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# The Sustainability Cone – A holistic framework to integrate sustainability thinking into manufacturing

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Integrating sustainability into manufacturing is a multifaceted endeavour. Global sustainability aspects and specific manufacturing success factors have to be combined with life cycle thinking in order to get the holistic view on manufacturing which is needed to make truly sustainability-oriented decisions in manufacturing. Industry, at the same time, is always deterred by possible high cost and time constraints related to implementing new approaches. Using examples from car manufacturing, this paper introduces and explains a new Sustainable Manufacturing framework – the Sustainability Cone -, as the missing link which closes these gaps by providing necessary holistic and consistent overview while being aligned with established stage-gate project execution models, thus ensuring practical applicability as shown for a highly automated production cell. The paper shows how to apply life cycle target thinking, as essential part of the Sustainability Cone, derived from customer-demanded functionality down to a production system.

Manufacturing System, Production Planning, Sustainable Manufacturing

## 1. Introduction

Manufacturing is more than production – it comprises the pathway from the idea and design, over raw materials transformation into finished goods that meet customers' expectations [1]. Sustainability can be assessed by using the holistic approach of life cycle thinking (LCT) which follows a similar pathway like manufacturing. Thus, a good basis to align both and achieve *sustainable manufacturing* exists. But why should manufacturing strive for sustainability? The sector contributes significantly to the global carbon dioxide emissions ($CO_2$), and plays a substantial role for the labour market and economy (GDP). And, although ever-more efficient *technology* (T, e.g. [2]) is developed, the foreseeable developments of *population size* (P) and *affluence* (A, the value created or consumed per capita) overcompensate the technology improvements, leading to overall increase in carbon dioxide emissions [3], i.e. increasing *impact on environment*, (I). This relation has been described by Commoner [4] (termed "IPAT Equation") and underlines the necessity for fundamental change in the view on the manufacturing field.

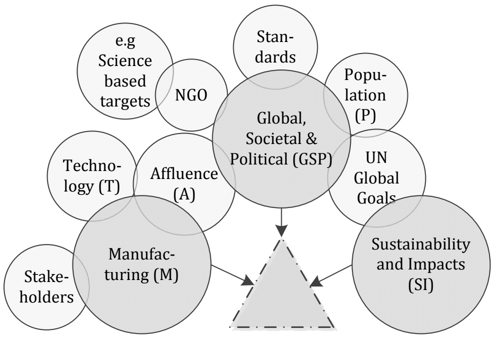


**Figure 1.** Stakeholders of and requirements towards sustainable manufacturing. Shown as triangle is the missing link between Global, Societal and Political requirements (GSP), Manufacturing requirements (M) and Sustainability and Impacts-related requirements (SI)

Hauschild [5] points out, that the three variables cannot be seen independently since increased eco-efficiency of products and technologies not always leads to less environmental impact, and that, rather, eco-effectiveness should be strived for instead. This may be achieved by broadening the term “technology” in the IPAT Equation to “manufacturing” in order to emphasize the lever effect of the sector. In order to achieve this, a transparent, quantitative and – most importantly – industrially applicable method for assessing sustainability impacts must be derived based on a new framework that encompasses external and internal requirements, and addresses the upcoming challenges – all in support of being able to move towards a more sustainable future (see Figure 1).

### 1.1. Global, societal and political motivation

Recognized by external stakeholders, sustainability became an import criterion [6] and manufacturers report today their environmental performance to several non-governmental organizations (NGOs, e.g. [7]). EFFRA [8] states that Sustainability can underpin Europe’s competitiveness, thus factories have to be environmentally friendly and socially sustainable. Standardization organizations like ISO support environmental sustainability work with their ISO 14000 series. The latest version of ISO 14001 on Environmental Management Systems (published in late 2015) includes taking a life cycle perspective on production activities [9]. Many Original Equipment Manufacturers (OEMs, e.g. [10]–[12]), have published Life Cycle Assessments (LCAs) according to ISO 14040 [13] in order to transparently show impacts of their products. In the automotive sector, specific fuel consumption of the manufactured vehicles has been reduced continuously [2]. Meanwhile, companies are exploring new markets and are exposed to new technological trends, and higher numbers of product variants and shorter product life cycles are expected [14] which likely leads to roughly 57 % more sales in 2025 compared to 2010 [15]. Additionally, total light duty vehicle (LDV) travel distance will continue to grow [16], and thus an increase in total fuel consumption is projected [2]. To tackle this, companies are already adapting their powertrain systems, e.g. towards electrified engines powered by renewable energy. This results in so-called burden shifting – from one life cycle stage to another or from one impact category to another [10]. From a production perspective, increased product variety leads to more complex production systems in terms of processes and machinery [14]. Seen over the entire vehicle life cycle, new propulsion systems and production technology complexity will most likely increase the environmental impacts and economic efforts relatively and absolutely. Regarding total transportation by LDV, the foreseeable worldwide sales suggest that all product-related environmental improvements will be eliminated by the so-called “rebound effect” – a higher overall impact due to higher sales figures of improved products. To avoid rebound effects, thresholds for environmental impacts from entire sectors can be defined or even thresholds for concrete product categories, like suggested for Greenhouse gases by “Science based Targets” [17]. Those absolute and concrete targets can be used in planning processes of both product and production. However, any new framework needs to take into account companies' reservations towards implementing new approaches (for high cost and time constraints [18]).

### *1.2. Objectives for a new framework*

In this context, three key objectives can be identified, that a new framework needs to fulfil: (1) Address the full scope of sustainable manufacturing and address all key drivers and obstacles. (2) Reflect the influence of manufacturing on global environmental requirements (ideally following the Planetary Boundaries concept [19]) and interpreted in a way that sustainability is understood as a relation between the three factors *demand for functionality* (i.e. products supplied by manufacturers fulfil customers functional requirements), the *product* and the *production system*, while always taking a life cycle perspective. Thus, the ultimate goal would be to (3) allocate absolute targets (e.g. tons of greenhouse gas emissions of entire transport sector) down to the very last production station in a feasible and operational way. Since common planetary targets do not exist today for manufacturing, a company today is likely to set its own absolute targets and adhere to them. Current definitions of sustainable manufacturing [20], [21] do not reflect those predetermined objectives, and henceforth a new definition is suggested:

"Sustainable Manufacturing satisfies the (societal) demand for functionality while adhering to environmental, economic and social targets over the entire life cycle of products and services."

Using this definition, products and productions can be developed in a way that ideally fulfil either planetary or their own cost, environmental and social targets for a demanded functionality and leads to more sustainable manufacturing.

## 2. Requirements towards an applicable framework

Core factors for combining profitable business and sustainable development are integration of economic, environmental and social requirements, the development of innovative products and services, and the comprehensive usage of available knowledge [22] as well as "planning efficiency", in particular for high-wage countries [23]. Within the acknowledged AREUS project, sustainability assessment and its integration has been discussed and several requirements could be identified. Thus, a sustainability framework needs to be aligned with existing decision-making processes (i.e. stage-gate models) in companies (top-down view), and fit to the existing product development process (PDP) and the production planning process (PPP) in order to ensure applicability in industry. It should consider the workflow with external companies as well as the workflow of internal planners, and it should be transparent in order to support gathering sustainability-related data at all levels of manufacturing (bottom-up view). The framework needs also to incorporate the life cycle approach to address latest developments in standardization [9] and policy [24] by linking any results to a demanded function that manufacturing companies supply via their products or services. Applicability must be given, which calls for a modular framework design where each designer, product manager or other decision-maker can easily "find" himself or herself in the framework. However, any new framework will only have a limited impact on industry unless it is translated into a quantitative and applicable assessment method.

Accurate and correctly specified requirements are extremely important in manufacturing to clearly document expectations and to prevent any failure with potentially far-reaching consequences. Therefore, the assessment method has to incorporate existing company specific critical *success factors* like annual output and cycle time, in order to provide data for well-established key result indicators (in retrospect) and performance indicators (in advance) for all different stages in the PDP and PPP. The framework must also entail *manufacturing-specific* success factors, e.g. shift-system, jobs per hour (jph) or engineering hours per product (ehp) and be linked to social, economic and environmental thresholds. Furthermore, the method should account for prospective trends (e.g. secondary use of manufacturing infrastructure) and reflect global and local requirements, to prove its applicability. It should consider (potential) trends, like increasing modularity of production lines, increasing product variety and software-controlled processes as well as the strive of companies to employ latest production technologies.. The developed method is meant to be used as planning tool in the PDP and PPP to gain highest improvement potentials and guide the *developers* and *planners* through the different alternative options during the project by providing the most relevant data in an understandable way.

For a successful implementation, *applicability* and minimal additional workload can be assured by using existing software and databases. Companies demand for integrated solutions in their individual *IT-Infrastructure* (i.e. PLM software) to provide substantial assistance to validate assumptions and transfer them from digital to the real production [14]. The method is meant to be implemented in a way, that it can be used easily, by providing an intuitive graphical user interface and operate stable. Usability of data for up- and downstream must be guaranteed and the data need to be prepared for reading out in a transparent way for possible audits and documentation. Finally, the whole implementation and use of the method have a positive economic cost-benefit ratio.

## 3. Gaps in currently suggested frameworks

Several publications have dealt with e.g. “sustainable manufacturing”, “sustainable production” and “green manufacturing” over the last decade. A literature review of the authors identified several frameworks and methods which all, to varying extent, aim at enhancing sustainability performance of manufacturing from different perspectives. In general, the existing frameworks are lacking alignment with stage-gate model process used in industry. Compared to the derived requirements from manufacturing in Section 2, several gaps can be identified. All three S*ustainability* pillars are acknowledged, but the majority of frameworks are dealing with the environmental perspective and neglecting the same level of detail for the economic and social dimension. In regards to the *life cycle* perspective, the product level is in focus, but facilities and production system are hardly considered. The proof of *applicability* as one of the primary goals of a sustainable manufacturing framework is often missing. Most of the methods are suggested to be used for *reporting* reasons (bottom-up) and only one method [25] seems suitable for implementation in *planning/design* stage (top-down). The alignment with industrial planning tools (i.e. PLM software) is barely mentioned. Most approaches differentiate between several levels within the manufacturing system – from factory and/or product down to production system and process. However the number of levels in the framework should ideally reflect the actual situation in companies in order to reflect the number of decision-making levels. In a broader perspective, some approaches have tried to link manufacturing with the socio-economic system [26], [27]. However, the link between Planetary Boundaries and the product has not been established yet. To solve this, the functional unit from Life Cycle Assessment could be used as a link in the 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 promote integrating planetary boundaries into the PDP and PPP to avoid rebound effects.

These points are not yet considered at all in sustainable manufacturing frameworks but should be inherent in any holistic approach.

## 4. Sustainability Cone – a holistic framework

To support the idea of making sustainability a profitable business case, the framework “Sustainability Cone” (see Figure 2) has been developed. Following the dictum to change as little as possible with the greatest impact, the framework is aligned with the stage-gate model and includes the PDP and PPP (top-down approach, vertical perspective in the cone). To exemplify application of the framework, a car development process is taken:

A new car is developed based on analyses from the strategy department that determines the market demand (*functionality, e.g. individual urban mobility*) and translates it into general product specifications. These are described in the functional unit (*FU*, *e.g. "Small, electrified urban car for car sharing for roughly 100.000 km over 5 years in Denmark"*). After passing the management board, the designers take over and create a first concept of the *product* up to 4-5 years before the start of production (SOP). Over the next roughly two years the concept is thoroughly examined against *several success* factors, and quality gates must be passed by several departments like technology planning, planning control, product and production planning as well as factory planning. At the end of this period, the suitability for series production will be issued. This whole process is summarized in the Sustainability Cone under the term *Manufacturability,* which entails several success factors for each level in the product development process (e.g. availability, expenditures for further education of employees). Within this process, the decision-makers in the management board have determined financial targets for each department, to be met already in the planning phase. The car itself consists of several *Modules* (e.g. car body, powertrain, chassis, electronics, interior and exterior) which, at the end of the production, will be assembled. They each represent organizational units, which have to fulfil appointed targets. The *Production* development, in-house or at suppliers, depends on the decisions made on module level, and the layout of the production *System* with several *Lines* has to fulfil those. Each line has their specific tasks provided by e.g. different *Technologies* (e.g. welding) or employees. Those technologies can only work properly, if they are scheduled in correct order, if suitable tools are chosen, and if they comply with the success factors. Overall, this can be summarized as *vertical decision-making process* (causality chain), but a certain degree of freedom is still given (e.g. choice of supplier) on the different levels (*horizontal responsibility*), and here a sustainability assessment can support finding the best option on each level.

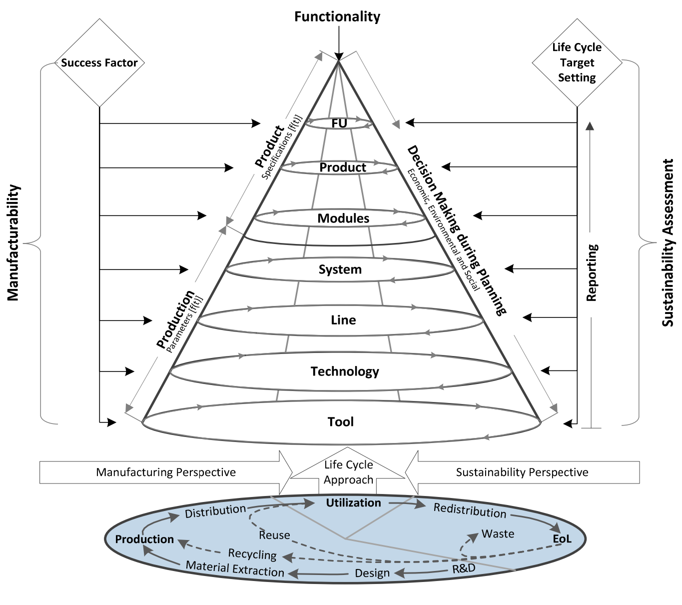


**Figure 2.** Sustainability Cone: Conceptual framework of merging life cycle perspective, product and production to derive life cycle targets (lct) thus optimizing product and production in an early planning phase

To integrate sustainability assessment in PDP and PPP in a consistent way, the new approach of life cycle target setting (LCTS) is introduced. These specific life cycle target (lct) should be expressed by one specific number for each required impact category of the chosen sustainability dimensions (e.g. Greenhouse gases [kg $CO_{2eq}$] for "Environment" and [€] for "Economy") per functional unit on each distinct level. Integrating those additional targets does not compromise the usual decision-making approach, but needs some additional management expertise (i.e. awareness of sustainability and life cycle thinking). These targets cover the whole life cycle – R&D, material extraction, production, use and end-of-life – thus the financial targets need to be extended from investment costs to environmental life cycle costs [28] in order to be comparable and to avoid burden shifting. Social targets are usually set on organizational level and reflect company's policy. The translation and integration in operational levels has been investigated, but so far no satisfactory method has been identified.

Exemplifying this framework in a body-in-white production system for $CO_{2eq}$ and costs would mean to get life cycle targets of roughly "150 €" and "106 kg of $CO_{2eq}$" per car-body (*FU = one car body of small electrified urban car*) from product developers. Subsequently, the production system design has to be aligned and usually consists of three lines (i.e. Z1, Z2 and Z3). Each line will get its specific target based on relative comparison which consists of specific critical success factors, like number of joining equivalents, number of processes, occupied area, number of machinery, vertical range etc. Assuming that Z2 and Z3 just get refurbished (i.e. less new machinery), Z1 (*FU= one underbody for a small electrified urban car*) would receive most of the budget (e.g. 52 kg $CO_{2eq}$ and 73 €). These lcts will be passed on to each subordinated level and therefore sub-optimization can be avoided as they have to fulfil the targets. The lcts are also intended to be used as targets for suppliers, as part of the tender. If suppliers cannot comply with the targets, due to technical constraints, the responsible manager of the OEM would choose the most suitable supplier (horizontal responsibility) and report or negotiate with the superior level the exceedance of the budget (bottom-up). All in all, this is a similar approach as in financial planning with the exception of integrating the life cycle perspective in the financial planning.

This approach has been applied in an existing highly automated production line (see Figure 3). It shows the target setting based on above-mentioned values for carbon dioxide equivalents ($CO_{2eq}$) of a production cell of an underbody part (lct=192 g $CO_{2eq}$/side member of an underbody part) with several joining technologies. Assuming 50 % overhead consumption (lighting, heating and ventilation) the other half can be used by in total four joining technologies including robots. One of those technologies is welding, and the target per process can be determined by using the number of joining equivalents for this specific production step combined with specific energy consumption, occupied area and required cycle time (14 g $CO_{2eq}$/welding task). Based on empirical data, the target for the welding gun can be determined and similarly for the welding robot. Those targets can even be separated into the three life cycle stages of a robot. Comparing those results with an existing LCA of robots [29] indicates consistency of the approach.

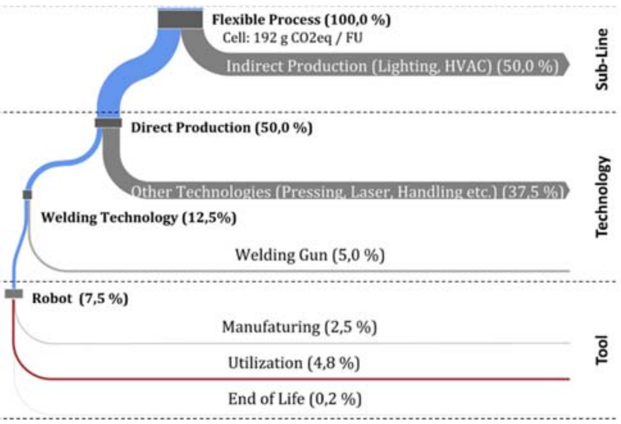


**Figure 3.** Example for target setting in production system planning downwards from production cell to robot, based on a car body-shop case.

To conclude, such targets can be directly used in internal and external research and development departments (R&D) to develop specific solutions while the final product stays within determined targets. Concise impact assessment – aiming at providing most valuable information without compromising the overall result - determines the selection of environmental impact categories. Those encompass main issues, e.g. chemicals- and/or resource-related questions. To ensure comparability and covering a broad range of impacts, midpoint categories with limited correlation according to Laurent et al. [30] are suggested to be used, i.e. Global Warming Potential (GWP), Acidification Potential (AP), Human Toxicity Potential (HTP), Abiotic Resource Depletion Potential (ADP) and Photochemical Ozone Creation Potential (POCP). While already covering some environmental and economic factors, the Sustainability Cone may provide social targets in the future. The translation of social policy on organizational level to the operation level might be possible by determining impact pathways. So far it is suggested to use the impact categories advised by Neugebauer et al. [31] as a beginning.

**5. Conclusions, Discussion and Outlook**

The suggested Sustainability Cone framework allows sustainability-oriented decision-making in manufacturing on several organisational levels in a consistent manner. Consistency is established in the framework between the decision-making levels inside and outside the company as well as between a superior level and subordinate level in the production chain, broken down from an overall demanded functionality.

The assessment method related to the framework is designed to be operational in industry and thus only employs existing success factors, performance indicators and data, and it is aligned with stage-gate project models typically applied in industrial manufacturing. The assessment method is also designed to use the Planetary Boundaries concept, and operationalises this in suggesting the use of absolute “life cycle targets (lct)” for environmental and economic performance of production systems. While the Planetary Boundaries concept requires methodological development (e.g. [5],[17]), the suggested lct can also be set based on any chosen maximum boundaries, since the lct exhibit their strength especially in the downwards-consistency when applied on a multi-levelled chain of decisions, as is typical in production planning. Thus, within a manufacturing company, the Sustainability Cone can be used to avoid sub-optimizations by using absolute targets for the functional unit set by the company. The framework and assessment method will be further tested in several case studies and be published at a later time.

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