

Chapter 4

Sustainability Assessment in Manufacturing and Target Setting in Highly Automated Production



Jan-Markus Rödger and Niki Bey

Abstract The interest in sustainability in manufacturing is growing. The European Commission elaborated in collaboration with the European Factories of the Future Research Association (EFFRA) a road map until 2030. The revised ISO 14001 standard, released end of 2015, emphasizes the integration of a life cycle perspective in production. External stakeholders like the Carbon Disclosure Project are striving for very detailed sustainability-related information. Therefore, this chapter will describe the latest approaches of how to assess sustainability in manufacturing, how production planning works in automated production and how sustainability thinking might be integrated in a feasible way. Additionally, a new framework is described which is able to link and allocate the product-related life cycle emissions in a consistent way from the large context down to the individual machine tool level in manufacturing. In essence, this chapter points out that efforts in manufacturing improvements need to be done with a view on entire systems rather than with a view only on single “island solutions”—and it shows a way how to do this.

4.1 Introduction

In Europe, the share of manufacturing of the gross domestic product (GDP) was 15% (equals 17.7 trillion USD) in 2011, employing 30 million people (about 16% of the working population) according to the ISIC Rev. 4 statistics of the OECD and World Bank (2011a, b). Irrespective of this relatively small share of societal activity, the environmental impact of manufacturing activities needs to decrease substantially in the future, for two reasons:

Firstly, when applying generic sustainability equations such as $I = P * A * T$ (Graedel and Allenby 1995), which related overall “Impact” (I) to the product of

J.-M. Rödger (✉) · N. Bey

Division of Quantitative Sustainability Assessment, Department of Management Engineering, Technical University of Denmark (DTU), Produktionstorvet, Building 424, 2800 Kongens Lyngby, Denmark
e-mail: januw@dtu.dk

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“Population growth” (P), “Affluence” (A), i.e. “Standard of living”, and “Technology” (T), the two factors P and A will increase steadily in value. This leaves the factor “Technology” (T)—and hereunder “manufacturing” in general including “highly automated production” in particular—as the only “lever” left to generate the required substantial reductions in overall Impact (I). This reduction of overall impact needs to be done in a balanced approach considering environmental protection, economic growth and social well-being—also referred as “the three pillars of sustainability”—in order to be in accordance with the generally accepted definition of sustainable development coined in 1987 by the so-called Brundtland Commission. Secondly, when extrapolating current developments in deployment of renewable energy sources and resulting reductions in product-use-stage impacts, it can be expected that impacts of manufacturing will become the dominating ones in the life cycles of any electricity-intensive product type. For example, in 2010 the manufacturing sector contributed with around 19% to the worldwide carbon dioxide (CO₂) emissions (World Bank 2011a, b). Between 2005 and 2010, these CO₂ emissions increased on average by 2.8% per year. In the same period, the population size increased by 1.2%, and the GDP per capita (i.e. the factor “Affluence”) increased by 5.6% (inflation-adjusted) annually.

In recognizing the described special influence that manufacturing can have on the reduction of overall impact and thus on improving sustainability performance, this chapter argues for the key understanding that efforts in manufacturing improvements need to be done with a view on entire systems rather than with a view only on single “island issues”. Failing to look at entire systems may provoke sub-optimizations or—in the worst case—even lead to directly unintended outcomes, such as problem shifting, e.g. from one impact category to another one (e.g. less CO₂ but more chemicals) or from one life cycle stage to another one (lower impacts during use but higher impacts in end-of-life). Possible improvements, only visible from the suggested “helicopter perspective” that covers the entire system, may otherwise not be identified and utilized—and the actual problem may not only remain unsolved but may unintentionally even be made worse.

In addition, assessing highly automated production systems within such a holistic context also yields potential for reaching win-win situations. Assessment results can be communicated as response to increasing company-external pressures, such as market and legislative requirements, and at the same time may release earlier not identified improvement potentials, which is a characteristic company-internal interest.

In addressing the challenge of making such holistic assessments, this chapter first gives a brief overview of main approaches suggested of sustainability performance assessment, then discusses sustainability aspects particular to automated production and further describes the way in which sustainability issues currently are included in typical decision-making processes for automated car production. Based on this, a key section introduces a new framework for sustainability assessment of highly automated productions, and the chapter closes with a number of conclusions and suggestions for further work.

4.2 Approaches Towards Holistic Sustainability Assessment

In the context of this chapter, the term “sustainability assessment” covers any systematic way of analysing and assessing human-activity-caused potential adverse effects on the environmental, social and economic sustainability of a system. Such a system would typically be a product system, covering all life cycle stages of that product (thus also any manufacturing activities) including all ingoing and outgoing flows crossing the system’s delimitations.

The theoretical foundations for sustainability assessment were laid in the 1960s by, for the first time, establishing cause–effect chains, i.e. relationships between emissions to the environment (causes) and effects in the environment. Focus was on single environmental causes, such as certain chemical pesticides and their harmful (side) effects in the environment—a prominent example being the insecticide DDT and the identification of its potential for human-health-impairing effects described by Rachel Carson in her book “Silent Spring” (Carson 1962). Already this example demonstrated the inherent issue that sustainability assessments typically have to cope with trade-offs consisting in the fact that the desired effects of the particular human activity may have unwanted side effects. In the DDT case, the intended protection of farming crops from destruction by insects had the unintended side effect of human-health impairments of people being exposed to the insecticide. Since such trade-offs are characteristic for sustainability assessments, they need to be identified and addressed by any practitioner.

Building on this, multi-issue approaches emerged such as Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA) and Life Cycle Assessment (LCA) (Hauschild 2005). LCA is ISO-standardized (in ISO 14040/44) and is the dedicated approach to assessing diffuse, i.e. not location-specific, sources through introducing the product life cycle perspective. Instead of “just” covering single sources (e.g. effluents from a production site), the life cycle perspective allows assessing diffuse multiple sources—this is enabled by looking at and in the assessment always relating to the “cause” of emissions, which is the product (or service) and the activities (processes) taking place over the product life. Taking such a life cycle view is referred to as “Life Cycle Thinking”, and the life cycle approach is the backbone in relevant legislation and standardization.

The “life cycle” of a product covers all stages during the products’ useful life; starting with extraction of raw materials (e.g. iron ore) and production of materials (e.g. steel), over manufacturing of the product (e.g. a car manufactured in a factory), use and maintenance of the product (e.g. driving a car) to end-of-life (e.g. landfilling, incinerating or recycling of the car). An advantage of using a life cycle approach is that shifting problems from one part of the life cycle to another part will not go unnoticed. Burden-shifting can thus be avoided, including potential unintended shifts from one impact type, e.g. energy-related emissions, to another type (e.g. toxic substances) since the view is always on the entire product life cycle system. In order to make comparisons of different products possible, incl. their individual entire life cycle systems, any LCA requires the definition of a so-called Functional Unit, a

description of the functionality that the product (or service) fulfils. Any comparison has to be done on the same Functional Unit, i.e. the functionality fulfilled by the compared product life cycle systems has to be the same.

Among the life cycle-based approaches, the methodology developed furthest is Life Cycle Assessment, LCA, allowing assessment of the environmental sustainability of a product system within defined system boundaries. Applying the same system boundaries, Life cycle costing (LCC, e.g. UNEP/SETAC 2011) can be used to map all costs and revenues in the life cycle of a product. Social or Societal LCA (SLCA, e.g. Jørgensen et al. 2010) covers the third pillar of sustainability. The latter method is still very young and under development, but it aims to cover the positive and negative social and socio-economic aspects along the life cycle of a product (Du et al. 2015).

While most approaches towards sustainability assessment in fact focus highly or even exclusively on assessing the environmental dimension of sustainability, developments are ongoing towards *holistic* assessments, i.e. towards life cycle system-wide assessments that consider all three sustainability pillars. An example is “Life Cycle Sustainability Assessment” (LCSA, e.g. Finkbeiner et al. 2010) which combines the methods LCA, LCC and SLCA.

The above methodological approaches inevitably produce complex, multidimensional results. An effort to operationalize result presentation was made by Traverso et al. (2012): in their so-called sustainability dashboard, ten indicators in each of the pillars of sustainability were selected. The indicators chosen by the developers of the sustainability dashboard are shown in Table 4.1. In order to arrive at an overall, single-figure sustainability score, a method to weigh each indicator, was suggested.

In another principle effort of improving the communication of such multidimensional results and support decision-making regarding individual key issues, simplified “footprinting” approaches are established. Most of them keep the product life cycle perspective, while focusing on single impact categories (e.g. global warming). Examples are Carbon Footprint (BSI 2011), Product Environmental Footprint (EU JRC 2014) and Water Footprints (Hoekstra 2010).

A prominent emerging type of sustainability assessment frameworks particularly recognizes the finite boundaries of Planet Earth (Planetary Boundaries, Absolute Sustainability). As opposed to assessing product systems and measuring relative improvements (under a regime of eco-efficiency), these emerging frameworks suggest assessing product systems (and services/activities) against absolute boundaries, thus particularly including “rebound effects” and other important effects, which otherwise are not considered. A “rebound effect” is the overall adverse effect occurring, when a product generation is improved relative to a previous product generation (e.g. by 10% in a given impact category) and when the producer then sells for instance twice as many units of this improved generation—meaning that the overall impact caused by the new product generation still increases. Examples for this type of approach are “Ecological Footprint” (Borucke et al. 2013), “Blue Water Footprint” (Hoekstra and Mekonnen 2012), “Planetary Boundaries” (Rockström et al. 2009; Steffen et al. 2015) and “Absolute Sustainability” (Bjørn and Hauschild 2013).

Table 4.1 Indicators used in the “Sustainability Dashboard” (Traverso et al. 2012)

Sustainability pillar	Background method	Indicators
Environment	Life Cycle Assessment, LCA	Embodied energy, global warming, human toxicity, photochemical oxidation, acidification, eutrophication, abiotic depletion, ozone layer depletion, terrestrial ecotoxicity
Economy	Life cycle costing, LCC	Extraction costs, manufacturing costs, finishing costs, waste disposal costs, electricity costs, equipment costs, revenues, fuel costs, raw material costs
Society	Social LCA, SLCA	Salary per employee, percentage of female workers, percentage of females at the administration level, percentage of employees with limited contracts, percentage of workers with yearly check up, number of accidents, percentage of child labour, number of discrimination cases, social benefits per employee

Related to manufacturing, there are numerous additional approaches, indicator sets and principles available to support companies in assessing their sustainability performance (Amrina and Yusof 2011; Schrettle et al. 2014; Warhurst 2002). Dufflou et al. (2012) described a structured approach for energy-related aspects where different system levels were distinguished: from a unit process over a multi-machine, a factory, a multi-facility to supply chain level. For instance, Garetti and Taisch (2012) have considered education and technology as additional factors in sustainable manufacturing.

The European Commission elaborated in collaboration with the European Factories of the Future Research Association (EFFRA) a road map in 2013 of factories in 2030, addressing several key aspects like lower resource consumption and sustainability in production processes to improve the competitiveness (EFFRA 2013). According to Thiede (2012), sustainable manufacturing might lead to some drawbacks for the manufacturability. Baldwin et al. (2005) and Bey et al. (2013) address that not the lack of strategies, models and tools are the main barriers, but how to implement them and more importantly how to introduce them into existing practices. To solve these concerns, an understanding of relevant aspects in production is needed and will be described in the following paragraphs.

4.3 Sustainability Aspects of Automated Production

The integration of economic, environmental and social requirements, the development of innovative products and services, and the comprehensive usage of available knowledge are core factors for business success and sustainable development (Herrmann 2010). The car industry, as one of the most automated sectors in particular (IFR 2013), which acts mostly on the international market, always struggles to predict the actual market demand (the so-called functionality) and is affected by several international and national regulations. This implies new chances but also new risks, uncertainties and dynamic changes. Each market has its own requirements towards the life cycle of a product, which can be expressed in quantitative way using the concept of a “Functional Unit” (FU) of a product, which is part of LCA methodology (see Sect. 4.2 of this chapter).

Today, total turnover and revenue are the key indicators for the companies and their stakeholders. But the market already asks for more sustainable products, which is reflected by, e.g., new CO₂ emission regulations (e.g. EU 2014). Although it is not statutory, companies assessing their products over the entire life cycle by using Life Cycle Assessment standards like ISO 14040/44 (2006). In those LCAs, a car is analysed over its entire life cycle in detail to assess different potential environmental impacts (e.g. global warming, eutrophication) during the manufacturing, use and end-of-life (EoL) stage.

The main car manufacturers publish simplified LCAs of their latest products to inform the customers or use it for internal purposes. Based on 21 publicly available analyses, it can be stated that around 17% of the carbon dioxide emissions are due to manufacturing, the use-stage accounts for 82% and the EoL stage only 1% to the overall life cycle (see Fig. 4.1). If all other greenhouse gases (e.g. methane) would have been reported consistently in the LCAs, the share of manufacturing would even increase slightly.

Improvements were achieved in lowering the specific fuel consumption of road vehicles over the last two decades (OECD/IEA 2012). This trend will be most likely amplified by additional research and development efforts for new technology like

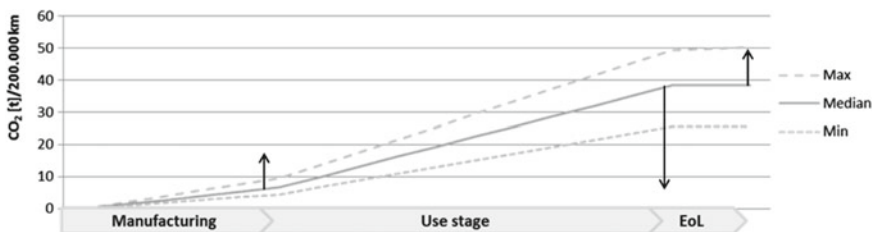


Fig. 4.1 Comparison of cumulative carbon dioxide emissions (CO₂) during manufacturing, use and end-of-life based on 21 different LCAs published by car manufacturers and normalized to 200.000 km travel distance and prospective development of the stages (black arrows)

electrified or hydrogen cars, with a prospective share of around 10% in 2020 (Schlick and Bernhart 2013). But these improvements in the use-stage will lead to additional environmental burden and financial efforts in the manufacturing stage of a car (Rödger et al. 2016). The production and provision of high-end batteries for electric cars cause environmental impacts and in the use-stage due to the additional weight as well (Helmers and Marx 2012; Frischknecht and Flury 2011). In terms of relative sustainability (each car seen in isolation) the sector is on a good way, but as soon as absolute sustainability (total impact of the car sector) is considered, a contradictory picture can be drawn. Increased global car sales diminish the specific savings per car due to larger population and higher prosperity around the world—the so-called rebound effect (as mentioned in Sect. 4.2). It can be concluded that a more sustainable car sector can only be achieved if the manufacturing and the EoL stage of the single car experience a similar interest of effectiveness compared to the use-stage of the product (Rödger et al. 2016).

To meet the increasing market demand for cars, automation technologies experienced a tremendous increase of interest (IFR 2013). Automated production is usually applied where it provides a possibility of capacity increase, improved productivity, reduction of manpower, reduction of repetitive and hazardous work tasks and higher product quality (Bellgran and Säfsten 2010). The car body production, as a good example due to its high degree of automation (>95%), consists usually of three separated production lines, which are producing the underbody, the body frame and the doors, fenders, etc. These lines are designed with the focus on two main indicators—the annual output and the required cycle time. In a typical body shop, around 300–500 parts are assembled by about 1.200 robots before sent to the paint shop (Galitsky and Worrell 2008). The degree of automation increased over the last years and the vehicles-produced-per-robot-ratio is declining, e.g. in Germany since 2007 from around 72 down to 62 in 2014 (Rödger et al. 2016). This trend is set to continue in the main robot markets (Japan, Rep. Korea, China, North America, Germany and Brazil), and an increase of industrial robots in operation of up to 23% until 2016 is expected (IFR 2013).

To illustrate the impact of automation, the direct energy consumption of robotic body shops compared to the entire production is shown in Fig. 4.2. Only 6% of the overall consumption is directly due to the body shop with all its different components. Of this, robots consume around 30%, the joining technologies 20% and the infrastructure (like ventilation, lighting and cooling) the remaining 50%.

The average CO₂ equivalent emissions over the life cycle of an industrial robot (with a payload up to 250 kg) used in Germany in a typical body-in-white line can be assumed with around 24–42 tons over up to seven years of operation (Drechsel et al. 2015; Dijkman et al. 2015). Klüger (2013) states that a typical body-shop robot consumes around 4.500 kWh of electricity per year. Based on the analysis from (Dijkman et al. 2015), it means that roughly 65% of the overall emissions are caused during the use-stage and additional 35% must be considered due to the production and end-of-life. It has to be mentioned that the direct energy consumption of the robot is highly dependent on the application and should be analysed case specific.

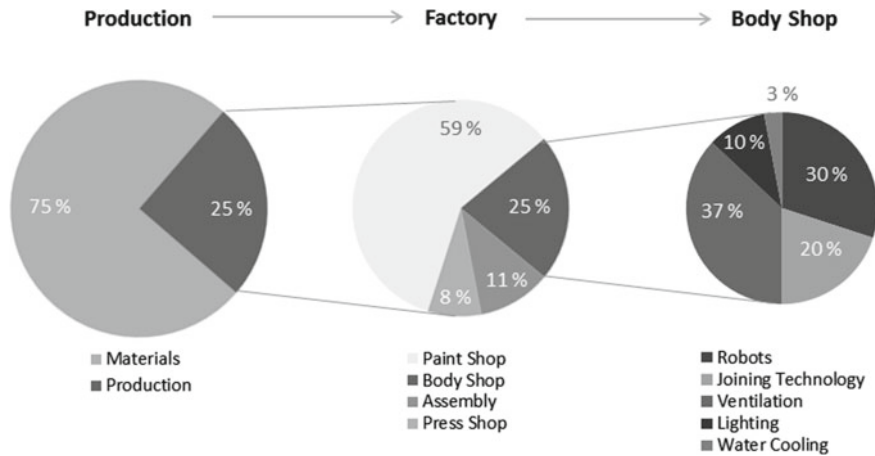


Fig. 4.2 Estimation of the share of energy consumers in a European car production from top down according to Heil et al. (2014) and Klüger (2013)

Another aspect is the additional initial investments for automation. A price of 20.000–35.000 € can be assumed for an industrial robot, although considerable discounts are often available, e.g. depending on the number of robots ordered. Considering an industry price for electricity of 0.08–0.12 Euro-cent per kWh (BDEW 2013) and an operating life of 6 years for a robot, total direct costs of around 27.000–38.000 € can be expected for the robot user. Considering the rise in robot units used per production facility expected in the future, increasing investment costs and increasing electricity expenses for the companies can be expected. Due to this fact, new methods for investment decisions are already applied in industry which consider the life cycle—total cost of ownership (TCO) or life cycle costing (LCC) (UNEP/SETAC 2011).

Social aspects are the last but not least pillar in sustainability. In automated production, social impacts are a challenging topic. The latest developments indicate that Social LCA (explained in Sect. 4.2) is used as a tool for corporate social responsibility (CSR) to screen an organization's supply chain for social hotspots or to support socially sustainable procurement (Norris and Revéret 2014). The planning of an automotive production line typically includes a number of stakeholders such as the original equipment manufacturer (OEM, car producer), the system integrator plus suppliers of application, software and equipment. Defining generically applicable social indicators for all stakeholders is challenging, since contexts are different for each stakeholder. The UNEP/SETAC methodological sheets do offer a great choice of indicators, but many of those are not suitable for the direct production as they capture impacts late in the impact pathway and do not offer enough detail to establish whether or not the current production is socially sustainable (Norris et al. 2013). To determine which type and composition of indicators may bring the most useful contribution to the planning of a socially sustainable industrial production, a characterization step

has to be discussed as an option. Especially, the quantification of potential impacts due to physical and physiological exposures on social and psychological mid- and endpoints is not solved yet.

4.4 Sustainability-Related Decision-Making in Highly Automated Car Manufacturing

The planning process of the production is closely linked to the product. Everything starts with a company's strategy and the product concept around six years before the serial production of a car can start. Along this process, several quality gates must be passed. After around 2.5 years, the quality gate "design freeze" has been reached, where design and concept of the car are finished. Based on the product data and design, the layout of the production line and specific machine tools will be developed. From that point until the start of production (SOP), there are several decisions to be made which may have impact on the sustainability performance. But the question is how and where these decisions should be implemented in the most feasible way without compromising the established production planning process.

In general, the planning process is a top-down approach and therefore targets should be considered as early as possible to exert the greatest influence with limited financial effort (Bellgran and Säfsten 2010). The production line of a car must be capable of several derivatives (i.e. versions of a car model), heterogeneous processes and meet the expected sales figures (VDI 2008). To achieve these needs, the planning is done with Digital Factory Planning software (e.g. from Dassault Systèmes or Siemens). The planning process is usually divided into three phases which are explained below, including a description of impacts which each phase has on the three dimensions of sustainability:

1. Original Equipment Manufacturer (OEM) supplies a complete resource list, and system integrator (SI) elaborates a functioning model of the production line including investment costs
Impacts:
 - a. Economic: High, due to the predefined resource list and the layout of the production line.
 - b. Environmental: A number of machinery and tools are defined that leads to—in terms of the life cycle perspective—a fixed amount of contributions to impacts already from the beginning. Although the use-stage is still dominating (as long as the carbon dioxide intensity of electricity is high), indirect effects like occupied area and occupied volume have been already decided upon as well and these are associated with additional contributions to impacts.
 - c. Social: Only small number of decisions, e.g. how many workers should be considered in the different line.

2. Subsequent product changes (like joining sequences) are integrated by the SI and the model is adapted. The SI assures a full functional line in terms of annual output and cycle time.

Impacts:

- a. Economic: Although a lot of important decisions regarding the manufacturability (e.g. detailed cycle times of each cell) or rather regarding the actual use of the line are made here, only small changes compared to the fixed initial costs from step one can be estimated. The expenses for direct energy consumption in automated manufacturing are very low, compared to the investment costs.
 - b. Environmental: The environmental impacts are fairly high, because the use-stage of the line will be defined. However, the direct energy consumption of automation systems is roughly 50% of the overall consumption in a production line; therefore, the impact is limited as well.
 - c. Social: Some impacts regarding noise and emissions have to be dealt with, due to the technology choice and design (e.g. gluing and welding have completely different emissions and noise levels).
3. New planning of the line with individual ideas. The provided machine operating times and non-productive times from the OEM Standard must be complied with. A new resource list, layout and cycle time diagram must be prepared incl. adjusted investment costs.

Impact:

- a. Economic: High, because the system integrator can supply a completely new solution.
- b. Environmental: Fairly high, the system integrator can design the line in the most sustainable way regarding direct energy consumption. The machine tools and so forth, still carrying a lot of impact, and the indirect consumption like lighting and some parts of the ventilation depend on the infrastructure of the factory.
- c. Social: Fairly high, because emission levels and working environment can be enhanced.

It can be concluded that the existing planning process is capable of three sustainability assessments with small additional time effort under the condition that all relevant information can be provided by the planning software. Additional benefit would be that the planners could compare their ideas in all stages, implementing improvements at the same time and use these results to create competitive edge. Especially, the first planning phase where the main decisions are taken could benefit from implementing sustainability performance data like life cycle inventory data from EcoInvent® or thinkstep® (formerly known as PE-International).

The above-mentioned decisions are only viable along the production line planning. Other sustainability-related impacts are made additionally during the realization and ramp-up phase. Especially, the social dimension is very important along the realization phase, because the facilities are tested regarding compliance of certain thresholds

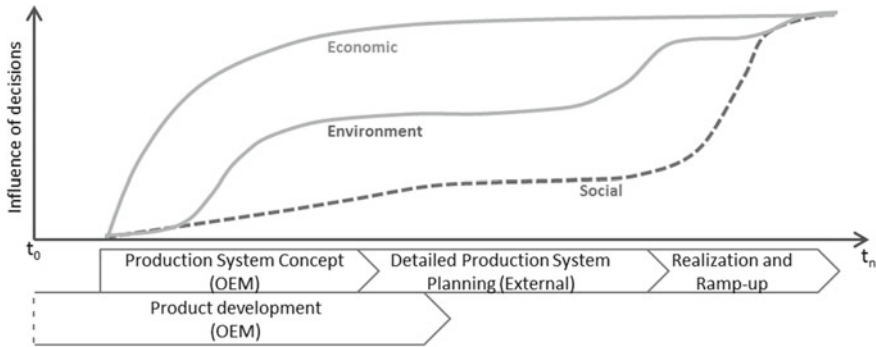


Fig. 4.3 Illustration of principle influence on sustainability aspects (economic, environment and social) exerted by the planners during the planning process of a production line for greenfield projects (Rödger et al. 2016)

like dust, noise and fumes. Figure 4.3 illustrates and summarizes the influence of the decisions on the three sustainability dimensions along the whole production planning process in a qualitative way.

The economic aspects are dealt with very early in the planning process compared to the environmental aspects. Also the basic layout, the joining sequence and therefore the number of robots have been designed early, which is represented by the increase of impacts at the end of the production system concept phase. Along the detailed planning, the direct energy consumption can be adjusted or even new concepts can be presented (illustrated by the second step increase at the end of the second phase). The possibility to influence social aspects increases along the planning process, and during the realization and ramp-up phase all measurements are implemented and adjustments are made, illustrated by the steep increase.

It can be concluded that the first phase of the planning process is most important, and within the first six months it seems possible to enhance the sustainability profile of the production significantly. To support this, a method is needed, but no methodological framework exists so far which links the product emissions to the production. Therefore, a new approach (Rödger et al. 2016) describes how to combine absolute targets for the product and the allocation to the various production levels. These sub-targets should be used and met by the production line developers.

4.5 Framework for Sustainability Assessment of Highly Automated Production

Automated manufacturing is part of a complex system with many layers that ultimately contributes to fulfilling a demand from the market for a given functionality. This demand is satisfied by new products and therefore new production lines have to

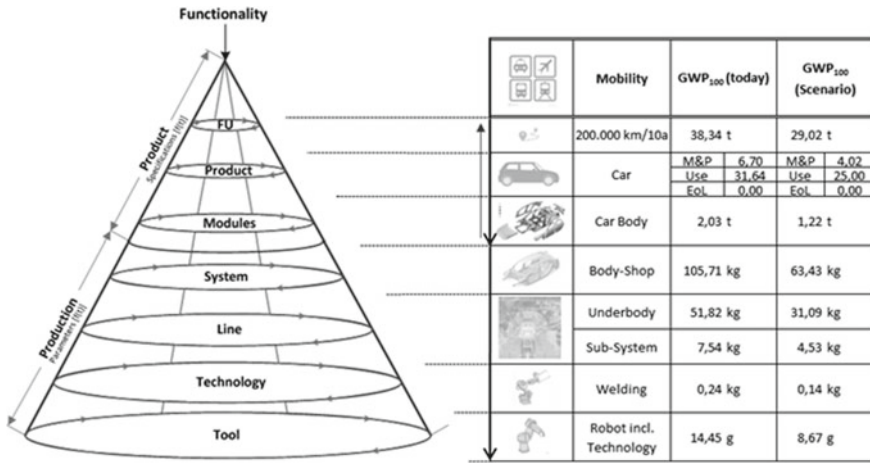


Fig. 4.4 Sustainability cone—framework of absolute goals for the functionality and allocation of specific targets to different levels in manufacturing (Rödger et al. 2016)

be developed. To meet this demand in a sustainable way, the life cycle impact of the product must be considered, specifications have to be passed, top down, from market demand (functionality) down to the resulting product, the components, the production system of these components, down to among others the automation solutions used. This is illustrated in the cone-shaped model in Fig. 4.4 and leads to a framework which combines absolute life cycle targets of products with the ones in production and is able to define sub-targets for the whole production chain and therefore avoid sub-optimization or problem shifting (Rödger et al. 2016).

Starting with the assumption that each of the levels will have its own life cycle and thus individual environmental and financial targets. To get comparable results, the system boundaries of the life cycle were adjusted slightly by including the research and development (R&D) as well as the design stage. This means in particular that, e.g., the price of a car includes the costs for R&D but most environmental assessments do not.

To understand the brief description above, a detailed real example of a car is given below. The customer asks for a new car that is able to provide a reach of 200.000 km over 10 years (the so-called Functional Unit in Life Cycle Assessment). The strategy department besides others sets absolute environmental and financial targets for this product and those are translated by the designers into base specifications of a car, e.g. middle-class version and fuel consumption. These assumptions predetermine more or less the shares of the manufacturing stage, use-stage and EoL stage in regard to the strategy goals and have to be at least fulfilled or even exceeded.

In the early stage of product development, specifications are set to fulfil the Functional Unit (FU) that actually influences the manufacturing system. Components of the product are developed, and further detailed specifications will evolve for the components and for how they will be manufactured in the production system (e.g.

layout of the body-shop line). According to, e.g., Heil et al. (2014), the material composition of the car body, the design, number of derivatives or even the location affect the layout of the system, the technology and the tools to choose. All this leads to specifications for the manufacturing technology, such as welding or cutting, and those need different machine tools (e.g. robots).

To explain the approach itself, the global warming potential over 100 years will be used as an exemplary impact category, but several other categories can be implemented in this approach to avoid sub-optimization between them, based on a middle-class car which emits 38.3 t CO₂ over the entire life cycle (see third column in Fig. 4.4) and reflects the median of the available simplified LCA results (as-is situation, see Sect. 4.3). If a successor has to be developed, the designer and developers have to consider and comply with various prospective circumstances. Assuming that the car manufacturing does not want to increase their total greenhouse gas emissions and comply with new directives (to avoid fines), the manufacturing emissions have to be reduced by 40% because of the increased number of sales until 2025 (in order to mitigate rebound effects) and fuel consumption by 21% to comply, e.g., the EU-directive 333/2014. This leads to about 8.3 t of CO₂ less along the life cycle compared to the predecessor, whereas manufacturing has to contribute with about 2.7 tons (1.7 t in material and 1 t in production). Assuming the same share between material and production intensity on the product level and similar energy intensity of the production steps (25% for body-in-white), the new car body is allowed to emit 1.2 t in total including material, infrastructure and indirect energy consumption. The body-in-white production line consists of three different lines, and it is assumed to consume around 40% in the as-is situation as well as in the scenario (63.4 kg). Including direct energy consumption for technologies and machine tools as well as infrastructure, indirect energy consumption for ventilation, heating and media supply, the production line is consequently allowed to a specific amount per underbody. The production system usually consists of three lines (e.g. Z1, Z2 and Z3), thus each line can get its specific target based on the superior level. Based on several widely used critical success factors, like number of joining equivalents, number of processes, occupied area, number of machinery, vertical range and empirical values, the targets can be determined and will be allocated. Assuming that Z2 and Z3 just get refurbished, Z1 (FU = one underbody) would receive most of the budget (e.g. 31.1 kg CO₂-eq). Those targets will be passed on to each subordinated level and therefore sub-optimization can be avoided. They can be used as targets for suppliers, e.g. as part of the tender. This approach can be applied in even more subordinated levels, and the carbon dioxide emission allowances for each robot in a specific cell can be determined (see Rödger et al. 2016).

To summarize, the above-mentioned amounts of carbon emissions always reflect the total amount of the life cycle of each level including the levels below. These specifications are determined always by the superior level and the levels beneath have to report their life cycle emissions to show if they have fulfilled or even exceed the targets. It can be concluded that by this approach the functionality and therefore the life cycle emission of the product can be allocated to the sub-levels to fulfil strategic targets of the product. To achieve this in a feasible way, these targets should

be included in the already existing and well-established process of specifications for the internal departments, which are involved in the production line planning process. Additionally, the planning software must be enhanced with life cycle inventory data to enable the planners and designers to develop the line in the most sustainable way.

4.6 Conclusions

The prosperity and the population are increasing steadily in the main Asian and African countries, and therefore, more products are demanded and have to be produced. To limit the environmental impact, or at least to keep it at the same level, the only lever to generate the required substantial reduction is the factor technology, which directly relates to products and manufacturing.

There are several approaches available in the scientific world to assess sustainability in manufacturing, but two crucial elements to reach holistic solutions are often not covered—firstly, considering the life cycle of the product in strategic planning and secondly, deriving product-related sub-targets for the production system which contributes significantly to the environmental and financial targets.

Automated manufacturing will play a major role in maintaining or increasing competitiveness of the companies globally. This implies that the sales of industrial robots will increase due to demand of capacity increase, improved productivity, reduction of manpower, reduction of repetitive and hazardous work tasks and higher product quality. However, this trend will also lead to some drawbacks like higher initial costs and environmental impacts in manufacturing.

As a response, the decision-making has to be improved by using already existing tools and software solutions and integrating specific targets for all levels in complex production systems. In order to achieve this, digital factory planning software should be enhanced with LCA and cost data to support, in particular, the crucial first phase of production line planning. In this way, the sustainability performance of the production line can be tracked and improved already from the early planning stages.

As a mean to set targets on each level of the product development process, the sustainability cone is introduced as a new framework. By using this framework, production line planners and others are able to break down life cycle emission targets of a product to subordinated levels, incl. the manufacturing. To implement resulting sub-targets in such a mature industry, we suggest to integrate them in already existing and used specifications sheets, which internal departments and external suppliers have to comply with.

There are several challenges ahead to integrate this framework in the decision-making process of such a mature industry. Firstly, the strategic department and product developers have to adopt the life cycle thinking approach and should be keen on integrating it into the planning procedure. Secondly, planning software must be enhanced with life cycle inventory data to enable planners and designers on the different levels to assess their ideas in a feasible way. Thirdly, the communication between the levels (e.g. between system integrator and robot supplier) should be

enhanced strongly. This might be the biggest challenge, because the subordinated levels always have to reveal a lot of information about their products (e.g. material compositions of what they supply). However, such a requirement can evolve into providing a competitive edge for those suppliers who are willing to share their information.

Applying this framework in several industries is planned in order to verify assumptions and the approach.

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