k=1}^{m}\left(\sum_{k=1}^{m}(te_k * je_k) + co_k\right) \right.$$

Eq. 2

The Body-in-White production is a core competence of the Original Equipment Manufacturers (OEM) and is usually kept in-house due to its relatively high contribution to the added value (i.e. R&D) (Schade et al., 2014). Nevertheless, some parts are produced externally (ex, see grey shadowed area in Fig. 5), thus the parameter vertical range (vr) is needed to determine the internal production efforts (in) (see Eq. 3). It is based on the sum of joining equivalents in-house and the total sum of joining equivalents in the production line, whereby a typical degree of > 95 % is a good estimate according to the confidential production white papers.

$$\boldsymbol{vr}_{\boldsymbol{vt},\boldsymbol{pr},\boldsymbol{z},\boldsymbol{in}} = \frac{\boldsymbol{je}_{\boldsymbol{in}}}{\sum_{k=1}^{m}\boldsymbol{je}_{\boldsymbol{k}}} * \mathbf{100}\ \%$$

Eq. 3

In combination with Eq. 2 the in-house life cycle target for each zone can be determined and concurrently targets for external suppliers are identified (cf. Eq. 4).

$$\boldsymbol{lct}_{\boldsymbol{vt},\boldsymbol{pr},\boldsymbol{in},\boldsymbol{z}} = \boldsymbol{lct}_{\boldsymbol{vt},\boldsymbol{pr},\boldsymbol{z}} * \boldsymbol{vr}_{\boldsymbol{vt},\boldsymbol{pr},\boldsymbol{z}}$$

Eq. 4

At this early stage of planning, uncertainties are inherent and must be taken into account. Therefore the approach of technology readiness levels (TRL) of NASA[1] (cf. classification of European Commission (2014)) has been adopted to support the current planning. To each parameter, depending on the TRL, an uncertainty

[1] National Aeronautics and Space Administration (USA)

factor (uf) (see suggestions in Table S4, Supplementary Information) is assigned. Based on this information, individual uncertainties (product=α, process=β, resource=γ) for each cluster (cf. and for every level (n) in BIW production can be considered (cf. Eq. 5, Eq. 6 and Eq. 7). The uncertainty of each cluster is described by the uncertainty of each individual parameter (e.g. mass of technologies (ma_{te}) is assumed to have a TRL of 8 which correspondents with a deviation of ± 2.5 %) and the multiplication of them to gain overall uncertainty of e.g. product related parameters (α).

$$\boldsymbol{\alpha_n = (1 - uf_{no,n}) * (1 - uf_{ma,n}) * (1 - uf_{di,n})}$$

Eq. 5

$$\boldsymbol{\beta_n = (1 - uf_{ct,n}) * (1 - uf_{te,,n}) * (1 - uf_{je,n})}$$

Eq. 6

$$\boldsymbol{\gamma_n = (1 - uf_{te,n}) * (1 - uf_{co,n}) * (1 - uf_{wo,n})}$$

Eq. 7

Within the product cluster (PR), all relevant CAD data of a car body is stored today on OEM's proprietary database. The number (no), specific product dimension (di) and weight (ma) have a significant impact on the layout of the production line (e.g. joining technology and the sequence). Additionally information about the material is given as well, which can be used in an earlier formula (see Eq. 1). The specific product related allocation factor following equation (cf. Eq. 8) should be determined, where n represents the level/zone to be determined and k to m all parallel zones.

$$\boldsymbol{pr_n = \left(\frac{no_n}{\sum_{k=1}^{m} no_k} + \frac{ma_n}{\sum_{k=1}^{m} ma_k} + \frac{di_n}{\sum_{k=1}^{m} di_k}\right) * \alpha_n}$$

Eq. 8

Process related parameters (pp), like cycle time (ct), joining equivalents (je) and number of steps within joining sequence (js) are specified as well. Other parameters like availability, idle- and non-productive periods, lead time and several other parameters (e.g. meantime between failures (MTBF)) are mentioned as well. However the first three parameters are sufficient, as they describe the activity distinctively enough (cf. Eq. 9).

$$\boldsymbol{pp_n = \left(\frac{ct_n}{\sum_{k=1}^{m} ct_k} + \frac{je_n}{\sum_{k=1}^{m} jt_k} + \frac{js_n}{\sum_{k=1}^{m} js_k}\right) * \beta_n}$$

Eq. 9

To fulfill the process requirements resources (RE) are needed in the form of operating equipment. This operating equipment (e.g. robot, welding guns, fence, conveyor etc.) is described in a company's proprietary database. This entails CAD data, which can be used in PLM software to establish a virtual model of the line. The full potential for sustainability assessment has not been completely exploited yet as PLM software libraries only comprise some additional investment data. If used to its full potential, PLM libraries could easily provide a lot of environmental inventory information (e.g. *weight (we)*, *volume (vo)*, *installed capacity (ic)*) for the technologies (te) and other components (co). To use them in the life cycle target setting, allocation factor λ is introduced. Data of each of the parameters (i.e. *we, vo, ic*) are weighted equally and are divided by the total percentage (cf. Eq. 10). By this approach a high level of detail is assured and can be used in proximate steps.

$$\boldsymbol{\lambda_n = \frac{we_n}{\sum_{k=n}^{m} we_k} + \frac{vo_n}{\sum_{k=n}^{m} vo_k} + \frac{ic_n}{\sum_{k=n}^{m} ic_k}}$$

Eq. 10

Combining the total number of technologies (te), the number of components (co), the previously derived factor (λ), the number of employees (em) and the uncertainty factor, a sufficient allocation factors re_n (cf. Eq. 11) can be determined.

$$\boldsymbol{re_n = \left(\left(\frac{te_n}{\sum_{k=n}^{m} te_k} + \frac{em_n}{\sum_{k=n}^{m} em_k}\right) * \frac{\lambda_{te,n}}{\sum_{k=n}^{m} \lambda_{te,n}} + \frac{co_n}{\sum_{k=n}^{m} co_k} * \frac{\lambda_{co,n}}{\sum_{k=n}^{m} \lambda_{co,n}}\right) * \gamma_n * 2}$$

Eq. 11

The three individual weighting factors of the clusters are weighted equally in order to reach an overall allocation factor (δn). An additional weighting of these factors could be used, however it is highly individual and up to the OEM to determine the importance of product, production and resource parameters. At this point all considered equal, thus the sum is divided by the total percentage and a specific allocation factor for each level and cell can be derived (cf. Eq. 12).

$$\boldsymbol{\delta_n} = \frac{(\boldsymbol{pr_n} + \boldsymbol{pp_n} + \boldsymbol{re_n})}{\mathbf{9}}$$

Eq. 12

Taking this allocation factor in conjunction with the previously identified life cycle target (cf. Eq. 4) for a specific zone, the individual life cycle target for each following level can be derived (cf. Eq. 13).

$$\boldsymbol{lct_n} = \boldsymbol{lct_{vt,pr,in,z}} * \boldsymbol{\delta_n}$$

Eq. 13

After identifying life cycle targets on cell level, the subsequent step is to determine factors within a cell. A cell or rather PLC[2]-unit may consist of up to 16 robots (ro), attached technologies and other components (co). Before focusing on the actual technology the lct of the components and employees have to be deducted. This can be done easily by putting the specific number of technology (te_n) in relation to the specific resource factor (re_n) (cf. Eq. 11) including the $\lambda_{te,n}$-factor (cf. Eq. 10). If the focus is rather on components or employees the numerator has to be replaced in Eq. 14.

$$\boldsymbol{lct_{te,n}} = \boldsymbol{lct_n} * \frac{\frac{\boldsymbol{te_n} * \boldsymbol{\lambda_{te,n}}}{\sum_{k=n}^{m}(\boldsymbol{te_k} * \boldsymbol{\lambda_{te,k}})}}{\boldsymbol{re_n}}$$

Eq. 14

For further calculation it is important, whether the technology is attached to a robot or a fixed installation (st).This information can be extracted from the resource data as well. For instance robots need additional energy, thus an additional factor for direct energy consumption (de) per joining equivalents (je) must be considered (see Supplementary Information, Table S4). By considering the actual production time (ti) of each technology as well a sufficient allocation factor ε within the cell can be derived (cf. Eq. 15).

$$\boldsymbol{\varepsilon_i} = \frac{\boldsymbol{de_i} * \boldsymbol{je_i} * \boldsymbol{ti_i}}{\sum_{k=i}^{m}(\boldsymbol{de_k} * \boldsymbol{je_k} * \boldsymbol{ti_k})}$$

Eq. 15

Indirect energy consumption (ie) for ventilation, heating, cooling and lighting (cf. specific shares in Table S4, Supplementary Information) must be not neglected, as it often causes up to 50 % of the potential impacts of a production line (Klüger, 2011). Therefore, the factor σ_i is introduced which can be derived by using Eq. 15 while substituting direct energy data with indirect energy data. Subsequently combining Eq. 14 and Eq. 15 leads to technology specific life cycle targets (cf. Eq. 16).

$$\mathbf{lct_{te,n,i}} = \mathbf{lct_{te,n}} * \boldsymbol{\varepsilon}_\mathbf{i}$$

Eq. 16

The technology can either be fixed on stationary installations or to a robot. To provide robot developers an aim they should strive for, a further separation is needed. By using the factor (τ_i) (cf. Supplementary Information Table S4) in combination with Eq. 16 an even more specific lct can be determined (cf. Eq. 17). τ_i is representing the direct energy consumption per joining equivalent, either for the robot or the technology. By putting them in relation to each other, either the share of the robot or of the technology can be determined.

$$\mathbf{lct_{te,n,i,ro}} = \mathbf{lct_{te,n,i}} * \boldsymbol{\tau}_\mathbf{i,ro}$$

Eq. 17

In order to identify the individual lct for each robot, Eq. 14 and Eq. 15 can be used again. All individual data is already available in the data sheets (see data in supplementary Information). Lastly the lct for the different life cycle stages of a robot. This way, an individual lct for material and production, the use-stage and End-of-Life of robots (cf. Eq. 18) can be determined. Hereby specific circumstances in automated manufacturing, like operating time, mean-time-between failure, payload, acceleration and trajectory need to be taken into consideration. Dijkman et al. (2015) analyzed the life cycle of robot in car manufacturing. It can be used as a

[2] Programmable Logic Controller

good estimate as it represents a typical industrial robot with a payload of up to 210 kg and an utilization time of 20 % of the overall time. For global warming impact following shares for the different life cycle stages can be assumed (e.g. GWP_{100} mpr ≈ 30%, us ≈ 70%, EoL≈ 1%). However, it must be noted, as soon the utilization is increased, it must be adjusted accordingly.

$$\mathbf{lct}_{ro,te,n,i,mpr} = \mathbf{lct}_{ro,te,n,i} - \sum(\mathbf{lct}_{ro,te,n,i,us}, \mathbf{lct}_{ro,te,n,i,eol}) \quad \textbf{Eq. 18}$$

The above theoretical procedure is in the subsequent section 6 applied in a case example in order to enhance the understanding and show the benefits of this applied approach.

6. Life Cycle Targets applied in highly automated manufacturing

The aim of this section is to demonstrate the applicability of the life cycle target setting approach and its informative value for different decision-makers within the production planning procedure. Based on real production planning data from a car manufacturer, combined with existing LCA results, life cycle targets for climate change (GWP), Primary energy demand (PED) and Life cycle costs (LCC) are here determined for each level in the sustainability cone (cf. Fig. 4) by using the equations from Section 5. In this section, results are only exemplified for Global Warming Potential (in CO_{2eq}) (cf. Fig. 6). The supplementary information contains results for Primary Energy Demand (cf. Table S6) and life cycle costs (cf. Table S7).

In order to be able to determine individual life cycle targets (lct), basic system boundary related facts are needed, such as the ones given below:

- Production period: 6 years
- Annual production: 250,000 cars
- Start of Production: October 2016
- Car body facts:
  - 300 kg
  - 90 wt% Steel sheet (deep-drawn)
  - 5 wt% Aluminum profile
  - 5 wt% carbon-fiber
- Drive Unit: Diesel
- Functional Unit: Car Body should last at least 150,000 km in 10 years
- Location of production: Germany
- Target state per car body:
  - GWP 100: 3.1 t CO_{2eq}
  - PED: 120.3 GJ
  - LCC: 2,566 €
- Life Cycle Stages: Extraction, Material & Production, Use and EoL

First of all, the share for Material & Production must be identified, while the impact of fuel consumption during use (cf. Fig. 6) incl. upstream processes and the EoL of the car body have to be subtracted from the overall target state. Thereby the target state for material & production is reduced to 1.4 t. Using the material composition combined with life cycle inventory data, the share of the material can be identified (1.1 t CO_{2eq}). By this, a production life cycle target of 305 kg can be determined, which represents about 9.7 % of the target state value of the entire car body.

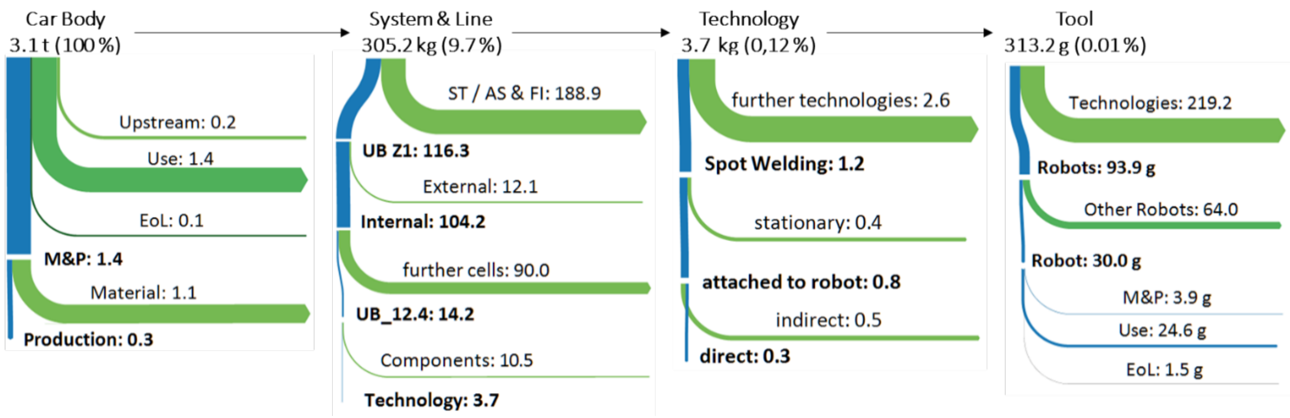


Fig. 6 Life Cycle Target (Global Warming Potential in CO_{2eq}) for four individual levels in the Sustainability Cone based on an existing car body production line in Germany. From Car Body level (in t] to tool level [in g] per functional unit.

From there on, the equations from Section 5 are used to calculate subsequent life cycle targets. By multiplying the number of installed technologies with the joining equivalents plus the number of components, a consistent allocation for each production zone is generated (cf. Eq. 2). By setting each zone in ratio, the Underbody Zone (UB Z1) gets, in total, 39 % (116 kg) of the life cycle target of its superior level. Under UB Z1 some production steps take place externally (12.1 kg), i.e. at suppliers, and their allocation is done by a comparison of the respective joining equivalents (cf. Eq. 4). As a result, the in-house (internal) production receives 104.2 kg as target. Every level gets more complex in respect to the level of detail, and more information is needed to determine those specific targets. Eq. 13 is used to combine the resource-, process- and product-related parameters, allowing to calculate the lct of UB_12.4 (14.2 kg). This cell is quite complex and entails 155 components incl. 28 joining technologies with 276 joining equivalents and has a cycle time of 45.2 sec. This information is needed in the next step (cf. Eq. 14). Resource data (cf. Eq. 10) and technology data (cf. Eq. 11) have to be put in relation to each other allowing to calculate specific lct's for individual technologies (i.e. joining with 3.7 kg). There are several joining technologies in this cell, of which spot welding has the highest λ-factor (cf. Eq. 10). Thus spot welding receives 1.2 kg as target. The spot-welding gun is in four cases attached to a robot (0.8 kg), while in two cases on stationary devices (0.4 kg). This distinction is achieved by using Eq. 16 incl. the specific allocation factor ε (cf. Eq. 15), which describes the workload of the joining step. Before determining lct for robots it is necessary to deduct the impact of the indirect energy consumption (0.5 kg) and of the attached technology (219 g). The indirect energy consumption (i.e. heating and cooling) highly depends on the production location, for instance in India the indirect energy consumption might be lower due to missing temperature regulations in the production (Klüger, 2011). At first, the direct energy consumption per joining equivalent has to be put in relation to the indirect energy consumption per joining equivalent (see Table S4, Supplementary information). Secondly, τ_i is used to compare the direct energy consumption of the robot and the technology. Eq. 17 is used to distinguish the different robots (30.0 g and 64.0 g), by putting the different $\tau_{i,ro}$ in relation. This lct can be even further separated by using Eq. 18. In this way even the lct for the different life cycle stages of the robot (M&P 3.9 g, Use 24.6 g and EoL 1.5 g) can be determined.

To demonstrate the informative value, the approach has been applied in three different cases (cf. Tab. 4), which are deemed to represent current industrial settings. *Case 1* assumes a reduction of CO_{2eq} - target by 10 % for the use stage of the car introduced by law. So the OEM has to decide how to reduce those emissions and what possible drawbacks might occur. The OEM decides, that a lighter car body is necessary. However, the production of a feasible lighter material leads to more GWP impact due to higher upstream emissions (+13%). In order to compensate this increase, adjustments in the production are investigated, and an additional reduction of 9 % is needed, although a more complex material composition typically leads to even more impacts in production. By using the life cycle approach, efficiency improvements in one stage can be examined on their effectiveness over the life cycle. In this case it can be concluded, that lightweight design is not an effective solution, although it increases the efficiency in the use-stage. Thus other reduction potentials (e.g. changed aerodynamics) should be focused on as well, since a combination might be the most effective solution.

Tab. 5: Life Cycle Target (Global Warming Potential in CO_{2eq}) for all cases. The table is organized according to the structure in the Sankey-diagram (cf. Fig. 6) to facilitate easy comprehension. The dark blue cells indicate the introduction of the new target, while the light blue are the affected up-and downstream levels. The grey cells indicate the remaining life cycle target on the same level.

				As-is Situation			Case 1 *Legislative change*		Case 2 *Re-Use*		Case 3 *New technology*	
Requirements of OEM				Production location: Germany; Target market: Germany; Weight: 300 kg; Year: 2016			10 % less direct CO_{2eq} emissions compared in the Use-stage to As-is Situation		10 % less target state for material & production compared to As-is Situation		CO_{2eq} emissions of joining technology have to be reduced by 10 % compared to Case 2	
Approach:							Weight reduction of car body by 10 % (less steel, more aluminium and carbon fibre)		Only UB Z1 is completely new, while ST and AS & FI line become refurbished		Spot Welding technology has to be adjusted to reduce peak load	
Level in Sustainability Cone			**Unit**									
Functional Unit			**[km / 10 yrs]**	150,000			150,000		150,000		150,000	
Module		***Target state***	**[t CO2eq]**	3.1			3.1		3.0		3.0	
		from which ***M&P***	[t CO2eq]	1.4			1.5		1.3		1.3	
		Upstream	[t CO2eq]	0.2			0.2		0.2		0.2	
		Use	[t CO2eq]	1.4			1.3		1.4		1.4	
	Eq.	***EoL***	[t CO2eq]	0.1			0.1		0.1		0.1	
System	①	**Body-Shop Production**	[t CO2eq]	0.31	Material	1.09	0.28	1.24	0.17	1.1	0.17	1.09
Line	②	**Underbody Z1**	[kg CO2eq]	116.3	ST / AS&FI	188.9	105.7	171.7	92.6	77.7	92.6	77.7
	④	**Ub Z1** Internal	[kg CO2eq]	104.2	External	12.1	94.8	11.0	82.9	9.6	82.9	9.6
	⑬	**UB_1 2.4**	[kg CO2eq]	14.2	further cells	90.0	12.9	81.8	11.3	71.6	11.2	71.7
Technology	⑭	**Technology**	[kg CO2eq]	3.73	Components	10.47	3.39	9.52	2.97	8.33	2.87	8.37
		Spot Welding	[kg CO2eq]	1.16	further technologies	2.57	1.05	2.34	0.92	2.05	0.83	2.04
	⑮	**attached to robot**	[kg CO2eq]	0.78	stationary	0.38	0.71	0.34	0.62	0.30	0.56	0.27
		direct impact	[kg CO2eq]	0.31	indirect impact	0.47	0.28	0.43	0.25	0.37	0.22	0.34
Tool	⑯	**Robot(s)**	[g CO2eq]	93.9	Technology	219.2	85.4	199.3	74.8	174.4	67.3	157.0
	⑰	***Robot***	[g CO2eq]	30.0	further robots	64.0	27.3	58.1	23.9	50.9	21.5	45.8
	⑱	***M&P***	[g CO2eq]	3.9			3.5		3.1		2.8	
		Use	[g CO2eq]	24.6			22.3		19.6		17.6	
		EoL	[g CO2eq]	1.5			1.4		1.2		1.1	

In *Case 2* a more efficient M & P phase is necessary to reduce CO_{2eq}-emissions by 10 % and reduce costs (by 25 %). As the car body itself should remain the same, a reduction can only originate from the production (40 % for GWP and 45 % for costs). A possible solution for GWP would be that the production lines (e.g. ST and AS & FI) get refurbished and receive only 40 % (77.7 g) of the previous target. However the UB line still receives 80 % (92.6 g) of its original target, as the Underbody line needs new technology to achieve accuracy targets. Those results can then be used by planners to verify and identify the most effective production line design, when taking all three categories (GWP, PED and LCC) into consideration (cf. Table S6 and Table S7). A GWP-efficient solution might lead to a less financially sound solution, e.g. development of new technology usually leads to higher costs. While a reduction by 10 % of GWP can lead to a reduction of 29 % of primary energy consumption. Thus this approach can be used to find an effective solution across categories and avoid sub-optimization in production planning.

In *Case 3* an additional reduction of 10 % of GWP for joining technology is assumed as it corresponds with a reduction of the peak load of the production plant. Spot welding, as a main contributor with its very high peak load, is chosen to be part of the solution. As those improvements are quite challenging only some process steps are chosen, in order to limit the development effort. Therefore the bottle-neck technologies (i.e. red-flag, almost 100 % utilization) are identified, and for those specific processes, additional tenders are written with clear targets for GWP and economic performance. By this approach, a financially sound solution is sought, and the suppliers know exactly, which goals they have to reach in order to get the order. Contrary to an approach of just setting general targets, using the life cycle targets approach supports effective solutions, since it allows identifying specific cells or technologies etc. to be improved.

7. Discussion

The methodological approach has its roots in the aspiration to

i) define and quantify cost targets and environmental targets already in the planning phase of a production system,

ii) do this in a manner that is fully consistent throughout the entire production and

iii) allocate target states to specific production technologies and equipment.

The approach is based on economic target setting, combined with activity-based target setting and life cycle assessment. Due to the similarity to cost target setting (likewise top-down), the approach is considered applicable in organizations and, in fact, expected to be highly valuable since it creates a transparent overview of the typically – on low system levels – diffuse picture of where contributions to environmental impacts occur (in terms of GWP and PED) and what target values would be desirable. The approach reveals trade-offs, allows to see decisions in context and thus supports addressing the inevitably arising trade-offs explicitly and consistently. The fact that the approach can be used for target setting of any type (relative and absolute targets) underlines the applicability of the approach. The approach provides for the practitioner three targets expressed as single scores: An energy target (a PED value), a CO_{2eq} target (a GWP value) and a cost target (a EUR value). The choice of using only GWP and Primary Energy Demand (PED) as key units to set environmental targets was addressed in Section 4 and reflects the insight that those are key impact categories in highly automatized manufacturing. However, on medium term the remaining four impact categories relevant for manufacturing should be included in the algorithm as well, i.e. Acidification Potential (AP), Human Toxicity Potential (HTP), Abiotic Resource Depletion Potential (ADP elements) and Photochemical Ozone Creation Potential (POCP). Yet, analyses for these four or other impact categories are still scarce in manufacturing, thus no indications can be seen of any validity of potential life cycle targets for these categories. In general, the approach is considered applicable in other industries as well, especially in discrete production (i.e. clearly separable items) and impacts thus can be allocated to individual products.

With the term ‘algorithm’, we refer to the combined set of equations elaborated in Section 5. This algorithm is at first sight a complex construct. Some 35 parameters are introduced and combined in order to establish the methodological frame for life cycle target setting within the Sustainability Cone. Irrespective of its complexity, the algorithm does enable making consistent calculations, as it is aligned to existing decision making processes in production planning, and also required data is typically available in companies. The breaking-down of higher-level targets to lower-level targets fulfils all overall requirements defined for it in Section 4. It is based exclusively on already existing parameters in widely used planning tools. It is possible to integrate all equations (cf. Section 5) into existing tools, e.g. spreadsheet applications, and in this way handle data input and result calculations in a very straight-forward manner. To strengthen the applicability of the approach and reduce time requirements, an automated extraction of data can be established as input to calculations. Thus, the main disadvantage may be seen in the circumstance that a potential practitioner (and the surrounding organization) has to get acquainted with the idea of life cycle target setting and its terminology.

A point of methodological critique is the use of uncertainty factors (uf), as they depend on the TRL chosen by the system designer and may, thus, lead to designer-specific results and related conclusions. This means that the uf need to be chosen very carefully and may even be subject to a sensitivity analysis in concrete cases (i.e. a check, whether alternative uf may change substantially any overall decisions). This concern may be addressed via a recommendation for practitioners but it may also be addressed via a particular guideline issued by the company after a learning experience has been established.

Target setting and thus also life cycle target setting, is a very strategic, i.e. highly internal, activity at an OEM. However, target-setting competency would not only have to be built up at the OEM, but for communication and enforcement of concrete targets, also suppliers would have to have appropriate competencies, though to a very lower extent and by using common communication means, e.g. specification sheets. Neither of the above aspects is considered an insurmountable obstacle for implementation, as soon as life cycle targets will become a part of the tendering process.

Comparing the life cycle targets of a robot determined in Section 6 with the results from the EU FP7 project AREUS (Dijkman et al., 2015) and a study published from Audi AG (Drechsel et al., 2015), similar results can be observed. The studies have slightly different system boundaries e.g. unknown total production volume and period (six and seven years), however the payload of the robots is in the same range (200 – 250 kg) and area of use (Germany) as well. However, assuming an annual production of 250,000 car bodies for each study, a GWP between 3.6 and 5.6 g CO_{2eq} for material and production of a robot can be assumed compared to a life cycle target of 4.8 g CO_{2eq}. For the use stage the motion profile of spot welding was chosen as well, but a higher impact can be observed in those studies (24 g CO_{2eq} compared to 26 – 27 g CO_{2eq}), which might be due to a slightly higher utilization rate (>15 spots & 45 sec) in the latter case. As there is no formal recycling system established for robots, a conservative approach was chosen for the end-of-life stage (5% of the total life cycle target) in the context of this paper, whereas Dijkman et al. (2015) used generic recycling data and Drechsel et al. (2015) did not consider any end-of-life treatment.

8. Conclusions and further research

Overall the approach presented here does fulfil its main purpose namely to enable the practitioner to keep focus on target states rather than “small” solutions. In such complex systems, with dependencies between production zones as well as between life cycle stages of the product and several technologies, a holistic system view is essential. As demonstrated in the case studies, the algorithm delivers representative results and proves valid.

The approach supports high-level effective solutions rather than individual, “just” locally efficient solutions by using target states for functional units and allocating those to subordinated levels in a consistent all-the-way-through manner. Thereby also transparency is increased, and trade-offs between life cycle stages can be identified and addressed. Thus sub-optimization is reduced and production system designers know at early planning stages which target they should strive for. Due to the alignment with the well-established decision-making process within the production planning process, reproducibility of results is assured. After identifying company-specific uncertainties (uf), the algorithm ensures meaningful life cycle target setting irrespective of the individual practitioner’s experience. Using only existing data from the early planning phase from PLM programs and other planning sheets, completeness is secured, whereas at other automotive companies some data might be lacking. A current drawback is the workload involved with this approach, as a lot of data still has to be extracted manually. This could be remedied by integration into PLM programs.

Tab. 6 Quality aspects of using Life Cycle Target Setting in highly automated manufacturing (✓= achieved •= to be checked ×= to be improved)

Representativeness	✓
Consistency	✓
Transparency	✓
Reproducibility	•
Completeness	•
Time / Workload	×

The approach presented here does not ensure sustainable solutions, but it enables the conscious integration of target states into the planning process. Meanwhile, any “sustainable target states” must be identified and agreed upon by science, companies, governments, and other relevant stakeholders. While such an agreement process may take time, companies are encouraged to apply the presented approach and implement self-defined targets in their production systems planning. LCA-based knowledge on automatized manufacturing is scarce, and it is thus recommended to expand the knowledge base by conducting a larger number of such production-related LCAs at all different levels of the Sustainability Cone (i.e. for machinery, technologies etc.). Thereby, a better understanding of the increasingly complex production environment can be provided and some potential refinements of the allocation factors can be identified. In this context, on medium term Life Cycle targets for Acidification Potential (AP), Human Toxicity Potential (HTP), Abiotic Resource Depletion Potential (ADP elements) and Photochemical Ozone Creation Potential (POCP) should also be identified. The life cycle target setting thinking should also be applied for different modules in automotive manufacturing (before and after the body shop), as those might have additional fascinating challenges and in order to enable life cycle target setting in a fully holistic view covering entire complex manufacturing systems enabling manufacturing industry to play its future role in a sustainable production and consumption.

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References

Alting, L., Jørgensen, J., 1993. The Life Cycle Concept as a Basis for Sustainable Industrial Production. CIRP Ann. - Manuf. Technol. 42, 163–167.

Audi AG, 2011. Life cycle assessment – the concept. Ingolstadt.

Bähre, D., Swat, M., Trapp, K., Vielhaber, M., 2016. Supporting Manufacturing Technology Definition through Multi-level Resource Consumption Analysis. Procedia CIRP 40, 378–383. doi:10.1016/j.procir.2016.01.071

Bjørn, A., Hauschild, M.Z., 2015. Introducing carrying capacity-based normalisation in LCA: framework and development of references at midpoint level. Int. J. Life Cycle Assess. 20, 1005–1018. doi:10.1007/s11367-015-0899-2

Bjørn, A., Margni, M., Roy, P.-O., Bulle, C., Hauschild, M.Z., 2016. A proposal to measure absolute environmental sustainability in life cycle assessment. Ecol. Indic. 63, 1–13.

Byrd, D., 2001. Principles of forecasting: A handbook for researchers and practitioners. Risk Anal. 21, 1121–1122.

Cooper, R., 2008. Perspective : The Stage-Gate idea to launch process – Update , what ' s new and nexgen systems. J. Prod. Innov. Manag. 25, 213–232. doi:10.1111/j.1540-5885.2008.00296.x

Dijkman, T.J., Rödger, J.-M., Bey, N., 2015. Managing the life cycle of production equipment: What does it matter? 7th Int. Conf. Life Cycle Manag.

Drechsel, M., Bornschlegl, M., Hackbarth, D., 2015. The Value and Necessity of Using Environmental Direct Comparisons as a Simplified Life Cycle Assessment Method in Industrial Planning Processes, in: Electric Drives Production Conference & Exhibition. Nuremberg.

Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Ann. - Manuf. Technol. 61, 587–609. doi:10.1016/j.cirp.2012.05.002

ecoinvent, 2014. ecoinvent Version 3.2.

Ellen MacArthur Foundation, 2016. The New Plastics Economy: Rethinking the future of plastics, Ellen MacArthur Foundation.

EPLCA, 2015. European reference Life Cycle Database 3.2.

European Commission, 2014. Technology readiness levels (TRL) - Horizon 2020 Annex.

European Commission, 2012. EU Emission Trading Scheme Handbook. Brussels. doi:10.2834/55480

Garetti, M., Taisch, M., 2012. Sustainable manufacturing: trends and research challenges. Prod. Plan. Control 23, 83–104. doi:10.1080/09537287.2011.591619

Guinee, J.B., 2002. Handbook on life cycle assessment operational guide to the ISO standards. Int. J. Life Cycle Assess. 7, 311. doi:10.1007/BF02978897

Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., Skerlos, S.J., Dornfeld, D. a., Jawahir, I.S., Clarens, A.F., Rickli, J.L., 2013. A Review of Engineering Research in Sustainable Manufacturing. J. Manuf. Sci. Eng. 135, 41013. doi:10.1115/1.4024040

Hauschild, M.Z., 2015. Better – But is it Good Enough? On the Need to Consider Both Eco-efficiency and Eco-effectiveness to Gauge Industrial Sustainability. Procedia CIRP 29, 1–7. doi:10.1016/j.procir.2015.02.126

Hauschild, M.Z., Herrmann, C., Kara, S., 2017. An Integrated Framework for Life Cycle Engineering 0, 2–9. doi:10.1016/j.procir.2016.11.257

Heil, U., Paulus, I., Schacht, M., 2014. Karosseriebautage Hamburg, in: Tecklenburg, G. (Ed.), Karosseriebautage Hamburg, Proceedings. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 3–13. doi:10.1007/978-3-658-05980-4

Herrmann, C., Thiede, S., Stehr, J., Bergmann, L., 2008. An environmental perspective on Lean Production. Manuf. Syst. Technol. New Front. 83–88. doi:9781848002661

Hunkeler, D.D., Lichtenvort, K., Rebitzer, G., Ciroth, A., 2008. Environmental life cycle costing. CRC Press, Pensacola, Florida.

IFR, 2016. Executive Summary of World Robotics 2016 Service Robots.

IPCC, 2014. Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), . Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–3459.

ISO 14040, 2006. Environmental management - Life Cycle assessment - Principles and framework. Geneva.

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 J. Manuf. Sci. Technol. 2, 144–152. doi:10.1016/j.cirpj.2010.03.006

Kampker, A., Burggräf, P., Welter, T., Kamp, S., Thul, J., 2014. Factory Carbon Footprint Design. Adv. Mater. Res. 907, 455–462. doi:10.4028/www.scientific.net/AMR.907.455

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. CIRP, Leuven, Belgium, pp. 681–686.

Klüger, P. (Kuka R.G., 2011. Energieeffiziente Produktion mit KUKA Robotern am Beispiel des Karosseriebaus [WWW Document]. URL http://www.industrieanzeiger.de/c/document_library/get_file?p_l_id=37998686&folderId=37351564&name=DLFE-25440509.pdf

Krinke, S., 2014. Ressourceneffizienz bei Volkswagen. Berlin.

Laurent, A., Olsen, S.I., Hauschild, M.Z., 2012. Limitations of Carbon Footprint as Indicator of Environmental Sustainability. Environ. Sci. Technol. 4100–4108. doi:10.1007/s13398-014-0173-7.2

Martinez-Blanco, J., Finkbeiner, M., Inaba, A., 2015. Guideance on Organizational Life Cycle Assessment. UNEP/SETAC Life Cycle Initiative.

Mercedes-Benz AG, 2010. Environmental Certificate for the new CLS. Ingolstadt.

Mittelstadt, J., 2010. Development , Release and Open-Sourcing of NACFAM ' s Sustainability Framework, White Paper. Washington D.C.

Montalvo, C., Peck, D., Rietveld, E., 2016. A Longer Lifetime for Products: Benefits for Consumer and Companies. Brussels.

Mousavi, S., Thiede, S., Li, W., Kara, S., Herrmann, C., 2014. An integrated approach for improving energy efficiency of manufacturing process chains. Int. J. Sustain. Eng. 37–41. doi:10.1080/19397038.2014.1001470

Neugebauer, S., Martinez-Blanco, J., Scheumann, R., Finkbeiner, M., 2015. Enhancing the practical implementation of life cycle sustainability assessment – proposal of a Tiered approach. J. Clean. Prod. 102. doi:10.1016/j.jclepro.2015.04.053

OECD, 2011. OECD Sustainable Manufacturing Toolkit. doi:10.1080/136627102200003447

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., 2009. Planetary Boundaries : Exploring the Safe Operating Space for Humanity. Ecol. Soc. 14, 22.

Rödger, J.-M., Bey, N., Alting, L., 2016. The Sustainability Cone – A holistic framework to integrate sustainability thinking into manufacturing. CIRP Ann. - Manuf. Technol. 65, 1–4. doi:10.1016/j.cirp.2016.04.033

Russell-Smith, S. V., Lepech, M.D., 2015. Cradle-to-gate sustainable target value design: Integrating life cycle assessment and construction management for buildings. J. Clean. Prod. 100, 107–115. doi:10.1016/j.jclepro.2015.03.044

Schade, W., Zanker, C., Kühn, A., Hettesheimer, T., Jäger, A., Kinkel, S., Schmall, T., 2014. Sieben Herausforderungen für die deutsche Automobilindustrie: Strategische Antworten im Spannungsfeld von Globalisierung, Produkt- und Dienstleistungsinnovation bis 2030, 1st ed. edition sigma, Berlin.

Science Based Targets, 2015. Mind the Science: Science Based Targets - Driving ambitious corporate climate action, Draft. ed.

Shuaib, M., Seevers, D., Zhang, X., Badurdeen, F., Rouch, K.E., Jawahir, I.S., 2014. Product Sustainability Index (ProdSI). J. Ind. Ecol. 18, 491–507. doi:10.1111/jiec.12179

Silva, N. De, Jawahir, I.S., Dillon, O., Russell, M., 2009. A New Comprehensive Methodology for the Evaluation of Product Sustainability at the Design and Development Stage of Consumer Electronic Products. Russell J. Bertrand Russell Arch. 335–340. doi:10.1504/IJSM.2009.023973

Steffen, W., Richardson, K., Rockstrom, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sorlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science (80-.). 347, 1259855–1259855. doi:10.1126/science.1259855

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice. Int. J. Life Cycle Assess. 16, 389–391. doi:10.1007/s11367-011-0287-5

Thinkstep, 2015. GaBi LCA Databases.

Umeda, Y., Takata, S., Kimura, F., Tomiyama, T., Sutherland, J.W., Kara, S., Herrmann, C., Duflou, J.R., 2012. Toward integrated product and process life cycle planning - An environmental perspective. CIRP Ann. - Manuf. Technol. 61, 681–702. doi:10.1016/j.cirp.2012.05.004

VDI, 2008. Digitale Fabrik Grundlagen Digital factory Fundamentals VDI 4499. System.

Veleva, V., Ellenbecker, M., 2001. Indicators of sustainable production: framework and methodology, Journal of Cleaner Production.

Volkswagen AG, 2014. Der e-Golf, Das Umweltprädikat. Wolfsburg.