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Absolute sustainability: Challenges to life cycle engineering

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ABSTRACT

The global society faces huge challenges to meet the expanding needs of a growing population within the constraints posed by a climate crisis and a strongly accelerated loss of biodiversity. For sustainability, the total environmental impact of our activities must respect the planetary boundaries that define what is a safe operating space for our civilization. Engineering must change the current focus on eco-efficiency to a search for solutions that are effective in terms of operating within the share of the total pollution space that they can claim. Engineering for environmental sustainability must be life cycle engineering, and the paper positions it relative to the constraints given by the boundaries of the ecosystems, the targets of the United Nations' sustainable development goals and the strategies for a circular economy. This top-down perspective is combined with a bottom-up perspective from the life cycle of the product and technology. For each stage of the life cycle, the contents of the toolbox for life cycle engineering are reviewed, and a perspective is given on how absolute environmental sustainability requirements can be incorporated in a target-driven life cycle engineering.

1. Introduction

Before embarking on the analysis of the challenges mentioned in the title of the paper, there are two questions that the title elicits: What is absolute sustainability, and what is life cycle engineering?

1.1. Definitions of sustainability and sustainable development

The United Nations' Commission on Environment and Development in 1987 presented the definition of a sustainable development as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [229]. With its focus on fulfillment of human needs now and in the future, the definition has been widely adopted, but the devil is in the details and the definition gives no specification of which type of needs are concerned. Later, Elkington operationalized the sustainability concept in a business context with his suggestion of the three dimensions of sustainability – social, environmental and economic - reflected in three bottom lines (people, planet, profit) that a company must ensure to balance in order to be sustainable [46]. In 2015 the member states of the United Nations adopted the 2030 Agenda for Sustainable Development, further specifying the three sustainability dimensions into 17 Sustainable Development Goals (SDGs) with a total of 169 underlying targets to be achieved before 2030 [215].

1.2. An absolute perspective on sustainability

Already in 1798, the English professor and priest Thomas Malthus observed that with its exponential growth, the human population was bound over time to exceed the ability of the planet to feed it [147]. This carrying capacity was subsequently demonstrated to be strongly dependent on technology development and not least the access to abundant fossil resources. Around 1970, a group of researchers developed the first computer models of the developments in global human population, food production, industrialization, pollution and consumption of non-renewable natural resources and analysed future scenarios to investigate whether changes in the growth patterns for these five parameters might allow emergence of a sustainable feedback pattern for the human civilization. They found that one out of three analysed scenarios lead to a "stabilized world" while the other two scenarios lead to "overshoot and collapse" and reported their results to the Club of Rome and to the world in the report "Limits to growth" [151]. The absolute boundaries posed by Earth's finite natural resources and the limited capacity of the environment to absorb pollution were challenged at the time, but lately the existence of absolute boundaries for man-made pollution of the atmosphere with greenhouse gases like CO_2 and CH_4 have gained not just scientific-, but also broad political acceptance. This was demonstrated by the adoption of the Paris agreement targets to keep our climate change impacts at a level where global atmospheric temperature increase remains close to 1.5° above pre-industrial levels.

Taking a broader perspective on climate stability, Rockström, Steffen and colleagues identified nine planetary environmental processes

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including the release of greenhouse gases to the atmosphere, use of land, and nutrient cycling, that they consider essential for the self-regulation of central planetary processes ensuring the stable environmental conditions that humanity has known throughout the Holocene since last glaciation [167] [196]. Based on natural science they proposed for each process a "safe operating space for humanity" delimited by critical impact levels ("planetary boundaries") that we need to avoid exceeding in order not to jeopardize the stability of our natural systems. Out of the nine proposed planetary processes, they found that the boundaries have been exceeded for three. While the work has inspired lively scientific discussions of suitable indicators and concrete boundaries for all the individual planetary processes, the overall concept with its absolute boundaries for sustainability has also inspired governments [157] and industries [182] to start thinking in absolute targets for environmental sustainability and benchmarking their activities accordingly. Bjørn and Hauschild introduced the absolute sustainability perspective into the field of product assessments [12]. They showed how absolute boundaries at the level of companies or even individual products may be derived from the boundaries presented by the Planetary Boundary framework or from other science-based bio-physical boundaries for man-made environmental impact that define a total pollution space that must not be exceeded [13] [14]. The environmental space concept was developed for policy use in the 1990′s [88] [191]. The pollution space can be considered a restricted resource similar to the limited natural resources for which societal actors compete. Determination of which share of the space (environmental or resource), an individual country or company can claim, requires an allocation of the total space. While there is good agreement about the principles for a science-based determination of the boundaries and of a safe operating space (noting that the methods for this are still under development), the allocation of the space between actors is still in its infancy [128]. The Science-Based Targets initiative presents the "grandfathering" principle according to which the companies have to reduce their total emissions of greenhouse gases by the same percentage, reflecting the reduction that is needed for society as a whole [182]. Assuming that the right to use the pollution space belongs to human individuals, the available space may be allocated among countries according to their population sizes as done by Nykvist and colleagues in their assessment of which nations stay within their share of the safe operating space delimited by the planetary boundaries [157] and by the Global Ecological Footprint Network in their calculation of ecological footprints for nations [57]. Different allocation approaches were tested and [128] and [172] demonstrated their influence on the absolute sustainability assessment of the service of laundry washing in Europe. Hjalsted and colleagues [89] proposed a method for assigning shares of global or regionally determined safe operating spaces to the level of the individual and then upscaling them to the level of a country, sector or product and analysed different ethical principles for performing the allocation (see Fig. 1)

1.3. Life cycle engineering and eco-efficiency

If engineering is creating or inventing a science-based technical solution to a perceived problem, life cycle engineering expands the perspective from the physical product to its entire life cycle (also termed product system) from cradle to grave.

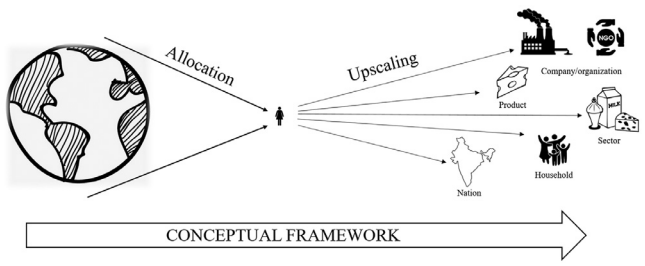

Fig. 1. Sharing safe operating space between different actors [89].

In the 1980′s, investigations in "Unified Life-Cycle Engineering (ULCE)" were carried out under the U.S. Defence Advanced Research Program Agency [22]. A more formal understanding of the life cycle engineering concept developed in the following years [1] [132]. LCE was conceived as a systematic "cradle to grave" approach, i.e. taking a life cycle perspective on the engineering object that provides the most complete environmental profile of goods and services. A decade later Jeswiet [115] defined LCE as: "Engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste." In their CIRP keynote, Hauschild and co-authors expanded this definition with several keywords, but the focus remained strong on products and on design for environment and efficient manufacturing [73]. Peças and colleagues presented an LCE taxonomy to classify existing tools and techniques under LCE, based on strategic management and system theories [159].

Efficiency is a traditional focus of engineering, aiming to maximize output or value creation while minimizing input or costs. For LCE, with an environmental performance perspective, efficiency may be determined as energy-efficiency, resource-efficiency or a broader eco-efficiency of the activity, product or provided service. The ISO 14,045 standard [103] defines eco-efficiency as an "aspect of sustainability relating the environmental performance of a product system to its product system value". Hauschild proposes the *eco-efficiency* defined accordingly as the ratio between the created value or fulfilled function for the product system on the one side, and the resource use or impact that is caused on the other side. For the eco-efficiency, the expression would be [76]:

$$Eco-efficiency = \frac{Value\ created\ or\ functionality\ provided}{Environmental\ impact\ caused} \quad (1)$$

The environmental impact of a product is assessed using life cycle assessment, LCA. With its coverage of the entire life cycle of the product, from cradle to grave, and its consideration of all relevant impacts that the product causes along its life cycle, from global climate change over regional acidification to local biodiversity impacts caused by land and water use, LCA captures potential problem shifting between life cycle stages and between categories of environmental impact when the environmental sustainability of products or services are compared [53].

The focus on increasing energy-efficiency or eco-efficiency promotes development of products that offer more functionality per caused environmental impact or resource use. Gutowski illustrates this with the example of lighting technologies [63]. Examining the development from the early 19th century Ausubel and Marchetti find that the energy efficiency of lighting technologies has undergone an exponential development, increasing more than two orders of magnitude from the paraffin candle to recent diode lamps [8]. Today, a given lighting service can thus be obtained with a minimal fraction of the energy used two centuries ago. Investigating human consumption of lighting, Tsao and colleagues show that despite the dramatically increased energy efficiency, the share of our purchasing power spent on energy for lighting has remained remarkably constant over the same period [207]. Since the purchasing power has grown dramatically over the last centuries, so has the use of energy for lighting over this period, despite the orders of magnitude increase in the energy-efficiency of lamps. Increased energy-efficiency might be expected to support a decoupling of consumption and environmental impacts, but since it is associated with reduced costs of lighting, it also inspires an increase in the demand and use of lighting. This is referred to as a *rebound effect* in the market, and in this concrete case, it more than neutralizes the efficiency gains. Instead of a decoupling, an increased use of electricity is observed in what environmental economists call a backfire effect [87]. Examining 57 cases of technological efficiency improvement covering different materials and technologies over the last decades, Magee and Devezas demonstrate that it is a general observation that rebound effects counteract efficiency

improvements, and they are not able to demonstrate in any of the investigated cases that the achieved efficiency improvements lead to dematerialization [146]. Their observation is corroborated at the global societal scale when taking a top-down perspective on the development in the environmental impact that our societies have caused over the last centuries. Steffen and colleagues map trends in earth system impacts like loading of the atmosphere with the main greenhouse gases CO_2, CH_4 and N_2O, loading of coastal waters with nitrogen compounds, loss of stratospheric ozone due to man-made emissions of persistent halocarbons, and degradation of the terrestrial biosphere [195]. All trends show strong increases after 1950 and for some of them the trend approaches an exponential development. These trends in impact mirror central socioeconomic trends like growth in population and urbanization, and growth in GDP, and trading of many fundamental commodities.

The IPAT equation (Eq. (2)) was developed in the 1970's based on work by Ehrlich and Holdren [44] and Commoner [30] in order to focus attention on the key factors driving man-made environmental impact. It presents the total environmental impact (I) as the product of three central drivers viz. the human population (P), the human affluence (A, the material standard of living), and the technology factor (T, the environmental intensity of our technology expressed as environmental impact per created value or functionality, T is the inverse eco-efficiency – see Eq. (1)).

$$I = P \cdot A \cdot T \tag{2}$$

When population and affluence grow, the eco-efficiency of the technology that provides the affluence of the growing population must also grow in order to avoid increased environmental impact. But by how much? What is the challenge that environmental sustainability of a growing consumption poses to technology?

Since eco-efficiency is the inverse of the environmental intensity of technology, Eq. (2) shows us that the overall requirement to eco-efficiency can be described by the variables in the IPAT equation as:

$$Eco-efficiency = \frac{1}{T} = \frac{P \cdot A}{I} \tag{3}$$

For the man-made contribution to climate change, Hauschild and co-workers estimate that overall average eco-efficiency of our technology has to be increased by an order of magnitude from now to 2050, in order to keep the global average atmospheric temperature increase below 2°, assuming an increase in population of 30%, a doubling of the global average affluence, and a need to cut the current level of climate impact by 70–80% in 2050 [78]. In order to follow the Paris agreement and limit temperature increases to the safer level of 1.5°, considerably stronger increases in eco-efficiency are needed [94]. Requirements to overall eco-efficiency increases of 4, 10 or even as high as 50 times have previously been proposed, for different types of environmental impact and reflecting different assumptions about time horizon and developments in population and affluence [52] [165] [180] [219]. Here, it is assumed that A and T are independent, which is rarely the case, since increased eco-efficiency often leads to a growth in consumption and affluence, as discussed above. While a strong increase in the eco-efficiency of products and technologies is clearly needed to ensure a sustainable level of environmental impact, the examples illustrate that a focus on eco-efficiency alone is insufficient to ensure a future sustainable consumption and production. There is a need to analyze the overall outcome in terms of environmental impact for a product or technology and relate it to the share of the operating space that this product or technology can claim, considering the size of its market, to ensure that the improvement leads to solutions that are not just more sustainable than what they replace, but sustainable in absolute terms [76].

2. Shifting focus from efficiency to effectiveness

In 2017, Hauschild and colleagues proposed to move away from the triple bottom line thinking and reorient the LCE discipline towards its original focus on the environmental dimension of sustainability. The motivation was to avoid that an increase in the environmental impacts from a technology is justified by its improved performance in the social or economic dimension [78]. Inspiring a movement away from industry's historic focus on eco-efficiency and relative improvements, this allows life cycle engineering to adopt a much-needed absolute perspective on the environmental sustainability for all engineering activities. To this end, they proposed a new definition of life cycle engineering as "Sustainability-oriented product development and manufacturing activities within the scope of one to several product life cycles, aiming to achieve sustainable manufacturing that allows fulfilling needs of both present and future generations without exceeding the boundaries of Earth's life support systems". In a new framework, they positioned life cycle engineering relative to other approaches and concepts of relevance to the field and illustrated how targets for life cycle engineering must be derived top-down from the larger scopes of concern while life cycle engineering achievements must assure that the targets are attained bottom-up.

With the absolute perspective on environmental sustainability, life cycle engineering of new products and technologies has to consider not just the single product and product life cycle (the technology factor, T in Eq. (2)), but also the foreseeable growth in market volume that results from increases in population and affluence, in order to allow the associated total environmental impact to be taken into account during the product development, as illustrated in Fig. 2. To respect the absolute boundaries for environmental sustainability (e.g. the planetary boundaries) and stay within the safe operating space, which they define (achieve environmental sustainability in absolute terms), the total environmental impact of the new product generation must not exceed the environmental space that is available for the activity.

Most methods, tools and techniques in the LCE toolbox have hitherto been focused on relative improvements in environmental performance, but this is often insufficient to achieve the order of magnitude improvements that are required to meet e.g. the 2050 targets for climate change (see Section 1.3). LCE practitioners need to apply the tools with a view to achieve the absolute targets and there may be a need for new tools and techniques that support fundamental function and system innovation in order to meet the ambitious targets.

The keynote presents state of the art for LCE and discusses what is needed to support a future target-driven LCE towards absolute environmental sustainability. It is structured according to the framework in Fig. 3, moving from the global perspective to the company. After introduction of absolute sustainability requirements and the IPAT equation (around which the figure is built), Section 3 discusses the boundary conditions that society poses to a target-driven life cycle engineering within absolute sustainability boundaries. Section 4 presents boundary conditions for LCE from higher levels of the

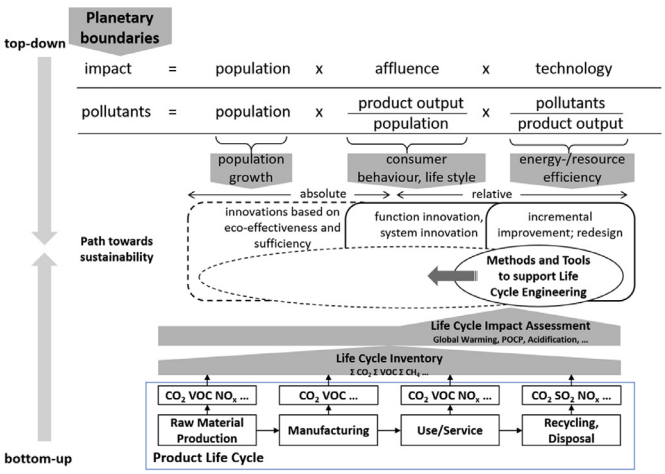

Fig. 2. In order to support eco-effectiveness towards absolute sustainability targets, life cycle engineering needs to expand from incremental product improvements to function and system innovations and ultimately eco-effectiveness and sufficiency (Based on [78]).

framework – from the UN Sustainable Development Goals over Industrial symbiosis and Circular economy to life cycle management. Section 5 and the ensuing sections present the LCE toolbox and its contents organized after the life cycle stages that they target, from Material selection (Section 6) over Manufacturing (Section 7) and Use and maintenance (Section 8) to End of life (Section 9), in each section discussing what an absolute sustainability perspective entails for future life cycle engineering activities in this field. Section 10 presents the central assessment tools and discusses their possibilities to support target-driven LCE towards absolute environmental sustainability, and Section 11 concludes and provides a look towards the future of target-driven LCE, including identification of the most pressing research needs to support the development.

3. Societal boundary conditions for absolute sustainability

As the previous sections demonstrate, economic activities have to respect the boundaries of processes that ensure the stable functioning of our natural environment as described by the planetary boundaries. In the terminology of ecological economics, these boundaries are referred to as *biophysical limits* to the human economy [35]. How business and other actors should try to cope with these limits, also involve social and ethical considerations. As an outset for introducing such considerations, it is important to emphasize the character of the challenges, societies are facing. Within fields such as industrial ecology and ecological economics, the key challenge is often seen in a long-term historical perspective focusing on energy, because humans, like other species, are dependent on energy [29] [64]. In terms of energy, human history has passed through three phases based on a different composition of the energy basis: in addition to just eating available biomass, hunter-gatherers commanded fire, while preindustrial agricultural societies added draft animals, wind- and hydropower, and industrial societies furthermore added fossil fuels and later nuclear energy [64]. During the industrial phase, the abundance of fossil energy enabled an exponential growth in the number of humans as well as a considerable increase in material living standards for large groups. This phase is now coming to an end, since the risk of climate change will limit the use of fossil fuels. Humans thus have to enter a fourth phase in their energy history based on new ways of appropriating energy – unless technologies to absorb carbon from the atmosphere can prolong the fossil phase. This challenge is daunting, since fossil fuels still constitute about 80% of global energy supply, and another nearly 10%is based on biomass, which competes with food production and adds to the pressure on biodiversity. The transformation must take place in a period where the number of humans has reached an unprecedented level and can be expected to increase even more, and the inequalities in living standards are huge. Another key challenge is thus to bring large groups out of poverty while keeping within biophysical limits.

3.1. An ethical challenge

Based on this understanding of the challenges, it is common within fields such as ecological economics and political ecology to argue that the existence of biophysical limits implies an ethical challenge: Since biophysical expansion is no longer possible, it will be hard to solve the problems of poverty without some redistribution of the access to resources and to the planet's capacity of absorbing pollution [35] [148]. As long as the biophysical resources seemed limitless and the concept of planetary boundaries was not even formulated, it might seem possible to bring large groups out of poverty without having to reduce the living standards of other groups, but the increasing acuteness of the boundaries makes this prospect more and more implausible. Although technological innovation is key to increase production without using more resources or giving rise to more pollution, the present challenges can hardly be met only through more efficient technologies, as argued in Section 1.3. Linking back to the IPAT equation, it is worth noting that a redistribution of resources from rich to poor may not only contribute to poverty alleviation, but also to the reduction of population growth: When people become richer, when social security is enhanced, and when women benefit from the improvements and girls are educated, women tend to have fewer children [166] [178].

3.2. Rejection of the ethical challenge

Before turning to the implications of this understanding of the challenges for sustainability strategies, it should be noted that a fundamentally different approach also exists. It was formulated most directly by the ecologist Garrett Hardin with his concept of lifeboat ethics [69]. In brief, the idea is that in a world of limited resources, there is not space for everybody in the lifeboat. If we try to bring everybody on board, the boat will simply sink. Hardin's specific concern at the time was population growth. He argued that this problem

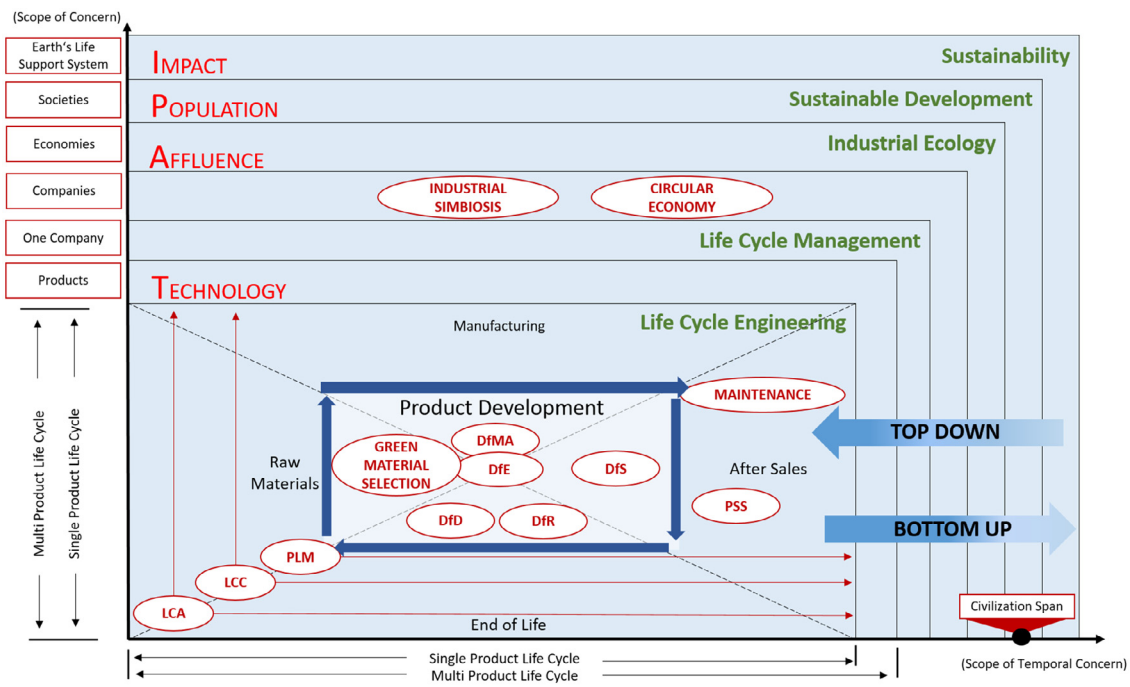

Fig. 3. Framework positioning life cycle engineering within the context of planetary boundaries and absolute sustainability (Based on [78]).

would only get worse, if the rich countries opened their borders for immigration from the poor countries or contributed food to these countries in case of famines. Hardin's arguments can be questioned, but this is not the point here. What is at stake is rather the question of how to handle large inequalities in a world of limits: When it is impossible for everybody to achieve the average living standards of say the richest fifth of world population, should the richest fifth then reduce living standards to make more space in the lifeboat, or should they struggle to keep their privileges? As argued by Andersson and Lindroth [4], rich countries may experience a real dilemma here, because political and economic power relies on access to resources: If rich actors accept to reduce resource use, they may lose out to potential rivals. The result may not be more equality, but just a different hierarchy. Similarly, Sachs [177] described how the rich countries may perceive the rise of the poor as a threat. He characterized this view as "the contest perspective" or more radically as "the fortress perspective" [176]. The following is based on a rejection of the lifeboat position and the contest perspective: If global cooperation does not succeed in achieving a fairer world, dramatic social conflicts will emerge and make it impossible to realize the transformations needed to keep within planetary boundaries. This emphasis on the need for cooperation mirrors the concern of Vancza and colleagues who argued that the key to sustainable production is in enterprises' cooperative use of the fundamental services provided by socio-ecological systems [218].

3.3. Combining efficiency with sufficiency

Sustainability is thus also about reducing poverty and achieving a fairer distribution. As Jackson has highlighted, the inclusion of fairness makes the sustainability challenge even larger [111]. Based on the IPAT equation, he calculated how much technological change has to reduce the energy intensity of GDP in order to achieve the 1.5 °C target in various scenarios based on different assumptions regarding the growth of affluence. As also demonstrated in Section 1.3, the exercise illustrates that it is very demanding to achieve the target in scenarios with continued economic growth, and it seems outright impossible to bring people in poor countries closer to the living standards of the rich countries, if these standards continue to increase. This sort of calculations contributes to the call for combining efficiency with limits to consumption. In the sustainable consumption literature, this is often referred to as a call for sufficiency: The increase of the living standards of the rich needs to be arrested, and policies should be put in place to avoid rebound effects when technologies are improved [192]. Some proponents of this position argue that sufficiency does not really entail any sacrifice. When people have high material living standards, they do not become any happier or more satisfied by further increases ([110] surveys the debate). A classic illustration from this debate [92] depicts the relationship between the level of GDP and reported subjective well-being in many countries. It shows that reported well-being tends to increase with the level of GDP for relatively poor countries, but at a certain level the increase fades out and the curve flattens. Similar conclusions emerge from more recent studies on the relationship between the growth of GDP over time and the development of indicators such as the Genuine Progress Indicator (GPI) or the Index of Sustainable Economic Welfare (ISEW) [58] [122]. Furthermore, it is a general observation that there is a wide spread in welfare within groups of countries with similar levels of GDP. In an influential study on this spread, Wilkinson and Pickett demonstrated the importance of relative equality for well-being in societies [227]. They have gathered a large amount of statistics demonstrating that the more unequal societies are, the more social problems they have. These problems relate to drug addiction, infant mortality, life expectancy, obesity, school dropouts, teenage births, homicides, imprisonment, mental health, and many more. In a sequel to this book, the authors discussed how to interpret the statistics. They observed that a shared feature of the problems is that they are all more common at the bottom of the social hierarchy. Furthermore, Wilkinson and Pickett argued that these problems are related to humans' sensitivity to social status – a psychological sensitivity that resulted from human evolution – and emerged as reactions to issues of status. It is demonstrated that people's anxieties about status increase with increasing inequality in society and that this holds for all income groups. In general, societies that are more equal are characterized by more trust and better social relationships, and even the high-income groups do better in many respects than they do in societies that are more unequal. When combined with a fairer distribution, sufficiency may thus make most people better off [228].

3.4. The relationship between inequality and environment

In addition to the ethical and social reasons for promoting more equal societies, it should be noted that inequality in itself may aggravate environmental problems. Within countries, the anxieties related to status serve as drivers of consumption. As Gough put it "Inequality spurs competitive consumption, emulation effects and excessive consumerism" [59]. In addition, inequality can impede the collective action needed for environmental policies. If large groups in society experience that they have to bear the brunt of the burden of sustainability transitions, while the rich continue their excessive consumption, the feeling of injustice can become a barrier to necessary changes. With redistribution as a component of sustainability policies, it should be considered that low-income groups spend a relatively large share of their income to buy basic goods with a relatively high energy-intensity [60]. The incomes of the rich may thus have to be reduced more than the incomes of the poor are increased. However, redistribution may also involve more public consumption in the form of health, education and culture – all of which have low energy-intensities [111] [114].

The inequalities between countries may also aggravate environmental problems. For instance, as Schor has pointed out, the low wages in the mines, fields and sweatshops in poor countries imply that prices of many consumer goods (electronics, apparel, toys, tools and other equipment) are kept very low, which makes it possible for large consumer groups in the rich countries to maintain a high level of material consumption and thus to generate considerable environmental impacts [181]. In addition, poverty at the other end of global supply chains can have serious environmental impacts. For instance, when ever more land in developing countries is seized for the provision of palm oil, biofuels, cotton and other export goods, poor peasants are driven to marginal lands where they tend to exhaust the soil and overexploit local forests [5].

3.5. Specifying social goals

In many ways, a trend towards increased equality can thus be considered an important part of sustainable development. In addition to this general point, more specific social requirements for sustainability are increasingly formulated. For instance, Raworth's formulation of the 'doughnut' as the safe and just operating space for humanity has gained considerable attention [163], see Fig. 4. On the one hand, human societies have to respect the planetary boundaries, which constitute the outer circle of the space within which we have to stay. On the other hand, human societies should ensure the basic social foundations for acceptable human lives. These foundations constitute the inner boundary of the doughnut. Since the formulation of social foundations can be controversial, Raworth suggests using the Sustainable Development Goals, formulated by the United Nations, as the point of departure. On this basis, she divides human welfare into twelve components ranging from food and health to gender equality and peace and justice. All these criteria should be fulfilled to be within the 'doughnut'.

Gough [58], who prefers the metaphor of 'lifebelt' to 'doughnut', agrees with Raworth's basic perspective, but instead of using the SDGs as the basis for formulating social foundations, he suggests applying a theory of human needs. In order to provide a framework that can form the basis for ethical obligations, he argues that it is decisive to have an objective conception of human well-being – an understanding of universal human needs that are independent of

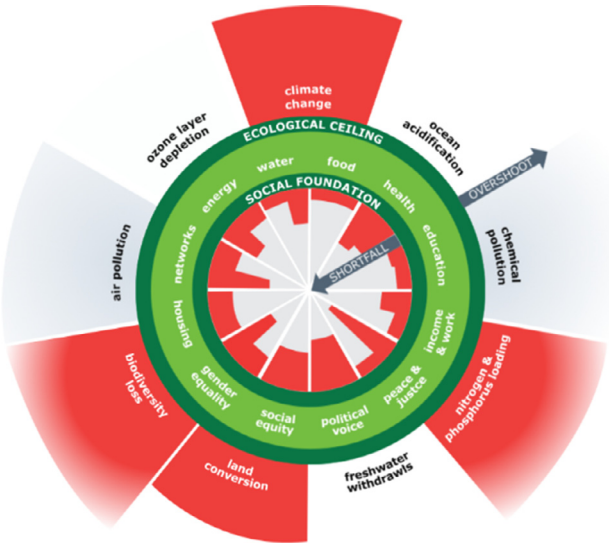

Fig. 4. The Doughnut of social and planetary boundaries [164].

cultures, class, gender and generations and have nothing to do with individual preferences. Gough identifies three basic human needs: social participation, health and autonomy. If these are not satisfied, then serious harm of some objective kind will result. To meet the basic needs, a set of intermediate needs have to be fulfilled, such as nutrition and water, housing, health care, security, education etc. In addition to these intermediate needs that are attributes of individuals, societies have to fulfill some institutional preconditions to ensure human welfare. In practice, there are many similarities between Gough's framework and the SDGs, but it is more systematic and broader and forms the basis for a clear message: needs trump wants, and sufficiency for all trumps maximization of utility for some [61].

3.6. Implications for life cycle engineering

The most immediate implication of these social aspects of sustainability for life cycle engineering relates to the choice of products and services to offer. From this perspective, it is better to provide products and services that fulfill the needs of low-income groups than to develop ever-new luxuries for high-income groups. This idea was promoted in the business community from the mid-1990s, for instance in the publication "Who needs it?" by John Elkington [45]. A few years later, Prahalad and Hart [161] popularized the concept Bottom of the Pyramid and argued that solving the problems of low-income groups offers good business opportunities. Over time, the actual strategies for creating markets from needs have developed considerably and now focus much more on co-creation [23].

At the production side, the call for a more just distribution suggests that wages should be raised in poor countries and working environment improved. Steps in this direction may not only ensure a larger share of the biophysical resources for the poor, but also contribute to making goods sold in the rich countries more expensive and thus reducing the ecological footprint of these countries [181].

The inclusion of social and ethical considerations into sustainability strategies does not change the need for more eco-efficient technologies. However, as mentioned in Section 1.3, it is important to avoid that efficiency improvements result in rebound effects that counteract the achievements. This cannot be done at the business level but requires anti-rebound policies that make the use of resources and the emission of pollution gradually more expensive [217]. Technological change should make it possible to do with less, not encourage increasing material living standards.

While efficiency improvements can be useful, it is also necessary to consider the role of these improvements in relation to wider systems such as provision systems and global product chains. As the global trading system works today, it often serves to transfer resources from poor to rich countries and to maintain provision systems that are basically unsustainable [3] [90]. For instance, the provision of food upholds a huge consumption of meat as well as a substantial use of energy for transport; the provision of cheap flights upholds unsustainable tourism; the provision of electronics upholds a buy-and-throw-away culture, and so on. It is a challenge that technological innovations, which increase the efficiency of a certain process, may contribute to sustain an ineffective system, because they serve to legitimize the continuation of the overall system. For instance, technological changes that reduce energy use in large-scale pig farming or transform the manure into biogas can extend the lifetime of a system that should undergo a more radical transformation [54]. The point is that efficient cogwheels in irrational machines offer no real solution to sustainable consumption and production at the societal level. This perspective thus calls for considering whether innovations and approaches really contribute to transform wider systems in a more sustainable direction: Will the transformation redirect the transfers to benefit the poor? And will it reduce the overall environmental impact in the long run? These are fundamental and systemic considerations that need to be deliberated prior to the life cycle engineering process, typically as part of the strategy development in a company.

4. Conditions from higher levels in the hierarchy of the framework

In the framework in Fig. 3, life cycle engineering is positioned relative to other concerns and systems that top-down define the requirements and conditions under which it must operate. At the highest level in terms of scope of societal and temporal concern are the global concerns about sustainability and sustainable development. With the adoption of the United Nations Sustainable Development Goals (SDGs) in 2015, the member states committed to a number of goals with relevance for the manufacturing sector, including Decent work and economic growth (SDG 8), Sustainable industry, innovation and resilient infrastructure (SDG9), Climate action (SDG 13) and Protection of life below water and on land (SDGs 14 and 15). One goal, in particular, concerns the way in which products are produced and used, the goal on Responsible consumption and production (SDG 12). Under this goal, there are 12 targets, addressing efficient use of resources, responsible management of chemicals, reduction of waste generation, and inclusion of sustainability information in company performance reporting. Given the commitment of the member states, life cycle engineering can expect requirements from governments to meet these targets, but only one of them is concrete and measurable, target 12.3 requiring halving of global per capita food loss at retail and consumers. At this point, the rest of the targets under SDG12 are stated as desired developments.

Other higher-level strategies in the framework of Fig. 3 are Circular economy and Industrial symbiosis. Their implications for LCE are discussed in the following sections.

4.1. Circular economy

The material flows of modern industrialized economies are predominantly linear (extract, refine, use, waste), and Circular economy has been proposed as an alternative way of organizing the economy. It builds on concepts from closed loop systems and inverse manufacturing [135] [206] and the Cradle to cradle design movement where the cradle to grave thinking is replaced by principles that ensure that the end of life of a product becomes the cradle of a new product [150]. The circular economy is thus coined as "an industrial system that is restorative by design" [47], avoiding the extensive wasting of materials and products by ensuring that linear material flows from resource extraction to waste are replaced by circular flows as illustrated in Fig. 5. For life cycle engineering, the main focus of this paper is on the manufactured products (right side of the figure), and here the loops involve:

- Extended product life through maintenance and sharing concepts where multiple users utilize the same product (closest circle).

- Multiple product lives through reuse and redistribution of the product for new users after the end of the first use stage (second circle).
- Utilization of residual functionality in the product or components hereof after end of life through refurbishing or remanufacturing (third circle).
- Utilization of remaining material quality in the product through recycling (outer circle).

Sections 8 and 9 on life cycle engineering of the product use stage and the end of life stage discuss life cycle engineering approaches that may support a more circular economy. The European Union has launched an action plan for circular economy [43] [50] incorporating all these loops.

The closer the loops are to the user, the stronger is the need to plan for the loop when designing the product. This calls for a long-term change in the way industry designs and plans the life cycle of products, considering the functionality and dynamics of societal systems for handling the end of life products (see Sections 4.3 and 9). In the shorter term, the EU action plan has a strong emphasis on recycling of the large volume materials, closing the loops for building materials, metals, plastics and paper and cardboard [51]. While less demanding than reuse and remanufacturing, the recycling of materials still poses strong requirements to the way materials are used in products. Efficient separation of different materials is needed in order to avoid cross contamination between different plastic types or metal alloys with poor compatibility, compromising the technical properties of the recycled materials. Composite materials are notoriously difficult to recycle and testify to the need for development of novel technologies that combine strength and lightweight of materials in a way that does not compromise the possibility of recycling [85]. The recycling of plastics may also be complicated by the use of additives like stabilizers, plasticizers or flame-retardants that remain in the plastic after recycling processing, altering the performance of the recycled polymer and potentially exposing users of the recycled plastic to hazardous chemicals. The latter is particularly a concern when recycled plastics are used in toys or food contact materials (packaging, kitchen utensils) [48]. In order to be successful, the circular economy will require product design in the future to enable the closing of loops at the end of life, and this will strongly restrict the current use and mixture of different materials that prevents an efficient recycling and safe use of the recycled materials.

Based on dynamic modeling of societal material flows applied to the case of steel until 2100, Wang and co-workers investigated how improved recycling will affect future production and use of this metal [221]. The study concludes that while recycling is beneficial, it addresses the material waste flows of the economy but ignores the building of stocks that for steel and many other materials is the main driver of increased extraction and production. In the greater picture, recycling thus remains an efficiency strategy. In order to decouple the growth in material use from the increases in population and affluence, as introduced in Section 1, there is a need to focus on all the loops in Fig. 5, and increase also the efficiency by which the products are used and reused. This will be the case in particular for the many materials where it is the stocks rather than the flows that determine the total size of the human use of resources. Since future availability of resources is an issue for sustainability, circular economy strategies have a role to play in meeting absolute sustainability requirements but need to balance the trade-off between the induced transport and processing against the avoided extraction and transport of virgin resources.

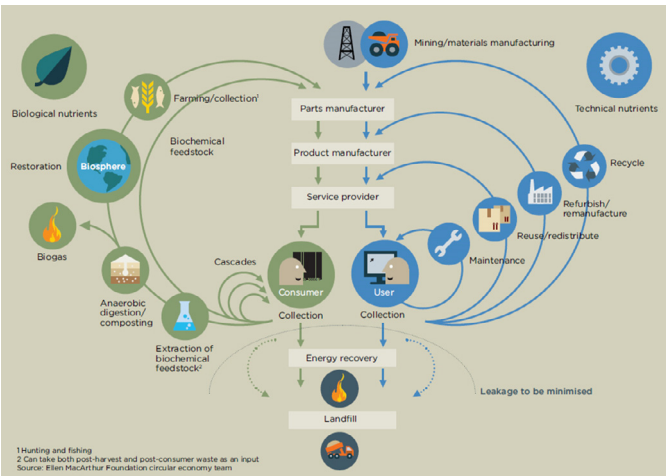

Fig. 5. Circular economy converting linear material flows into circular flows through closing of loops around the user [47].

4.2. Industrial symbiosis

Where circular economy is focused on the product and closing of loops close to the user of the product, industrial symbiosis is focused on the company. With inspiration from the mutually beneficial interactions between separate species in an ecosystem, industrial symbiosis is thus used to describe the exchange of flows of materials or energy between independent companies where one company utilizes waste streams from another company as feedstock. Chertow gives the following definition: "Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products" [26]. An important characteristic of industrial symbiosis is thus that the industries exchanging the waste flows are separate. Internal recycling involving different departments or subsidiaries of the same enterprise is not considered industrial symbiosis. Herczeg and co-workers analysed industrial symbiosis relationships from a supply management perspective, [80] and highlight some of the restrictions that they pose on the receiving company in the form of dependence on the production volume and hence the market situation of the waste producing company (since waste generation follows production), and the need to be able to operate on feedstock consisting of both virgin resources and waste streams from the industrial symbiosis relationship. To facilitate symbiotic relationships, engineering must accommodate the use of such secondary resources through both product design, material choice and process design. The role of industrial symbiosis in meeting absolute sustainability targets depends on the importance of the concerned material flows in the life cycle of the involved products and on the trade-off between the induced processing, transport and upgrading of the waste stream and the avoided extraction and transport of virgin resources [39]. It is also a concern that the contractually based exchanges of waste flows may motivate the continuation of a wasteful production rather than avoiding the waste production altogether [39].

4.3. Life cycle planning and management (LCP and LCM)

In the literature, Life Cycle Management (LCM) has been defined in various contexts [226]. Traditionally life cycle management is seen as a *product life cycle management (PLM)*, a holistic business concept with a business perspective and a focus on software solutions. PLM is thus seen as a set of tools and techniques, which has evolved from a set of engineering-oriented tools into an enterprise-level solution [32]. A central PLM definition is offered by the National Institute of Standards and Technology (NIST), defining PLM as "a vision or a business strategy for creating, sharing, managing information about product, process, people and services within and across the extended and networked enterprise covering the entire life cycle spectrum of the product" [197]. As illustrated in Fig. 6, PLM, therefore, should be considered a strategic business approach in order to help enterprises achieve business goals.

Although these definitions do have a product life cycle view, their focus is on the economic performance of organisations, and they

completely lack the environmental dimension. There has been an attempt to integrate the sustainability knowledge with PLM tools to help designers to consider all three dimensions of sustainability. The applicability has been demonstrated on a case study. However, it is argued that in the existing implementation of this approach only the environmental dimension of the sustainability is addressed [194].

As a result, United Nations Environmental Program (UNEP) has introduced life cycle thinking into life cycle management, with triple-bottom line view, in order to help organisations to consider, not only the economic, but also the environmental implications of their activities in management activities across the life cycle. In this context, UNEP has defined LCM as "the application of life cycle thinking to modern business practice, with the aim to manage the total life cycle of an organization's products and services towards more sustainable consumption and production" [113]. LCM is about systematic integration of product sustainability e.g. in company strategy and planning, product design and development, purchasing decisions and communication programs. LCM is not a single tool or methodology but a flexible integrated management framework of concepts, techniques and procedures incorporating environmental, economic, and social aspects of products, processes and organizations. Central to this idea is the relative improvement of the environmental performance of an organization in a life cycle perspective, hence moving towards relative sustainability. There are other frameworks such as the total life cycle management framework based on the viable system modeling, which further structures LCM into a strategic and an operational layer and distinguishes between life cycle spanning (e.g. environmental life cycle evaluation) and life cycle stage-related disciplines (e.g. after-sales management) that have to interplay synergistically [81] [83].

In this context, life cycle planning plays a critical role in successfully implementing the LCM concept. Despite the importance, implementation of life cycle related concepts in organisations are still ad-hoc, and companies have adopted very different approaches because no standard holistic approach currently exists for the planning and management of a product life cycle. The literature on life cycle planning is very limited. Umeda and colleagues proposed a framework for *life cycle development and planning* which denotes holistic and concurrent development of a product and its life cycle flow and the concept of life cycle planning as shown in Fig. 7. They proposed the integration of product design and life cycle flow design to reduce the resource consumption and environmental loads of the entire product life cycle, which requires the establishment of life cycle planning at the first step in life cycle development. This is one of the pioneering works in the field.

The authors stated that further work is required in this domain in order to plan, implement, and manage product life cycle in organizations towards achieving absolute sustainability [211]. The main focus of these frameworks is on relative improvements towards a more sustainable development without addressing the need for an absolute perspective. The framework illustrated in Fig. 3 positions LCM within the context of planetary boundaries. In this context, life cycle Management has a scope addressing the activities of a company, potentially comprising a multitude of different products and activities related to an integrated product and process life cycle planning with a temporal scope of one or more product life cycles [78]. Life cycle management has to support this new understanding on a company level for instance with redefining the vision and mission of the company towards moving from relative to absolute sustainability in order to stay within the planetary boundaries and guide all company activities around the production (procurement, distribution, marketing, ...) towards absolute environmental sustainability. In this context, life cycle management and planning play a key role in bridging the gap between top-down and bottom up activities as shown in Fig. 3

5. The LCE toolbox and absolute sustainability

Life cycle engineering was originally concerned with environmental sustainability. However, with the introduction of triple bottom line thinking in the last few decades, the majority of LCE activities have shifted to improving the eco-efficiency of products. As a result, several methods and tools have been developed over the years in order to improve eco-efficiency of product and services, which resulted in dramatic increase in the eco-efficiency of various product technologies. These methods and tools will be discussed in the following sections with respect to the applicability of their life cycle stages. Despite widespread eco-efficiency improvements, the total environmental impact has gone up dramatically due to the increase of population and affluence increase during the same time as discussed in Section 2. Fig. 2 shows how new product technologies need to be life cycle engineered, not only for the single product and product life cycle (technology effect), but also for the anticipated volume growth as a result of consumption and population increase (volume effect) so that the associated total environmental impact can be taken into account and addressed during the product development stage [128].

In order to stay within the boundaries for environmental sustainability (e.g. the planetary boundaries) and achieve sustainability in absolute terms, the total environmental impact of the new product generation as the result of the combined change in eco-efficiency and market volume must not exceed the space that is available for the activity, hence requires eco-effective solutions. As discussed in Section 4, this requires not only engineering and management of product life cycles, but also the careful planning and operation of supply chain activities. Furthermore, as shown in Fig. 3, life cycle engineering activities need to be carried out with an absolute perspective in order to stay within the planetary boundaries. Therefore, life cycle engineering of product technologies needs to take a structured and iterative approach in order to bridge the gap between top-down and

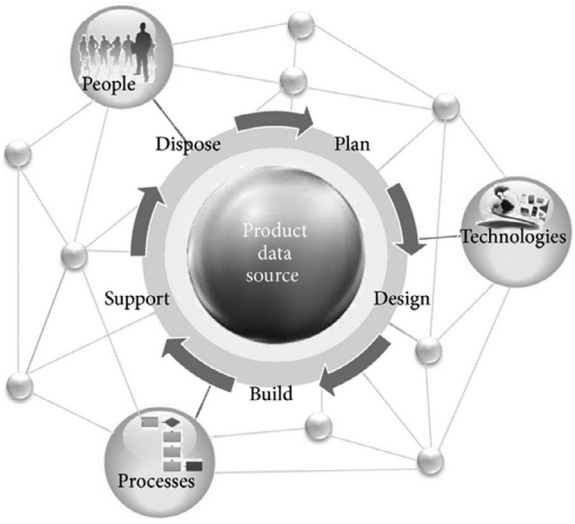

Fig. 6. The PLM landscape [32].

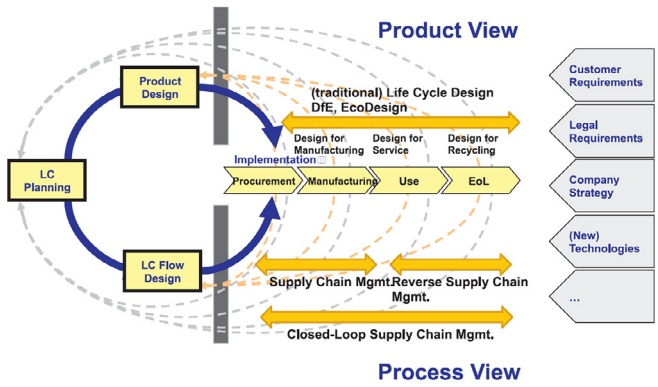

Fig. 7. Overview of life cycle development and planning [211].

bottom up approaches. The approach allows practitioners to engineer product, product foreground and/or background system where the biggest environmental impact reduction can be achieved. Planetary boundaries set the target for the life cycle engineering towards an eco-effective solution and life cycle assessment allows systematic assessment of the technology under investigation until a best possible solution is found. This approach is critical as a technology solution that leads to increased environmental impact at a given product life cycle stage, may lead to higher impact reduction in other life cycle stages, hence a total environmental impact reduction. For instance, Helu and colleagues demonstrated that, in the automotive industry, the increased environmental impact as a result of achieving tighter tolerance and high quality surfaces due to increased energy consumption in the camshaft and crankshaft bearings can help to reduce fuel/energy losses in the use phase; hence leads to an overall impact reduction [79].

Fig. 2 illustrates how most methods and tools to support LCE has been aimed at efficiency (incremental) improvement. In this context, eco-efficiency and eco-effectiveness are complementary e.g. eco-effectiveness sets the target and the eco-efficiency provide a means to get there.

6. Material selection and material production

The primary production sectors comprising mining industry and agriculture are important contributors to the man-made environmental impacts in many impact categories including climate change, land use, water use and toxicity to humans and ecosystems. The use of non-renewable resources furthermore has implications for their future availability and hence for the ability of future generations to meet their needs and this goes for renewable resources, when they are exploited in an unsustainable manner. This is reflected in the assessment of resource use as a separate group of impact categories in LCA.

In product development, technical performance, process choice and material selection are closely coupled, and a product's overall performance is thus directly linked to the materials used. The resource extraction and material production stage are an important contributor to the life cycle impacts of many products, and the recyclability is highly variable between materials depending on both material properties and the existence of societal systems to receive and process the materials for recycling. Material selection is therefore a critical part of the product development process, when considering environmental sustainability of the product. Over the years, several tools have been developed to help engineers finding the right material combination in order to optimize a product's technical performance [145]:

1 Environmentally friendly material selection and substitution (green material selection).
2 Using Renewable materials.
3 Using recycled and recyclable materials.
4 Using less material to achieve the functional requirement.

Most eco-design guidelines related to material selection focus on either choosing or substituting materials to avoid use of toxic elements or on promoting the use of less material through developing long life products to minimize environmental footprint [145]. Jahan and co-workers argued that material selection should encompass material properties, a holistic view on economic and environmental considerations, the processing of materials, effects from producing large quantities as well as future raw materials accessibility [112]. Among the reported methodologies in the literature, Ashby's generic material selection methodology is widely used to support material selection with respect to technical, economic and environmental requirements [6] [7]. In this approach, constraints are given by the design requirements to screen materials until a set of optimal materials is found. Corona and colleagues used the Ashby approach to compare the functionality of different structural applications and uses LCA for the assessment of the environmental impact. They tested their methodology for material selection on the case of natural fiber composites by considering mechanical properties of the constituent materials and the application type [33]. Tao and colleagues provided a green material selection methodology for material selection in order to minimize environmental footprint based on the embodied energy [202]. Hermann and colleagues provided a detailed classification of material selection in the context of life cycle engineering and applied it in an extensive review of the life cycle engineering of lightweight materials [85]. In addition, they provided a classification based on application, material type, form/topology, life cycle stages, cost and environmental impact categories. All these methodologies and applications are aimed at relative improvement of a product's environmental footprint with respect to functional and economic requirements and hence represent eco-efficiency improvements.

Materials, as a key resource, renewable or non-renewable have far reaching consequences for the sustainability of our society through their fundamental role in meeting the needs of current and future generations [229]. Although resources are not included within absolute environmental sustainability frameworks like the Planetary Boundaries [196], there are still absolute limits to their use. For renewable resources, the limits are defined by the regeneration capacity of the resource stock (e.g. wood) or flow (water) relative to the rate at which they are used. For non-renewable resources, the limits are influenced by the reserve and by the dissipative character of the use, which is strongly affected by the design of the product and its life cycle [201]. **Dissipative use** means that the resource will not be feasible to extract for future generations. This is discussed further in the section on life cycle engineering for the end of life stage. Following this line of thinking, Wang and co-workers, provided a structured assessment for material availability in the case of steel consumption [222]. They tested various material efficiency strategies in relation to population and affluence growth. They concluded that manufacturing plays a key role in relation to future availability of resources, and that stock building is essential for both resource use and future availability of a metal resource like steel. Traditionally, material selection is done based on cost, properties and environmental impact. Target-driven life cycle engineering requires, in addition that resource availability and dissipation now and into the future are considered during the material selection stage in the context of absolute sustainability.

7. Manufacturing

"Manufacturing" is often used synonymously with "production or fabrication." However, it has a broader scope than "production" since it also encompasses managerial functions. Manufacturing is part of the supply chain between suppliers and customers of a manufacturing company, which includes the entire value chain, including design, fabrication and assembly, as well as the organizational functions, process planning and production planning and control [27]. In this context, manufacturing is critical to achieve sustainability and sustainable development [119] [210]. Due to rapid globalization, manufacturing organisations now operate in the form of global production networks, and their value creation process spans across the globe [140]. As a result, value creation takes different forms in different parts of the supply chain network, such as profits and dividends for shareholders, or salaries for workers, which is a key concern in the context of social sustainability [200], and it also holds the potential to affect environmental sustainability strongly [86]. However, the core function of manufacturing is to create value through a process of material transformations. When seen from this perspective, there are unintentional external effects involved in all manufacturing activities. In other words, just as global production networks create value they also have the capacity – intentionally or unintentionally – to destroy value in their environment [36]. This may occur through exploitation of non-renewable and renewable resources, over-burdening of natural environmental 'sinks' through increased concentration of greenhouse gases in the earth's atmosphere and of toxic materials in the environment, and destruction of growing numbers of ecosystems to create space for urban and industrial development as discussed

in Section 1. While these negative externalities impact both local and global ecosystems, logistics and outsourcing decisions of manufacturing organizations have a wide-ranging environmental impact [82] [154], and careful selection of suppliers and more efficient means of logistics can improve the environmental impact of products [126].

7.1. Organizational level

For manufacturing organizations to move towards sustainable practices, sustainability needs to be embedded into the planning from strategic, long term, to operational, short term, planning. Several researchers have investigated how to incorporate sustainability into manufacturing organizations [10] [11] [24] [137] [152]. Although the reported literature clearly states the importance of planning in implementing sustainability into manufacturing, the main focus of the studies has hitherto been on the relative improvement with a triple-bottom line improvement. Analysing more than 40,000 corporate sustainability reports from the period 2000–2014, Bjørn and colleagues found that only around 5% of the companies related to absolute targets (mainly for climate impacts) in their reporting [16]. To operationalise absolute sustainability, it is crucial for manufacturing organisations to have a strategic plan towards achieving the reductions in environmental impact that is needed to stay within the space allocated to their organisations [128]. This requires strategic planning of product and product technologies that need to be targeted for the necessary impact reduction while maintaining viability of the business [211]. In this context, Rödger and colleagues introduced a conceptual framework, which aims to link life cycle targets to the different levels of a production system with an absolute sustainability perspective [169]. The cone framework is aligned with a stage-gate model and allocates the target in a top-down perspective. All the defined enablers in each stage are linked to a full life cycle model and to the externally determined overall targets. The framework is demonstrated in a case study from the automotive industry

7.2. Technology and product development

Technology and product development are crucial since most of the environmental footprint of product technologies is decided during the product development phase. Accordingly, a challenge for companies is to reformulate their competitive strategy to integrate environmental considerations into the business and product strategies. However, product planning is closely tied to product strategy and directly determines a product's success or failure. Therefore, the technology strategy of an organization is closely linked to its long-term environmental performance [203] [204]. Manufacturing organizations need methodologies and tools for developing product technologies that allow them to reduce their environmental footprint. Bonou and colleagues highlighted the importance of having life cycle thinking in product development and they used life cycle assessment data to inform the decision made on material selection, product and process design and supplier selection [18]. In this context, it is critical that the product development activities should consider environmental impact of all activities associated with background and foreground systems in order to identify the highest achievable environmental impact reduction potential and to stop problem shifting. It is also critical that the entire product life cycle is planned prior to the technology and product development activities [211].

Design plays a critical role in achieving environmental sustainability of product and services [71]. Eco-design, also known as *Design for Environment (DfE)*, has been developed as a concept to consider environmental objectives during the product design. Several tools and techniques have been developed to help designers practice eco-design [37] [41]. There are two main categories of eco-design tools: rules and guidelines, and analytical tools. Rules and guidelines are particularly suitable for the early design stages of product development where there is very little data available. Analytical tools (e.g. LCA for focusing and evaluating design alternatives – see Section 10) are more critical during the later stages of product development e.g. detail design where there is more quantitative data. However, the design guidelines for implementation during the early design stage need to be calibrated with the analytical tools later to make sure that they are complementary [72]. Eco-design concepts have been developed to focus the design activities around a specific product life cycle stage. Design for manufacture and assembly (DfMA) has been introduced to reduce part count and associated energy and material use, which in return leads to reduction in environmental impact. Design for Disassembly (DfD) has been introduced to make the end of life (EOL) product disassembly easier [70] [189], whereas design for remanufacturing (DfRm) and recycling (DfR) has been introduced to make the remanufacturing and recycling of EOL products easier [205] [232].

However, these life cycle-stage oriented concepts have potential shortcomings. DfD, DfRm, and DfR, have typically been introduced without considering a full life cycle perspective, which means that they may lead to sub-optimal solutions in terms of reducing the total environmental impact of products over their life cycle. In addition, some of these concepts are not mutually supportive. For instance, DfMA encourages reduction of the use of fasteners, which often leads to combining parts and/or permanent assembly. This in return makes the EOL disassembly of products infeasible. Furthermore, life cycle-oriented concepts do not consider possible volume increases and technology changes, and as a result, the eco-efficiency improvement may not be adequate to offset environmental impact increases due to volume increase from one generation to another generation [133]. Finally, without an absolute sustainability perspective, they may target design solutions for which the expected environmental impact reduction potential falls dramatically short of what is needed to allow the manufacturing organization to achieve the absolute sustainability targets. Nevertheless, Eco-design tools and techniques are useful in the context of absolute sustainability once the targets are set. As shown in Fig. 8, the existing eco-design tools can be used to target the pre-defined sustainability level. This may require redesigning one or more of the enabling technologies by using existing eco-design tools within a product until the eco-efficiency limits of the targeted technology are achieved.

This process can be repeated until the required sustainability level is attained. Taking the example of electric cars, there are several enabling technologies such as battery, electric motor, power electronics, car structure etc. Once the allocated environmental space and timing are determined, each of these can be redesigned by using the existing tools and techniques by considering the volume growth of the car within the allocated time. If the targets are not achieved, one or more of the enabling technologies can be further redesigned until the required reduction is attained. It may also be possible to attain the required sustainability level with a *function or system innovation* or breakthrough technology [21]. In this context, existing eco-efficiency oriented DfX tools are complementary and useful once they are guided by absolute targets.

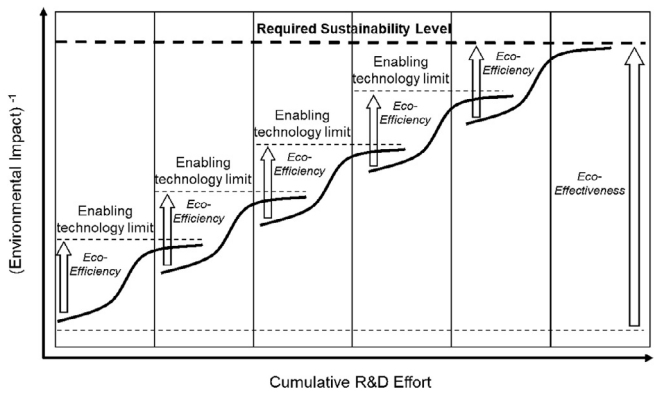

Fig. 8. Target-driven and consecutive eco-efficiency improvements leading to eco-effectiveness.

7.3. Operational aspects

Manufacturing operations create value by transforming raw materials into finished products by using energy, material and other resources, which, in return, may cause environmental impact. Therefore, increased operational efficiency may result in reduction of using these resources and their associated environmental impact [171] [222]. Manufacturing industry has achieved significant *material efficiency* improvement over the years through operational efficiency improvement measures. Further improvement has also been achieved by redesigning products with less material through light weighting strategies [85]. The main driver has always been the economics; hence, materials with high cost, e.g. gold, have a very high material efficiency associated with its use throughout the life cycle. However, materials efficiency is not a main concern for low-cost materials, even though they may be associated with a high environmental footprint as is the case with cadmium or chromium (VI). Therefore, it is critical that material efficiency should be encouraged, not just for economic reasons, but also to address the environmental impact that the material use [2].

Manufacturing activities dominate industrial energy consumption, causing 90% of industry energy consumption, and 84% of energy-related industry CO_2 emissions [39]. This reflects not only the increased production to meet growing demands for product and services, but also the increased energy intensity of many new processes used in the manufacture of these products as shown in Fig. 9 [62]. As a result, significant efforts have been invested in improving the *energy efficiency* in manufacturing in the last decade. The efforts have targeted five different levels of the manufacturing: namely device/unit process, line/cell, facility/factory, multi-factory system and supply chain. A major research activity has focused on predicting the energy use in manufacturing and its associated environmental footprint.

At the *unit process level*, the main focus has been on developing models to predict energy consumption of manufacturing processes [62] [127]. These models are used for defining eco-efficiency of manufacturing process as shown in Fig. 10.

At the *line/cell level*, the main focus is on the eco-system of network of machines within a factory, which are connected to each other with input-output relations. In this environment, multiple forms of energy use and waste energy recovery are of concern [39]. Predictive models and methodologies can later be used for designing production lines with an improved energy efficiency. However, in order to reduce the environmental impact, and increase the efficiency of manufacturing and achieve its global optimum, one must consider the operation of the factory at the *facility/factory level* with a holistic view. This should not only include production machinery, but also building shell, technical building services and building climate, production machines/material flow, and production management, including production planning and scheduling (see Fig. 11).

The majority of the energy consumption in a factory is thus a result of infrastructure like technical building services (indirect energy consumption) that is needed in order to support production (direct energy consumption). At this level, simulation-based methodologies have been developed and used to predict and assess the energy efficiency and the associated environmental footprint of factories [84]. Energy efficiency at the plant level can be achieved either at the level of product, machine, facility and supply chain design or at the level of product design, process design, process adjustment and post-processing [39].

Moving higher up to the level *beyond factories*, energy efficiency can be achieved via either interaction between economically independent companies or interaction between suppliers and customers. Efficiency improvement in the interaction between independent companies may happen through exchanging and utilizing flows of materials and/or energy to their mutual benefit, increasing overall output from the given input; hence increasing efficiency through the use of flows that would otherwise have to be treated as waste. This concept is also known as industrial symbiosis, and as discussed in Section 4, the potential for environmental impact reduction through energy and resource efficiency at this level depends on the trade-off between the induced processing, transport and upgrading of the waste stream and the avoided extraction and transport of the virgin resources that are replaced by the waste stream [39].

At the *supply chain level*, interaction between upstream and downstream suppliers and customers takes place through transportation of goods and use of non-renewable energy and resources. Energy efficiency at this level is influenced by climate, distances, and energy sources and its associated price structure [39]. Therefore, the focus is not only on the energy efficiency of manufacturing systems, but also on the energy embodied into producing a product and the associated environmental impact as a result of supply chain activities. At this stage, a product life cycle view is critical since each product life cycle stage can be carried out in different geographical locations. As the above-mentioned country specific parameters may vary significantly along the product life cycle, the environmental impacts associated with the energy use along the value chain are highly dependent on the locations. Therefore, 'embodied energy' is used widely as a more objective measure since the types of primary energy used may vary from electricity to coal and petrol [39].

Irrespective of the level of energy efficiency measures considered, environmental impact associated with energy consumption depends on the energy mix at the source. The on-going decarbonisation of energy grids around the world via increasing the use of renewable energy sources will significantly reduce the current coupling of energy use and climate change impacts and potentially weaken the

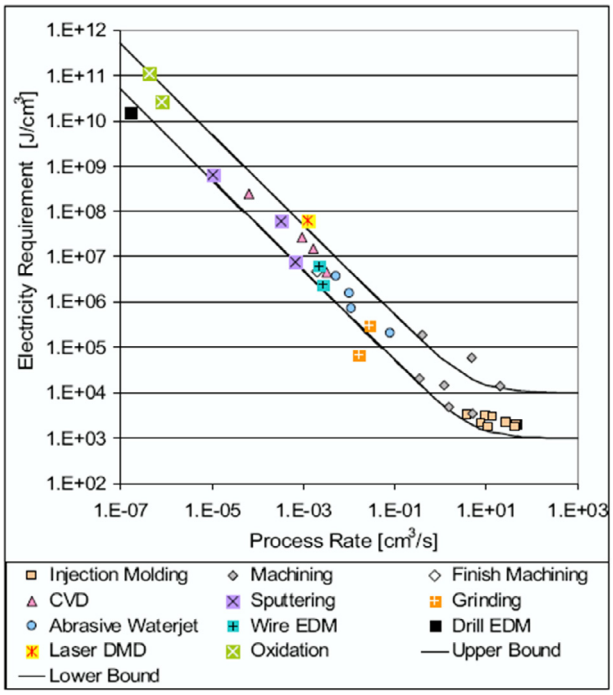

Fig. 9. Energy intensity of manufacturing processes [62].

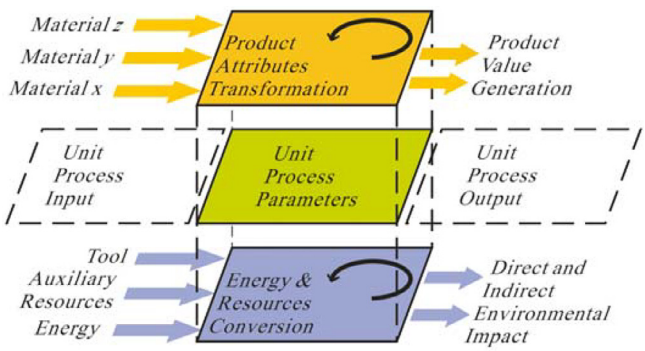

Fig. 10. Unit process eco-efficiency of manufacturing processes [143].

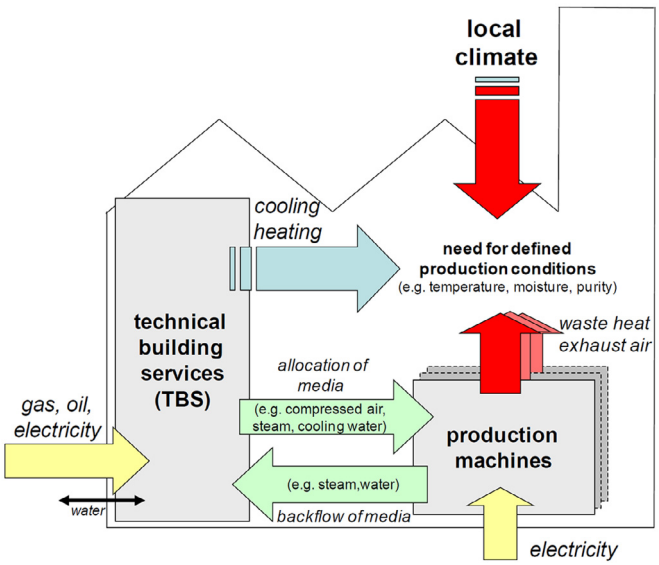

Fig. 11. Holistic view of a factory for energy efficiency [82].

focus on energy efficiency in the future. However, caution should be exercised since the level of impact reduction required to meet the absolute targets may not be achieved through increased use of renewable energy alone. Renewable energy technologies also have environmental impact e.g. due to their dependence on non-renewable resources and chemicals. Furthermore, for the coming decades, the effort required to transition the energy system to renewable energy sources will depend on our ability to economize the energy use. Therefore, energy will also be relevant and in focus into the future.

7.4. Target-driven life cycle engineering of the manufacturing stage impacts

The life cycle engineering focus on the discussed efficiency measures for manufacturing should be determined by the role that manufacturing plays in the product's total environmental impacts over the life cycle. For single use products like packaging or disposable razors, manufacturing (and potentially end of life – see Section 9) typically dominate the life cycle impacts, and eco-efficiency improvements through life cycle engineering of product and manufacturing processes may help achieving absolute sustainability targets as discussed above.

8. Use and maintenance

For most product categories, the use stage in a product life cycle is often the most critical stage from an economic as well as an environmental perspective. For portable active devices like mobile phones and tablets, the energy efficiency is often so high (to ensure a decent battery life) that the resource and manufacturing stages dominate the life cycle impacts. For most active products that require energy or consumables during their use, e.g. washing machines, cars or TV sets, the use stage is however the main environmental hotspot in the life cycle meaning that the major part of the total environmental life cycle impact is linked to the use stage energy and resource consumption. The environmental impact associated with the use stage can be reduced from several perspectives.

8.1. User behavior and product performance

As a first step, manufacturers should target the *energy and resource efficiency of the product* during the use stage through optimization of the product design. Mandatory international standards have been established for different markets to enforce industry to increase the use stage energy efficiency of their active products. Examples of such standards are Minimum Energy Efficiency Standards (MEES) in the European Union, National Energy Conservation Act (NEACA) in the US and Minimum Energy Performance Standards (MEPS) in Australia. These standards specify a minimum level of energy performance that products must meet or exceed in order to be certified for sale or used for commercial purposes in that market [230]. Market transparency regarding the energy efficiency performance of products is supported by the energy labeling schemes, rating the product against a common product-specific scale at the point-of-sale, to allow customers to compare similar products through their energy class rating and estimated annual energy consumption. The manufacturer perspective may also leverage lower environmental impact through designing the product in such a way that it functions longer than usual. When the *product life is extended*, the consumer needs fewer product units to obtain the same service, and the activity of and environmental impacts from the other stages of the life cycle (production and end of life) are reduced. As discussed in Section 4, extending product life through maintenance is the most efficient and preferred circular economy strategy in most cases. The results of manufacturers' efforts depend on the willingness of consumers to buy the best performing products. labeling schemes are helpful, but more effective advertising may be needed, as Shu and co-workers put it: "Future information-based interventions can no longer take the form of dry warnings from government and scientists, but should exploit the same advertising forces that drove overconsumption in the first place" [188].

The environmental impacts of the use stage also depend on *how products are used*, for instance, whether the lights are turned off when not in use, and whether detergents are dosed appropriately. Shu and co-workers argue that the utilization of products by end-users can be influenced by product design, and they describe two main approaches that designers can apply to reduce the resource consumption related to the way products are used. First, interventions can aim to convince consumers to adopt the desired use behavior through information and feedback, physical affordances etc. Second, automated systems can take over and perform the desired behavior. For both approaches, advantages and limitations of various methods are discussed.

The paper by Shu et al. is informed by insights on pro-environmental behavior from social psychology and behavioral economics. These fields focus mainly on individual values, attitudes, choice, and behavior combined with some attention to social norms and external conditions for individual behavior. In contrast, researchers from the field of social practice theory focus more on the collective construction of shared practices and emphasize the limited autonomy of the consumer. For instance, it is explored how the social practice of daily showering emerged through the interplay of technological, social and cultural changes [68] [190]. This practice is an example of the more general phenomenon that much resource consumption in daily life is related to mundane activities that consumers hardly consider in environmental terms. Social practice theory is increasingly dealing with environmental issues [174] [187], and the approach is applied in design studies [93] [138] [139] [185] [186]. Concerning interventions to reduce resource use in daily life, Spurling and colleagues compare the recommendations from the behavioral and the practice approaches, respectively, and find both overlaps and differences. For instance, the practice approach calls for involving a broader set of actors [193].

8.2. Product service systems and product-sharing strategies

Industry can also achieve higher energy and resource efficiency either through developing products with longevity or introducing a dematerialization strategy such as *product service system (PSS)* or sharing economy. Both strategies entail a shift in the ownership of the product. In PSS, the producer's business model shifts towards selling the service of the product rather than the product - the product ownership stays with the original equipment manufacturer (OEM), and only the service is provided to consumer [153]. In the *sharing economy*, the product ownership may not stay with the OEM,

but, from the consumer perspective, it provides the same value e.g. providing service without the consumer owning the product. Tukker identifies eight different classes of PSS and argues that they all have the potential to provide the same product functionality to the user with reduced resource loss and hence a lower environmental footprint. For most of them, the improvements are, however, judged to be incremental, and also with PSS and sharing economy solutions there is the risk of a rebound effect countering these efficiency gains, depending on the extent to which increased and cheaper access to the service inspires increased use of it or spending of the saved money on other activities with higher environmental impact [208]. Furthermore, there is the risk that users will care less about the product than owners, leading to a shortened service life of the product [153]. This will vary with the type of service, the system offers, but taking the example of car-sharing systems, several studies have looked into this aspect and they all found that in the cases that they studied the car-sharing system is associated with lower environmental impacts than the individual car ownership alternatives. This advantage of car-sharing over car-ownership systems resides in the fact that fewer vehicles have to be produced in order to meet the transport need (which is the core of a sharing economy concept). Furthermore, there seems to be no immediate rebound effect in this case (the studies did not consider other potential consumption arising from any financial savings with the users). Car-sharers tend to drive fewer kilometres in total which is essential since the main impacts of the car product system lies in the use stage [25] [129] [156].

8.3. Maintenance

The physical value of the product is preserved through maintenance, reuse and remanufacturing strategies. In all these strategies, maintaining the proper functionality of products is critical for the consumer. Therefore, proper *planning of maintenance* is critical for minimizing the environmental impact as well as reducing the life cycle cost of products. To this end, Iijima and Takata proposed a condition-based methodology for integrated planning for maintenance by using design tree and failure index based on mean time to failure [91]. Maintenance is also a key enabler for product service systems (PSS). Cunha and colleagues [34] developed a framework for managing maintenance to reduce the operational cost and match the planned output and quality levels.

8.4. Target-driven life cycle engineering of the use stage impacts

For the use stage, the additional task of target-driven life cycle engineering is to identify potential rebound effects that may result from efficiency improvements of the product, take them into account when determining the share of the operation space that the product can claim [133], and consider what can be done (if anything) from engineering side to avoid that they neutralize the achieved improvements. For the car-sharing case, a next step could be introduction of autonomous vehicles that will increase the number of potential users by making individual driving available to users without a driver's license, potentially leading to a rebound effect that neutralizes the previously mentioned environmental benefits of car sharing. There are at this point only few studies of the environmental performance of autonomous driving (e.g. [55]), and the extent of such rebound effects remains hypothetical at this point, but it is an important task to consider design solutions for the car and the autonomous driving system that may help counter them.

In continuation of Section 3.6, a broader systemic perspective can go a step further by not taking the demand for a certain functionality as given and instead knowing that provision and demand are co-constructed [210]. Studies have demonstrated the historical coevolution of provision systems and demand, for instance, in relation to the diffusion of air conditioning [31] [184] and the use of other resource consuming equipment [190]. Looking back, the *coevolution of provision and demand* often implied increased resource consumption. Today it is often argued that the application of information and communication technologies (ICT) opens large opportunities for resource-savings, but in practice, many other opportunities related to ICT are also realized and develop as transitions in the wrong direction [175]. Considering the challenge of absolute sustainability, the question is how to develop provision systems that coevolve with reducing demand and avoiding the development of new resource-intensive practices. This will require a considerable change of perspective.

9. End of life (EOL)

The end of life stage of the product's life cycle is critical due to the economic and environmental impact associated with EOL treatments like landfilling and with depletion of non-renewable resources. In early life cycle assessment literature, this stage was called the disposal stage (e.g. [224]) indicating that the purpose was to get rid of the waste, but with the emergence of circular economy thinking, final disposal in the form of landfilling is the last resort for most products. As introduced in Section 4, the circular thinking hence operates with several EOL scenarios closing the loop to different parts of the product life cycle for managing these products, as illustrated in Fig. 12.

Among these scenarios, maintenance and repair (Scenarios 1 and 2) are about extending the useful life of products during the use stage, as discussed in Section 8. Other possible EOL scenarios involved during this stage are product reuse, product upgrading, downgrading, remanufacturing, material recycling, incineration and landfill. These scenarios involve multiple processes like disassembly, shredding, sorting, cleaning and inspection. Successful management of EOL products thus requires various stakeholders to work together from users, over waste regulators at municipal level and logistic service providers, to waste management centres.

9.1. Logistics for collection of EOL products

Collection of EOL products plays an important role as an enabler since it dictates the efficiency that can be reached with any of the EOL scenarios. EOL product collection, referred to as reverse logistics, is the coordination of material movement and resources to collect products at the end of their life. Various issues need to be addressed for successful operation of *reverse logistics systems*. Collection strategies need to involve the local stakeholders (e.g. retailers, local councils and their collection systems) and the existing infrastructure (e.g.

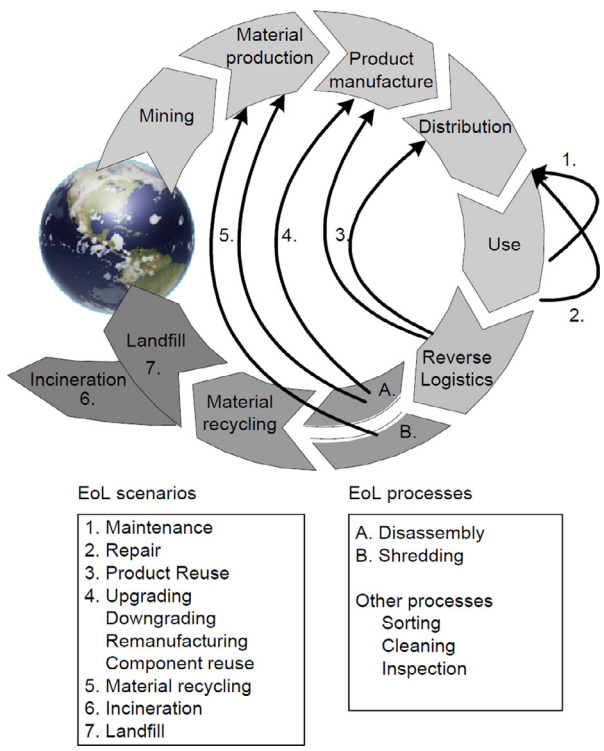

Fig. 12. Product life cycle with end of life scenarios and related processes [38].

waste management systems) in order to increase the efficiency of the collection system [66] [67]. In addition, viability of such collection strategies heavily depends on the volume of returned products. As opposed to the market forecasting in a forward logistics system, which is directly controlled by the Original Equipment Manufacturer, forecasting of flows of EOL products has various challenges and uncertainties. These stem from various reasons including the lack of involvement of OEMs in managing EOL products and the fact that the decision of disposal typically is made solely by the end user who is influenced by the demographics of the locations. These uncertainties can be addressed in EOL planning by using techniques such as fuzzy logic and color petri-nets [65]. Once the existing stakeholders and the volume of EOL products are determined, reverse logistics networks can be designed, taking into account factors like the number and the type of participants in the system, the number and location of facilities, collection points, characteristics of the material flow and product characteristics. Similar to the forward logistics network design, different methodologies can be used for designing reverse logistics networks. Kara and colleagues used simulation modeling to design a reverse logistics network for EOL household appliances with the aims to minimize cost and environmental impact [124]. Seliger and co-workers developed an optimization methodology to find optimum capacity planning for remanufacturing of mobile phone factories. The authors argued that simulation could be used to test different scenarios that are optimized by the optimization model. eM-Plant simulation software was used to automatically generate a simulation model from the optimization results [183]. Jin and colleagues [116] introduced an approach for designing reverse logistics networks for rare earth materials. Fuzzy logic is used to address the uncertainty in the supply of the products and uncertainty in customer demand. Genetic algorithm is used as optimization method to configure the network in terms of deciding which dismantler and recycler should be open for operations. Although, the main objective is to maximize the profitability of the network, environmental impacts are also addressed in the optimization model as a function of different parameters such as transportation between entities.

9.2. Determining remaining useful life

In the next step of the EOL management of products after the collection, a decision needs to be made for the most suitable EOL scenario. This requires determination of remaining useful life of products and components in relation to their physical and technological life [125]. For instance, a product may have adequate useful physical life, but the technology may have become obsolete to allow reuse of components in new products as an EOL scenario. The first part of this, remaining physical life, is a function of the intended and designed operating life and usage life. *Operating life of products* can be estimated by using various means such as Mean Time to Failure and empirical data from life cycle monitoring if available by using Weibull analysis. They employed various techniques such as multiple linear regression analysis, Ordinary Kriging, or artificial neural network. The results of the second step show the lifetime prediction of the components in addition to the generated results in the first step. The methodology was applied in a case study of an electric motor to show its applicability and usefulness. However, the estimation of usage life is very challenging since it strongly depends on the behavior of the user/operator and conditions of use. It is a critical parameter that indicates the actual age measured in operating time (hours, cycles, kilometers, etc.) that a product or a component has been used. A simple way to determine the actual age is by measuring in calendar time units (i.e. days, weeks, months, and years) and/or assume a constant usage intensity throughout its lifespan [125]. However, this approach rarely produces a realistic estimate, and therefore, various methodologies have been developed to support a more realistic assessment of this critical parameter. Most of these methodologies utilize life cycle data collected from various sources, for example, data recording units in consumer products, such as electronic data log (EDL), life-cycle data acquisition units or using filed surveys. The collected data can be analyzed using regression analysis, artificial neural networks etc. to establish a degradation pattern in order to estimate the usage life. As mentioned before, the *remaining useful life* of a component is not only governed by its physical life, but by its technological life as well. In order to have a realistic estimate, the technology life of a product must be considered, which requires the forecasting of the technology of a given product [125]. Growth-curves commonly used in technology forecasting can also be used in this context to determine the remaining technological life of products. If the remaining physical and technological life of products or components is sufficiently long for another operating life, they can be considered for reuse and remanufacturing as an EOL scenario (see Fig. 12). Otherwise a suitable EOL scenario would be an option as shown in Fig. 12.

9.3. Disassembly

In order to prepare products or components with adequate remaining useful life for the different reuse, repurposing, and remanufacturing EOL scenarios, they need to be properly disassembled. Disassembly is one of the critical steps in the EOL management of products and involves extraction and segregation of the desired components, parts or material from the products in which they are used. Proper disassembly of EOL products allows higher material recovery efficiency and reduces the share of materials going to landfill, and it is hence one of the key steps towards closing the material loop and achieving circularity [205]. However, disassembly of EOL products is challenging due to the general lack of information about the product and its use history, and the uncertainties around the product volume and condition [38]. Due to these challenges, it has been one of the most investigated research areas in life cycle engineering within and outside the CIRP community since the early 1990s [19] [38] [118] [232]. Specific research efforts have been focused on disassembly planning [56] [179], disassembly sequencing [121] [123], and, more proactively, design methodologies for disassembly [158] [189] [213] [233]. There has also been research into the automation of disassembly processes [220]. Other researchers have developed active disassembly techniques based on product design [38] [231]. Despite the academic efforts and the strong importance for sustainable processing of EOL products, disassembly remains a huge challenge today, partially due to economic feasibility and the fact that products are rarely designed with an EOL disassembly in-mind.

9.4. Reuse and remanufacturing

Properly separated and sorted subassemblies and components can be considered for reuse and remanufacturing as feasible EOL scenarios. Economic and environmental benefits of reuse and remanufacturing have been widely discussed in the literature [183] [198] [199] [225]. Others have developed tools and methodologies to enable reuse and remanufacturing during the planning and operational stages [117] [155] [144] [205] [214] [223]. Despite the argued economic and environmental benefits, there are several social and economic challenges in implementing reuse and remanufacturing that need to be overcome in the near future, including poor information about the returned products, high variability on the condition of post-use products, short product life cycles, increasing product complexity, and quality of returned products [205].

9.5. Recycling

After the separation and sorting, components that cannot be reused or remanufactured can be sent to shredding and material recycling. Due to the challenges in disassembly and separation of product components, material recycling is a prevailing EOL strategy within the circular economy, although the other loops in Fig. 12 are given priority. Recycling as a material recovery strategy has been examined from various perspectives focusing on design (for recycling), recycling process planning and technologies, and economic and environmental impacts. Sodhi and Knight introduced a design methodology to assess product recycling as an EOL scenario [189].

Umeda and colleagues introduced a life cycle simulation model that can be used during product design to assess various EOL scenarios, including recycling [212]. Zussmann and colleagues introduced a disassembly-oriented assessment methodology to support design for recycling by using graph theory [232]. In relation to recycling process planning and technologies, Mativenga and colleagues introduced a new methodology for recycling glass fiber composites by using high voltage fragmentation (HVF) and compared with the existing mechanical recycling. They concluded that the HVF shows a better performance in terms of recycled material quality, but it is more energy intensive [149]. Colledani and Tollio introduced an integrated process and system modeling for the design of material recycling systems [28]. Lee and Rahimifard introduced a new approach for particle separation in a recycling process (air column classifier). Experiments were done showing that the new approach is more efficient in terms of the purity of the particles compared to the traditional technologies [142]. Rahimifard and colleagues introduced recycling process planning for the end of life management of waste from electrical and electronic equipment [162]. Economic and environmental feasibility of recycling in various context has also been the focus of several studies [40] [160] [209].

9.6. Target-driven life cycle engineering of the EOL stage impacts

There has been a strong focus on the EOL stage in life cycle engineering literature. However, the majority of the work has aimed for improving the economic and environmental feasibility of EOL scenarios, i.e. improving the eco-efficiency of the different techniques. It is clear from the circular economy perspective in Fig. 12 that the EOL stage needs to be seen and planned in relation to the other stages and activities of the product life cycle in order to be effective. In the context of absolute sustainability, there has however been no research on to what extent the EOL stage and different EOL scenarios are the relevant hot spots on which to focus in order to achieve the reduction in environmental impacts that is required for companies or their product portfolio to stay within the planetary boundaries. As illustrated by Wang and colleagues, the ability of circular economy strategies to leverage absolute sustainability in terms of future availability of mineral resources, in particular steel, is questionable [221] [222]. Without reductions in consumption it is not possible to envision a sustainable society – the EOL strategies under circular economy are not sufficient.

As a further challenge to life cycle engineering, the efficiency and impact reduction potential of most of the EOL scenarios are heavily dependent on parts of the background system e.g. product collection or centralized disassembly and sorting units, that lie outside the control of the company that engineers the product. With increasing societal focus on absolute sustainability goals, it could be imagined that changes in these systems may facilitate future life cycle engineering for eco-effective EOL treatment.

10. Assessment tools for the life cycle engineer

Life cycle engineering targeted towards absolute sustainability must rely on assessment tools that represent a life cycle perspective on the product or system that is engineered.

10.1. Life cycle assessment, LCA

LCA is the analytical backbone of life cycle engineering. It helps identify the hotspots in terms of environmental impacts throughout the product life cycle and support identification of focus points for the engineering, and it is used to assess the improvement that is achieved with alternative designs of the product or the product life cycle.

LCA has been standardized in a series of ISO standards covering the methodology [97] [98] and various applications of LCA like eco-efficiency assessment of product systems [102], environmental labeling and communication [95] [99] [100] [105] [106], product development [96], carbon footprint [101] [107] [108] [109] and water footprint [104]. Building on the ISO standards, the European Commission has developed detailed guidelines for the method [42] and its application in assessment of the environmental footprints of products and organizations (PEF and OEF) [49].

The most important characteristics of LCA in order to support life cycle engineering targeted towards environmental sustainability are three:

The first characteristic is the method's *focus on the function* that is provided and thereby its support of a systemic perspective on the product or technology that is engineered. The function is quantitatively defined as part of the scoping of the LCA and serves as the anchoring of comparisons between different alternative solutions. This aligns very well with the functional focus of life cycle engineering – the compared alternatives need to be functionally equivalent, but the upscaling to the societal level requires that the total number of products be taken into consideration, as discussed in [134] and [211].

The second important characteristic is the method's *life cycle perspective*, considering all the activities that are needed for the product or solution to deliver its function – from the extraction of resources and production of materials (the cradle) over the manufacture, distribution use and maintenance to the end of life processing (the grave). Sustainability assessment requires such a systems perspective to identify and preferably avoid problem shifting when engineering solutions to a problem in one part of the life cycle create new problems in another part of the life cycle.

The third important characteristic is the method's *broad coverage of environmental impacts*. According to the ISO 14,044 standard [98]: "The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration." This requirement is intended to ensure that burden shifting between environmental impacts are revealed when engineering solutions to reduce an environmental impact (e.g. climate change) increases other impacts (e.g. environmental toxicity from discharge of chemicals from processes along the life cycle).

The development of the LCA methodology has mainly taken place over the last three decades [17]. An initial emphasis on the conceptual foundation and the overarching principles as laid down in the ISO standards has been followed by a strong focus over the later decades on development of inventory data for life cycle processes (for manufacturing e.g. [130] [131]), impact assessment methods for the many categories of environmental impact that are covered in LCA, and development of international scientific consensus on methodological recommendations [53] [75].

A recent research effort of interest for the absolute sustainability perspective in life cycle engineering is the development of spatially differentiated impact assessment that allows taking regional variations in environmental sensitivity into account when assessing regional and local impacts like acidification, particle air pollution, environmental toxicity, water use and land use [77]. Apart from increasing the environmental relevance of the results of the impact assessment, the regionalization also supports relating the impacts caused by the product to environmental boundaries or carrying capacities of the systems that are actually impacted by processes in the life cycle of the product [15].

Another important research effort in this respect has been the attempt to move LCA from just supporting relative comparisons ("is alternative A better than alternative B?") towards also supporting *absolute assessments of environmental sustainability* ("is any of the alternatives environmentally sustainable?"). Bjørn and Hauschild proposed introduction of the absolute sustainability perspective into LCA via the normalization of product impacts against the environmental space available for an average person [13] – see Table 1. Ryberg and colleagues took a different approach and developed a new life cycle impact assessment method based on the Planetary Boundary concept [173] and implemented it in a case study of laundry washing to assess which among a series of system changes and life cycle engineering activities could make the activity environmentally sustainable in absolute terms [172]. The latter requires an

allocation of the environmental pollution space that is available (as determined by environmental boundaries), to the level of an individual product, or in this case activity, as discussed in Section 1.2, and Ryberg and colleagues test different allocation principles and show the sensitivity of the result to the choice of allocation principle [172].

10.2. Life cycle costing and social life cycle assessment

Sustainability assessment requires tools that cover all three dimensions of sustainability, the environmental, the economic and the social. Although the focus of this keynote is on the environmental sustainability as argued previously, a brief introduction is also given to life cycle-based assessment tools that cover the other two dimensions.

A candidate for the assessment of the economic sustainability of a product is *Life Cycle Costing (LCC)*, which examines the economic costing issues of the product, applying a life cycle perspective similar to what is done for the environmental sustainability dimension with LCA. Synonyms of LCC are Total Cost of Ownership (TCO), Through-Life Costing (TLC) or Whole-Life Costing (WLC) [20]. As a methodology, LCC predates LCA with its early roots in the 1930′s where the United States General Accounting Office (GAO) in a tender for tractors requested an assessment of the costs considering a life cycle perspective on the tractors [216]. In contrast to LCA, it is not obvious how to scope the LCC in terms of which costs to include in the study. What is a cost to one actor along the life cycle (e.g. the customer and user of the product) is a gain for another actor (e.g. the manufacturer of the product). Furthermore, there is an ambiguity about which costs to include – only financial costs or also external costs in forms of social implications or environmental damages.

These ambiguities inspired Rödger and co-workers to distinguish three types of LCC as illustrated in Fig. 13: Conventional LCC (financial LCC) focusing on the direct financial costs (e.g. to the owner of the product), Environmental LCC including the external costs (to society) due to environmental damages, and Societal LCC also including external costs (to society) due to social impacts like affected well-being or job quality [170].

While conventional LCC has a single actor perspective, environmental LCC has the perspective of the whole life cycle and includes monetarized costs from the environmental damages caused by the product in its life cycle. As such, the environmental LCC is best aligned with the scoping of the product system that is applied in LCA, but with its inclusion of external costs from environmental damages, it entails a double counting of the environmental impacts from the product system, which are already quantified by the LCA.

The manufacturing company has influence on multiple actors along the life cycle of its product, and this entails responsibility for the social impacts as well as the environmental impacts as illustrated by Fig. 14.

Assessment of social sustainability should thus take a life cycle perspective which also enables the identification of trade-offs between different parts of the life cycle. The strongest social impacts are often found in the raw material extraction and manufacturing stages [200] and may also show problem shifting with environmental impacts, the disclosure of which requires the combination of *social LCA (sLCA)* and environmental LCA. sLCA is a relatively young discipline and the methodology is less mature than environmental LCA. Nevertheless, an authoritative set of guidelines has been released by the UNEP-SETAC Life Cycle Initiative [9]. In the summary of main learnings from development and use of sLCA, Hauschild and colleagues emphasized that 1) social impacts are highly locally specific and difficult to predict from the type of process applied in the life cycle, since they are determined by the behavior of the company rather than the characteristics of the process; 2) social impacts are not straight forward to relate to the process and hence the product since they are dependent on the policies of the company rather than characteristics of the process. The objective physical connection that exists between the process and the emission flows for environmental LCA has no parallel in sLCA. And vice versa, the most important current social challenges cannot be linked to individual products or technology choices as discussed in Section 3.6; 3) the product life cycle can have both positive social impacts like capacity building among employees and negative impacts like discrimination (in contrast to environmental LCA where impacts from the emission flows are all negative) [74]. Sutherland and colleagues give a summarizing review of the existing methods and application studies of social LCA [200], and so far, the applications in life cycle engineering context have been limited.

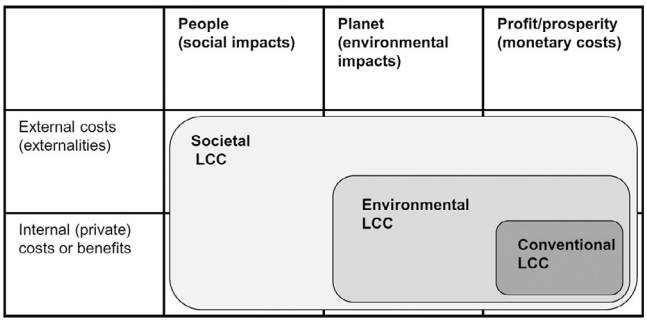

Fig. 13. Different types of LCC distinguished according to included costs and scoping in terms of sustainability dimensions (from [170]).

10.3. Life cycle sustainability assessment

Together, LCA, LCC and sLCA cover the three pillars of sustainability, and a combination of the three into a life cycle sustainability assessment (LCSA) has been proposed [136] [216]:

$$LCSA = LCA + LCC + sLCA \quad (4)$$

The summation requires that the outcome of the three assessments is expressed in a common metric, which typically entails a translation of the social and environmental impacts into monetary metrics with the uncertainties that this introduces (substantial for an impact like climate change), but there are other and more problematic issues. The dependence of the resulting life cycle costs on the chosen perspective was mentioned previously, and along this line Jørgensen and colleagues question the relevance of the LCC results in

Table 1
Annual per capita impacts that represent the current (2010) situation and a situation where ecosystem carrying capacities are respected for the impacts normally quantified in LCA (data from [13] and [141], global population 6.9 billion).

Impact category	Current impact	Sustainable impact
Climate change	8.1 ton CO_2-eq	0.98 ton CO_2-eq
Ozone depletion	0.041 kg CFC-11-eq	0.078 kg CFC-11-eq
Photochemical ozone formation	57 kg NMVOC-eq	2.5 kg NMVOC-eq
Terrestrial acidification	$7.8 \cdot 10^2$ mol H^+ eq	$1.4 \cdot 10^3$ mol H^+eq
Terrestrial eutrophication	$3.5 \cdot 10^2$ mol N eq	$1.8 \cdot 10^3$ mol N eq
Freshwater eutrophication	0.62 kg P eq	0.46 kg P eq
Marine eutrophication	9.4 kg N eq	31 kg N eq
Freshwater ecotoxicity	$6.7 \cdot 10^2$ [PAF].m^3.day	$1.0 \cdot 10^4$ [PAF].m^3.day
Land use, soil quality	9 tons eroded soil	1.2 tons eroded soil
Water depletion	395 m^3	490 m^3

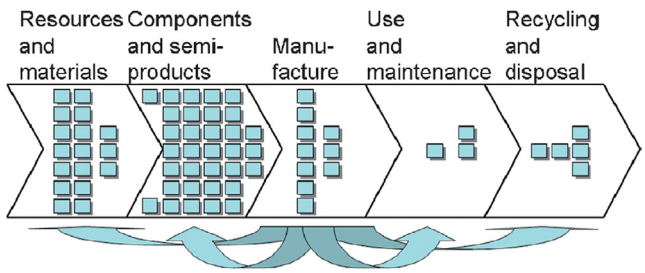

Fig. 14. The manufacturing company may influence the behavior of actors and processes (blue boxes) in all stages of the product life cycle as illustrated by the arrows (from [74]).

a sustainability assessment, unless it is focused on the economic consequences for the poorest population groups [120]. If, on the other hand, it is focused on these groups, the impacts should be covered by the sLCA results in the equation, and the LCC becomes superfluous in the equation.

In the context of absolute sustainability, the largest issue is the assumption that impacts in the three sustainability dimensions can be summed and thereby compensate each other as illustrated by the view in Fig. 15a. This is incompatible with the fundamental premise that there are absolute boundaries for the environmental impact that need to be respected to avoid collapse of ecosystems and climate systems that would undermine both the social and economic sustainability dimensions. The social and economic dimensions are nested inside the environmental dimension and trade-offs are only possible if the boundaries of the latter are respected, which is currently not the case for e.g. climate change and loss of biodiversity, according to Steffen and colleagues [196].

In summary, while the assessment toolbox for life cycle engineering has tools for both social and economic impacts, it is the environmental LCA that is and should remain the analytical backbone of life cycle engineering.

11. Conclusions and outlook

Our civilization is facing daunting challenges to transition our current societies and lifestyles into sustainable forms that will allow meeting the expanding needs of a growing population within the constraints posed by a climate crisis and a strongly accelerated loss of biodiversity. This requires changes in consumption patterns, reflecting the notion of sufficiency on top of the current focus on efficiency, but it also requires fundamental changes in the technology and the products that are consumed. Life cycle engineering has a crucial role to play and the existing LCE tools must be used, but in order to leverage sustainable consumption and production in absolute terms, life cycle engineering must qualify its traditional quest for technology (eco)efficiency with information about the goal. For sustainability, we propose as a goal that the total environmental impact of our activities must remain within the carrying capacity of the natural ecosystems and respect the planetary boundaries that define what a safe operating space for our civilization is. In order to enable life cycle engineering activities to contribute to achieving this goal, a top-down perspective and a bottom-up perspective must meet. The top-down perspective analyses man-made impacts on the natural environment and climate and quantifies the limits that they must respect. The resulting operating space is translated from global and regional scales to the scale of the individual life cycle engineering activity (products and product portfolios) with input from larger scale concepts like circular economy and industrial symbiosis. The bottom-up perspective starts with the existing LCE tools, positions them according to their focus on different parts of the product life cycle and investigates their leverage in terms of efficiency improvements. When the two perspectives meet, the efficiency improvements turn into a quest for effectiveness and life cycle engineering solutions can be judged on whether they have the potential to deliver the level of improvements that is needed to achieve future consumption and production patterns that are not just *more* sustainable but sustainable in absolute terms ('from better to good enough' [76]).

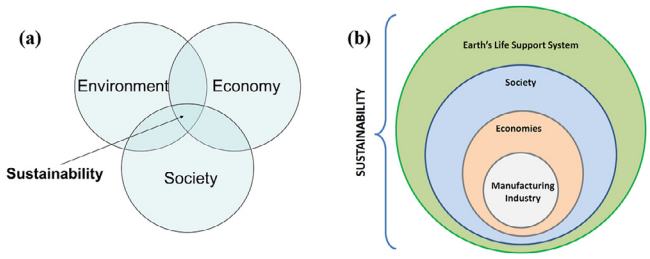

Fig. 15. The three sustainability dimensions from triple bottom line (a) to absolute environmental sustainability (b) (from [78], based on [168]).

Target driven life cycle engineering that allows us to stay within the safe operating space is a very demanding and ambitious task, and it poses a series of *future research challenges* as presented throughout this paper. These are:

- Quantifying the boundaries, also for other impacts than climate change and finding ways of distributing the space within the boundaries among different societal activities.
- Distributing the space between different life cycle engineering activities and enabling a global perspective that positions these activities in a total view on the product life cycle and ensures that together they are able to offer the improvements that are needed to become eco-effective.
- Tailoring the different tools in the toolbox of life cycle engineering to incorporate an absolute environmental sustainability perspective.
- Developing new tools and approaches that support the more fundamental function- or system innovation that is needed when incremental improvements from efficiency-focused engineering result insufficient to meet the absolute sustainability targets (See Fig. 2).

While we have looked into the predictable and tangible conditions and requirements to our future development of technology, we must keep in mind that also the future development in societal conditions is fundamental for our ability to create sustainable consumption and production in the future.

We believe that this requires:

- Equity and just distribution and use of the limited resources to allow the transition to sustainable consumption and production to occur in parallel with a socially sustainable development for the large population groups that still today live in poverty.
- Functioning and well managed societies with economies that support a sustainable transition (e.g. through internalization of the environmental and climate-related externalities ensuring that prices better reflect the costs to society) and that through regulation avoid that rebound effects counter the improvements that are achieved through technological efficiency improvements.

Educators have an important role in disseminating the mindset of a sustainable citizenship among the new generations. Educators of future engineers have a particular role in giving them an understanding of the role of engineers in creating technologies for sustainability, in disseminating assessment and synthesis competences for sustainability.

We have argued that societal and behavioural changes are essential for sustainable development, but technology development and engineering are also essential for allowing us to meet the majority of the United Nations' sustainable development goals. *The manufacturing industry has a central role* to play and there are obvious business opportunities for companies that align their business with the targets under the goals and make sustainability their business. It is of highest interest for all strategically thinking companies to start gauging the environmental impacts of their activities and product portfolios against their share of the safe operating space and plan their future development in a way that fits within this space. This is to ensure that they in the future become part of the solution rather than part of the problem.

The main focus of academic research in scientific communities has hitherto been on energy efficiency and on specific engineering activities (notably disassembly, as mentioned in Section 9) with at best a relative life cycle perspective but without any consideration of the effectiveness. This needs to change in the future – engineers and technology development have a pivotal role in enabling a development that allows us in the future to respect the boundaries of environmental sustainability.

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