Sustainable Futures from an Engineering Systems Perspective

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Sustainable futures from an engineering systems perspective

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Abstract

Never before has the recognition of the need for solutions to the challenges of sustainability been greater. With a rising population of increasing wealth, we have recognised that humankind is "out of planetary compliance". Or in other words, we are borrowing from next generations, each and every day, with the direct negative effects of raising atmospheric temperatures (global warming), poisoning of our land and waterways, and threatening the biodiversity of the planet – to name but a few.

The response to these challenges is finally reaching critical mass. From Climate Summits, through United Nations Sustainable Development Goals, to Circular Economy campaigns – global action is happening. International associations, geographical regions, and individual countries are making bold moves to enact action against climate change. Measurements are being made on numerous sustainability goals. And the younger generation is successfully increasing its pressure on the incumbent world- and industry leaders.

But how can engineering systems interpret these agendas and make a contribution to sustainability transition? What is the potential of taking a socio-technical holistic view on large and complex engineering systems, with a view to improving its sustainability performance? This chapter provides a brief overview of key sustainability developments in the past, which have laid the foundation for how engineering systems can contribute to a sustainable future through holistic socio-technical design. It also provides some paths forward for engineering systems, but some of the paving stones are still missing, so this chapter is also intended as a call to action.

1. What is sustainability?

The year 1972 saw the publication of what would become a seminal report on the pressures of humans on the world's carrying capacity. The report, "Limits to growth", was submitted to the action group, the "Club of Rome", and the authors utilised the term "sustainable", to describe a global system that that is: *"1. sustainable without sudden and uncontrolled collapse; and 2. capable of satisfying the basic material requirements of all of its people"* [Meadows et al., 1972]. Some years later, in 1987, United Nations'

Commission on Environment and Development defined "sustainable development" as a *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [World Commission on Environment and Development, 1987]. The focus in both definitions is on fulfilment of human needs now and in the future, but the definitions do not specify which needs they are talking about. Whether it is the basic physiological needs, such as sufficient nutrition or shelter against a harsh climate, or needs belonging to higher existential levels, such as social recognition and self-actualisation [Maslow, 1954], a fair definition of needs has become a central issue in defining sustainable futures. British entrepreneur and thought-leader, John Elkington, interpreted sustainability into a business context by identifying three dimensions of sustainability – the social, the environmental and the economic – and introduced the concept of expanding from one (financial) bottom line to a so-called triple bottom line (subsequently popularly dubbed 'people, planet and profit') that a company that aims for sustainability needs to balance [Elkington, 1997], see Figure 2(a).

In 2015, the three sustainability dimensions were further elaborated by the United Nations (UN) into 17 goals for a *"universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030"*. UN describes these Sustainable Development Goals as *"a call for action by all countries – poor, rich and middle-income – to promote prosperity while protecting the planet"* [Figure 1]. They recognise that "ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental protection" [UN, 2020].

Figure 1 - Seventeen goals to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030 [UN 2020]

The first five goals specify the social dimension (People) of sustainability; the next seven goals the economic dimension (Prosperity); the next three the environmental dimension (Planet); and the last two goals introduce two new "P"s: Peace, justice and strong institutions and Partnerships. The 17 Sustainable Development Goals (SDGs), with a total of 169 underlying targets, were adopted by all member states of the United Nations in 2015 and progress of the member states towards the targets is reported and monitored on an annual basis [e.g. Bertelsmann Stiftung, 2020].

1.1 Emerging concepts of sustainability

In the early 1970ies, the researchers behind "Limits to growth" created future scenarios of the developments in global human population, food production, industrialisation, pollution and consumption of non-renewable natural resources. These scenarios were used to investigate whether changes in the growth patterns for these five fundamental parameters might allow emergence of a sustainable feedback pattern for the interaction between human civilisation and the bio-geosphere. A significant finding was that one out of their three analysed scenarios led to a "stabilised world", while the other two led to "overshoot and collapse" [Meadows et al., 1972]. The idea that Earth's finite natural resources and the limited capacity of the environment to absorb pollution posed absolute boundaries to the development and expansion of human societies were contested at the time. Over recent decades, however, the existence of absolute boundaries for our pollution of the atmosphere with greenhouse gases like CO_2 and CH_4 has gained not just scientific- but also broad political acceptance. This was demonstrated in 2015 by the adoption of the so-called "Paris Agreement" targets, to keep our climate change impacts at a level where global atmospheric temperature increase remains close to 1.5 degrees above pre-industrial levels [UNFCCC, 2020].

The acceptance of absolute boundaries for environmental sustainability represents a shift in perspective from the traditional triple bottom line thinking, where the three sustainability dimensions (People, Planet and Profit) can be traded off and a poorer performance in the environmental dimension can be compensated by an improved performance in the social and economic dimensions (Figure 2a), to a new perspective (Figure 2b), where the social and economic dimensions are nested inside the environmental dimension reflecting their dependency on the latter and the fact that while society would collapse without the services that it draws from the environment (mineral and biological resources, regeneration of clean air and water, soil fertility, …), environment would thrive well without society. The absolute limits posed by the environmental dimension (the planet's life support functions) have to be respected and only when this is fulfilled are trade-offs between the three dimensions acceptable.

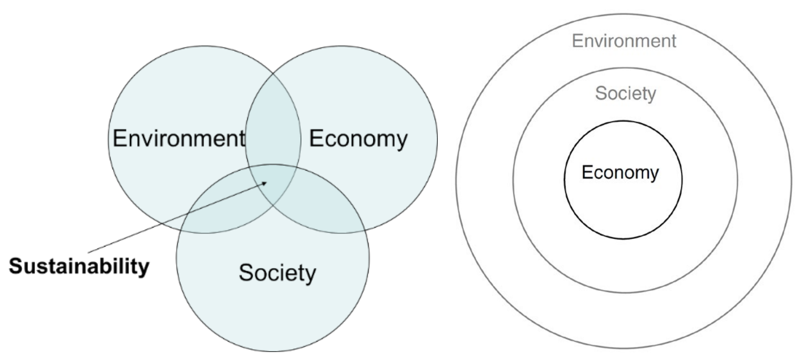

Figure 2 - Three dimensions of sustainability – from trade-off (a) to nesting (b) [from Giddings et al., 2002]

The implications of subscribing to the notion of absolute sustainability entail important changes in the way in which we understand the relationship between the triple bottom line considerations. Developing from an understanding trade-offs (between two or all three triple bottom line dimensions), towards an understanding of nested sustainability dimensions (within ultimate environmental boundaries, social and economic sustainability must be achieved) requires a necessary shift in thinking about interdependencies to achieve sustainability. All five of the parameters modelled in "Limits to Growth" (global human population, food production, industrialisation, pollution and consumption of non-renewable natural resources) [Meadows et al., 1972] are in themselves socio-technical and systemic in nature. The choice of trading one dimension off against another is thus exchanged with a more complex and system-oriented problem. And the possibility of applying technical solutions alone to sustainability challenges develops into the need to think in terms of designing dynamic socio-technical systems, able of handling technical, social, economic considerations and their interdependencies.

1.2 Absolute sustainability to respect our planetary boundaries

Taking a broader perspective on climate stability, Rockström, Steffen and colleagues identified nine planetary environmental systems including the release of greenhouse gases to the atmosphere, use of land, and nutrient cycling. These are considered essential for the self-regulation of central planetary processes, ensuring the stable environmental conditions that we have known throughout the Holocene since last glaciation. Based on natural science they propose for each system "safe operating spaces for humanity" delimited by critical impact levels ("Planetary boundaries") that we need to avoid exceeding in order not to jeopardise the stability of our natural systems. Out of the nine proposed planetary processes, they have proposed indicators for seven, and among these they find that the boundaries have been exceeded for three [Rockström et al., 2009], [Steffen et al., 2015]. While the work has inspired lively discussions of suitable indicators and concrete boundaries for all the individual planetary processes, the overall concept with its notion of absolute boundaries for environmental sustainability has inspired decision makers in governments [Nykvist et al., 2013] and industries [Science-based targets 2020, Ryberg et al., 2018b] to start benchmarking their activities according to absolute boundaries for environmental sustainability. For the latter case, absolute boundaries at the level of companies or even individual products have to be developed. They may be derived from science-based limits (like the planetary boundaries or ecosystem carrying capacities) for man-made environmental impact that define a total pollution space that must not be exceeded [Bjørn et al., 2015a], [Bjørn et al., 2015b]. Such a 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, an individual country or company can claim, requires an allocation of the total space. 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 proposed by Nykvist and colleagues in their assessment of which nations stay within their share of the safe operating space delimited by the Planetary Boundaries [Nykvist et al., 2013] and by the Global Ecological Footprint Network in their calculation of ecological footprints for nations [Global Footprint Network, 2020]. Hjalsted and colleagues discuss the ethical implications of different approaches to allocating the space between industries and individual companies [Hjalsted et al., 2020], and Ryberg et al. test a number of allocation principles and demonstrate their influence on the absolute sustainability assessment of the service of laundry washing in Europe [Rydberg et al., 2018b]. While there is some agreement about the principles for a science-based determination of the environmental limits and of a remaining pollution space, the allocation of the space between actors is in its infancy [Kara et al., 2018].

2. Engineering's role for sustainability

2.1 Standardised and globalised views on sustainability

Engineering traditionally has had a strong focus on efficiency, aiming to maximise output or value creation while minimising input or costs. In an environmental sustainability perspective, efficiency may be expressed by an *eco*-efficiency of the activity, product or provided service that is engineered. The International Organisation for Standardisation (ISO) defines eco-efficiency in the ISO 14045 standard as an *"aspect of sustainability relating the environmental performance of a product system to its product system value"* [ISO 14045, 2012]. 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 environmental impact that is caused by the product system on the other side [Hauschild, 2015]:

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

The focus on increasing eco-efficiency promotes development of products and systems that offer more functionality per caused environmental impact or resource use. As a side-note, however, we need also to be aware that the new products and systems created do not create newer, more difficult problems, (e.g. shifting to smart systems to control energy usage, but where the smart system consists of increasing amounts of scarce and problematic materials) [Bihouix, 2020].

In the context of the SDGs, the eco-efficiency can be seen as representing the balance between the SDGs related to human wellbeing (SDGs 1-5) and the SDGs representing the state of the environment (SDGs 13-15) (Figure 3). The SDGs related to our prosperity and societal infrastructures (SDGs 6-12) represent the levers by which we can aim to increase the eco-efficiency – generating more wellbeing while causing less environmental damage and SDG 10 (reducing inequality) as a linking goal helps ensuring efficiency in the way human needs are met.

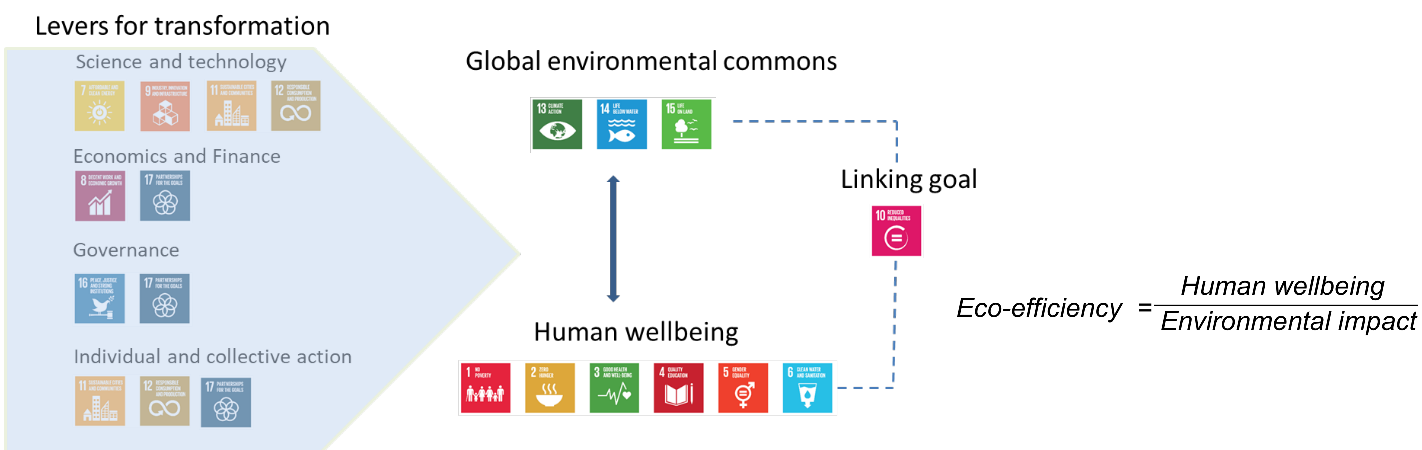

Figure 3 - The 17 SDGs and eco-efficiency (based on Richardson, 2019)

2.1 The sustainability challenge to engineers

The **IPAT equation** (Eq. 2) was developed based on work by Ehrlich and Holdren [Ehrlich and Holdren, 1971] and Commoner [Commoner, 1972]. It analyses the environmental impact from human development and presents the total environmental impact (I) from human activities as the product of three central drivers - the human population (P), the affluence (A, the material standard of living), and a technology factor (T, representing the environmental intensity of our technology). T is expressed as environmental impact per created value or functionality and is hence the reciprocal of the eco-efficiency as defined in Eq. 1.

$$I = P \cdot A \cdot T \qquad \text{(Eq. 2)}$$

In a world where population and affluence grow, the technology factor or the environmental intensity of the technology with which we provide the growing affluence of the growing population must shrink, in order to avoid increased environmental impact. In some cases the environmental impact is already exceeding sustainable levels as e.g. demonstrated by the planetary boundary studies [Steffen et al., 2015] and acknowledged for climate change by many nations through their ratification of the Paris Agreement [UNFCCC, 2020]. This further exacerbates the need to reduce the environmental intensity of our technologies. But by how much must it be reduced? How big is the challenge that environmental sustainability of a growing consumption poses to our technology?

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

$$Eco - efficiency = \frac{1}{T} = \frac{P \cdot A}{I} \qquad \text{(Eq. 3)}$$

In order to follow the Paris Agreement and limit temperature increases to the level of 1.5 degrees, reductions of around 45% in the 2010 emissions of CO_2 are needed by 2030 and around 2050 reductions must reach 100% [IPCC, 2018]. Considering forecast increases in population and affluence in the same period, this corresponds to eco-efficiency increases for climate change impact by a factor three between 2020 and 2030. Indeed, the need for eco-efficiency increase by factors of 4, 10, 20 or even 50 have previously been proposed, for different types of environmental impact, over different time horizons and with different assumptions about developments in population and affluence [Factor 10 Club, 1994], [Von Weizsäcker et al., 1998], [Reijnders, 1998], [Brezet et al., 1999], [Schmidt-Bleek, 2008].

These requirements to eco-efficiency improvements are derived from an assumption that A and T are independent, i.e. that increase in affluence is unaffected by developments in the eco-efficiency of the technology that supports the consumption. Unfortunately, this is rarely the case, as can be illustrated by the case of lighting technology. Over the last three centuries, we have witnessed energy-efficiency increases of lighting technology (from candles all the way to LED lamps) in the order of three orders of magnitude [Ausubel and Marchetti, 1997], while over the same period, the share of our available income that we spend on lighting has remained constant [Tsao et al., 2010] (in spite of the fact that the available income has also grown strongly over this period). Here, as in many other cases, increased eco-efficiency leads to a growth in use [Magee and Devezas, 2017], [Hertwich, 2005]. It is clear that a strong increase in the eco-efficiency of products and technologies is required to ensure a sustainable level of environmental impact when meeting the needs of a growing and more affluent population, but these examples show that a focus on eco-efficiency alone is insufficient to ensure a future sustainable consumption and production. We must analyse the overall outcome for a product or technology, from a systems perspective, and relate it to the share of the pollution space that it can claim in order to ensure that the improvement leads to solutions that are not just more sustainable than what they replace, but sustainable in absolute terms – to move the focus of engineering beyond eco-efficiency to aim for eco-effectiveness [Hauschild, 2015].

In order to address the rather daunting task to develop technical systems that enable development towards absolute sustainability, engineering skills are needed both in analysing the eco-efficiency of the technology and in designing technology that is eco-effective.

3. Taking a life cycle perspective

The eco-efficiency of a technical system is the ratio between the value or functionality that it provides us and the environmental impact that it causes (Eq. 1). The functionality is intended and typically defined as target for the product development, while the environmental impact is normally unintended, an unwanted price for obtaining the functionality. But how is it determined?

There are two fundamental principles when we want to quantify the environmental impact of a product. The first principle is that we need to consider the product system that comprises the whole life cycle of the product, from the extraction of the resources that are used in the materials and components of the product, over the manufacturing of the product through its distribution, use and maintenance to the end-of-life treatment with possible remanufacturing, recycling or landfilling (see Figure 4). The many processes that constitute the product system interact with the environment, extracting resources and discharging emissions and waste to air, water and soil, and it is these exchanges between the product system and the surroundings that cause the environmental impacts of the product that we need to quantify in order to determine the eco-efficiency.

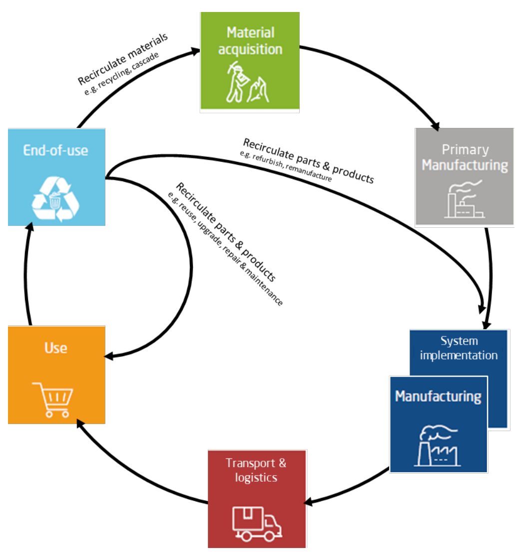

Figure 4 - A typical product or system life cycle (own figure)

The second principle is that we need to consider all relevant environmental impacts created by the exchanges between the product system and the surroundings, from the global impacts (climate change and stratospheric ozone depletion), where the pollutants are so long-lived that they reach global distribution so the impact is independent on where the emission occurs, to the more regional and locally dependent impacts (acidification, photochemical ozone formation, airborne particle pollution, chemical toxicity to humans and ecosystems, use of land and water).

Life cycle engineering is the name given to the engineering of the whole product system [Hauschild et al., 2017]. It targets the eco-efficiency, taking the entire life cycle into account and considering all relevant environmental impacts to arrive at realisations of the product and its life cycle that minimise the unwanted environmental impacts associated with achieving the desired functionality. Life cycle thinking is essential for developing more sustainable products and systems, but it is also important to be able to quantify the impacts, in order to focus the development on the parts of the product system that contribute most for each of the considered environmental impacts and to document and benchmark improvements.

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, LCA captures potential problem shifting between the different stages of the life cycle and between categories of environmental impact when the environmental sustainability of products or services is compared [Finnveden et al., 2009].

The development of the LCA methodology has mainly taken place over the past four decades. Initially, the emphasis was on the conceptual foundation and on the overarching principles, and they were laid down in the ISO standards [ISO 14040, 2006], [ISO 14044, 2006]. Later followed a strong focus on inventory data for the multitude of processes of the product system and impact assessment methods for the many categories of environmental impact that are covered in LCA targeting development of international scientific consensus on methodological recommendations [Hauschild et al., 2013].

LCA is the tool used to assess the environmental impacts associated with obtaining a service, a functionality (the ratio between the service and the environmental impacts was defined as the eco-efficiency in Equation 1). The anchoring in the provided functionality and its holistic perspective allows it to be used for assessing not just a product (system) but also other types of systems and even organisations. From a starting point in product assessments, the use of LCA has thus expanded to cover many types of systems and even policies. From an initial focus on environmental impacts it has also gradually expanded to cover the other sustainability dimensions, the social [Benoît and Mazijn, 2009] and the economic, and their combination into what has been coined life cycle sustainability assessment, LCSA [Zamagni, 2012].

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 [Hauschild and Huijbregts, 2015]. Apart from increasing the environmental relevance of the results of the impact assessment, the regionalisation 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 [Bjørn et al., 2016].

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 [Bjørn and Hauschild, 2015] while Ryberg and colleagues developed a life cycle impact assessment method based on the Planetary concept [Ryberg et al., 2018a] and implemented it in the previously mentioned 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 [Ryberg et al., 2018b].

Detailed guidelines for LCA comprise the Product and Organisational Environmental Footprints from the European Commission, building on the ISO standards [European Commission 2016]. A comprehensive introduction to the generic methodology and its application within numerous application areas is offered by [Hauschild et al., 2018].

4. What is design for sustainability?

In recognition of the potential to affect the sustainability performance of products and systems, the discipline of **design for sustainability** has developed over recent decades [Pigosso et al., 2015]. In both industry and academia, increasing focus has been placed on sustainability awareness in the product development process, supported by an ever-increasing catalogue of tools and methods towards sustainability enhancement [Issa et al., 2015]. From a triple bottom line perspective, early contributions and examples (from the early 1990ies) have focused on improving the environmental footprint, both in terms of assessing the environmental burden of the product or system, and in terms of the design of environmentally improved solutions. **Ecodesign** is often the term used to describe such approaches. As the methodology developed and as a growing number of industrial examples of ecodesign implementation were shared, the dimensions of social and economic sustainability considerations have been added to the palette of approaches.

In their meta-review of ecodesign tools and methods, Pigosso et al. chart the development of the body of knowledge regarding design for sustainability support from 1990 to 2015 [Pigosso et al., 2015]. They show that companies have increasingly integrated sustainability into their business activities, taking it from a generally passive and reactive stance in the beginning of the period, towards adoption of more preventive and proactive approaches towards the end.

4.1 Focus on ecodesign

Ecodesign is a proactive approach, where environmental considerations are integrated into the design and development of products and systems. The aim of ecodesign is to achieve improved environmental performance of products and systems, throughout their life cycles. Ecodesign is built on the two fundamental principles, introduced earlier, namely life cycle thinking and environmental impact reduction. This means that with ecodesign, considerations of raw material extraction, manufacturing, transport, use and end-of-life are made, throughout the design and development processes of products and systems.

Hundreds of ecodesign tools and methods are available today [Pigosso et al., 2015], [McAloone & Pigosso, 2020]. Many ecodesign tools are provided to support specific environmental decisions within specific parts of the development process (e.g. materials selection, energy source definition, mode of transport), whereas others help the designer to create a holistic ecodesign support, from the very first ideation of the product or system, all the way through detail design and to launch of production. To ensure success, ecodesign should build upon the foundation of an in-depth understanding of the product or system's actual or potential environmental impacts, typically by carrying out some form of (abridged or full) life cycle assessment (LCA). Ecodesign stimulates the designer to be innovative and creative in the development process, supporting the process of seeking alternative solutions, whether they be at the material-, component-, product- or systems level.

In addition to single tools and methods, various proposed processes or reference models for ecodesign also exist. One such proposal of a holistic ecodesign approach is provided by McAloone and Pigosso [McAloone & Pigosso, 2021], who propose a reference model for the integration of ecodesign into product development. The reference model takes both the life cycle and the environmental impact principles into consideration and provides two ways of tackling an ecodesign task, namely: (i) a top-down, design-driven approach; and (ii) a bottom-up, environmental life cycle approach, see Figure 5. Given the integrated nature of modern companies, both viewpoints are essential to understand. In some circumstances, a company may desire to design a complete system from an ecodesign perspective, keeping all environmental improvement options and eventualities open. In other circumstances, punctual environmental improvements may be necessary, for which the bottom-up approach is more suitable. Figure 5 displays the ecodesign reference model provided by McAloone and Pigosso.

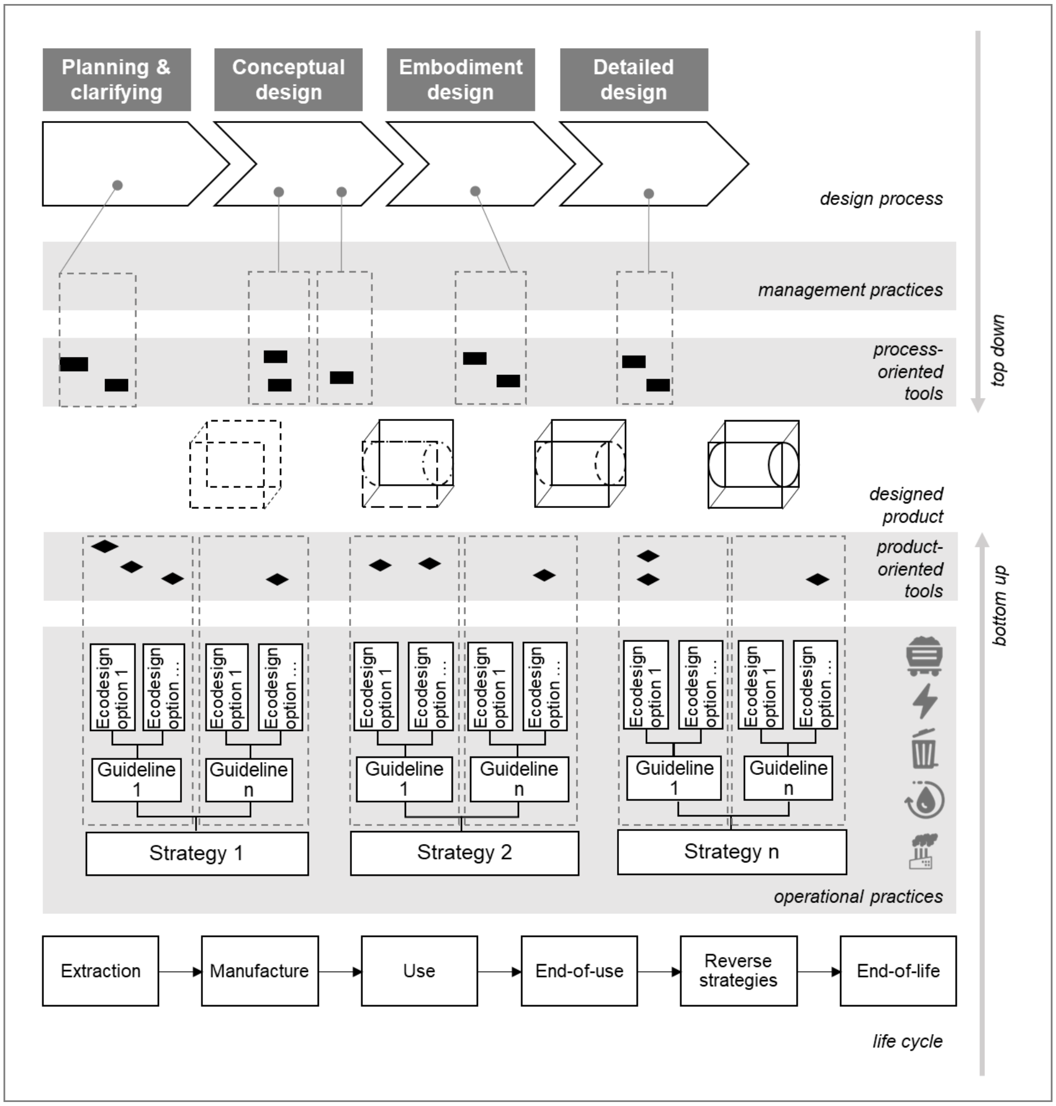

Figure 5 - Ecodesign reference model, displaying top-down (design process) and bottom-up (environmental life cycle) perspectives [McAloone & Pigosso, 2021]

Reflecting the development of industry's capabilities regarding the integration of ecodesign into their business, the International standard on Environmental management systems, ISO 14001, has augmented its guidance and expectations in the latest release of the standard (2015). The updated standard requires that the overall ecodesign process and approach should be detailed, within any company with product development activities wishing to renew its certification from 2015 onwards [ISO, 2015].

4.2 From ecodesign to design for sustainability

As industry has developed its understanding and expertise within ecodesign, so has the need to integrate economic (business) and social considerations into the development process for products and systems. Many companies have developed over the past decade or so, from considering corporate social responsibility (CSR) as a chiefly reporting initiative [Tu et al., 2013], to now aiming to fully integrate social sustainability and social innovation into their core business, from strategy all the way down to deployment within product development [Chang, 2015], [Kim et al., 2015]. Such a broadened understanding and intention regarding sustainability within business leads to a need to significantly augment the support through frameworks and tools. Companies today are working to understand how to integrate the goals and measures provided by the seventeen earlier-mentioned UN Sustainable Development Goals, into their business- and product development processes [Mascarenhas et al., 2020], [Park et al., 2017], [Stead, 2019]. Thus, an increasingly holistic view on sustainability in business and product development requires a systems view, and the development of comprehensive tools to evaluate the sustainability performance of products. There is a clear trend towards the development of unified tools that can measure the sustainability performance of products considering the environmental, social and economic dimensions [Roostaie et al., 2019].

4.3 An engineering systems perspective on sustainability

As mentioned in the introduction to this section on Design for Sustainability, the body of knowledge in this field has been developing now since the early 1990ies, both through scientific research efforts and bold, early-mover companies [Pigosso et al., 2015]. Yet, only within recent years, after almost three decades of effort, do we see emerging maturity in the way in which companies integrate sustainability into their businesses, with regards product-related organisations. Adding "sustainability" to not only the requirements specification but into the product development processes, company governance systems and the designer's toolbox seems not to have been that easy to achieve – and here we are still considering a product level. Augmenting our scope to complex and large-scale socio-technical engineering systems is a next step that is relatively uncharted in the literature. Cluzel et al. provide the most convincing contributions to ecodesign of complex industrial systems, with reference to large electricity conversation stations [Cluzel et al., 2016]. In addition, Tchertchian and Millet provide some insights into providing life cycle screening as a support to the consideration of sustainable complex systems design, with a maritime case as an example [Tchertchian & Millet, 2017]. There are more studies and methodologies to support the full life cycle assessments (LCA) of complex systems (e.g. [Wang et al. 2013]), but LCA alone is not enough to support the process of socio-technical design. The good news is that many of the principles, methods and tools from sustainable product design can be used for sustainable engineering systems design. The scope broadens and the causalities between decisions become, by nature, more complex. What does not yet exist is a process or number of proposed processes towards sustainable complex engineering systems design.

5. Why an engineering systems approach to sustainability?

Continuing the story of how companies have developed their understanding, and therefore also their business activities, from passive/reactive approaches to sustainability, through to preventive/proactive approaches, the current era of sustainability leadership in industry is seeing integrative approaches to sustainability. This includes active adoption of environmental, social and business-related sustainability goals into company strategies, and further deployment into numerous parts of the organisation. Two significant agendas stand out as being of particular interest for companies, as they seek to "do more good" as well as "do less bad", as the adage regarding complementary approaches to sustainability states [Toxopeus et al., 2015]. The two agendas are: **product-as-a-service** (or product/service-systems, PSS); and **circularity** (or circular economy, CE). Both agendas are supported by the basic premise that the necessary improvements in global sustainability performance to just maintain status quo in our ecosystem need to reach up to a factor 20 in performance improvement [Reijnders, 1998], [Brezet et al., 1999], and that single-product, transactional sales, linear economic thinking lies at the core of the problem of industrial production and modern day consumption.

5.1 Product-as-a-service

Product-as-a-service (referred to in academic literature as product/service-systems, or PSS) emerged in the early 2000's and has grown strongly in society, in recent years. From a sustainability perspective, the emergence of PSS as a scientific research theme was motivated by the ambition of finding alternative ways of contributing to the projected factor 20 need [Roy, 2000]. The basic hypothesis was that by combining the physical artefact and the service that the product provides to the user as design objects – and as combined offerings to the user – greater sustainability improvement potential can be realised. In such cases, the company retains (greater degrees of) ownership of the physical artefact and adds a responsibility and influence upon the sustainability performance of the product throughout its lifetime. From a technology perspective, the dawn of fast and wide-coverage internet, smartphone technology, and smart sensory devices and actuators (also known as Internet of Things, or IoT), has seen the availability of PSS solutions that hitherto were not possible to provide. Car-sharing systems rely on electronic door-locks, actuated by smartphone apps. Pay-per-use photocopy machines depend on login and counter technology. And home-delivery of ecological fruit and vegetables rely on fully integrated, web-based order systems, connected to complex logistics setups. The most famous ontology of PSS types comes from Tukker [Tukker, 2004], who describes eight PSS solution types, ranging on a scale from straight product-offerings to straight service-offerings. Tukker's work was also motivated from a sustainability background, in an attempt to find a route to decoupling of consumption from production.

It is an ideal of the development of PSS that the three main stakeholder groups – customer, provider of the service and society – all must benefit from the service systems through their product-as-a-service solutions, and that value creation is decoupled from production and consumption of multiple products. However, like all things, there is neither a one-to-one correlation nor a guarantee of increased sustainability performance, simply due to a switch to PSS [Pagoropoulos et al., 2018] and there are even examples of a more negative sustainability performance through PSS solutions [Barquet et al., 2016]. PSS merely opens up the solution space and the sphere of influence, due to reconfigured responsibilities and motivations; the remainder of the task of achieving sustainability improvements is still up to the provider to ensure. Thus, the task becomes more complex and requires more careful insight and consideration.

5.2 Circularity

Circular economy, CE, has become widely recognised in a very short time, as being of key potential in promoting and achieving a better balance, from a material and resource perspective, within modern society. The design of innovative circular business models, together with circular product and service solutions is accepted as being critical, with the potential of affecting fundamental changes to the resource consumption that the linear economy has been responsible for.

The notion of circularity may not be new to you. Anyone with family members who were alive in the middle of the 20th century will, for example, tell stories of how every product, every material, every item of clothing was saved for a second, third or fourth usage, including necessary repurposing along the way. And there are parts of the world where frugality gives rise to circularity, at local and personal levels, still today. The difference with the current focus on circular economy is that an attempt is being made to apply ***circularity at a systemic level***, and in times of economic growth, as opposed to depressed economic necessity.

From a product and engineering systems design perspective, this latest development along the trend of positive attention to ecodesign and sustainability by companies is marked by the successful campaigns of 'cradle-to-cradle' and 'circular economy', respectively.

The 'Cradle-to-cradle' concept was first launched in 2002 by Braungart and McDonough and gradually reached considerable industry attention towards the early 2010s [McDonough and Braungart, 2010]. 'Cradle-to-cradle' challenged the industry's dominating linear mindsets of 'cradle-to-gate' (from raw material, through production, to the factory gate) or 'cradle-to-grave' (from raw material, through production, sales and use, to final depositing of the waste stream – the grave). Instead the authors proposed a new way of thinking in a cyclical manner. One cradle-to-cradle dictum is 'waste equals food', reflecting the overarching philosophy behind the concept that we should learn from and mimic nature in our engineered world. Nature is thus not *efficient* (as engineers are trained to be), rather it is *effective* (meaning that it has evolved in an adaptive manner so waste of the right type is of value in another product or system's life cycle). To make this philosophy operational, the cradle-to-cradle methodology is based on principles for ***materials health*** (toxic materials and incompatible combinations of materials must be avoided), ***material reutilisation*** (enabling recovery and recycling of all materials at the end-of-life of the product), use ***renewable energy*** (focused on the production, not the use stage of the product) and ***water preservation*** (particularly usage and discharge quality). The 'closed loop' approach to the product life cycle that is advocated in cradle-to-cradle is split into a 'technical cycle' and a 'biological cycle' view on product and system flows according to the nature of the materials.

The renascent 'circular economy', builds on top of and has found inspiration in the cradle-to-cradle concept, and broadened the perspective from a strong materials chemistry focus to advocating for sound business thinking about how to maximise value output while minimising the production, consumption and wasting of material goods. This thinking has in particular been championed by the Ellen MacArthur Foundation [Ellen MacArthur Foundation et al. 2015], and it has now been broadly adopted and reinforced by scholars, industry practitioners, politicians and interest organisations, as a promising means to achieving a better balance, regarding resource consumption and production. The circular economy thinking is reaching industries and public societies across the globe. For companies, it is supporting sustainability becoming an integral part of their way of doing business, introducing changes in their business models and how they deliver value, by means of the previously mentioned product/service-systems [Kjaer et al., 2018].

At the time of writing, the full picture of the circular economy life cycle model is still being drawn, through various contributors' additions to this new lens on sustainability. The currently most dominant model is the so-called 'Butterfly Diagram', provided by the Ellen MacArthur Foundation [Ellen MacArthur Foundation et al, 2015] showing a number of secondary flows in both the technological and biological cycles.

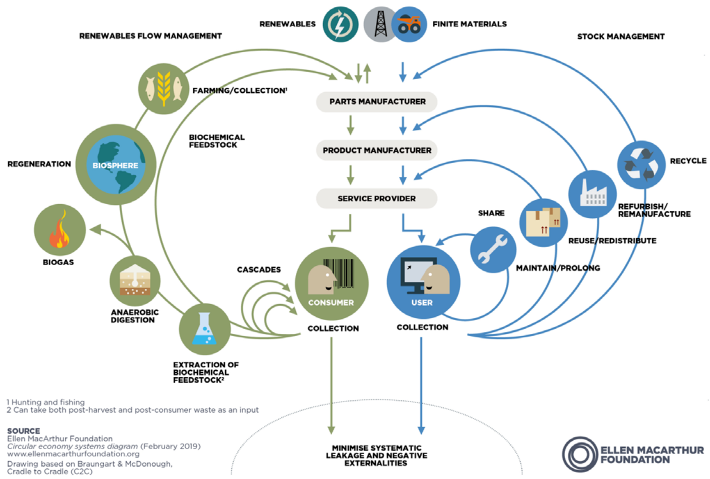

Figure 6 - Butterfly diagram by EMF (2019), based on McDonough and Braungart (2010)

Although focused on eco-efficiency rather than eco-effectiveness many of the existing ecodesign tools are fully useable and relevant for developing also cradle-to-cradle inspired designs, or products that are designed to play a role in a circular economy. In its simple and recognisable schematic, Figure 6's butterfly diagram depicts a number of alternative routes for material resources, to divert from the linear model of "take-make-use-waste". Closer consideration of each alternative route (the arrows) for material resources brings us to an understanding that the panacea of achieving circularity requires consideration of not just artefacts, but also policy, business model, design, logistics, and a host of other considerations. A large number of circular strategies have been developed and ordered, to help to consider circularity [Blomsma et al., 2019]. And numerous resources emerge, supporting the value chain considerations to be made when attempting to design for and operate within a circular economy [Kalmykova et al, 2018].

5.3 Transitioning to Circular Economy

But how to make the change, from our linear system to a circular economy? According to economist, Tim Jackson, it is important to not only question how to decouple wealth creation [Jackson, 2009] (often measured in economic growth) from resource consumption, which can be argued as being the main aim of both circular economy and SDG 12. Jackson's career has been dedicated to prompting us to question the whole notion of economic growth – at least in developed economies. It seems that the only way to truly reach a circular economy is to create … a new economy!

Steps towards circular economy, however, can be taken. Transitioning to circular economy is not just about changing the product/system design or beginning to recycle products, component and materials. It is also about: transitioning the organisation; innovating the company strategy and business model; redesigning the system, product or service for circularity; assessing and adjusting manufacturing processes and value chain considerations; interpreting and employing technology and data to ensure system health and longevity; understanding how better to support engineering systems through maintenance; being able to make informed choices about take-back and end-of-life strategies; and understanding the policy and market conditions for circular economy [Pigosso and McAloone, 2021]. Understanding and acting on readiness within all of these dimensions will ensure a holistic, systems approach to circular economy transition. Or in other words, we can only expect to make a circular economy a reality, if we take a systems perspective to the multitude of dimensions listed above.

The ultimate goal with circular economy is to reach “an industrial economy that is restorative or regenerative by intention and design”, as defined by [Ellen MacArthur Foundation, 2013]. Restorative entails a circuit of infinite use, reuse, and repair. Regenerative refers to a cycle of life that maintains and upgrades conditions of ecosystem functionality [Morseletto, 2020]. The design of engineering systems play, therefore, a key role in achieving restorative and regenerative systems.

5.4 The contribution of engineering systems to sustainability

Both product as a service or product/service-systems (PSS) and circular economy represent considerable complexities, in comparison to the single-product, single life cycle, transactional world view. Vast amounts of research are being carried out in both areas, both of which are in need of support regarding how to design and develop; how to implement and operate; and how to assess the sustainability performance of circular PSS solutions. As the knowledge on circular economy develops, it is also becoming clear that PSS is a means to circular economy and circular economy is, in turn, a means to sustainability. Neither are *the* sole means, but this supporting and causal relationship makes the role of each approach clearer.

It also becomes clear when one begins to talk of product/service-systems, of multiple life cycles, and of materials and waste hierarchies, that the potential of an engineering systems approach begins to manifest itself clearly. In this context, it is important to embrace the “sciences of complexity” required to address ever-increasing “wicked” problems [Broadbent, 2004] within complex socio-technical systems through the understanding of the complex dynamics of economic, environmental and social factors in sustainable design, across the system life cycle [Fiksel, 2003]. Furthermore, there is a need to expand the role of the design process as a powerful leverage point at which to intervene in production and consumption systems [Sterman, 2002], despite the increased recognition that wider-scale systemic changes can be addressed by design [Gaziulusoy and Brezet, 2015] of engineering systems.

6. Conclusions

This chapter has provided a brief insight into the history, key terms, important considerations and possible future role of engineering systems with respect to sustainability. Not all the answers are provided – indeed there are gaps to be filled and knowledge to be generated, in order to develop a comprehensive support for how engineering systems can make a contribution to sustainability through socio-technical engineering systems design. The key takeaways from this chapter are as follows.

- The current sustainability emergency has been created by humans and cannot be fully fixed by technology alone, or by looking at discrete activities, products, companies or technologies. *Sustainability is a socio-technical challenge that requires holistic socio-technical design solutions.*
- Our understanding of sustainability, over the past five decades, has developed. Increasingly, we need to think in terms of absolute sustainability, which will imply setting limits for how “much is enough and acceptable”.
  Absolute sustainability will become an instrument of future engineering systems.

- To aid our approach to designing engineering systems for sustainability, it is important to understand the life cycle, in order to assess the environmental performance of the engineering system under consideration.
  Life cycle assessment is an important instrument to enable the dimensioning of sustainable engineering systems.
- Design for sustainability is a well established discipline, with many potentially useful methods and tools to enable sustainable engineering systems, but there is limited material on actual process support to aid the design of sustainable engineering systems.
  There is a need to create design support for sustainable engineering systems.
- Engineering systems as a discipline should be able to contribute to sustainable product/service-system design and to circular economy. Both require a systems perspective to succeed. Both constitute part of a causal chain to an attempt to achieve sustainability, such that: PSS contributes to the goal of reaching a circular economy; and circular economy contributes to the goal of sustainability.
  PSS and circular economy – which both have the potential to contribute to sustainability – require a systems approach, which could be provided by an engineering systems design approach.

We hope that this chapter can provide the basis for a sustainability goal, when reading the other subsequent chapters in this handbook.

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