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Review

Updated Principles of Sustainable Engineering

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Abstract: A change in human development patterns is needed, including mankind's environmental, economic, and social behavior. Engineering methods and practices have a substantial impact on the way to sustainable development. An overview of the guiding principles of sustainability, sustainable design, green engineering, and sustainable engineering is presented first. Sustainable engineering principles need to be updated to include the present state of the art in human knowledge. Therefore, the updated principles of sustainable development are presented, including traditional and more recent items: a holistic approach, sustainability hierarchies, sustainable consumption, resource scarcity, equalities within and between generations, all stakeholders' engagement, and internalizing externalities. Environmental, social, and economic impacts that respect humans' true needs and well-being are of importance to the future. The updated 12 principles include the tridimensional system's approach, precautionary and preventive approaches, and corporate reporting liability. The environmental principles comprise a circular economy with waste minimization, efficient use of resources, increased share of renewables, and sustainable production. The social pillar includes different views of equality, the engagement of stakeholders, social responsibilities, and decent work. Economic principles embrace human capital, creativity, and innovation in the development of products, processes and services, cost-benefit analysis using the Life Cycle Assessment, and the polluters must pay principle. The principles will require further development by engaging individual engineers, educators, and their associations.

Keywords: sustainability; engineering; design; principle; responsibility

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1. Introduction

The human population has had an exponential development, which has been very intensive in the last century and has exceeded the planetary limits in the last decades. The population has increased from 2 G (billion, 10^9) in 1927 to more than 7.9 G today and will likely reach around 9.7 G by 2050, and 10.9 G by 2100 [1]. The population growth rate has decreased from 2.2%/a (percent per year) 50 years ago to about 1.0%/a now and is projected to decline to 0.13%/a by the year 2100; the world average life expectancy has increased from 31 a in 1900 to 73.2 a now and is expected to reach 81.7 a by 2100 and 100 a by 2300 [2]. In addition, the household final expenditure per capita has doubled since 1960, from USD 3k (thousand US dollars) to USD 5.9k [3]. As the global source and sink capacities are final, this type of evolution has increased pollution and reduced resource availability to critical values.

The United Nations (UN) responded to the uncontrolled development by establishing the World Commission on Environment and Development (WCED), known better as the Brundtland Commission [4]. In 1987, the Commission issued the document Our Common Future (Brundtland Report) defining sustainable development, SD, as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The long-term environmental strategy with 3 pillars (economic growth, environmental protection, and social equality) was proposed. The Commission called for an international meeting where more concrete initiatives and goals could be mapped out. This meeting was held in Rio de Janeiro in 1992 as a World Summit on Sustainable Development (WSSD, also called the Earth Summit). A comprehensive plan of action, known as Agenda 21, came out of the meeting. It entailed actions to be taken globally, nationally, and locally to make life on Earth more sustainable. Earth Summits 2002 Rio+10 (2002) in Johannesburg, and Rio+20 (2012) in Rio de Janeiro continued the endeavors. The result of the third Summit was the document The Future we Want [5], which, with the 192 governments in attendance, renewed the political commitment to sustainable development and declared the commitment to the promotion of a sustainable future.

The Brundtland Report recognized that human resource development in the form of poverty reduction, gender equity, and wealth redistribution was crucial to formulating strategies for environmental conservation. The social component became necessary after the neoliberal globalization introduced by USA President Ronald Reagan and UK Prime Minister Margaret Thatcher took the free market too far—the economic pillar started to erode the social one. For decades, the USA arms industry was producing wars, causing migrations and terrorism. The second disaster is climate change, causing climate refugees.

In 2000, the UN Millennium Summit committed to achieving the eight Millennium Development Goals (MDGs) to eradicate poverty and hunger, promote gender equality, achieve universal primary education, reduce child mortality, improve maternal health, combat diseases, ensure environmental sustainability, and improve global partnership for sustainable development by 2015. At the end of the MDGs era, the Sustainable Development Goals (SDGs) with 17 "Global Goals", and 169 targets was adopted by the 193 UN member states [6]. The social pillar was extended by including reduced inequalities, peace, and justice. The economic pillar included decent work, responsible consumption and production, and climate action. In total, 230 indicators were proposed to monitor the SDGs' success.

The present situation on sustainability is critical. Our civilization has crossed four of nine "planetary boundaries": the greenhouse gases' (GHGs) concentration is causing climate change, species extinction, deforestation, and pollution from nitrogen and phosphorus [7]. The other four boundaries (ocean acidification, freshwater use, atmospheric aerosol loading, and chemical pollution with radioactive and nanomaterials) are approaching the boundary limits fast. Planetary boundaries are determining the references to environmental sustainability [8].

The European Environment Agency (EEA) in its 5-yearly State and Outlook of the European Environment Report, SOER [9] stated that decoupling environmental pressures from economic growth was incremental with only partially improved ecosystem resilience and human health. We need to accelerate progress towards decoupling in a rapidly changing global context. To achieve its 2050 vision of "living well within environmental limits", it must fundamentally transform its core societal systems: food, energy, mobility, and the built environment. Achieving such changes will require "profound changes in dominant practices, policies and thinking". Oxfam reported that eight men owned the same amount of wealth as the poorest half of the world—"A world where 1% of humanity controls as much wealth as the bottom 99% will never be stable" [10]. In total, 8% of the global workforce is "working poor"—having less than 60% of the average income [11]. In September 2017, the UN General Assembly focused on people striving for peace and a decent life for all on a sustainable planet.

Engineering has brought faster development to all countries and most people and created more equal societies with fewer existential problems. On the other hand, it has contributed to strong environmental impacts, climate change, species extinction, and increased pollution. We need technical solutions that will not cause long-term negative impacts on the environment, making human society resilient and sustainable. New approaches are needed that require (among others) a new type of engineering—a sustainable engineering approach in the design and control of systems, processes, and products. Regarding the open question: "Is technology the culprit or the saver?" [12], the right answer is: "It shall be sustainable in long term." Sustainable consumption and production goals, zero waste, a circular economy, and resource efficiency are some concepts that we are encountering in this respect. However, the environmental pillar is not enough—we must, equally as well, consider the social and economic pillars: equality, decent jobs, the engagement of all stakeholders, social responsibility, innovations, life cycle analysis, the cost–benefit approach, reporting to public, etc.

This paper builds on a review and evaluation of engineering aspects of sustainability and sustainable development, engineering design and sustainable engineering (green engineering), and sustainability principles and practices for engineers. It intends to update and refine the existing sets of sustainable engineering principles by integrating the knowledge developed in the last decade. The new set of principles shall be utilized to help fulfil the 17 SDGs and the Paris agreement more effectively and enable humanity to "Accelerate the transition to equitable, sustainable, livable, post-fossil fuels society" [13].

2. Methodology

A literature review, foreseeing the engineering developments from international organizations along with their analysis and synthesis, and personal experience are used as the methodology.

3. Engineering and Sustainable Development

Many predecessors of sustainable engineering have been developed. Some of them that still exist will be described. One of the oldest is Environmental Engineering, which existed from the beginning of our civilization. Its modern approach started in the 1970s. This is a branch of engineering that deals with the adverse environmental effects of nature and human activities on fresh water supply, water and air pollution, wastewater and waste management, energy preservation, global warming, acid rain, sanitation, and agricultural systems [14]. Courses in civil engineering as well as in chemical engineering studies exist; they are well connected with environmental science and technology.

Ecological engineering (EE), which started in the 1960s, is the "design of sustainable ecosystems that integrates human society with its natural environment for the benefits of both" [15]. It deals with restoration of "rivers, lakes, forests, grasslands, wetlands . . . , and phytoremediation sites". EE enables the design, construction, restoration, and management of ecosystems. Mitsch and Jørgensen [16] identified five classes of EE design: (1) ecosystem utilization to reduce/solve pollution problems, such as phytoremediation, (2) ecosystem imitation to resolve a source problem, e.g., forest restoration, (3) ecosystem recovery, e.g., mine land restoration, (4) ecosystem ecological modification, e.g., selective plant harvesting, (5) balanced use of ecosystems, such as sustainable agricultural systems. They identified 19 possible design principles of EE.

Cleaner production (CP, in USA Pollution prevention, PP) was initiated in the 1990s by UNEP [17] to minimize resource use, pollution, and waste in companies. It was developed by researchers, policy makers, and practitioners from many countries. UNIDO has assisted in the development of very successful National Cleaner Production Centers (NCPCs) and Programs (NCPPs) all over the world. The research field is still very active with several hundred papers every year. CP was soon enriched with the Eco-Design approach, which takes into consideration the environmental impacts of a product throughout its entire life cycle, from resources to the end-of-life scenario. Energy and material efficiencies are an important part of the eco-design, and so are renewable and/or recycled resources.

Industrial Ecology (IE) is a predecessor of circular economy—it is about shifting processes from open loop (linear) systems to the closed loop ones. IE is based on mimicry since natural systems do not know any waste. They use "industrial metabolism" (material and energy flows, design for environment or eco-design), life cycle planning, eco-industrial parks ("industrial symbiosis"), etc., to mimic natural systems. The Danish industrial park at Kalundborg [18] is the best-known example where industrial outputs from one industry serve as inputs to another one, thereby "reducing use of raw materials, pollution, and saving on waste treatment" [19]. Graedl and Allenby [20] devoted their book to IE, and green engineering principles and cases to offer practical and reasonable approaches to design decisions. Links between IE and circular economy can be found in Ghisellini et al. [21]. Saavedra et al. [22] analyzed the theoretical contribution of IE to circular economy.

All the above-mentioned engineering approaches are environmentally oriented; they are lacking the social component to be sustainable. An overview of guiding principles in engineering for sustainable development (Sustainable Engineering) is presented in the sections below. Figure 1 illustrates the hierarchy of sustainability.

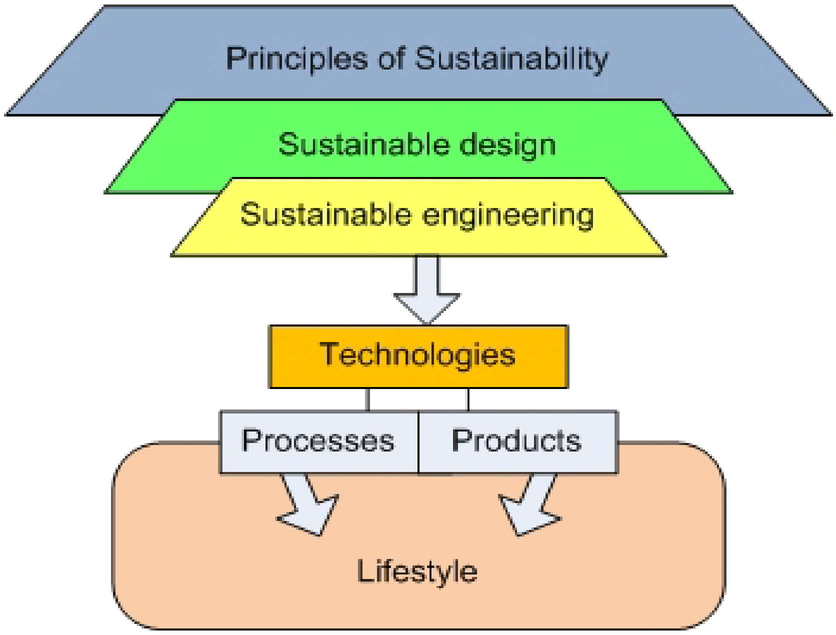

Figure 1. Hierarchy of sustainability principles, technologies, processes, and products is determining humanity lifestyles [23].

The Principles of Sustainability on the top guide the Sustainable Design, the process of thinking. The stage of Sustainable Engineering deals with the technical implementation of ideas. Sometimes it is not an easy process, and some aspects of the design may be changed or alternative solutions used. The design and engineering stages determine the Technologies, which provide the Processes and Products. The latter are sold. It is some sort of a portal through which the established principles of sustainable design and engineering affect people's lifestyle creating changes in society. Because of people's strong dependence on multiple technologies, these become the factors that can facilitate change in society and can even become tools of manipulation and initiation of global trends [24].

Engineering activities from the design and planning to operations follow the above-mentioned international activities. The content of socio-economic principles has increased with time, although the environmental ones are still predominant.

Principles of Sustainability and Sustainable Development

What is the difference between sustainability and sustainable development? Sustainability and sustainable development have somewhat different meanings. Sustainability is future oriented, while sustainable development concentrates on the methods and strategies to achieve sustainability [25]. "Sustainable development is the pathway to sustainability" [26]. Mulder et al. [12] examined the methods to be used in engineering design to achieve sustainable development. The book contains case studies and presents the results of several design projects. Table 1 presents three sets of sustainability principles, and three sets of the sustainable development ones.

Table 1. An overview of sustainability and Sustainable Development (SD) principles.

Initiative	Principles
Natural step (FSSD), sustainability principles	(1) Resource extraction, (2) Removal of chemicals, (3) Planetary equilibria, (4) Basic needs of others
Ben-Eli, core principles	(1) Resource scarcity, (2) Internalize externalities, (3) Biodiversity, (4) Equality, (5) Social life and ethics
UK Engineering Council, sustainability principles	(1) Sustainable society, (2) Professional and responsible judgement, and leadership, (3) More than legislation, (4) Resources efficiency, (5) Multiple views, (6) Risks to people and environment
Harris, basic principles of SD	(1) Inequalities and environmental damage, (2) Natural capital, (3) Population, resources, and biodiversity limits, (4) Equity, health, education, and democracy
Csaba and Nikolett, basic principles	(1) Holistic approach, (2) Solidarity, (3) Justice, (4) Resources, (5) Integration, (6) Local resources, (7) Participation, (8) Responsibility, (9) Precaution, (10) Polluter pays
University of PEI, guiding principles	(1) Professionalism, (2) Respecting diversity, (3) Collaboration, (4) Education, (5) Championship, (6) Leadership

Two years after the Brundtland report, the Natural Step framework, a non-profit NGO, was founded by Swedish scientist Karl Henrik Robért. Their approach is collectively called the "Framework for Strategic Sustainable Development"; it is a comprehensive model for planning in complex systems [27] based on four Sustainability Principles: (1) "we cannot dig stuff up from the Earth at a rate faster than it naturally returns and replenishes; (2) we cannot make chemical stuff at a rate faster than it takes nature to break it down; (3) we cannot cause destruction to the planet at a rate faster than it takes to regrow; (4) we cannot do things that cause others to not be able to fulfill their basic needs".

The Natural Step's understanding of human needs was based on the work of the Chilean economist Manfred Max-Neef [28]. He identified nine fundamental human needs that were consistent across time and cultures: subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom. "These fundamental human needs cannot be substituted one for another and a lack of any of them represents a poverty of some kind".

In contrast to the Brundtland report, Ben-Eli [29,30] published a definition and five Core Principles of Sustainability. They were related to five fundamental domains: (1) material (material and energy flows), (2) economic (wealth formation and management), (3) life (biosphere), (4) social (human interactions), and (5) spiritual (attitudes and ethics). The resulting five Core Principles included policy and operational implications foreseeing their interplay. In short, the corresponding five Principles aimed to: (1) reduce throwing away resources, (2) internalize external costs, (3) maintain biodiversity, (4) respect equality of all humans, and (5) take care of their social life and ethics.

The UK Engineering Council has issued a set of six high-level sustainability principles and related guidance [31]: "(1) contribute to building a sustainable society, present and future; (2) apply professional and responsible judgement and take a leadership role; (3) do more than just comply with legislation and codes; (4) use resources efficiently and effectively; (5) seek multiple views to solve sustainability challenges; and (6) manage risk to minimize adverse impact to people or the environment".

Harris [32] wrote a working paper on the basic principles of sustainable development (SD): (1) rectify social inequities and environmental damage with sound economics, (2) conserve natural capital beyond market mechanisms, (3) respect population, resources, and biodiversity limits, and (4) maintain social equity, basic health, educational needs, and participatory democracy.

Csaba and Nikolett [33] defined the 10 basic principles of SD presented in Table 1.

The Environmental Advisory Council [34] of the Canadian province of Prince Edward Island (PEI) identified the guiding principles for sustainable development. They are community oriented and grouped in two chapters covering all the three pillars of SD:

1. Changing the way we work, with 12 principles addressing people and communities, needs and opportunities, problems and critical issues, policies and programs, funding and spending plans, short term decisions, awareness raising and education, etc.
2. Government shall take care of the present and future generations' interests by using 10 principles: placing people and their information at the center, including healthy and resilient environment, cost-effectively preventing environmental damage, long-term planning by using scientific knowledge, respecting risks, and uncertainties, etc.

The 22 principles were designed to build a sustainable economy, improve living standards while conserving the environment, and protect the land- and seascape. Environmental strategy and the government's environmental policy are dealt with in more detail.

The University of PEI has accepted six guiding principles on sustainability and energy management activities: (1) conduct professionally, (2) respect diversity of opinions, options, and ideas, (3) collaborate on campus to promote the development of a sustainability culture and energy efficiency, (4) education—raise awareness of sustainability fundamentals and initiatives, and energy efficiency activities, (5) work to foster change by demonstrating sustainable and energy efficient principles on campus, (6) provide guidance to the campus community to foster a sustainable and energy efficient community.

The sets of sustainability principles in Table 1 deal with the environmental, economic, and social pillars. Ben-Eli also includes the biosphere and spiritual domains. The principles are goal oriented. The UK's Engineering council deals with ethical and legislative components as well as social ones (multiple views and risk management). The UK principles are behavior oriented and in some way a step towards sustainable engineering ones.

Harris includes two or even three pillars in each basic principle. Social and environmental components are present in three basic principles each, and economic ones in two. Csaba and Nikolett include social matters in six out of ten basic principles, three from environmental ones, and only one from economics; they basically apply a management approach. Prince Edward Island's guiding principles are, in the foreground, social ones, and two of them are economic and only one is environmental—they are policy oriented.

Table 1 reveals that the most often cited principle relates to resources including their scarcity, and the need to conserve and use them efficiently; their recycling is not mentioned but natural capital should be managed sustainably and not thrown away. Biodiversity, precaution and prevention, chemicals' pollution, and land- and seascape protection are mentioned within the environmental principles. The most often cited social principles are equality and diversity of opinions, participation, and integration. Solidarity, health, education, justice, democracy, basic needs of others, social life, and ethics are mentioned, too. Internalizing externalities and the polluter pays principles are mentioned within the economic pillar. Holistic approach and professionalism are very important overarching characteristics of engineers; the latter includes professional and responsible judgement, risk management, and leadership. More than just respecting the legislation is expected from them.

4. Design for Sustainability

Design for sustainability, also called (environmentally) sustainable design, or eco-design is the way of designing products, processes, and systems that enable sustainable development. Some of its principles are summarized in Table 2.

Table 2. An overview of sustainable design principles on the time axis.

Initiative	Principles
Hannover principles	(1) Co-existence with nature, (2) Interdependence, (3) Spirit and matter, (4) Responsible design, (5) Long-term value, (6) No waste, (7) Natural energy flows, (8) Design limitations, (9) Constant improvement
Todd, eco-design principles and practices	(1) Living world matrix, (2) Laws of life, (3) Biological equity, (4) Bio-regionality, (5) Renewable energy, (6) Living systems integration, (7) Co-evolution, (8) Healing the planet, (9) Following ecology
Ryn and Covan, ecology principles	(1) Solutions from place, (2) Ecological accounting, (3) Design with nature, (4) Everyone is a designer, (5) Make nature visible
McLennan, sustainable design principles	(1) Learn from nature, (2) Respect natural resources, (3) Respect for people, (4) Respect for place, (5) Respect for future, (6) System thinking
Riel, integrated skills	(1) Product Life cycle, (2) Innovation, (2) Responsibility, (3) Networked collaboration, (4) Intercultural skills, (5) Knowledge engineering
Mattson and Wood, design principles for developing countries	(1) Local population, (2) Testing the product locally, (3) Adapting imported technology, (4) Poverty elimination, (5) Women and children, (6) Country needs, (7) Interdisciplinary teams, (8) Cooperation with governments, (9) Adaptation to world markets
Econation, design for sustainability	(1) Doing right things to support individuals, human intrinsic values, social equity and common good, local communities, health, sustainable production, and consumption, (2) Doing things right: thinking in systems, dematerialization, renewable and natural materials, biomimicry, cradle to cradle

The Hannover principles [35] contain nine principles: "(1) Insist on rights of humanity and nature to co-exist; (2) Recognize interdependence; (3) Respect relationships between spirit and matter; (4) Accept responsibility for consequences of design decisions; (5) Create safe objects of long-term value; (6) Eliminate the concept of waste; (7) Rely on natural energy flows; (8) Understand limitations of design; (9) Seek constant improvement by the sharing of knowledge".

Principles and practice of eco-design [36] are: "(1) The living world is the matrix for all designs; (2) Design should follow, not oppose, the laws of life; (3) Biological equity must determine design; (4) Design must reflect bio-regionality; (5) Use renewable energy sources; (6) Proceed by integration of living systems; (7) Design should be co-evolutionary with nature; (8) Building and design should heal the planet; (9) Design should follow a sacred ecology".

Principles of physical and social ecology [37] are: "(1) Solutions grow from place; (2) Ecological accounting informs design; (3) Design with nature; (4) Everyone is a designer; (5) Make nature visible".

McLennan [38] urged for a different design approach to abandon all negative environmental impacts. It should be purpose oriented. The six principles of sustainable design include [24]):

1. "Learn from and as natural systems (Biomimicry Principle). Nature shall serve as a model (recycling everything), as a measure (limits) and as a mentor (mimicry of natural designs).

2. Respect natural material and energy resources (Conservation Principle). Energy originates from the sun—it is abundant, every day it meets our needs for 27 years, but it must be concentrated and stored by physical, biological or chemical processes.
3. Respect for people (Human Vitality Principle) by creating healthy and friendly products, and infrastructure.
4. Respect for place (Ecosystem Principle): use local materials and local conditions.
5. Respect for the future ('Seven Generations' stewardship Principle), e.g., to consume non-renewables at a rate below replenishment, and approach zero waste.
6. System thinking (Holistic Principle)—considering impacts of design on environment (ecology), people (equity), and business (economy)".

Practical design applications vary among disciplines (process or product design, ICT, architecture, services, etc.) but some common principles have been. Sustainable design requires a holistic approach to development including the protection of natural resources and energy usage [39].

"Integrated Product Development requires understanding and predicting the whole Product Life cycle [40]. It has significant implications on the competence profiles of engineers. Integrated Design Engineers need "integrated skills" including Product Life Cycle Engineering, Innovation Driven Design, Responsible Design, Networked Collaboration, Intercultural Skills, Requirements and Knowledge Engineering. Certification rules of the ECQA (European Certification and Qualification Association) can be used to leverage these assets to a worldwide unique qualification and certification platform for Integrated Design".

Ranky [41] published 18 product design engineering principles and rules, which are very complex. They are based on a sustainable green, lean design, and assembly approach, also known as concurrent or simultaneous Green PLM (Product Lifecycle Management). The principles and rules also include Ranky's intelligent Sustainable Enterprise Engineering (iSEE:Green) concept.

Mattson and Wood [42] summarized the experiences of engineering researchers and practitioners of design for developing countries into nine guiding design principles. The social pillar is included within design as the most important one. The nine principles are: (1) design with respect to the local population and its needs, (2) test the product in the actual environment, (3) adapt imported technology to specific local and regional needs, (4) take care of urban and rural poverty elimination, (5) regard especially women and children, (6) adapt project design and management techniques to the specific needs of developing countries, (7) engage interdisciplinary teams, (8) cooperate with local and regional governments, and (9) adapt distribution to developing world markets.

Design for sustainability is an approach that puts the well-being of people and the sustainability of the environment first [43]. It is a whole system approach that considers the overall impacts of designs. As a multidisciplinary and interdisciplinary approach, it can be applied in all fields. To design and create sustainability, there are two key questions to consider:

(1) Are you doing the right things to support: individual well-being, human intrinsic values, social equity and the common good, diverse, and thriving local communities, healthy environments, and environmentally sustainable production and consumption?
(2) Are you doing things right: thinking in systems, dematerialization, renewable and natural materials, biomimicry, and cradle to cradle?

The early principles required equilibrium between human and nature rights. Later, social requirements prevailed, except in Todds' principles and practice of eco-design where environmental principles are dominant. Economic principles are regarded only in third place. McLennan pointed out three of the environmental principles (biomimicry, natural and local resources), two social ones (respect for people and future), and an overarching one (holistic or systems approach). Mattson and Wood elaborated on nine guiding design principles for developing countries, respecting local and regional population, environment, needs, social circumstances, local cooperation, management, and export. Design for sustainability is about well-being and environmental protection.

5. Sustainable Engineering

Sustainable engineering refers to the integration of social, environmental, and economic considerations into product, process, and energy system design methods. Additionally, sustainable engineering encourages the consideration of the complete product and process lifecycle during the design effort. The intent is to minimize environmental impacts across the entire lifecycle while simultaneously maximizing the benefits to social and economic stakeholders.

A review of the principles from green engineering and sustainable engineering is presented in Table 3.

Table 3. An overview of sustainable engineering principles.

Initiative	Principles
Anastas and Warner, 6 out of 12 Principles of Green Chemistry	(1) No waste production, (2) minimum risk to humans and environment, (3) minimum energy, (4) renewable resources, (5) benign end-of-live products, (6) real time analysis for pollution prevention
Anastas and Zimmerman, 12 Principles of Green Engineering	(1) Non-hazardous inputs/outputs, (2) waste prevention, (3) min. resource usage, (4) max resource/time efficiency, (5) "output pulled" resources, (6) recycle, reuse, refurbish, (7) durability not immortality, (8) no overcapacity, (9) easy recycling, (10) recycle within process, (11) extended use, (12) renewables
Sandestin, Green Engineering principles	(1) Holistic approach, (2) natural ecosystem conservation, (3) life cycle thinking, (4) safe/benign inputs, (5) min natural resources, (6) waste prevention, (7) local conditions, (8) engage all stakeholders
BASF, Eco-efficiency Analysis	(1) Customer viewpoint, (2) societal factors by using LCA, (3) economy vs. ecology, (4) social aspects
WBCSD, Eco-efficiency principles	(1) Fewer materials and (2) energy, (3) disperse toxics, (4) recyclability, (5) renewables, (6) durability, (7) greater service intensity
IPENZ principles	See Table 4
RAE principles	(1) Beyond locality and immediate future, (2) innovate and create, (3) balanced solution, (4) all stakeholders, (5) needs and wants, (6) plan/manage effectively, (7) benefit sustainability, (8) polluters pay, (9) holistic approach, (10) do right things right, (11) no cost reduction masquerade, (12) practice what you preach
SE principles	See Figures 2 and 3
Rosen, Key requirements for SE	Sustainable (1) resources and (2) processes, (3) increased efficiency, (4) reduced environmental impact when using LCA, (5) other aspects: economic affordability, equity, resource demand, safety, community, social acceptability, human needs, land use, aesthetics, lifestyles, population

Table 4. Three key principles with 15 principles of sustainability and engineering in New Zealand.

Maintain the Viability of the Planet	
1	Humans need to maintain the integrity of global and local biophysical systems.
2	Renewable resources must be managed within sustainable harvest rates and non-renewable resource depletion rates must equal the rate at which renewable substitutes take their place.
3	Technological options must favor choices that minimize the use of resources and reduce risks.
4	The material and energy intensity used in products, processes or systems needs to be reduced significantly—by 10 to 50 times—using recycling and minimization techniques.
5	Waste streams during the life cycle of products, processes or systems must be minimized to the assimilative capacity of the local and global environments.
6	Any use and production of environmentally hazardous materials must be minimized and carried out prudently if necessary.
Providing for equity within and between generations	
7	Humans, now and in the future, must have equal access to choices in life that reduce significant gaps between people in areas such as health, security, social recognition, and political influence.
8	Total consumption of resources needs to be within the environment's sustainable capacity and balanced between the affluent and those yet to fulfil their basic needs.
9	Present resource use and development must be considered over a sufficiently long timescale that future generations are not disadvantaged.
10	Those directly affected by engineering projects, products, processes, or systems must be consulted and their views incorporated into the planning and decision-making processes.
Solving problems holistically	
11	Problem solutions must be needs-based, rather than technology-driven.
12	Demand growth targets must be realistically assessed and if necessary managed, rather than simply meeting predictions.
13	A holistic, systems-based approach must be used to solve problems, rather than technology focusing on only single aspects of problems.
14	Unsustainable practices must be reduced to zero over time, and where practicable past degradation shall be addressed.
15	Problem solutions must be based on prudent risk management approaches.

5.1. Green Engineering Principles

Anastas and Warner [44] published 12 Principles of Green Chemistry—they are mainly chemicals oriented but half of them apply to engineering, too: "(1) Avoiding waste production is far better than treating or cleaning it up afterwards; (3) Feeds and products to and from a chemical process should pose as little risk to human health, and be as environmentally benign as possible; (6) Reduce energy waste and consumption by striving to operate at ambient conditions; (7) Where technically and economically possible, (chemical) feeds and raw materials should be sourced renewably; (10) Materials and chemicals should be designed, where possible, to degrade into benign and non-toxic substances at the end of their functional lives; (11) Use real time analysis for pollution prevention".

The 12 principles of green engineering [45] include: (1) non-hazardous material and energy inputs and outputs, (2) waste prevention, (3) minimum resource usage, (4) maximum resource and time efficiencies, (5) use "output pulled" energy and materials, (6) recycle, reuse, or dispose for usable purposes, (7) the design goal shall be durability, rather than immortality, (8) avoid overcapacity, (9) design for easy recycling, (10) recycle and reuse resources within your production process, (11) design for extended use, and (12) use renewables. The principles are chemical process oriented.

The nine Sandestin principles are the result of a conference entitled Green Engineering: defining the principles, which took place in May 2003 at the Sandestin Resort in Florida [46]. The Sandestin Declaration agreed upon the following draft principles: (1) holistic approach, (2) natural ecosystems conservation, (3) life cycle thinking, (4) safe and benign material and energy inputs, (5) minimum depletion of natural resources, (6) waste prevention, (7) respect local conditions, (8) improve–innovate–invent new technologies, and (9) engage all stakeholders.

At the same time, BASF developed and tested the Eco-Efficiency Analysis using over 180 industrial applications [47]. The work mostly confirmed the 12 principles listed in the Anastas and Zimmerman paper, but it was more practice oriented, and included economic and social principles. As well as the preliminary conditions in the analysis, the environmental efficiency analysis was developed using 10 principles including: (1) customer viewpoint when calculating total cost, health, safety, and risk analysis, (2) weighting societal factors by using LCA, (3) comparing the relevance of economy versus ecology, and (4) regarding social aspects (optionally).

Eco-efficiency has developed in the last two decades. As defined by the World Business Council for Sustainable Development [48], "Eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity. It is concerned with creating more value with less impact." According to Lehni [48], "the most critical features of eco-efficient companies are: (1) Producing goods and services with fewer materials. (2) Producing goods and services with less energy. (3) Dispersing lower volumes of toxic materials. (4) Improved recyclability. (5) Striving to use renewable resources. (6) Making goods that last longer, and (7) Greater service intensity of products and services".

Garcia-Serna et al. [49] presented a "broad review of disciplines and technologies concerning the design trends: The Natural Step, Biomimicry, Cradle to Cradle, Getting to Zero Waste, Resilience Engineering, Inherently Safer Design, Green Chemistry and Self-Assembly". The core of the review paper was "Green Engineering, its main definitions, scope of application, different guiding principles, a framework for design and legislative aspects". Thirteen sets of principles were presented, and a quick selection guide about using each one was given. Some of them are described in this paper; here is the list of six not yet described sets of principles: The Earth Charter Principle, The Coalition for Environmentally Responsible Economies (CERES) Principle, The Bellagio Principles, The Ahwahnee Principles, The Interface Steps of Sustainability, and Design for Environment (DfE) Key Strategies.

These green engineering principles were and still are environmentally stressed as shown by the name. Industry introduced additional economic and social components, which helped them to survive until the present. Eco-efficiency has slowed down the rate of hazardous human impacts on the environment. Sets of principles were described to help engineers design their objects easier and better.

5.2. Sustainability Principles and Practice for Engineers

The Institute of Professional Engineers New Zealand (IPENZ) started work on sustainability principles in 2003. Their time horizon was 1000 a, and they assumed that basic human needs will not change. Two years later they presented the first draft of their updated principles for engineers [50] that were further improved by numerous case studies and checklists. On this basis, they postulated three key principles (Viability of the Planet, Equity within and between generations, Solving problems holistically) with 15 principles in all [51] (Table 4).

The Royal Academy of Engineering (RAE, United Kingdom) presented 12 "Principles of Engineering for Sustainable Development" [52], which are very useful from the operational point of view. The 12 principles (Table 3) are: "(1) Look beyond your own locality and the immediate future; (2) Innovate and be creative, (3) Seek a balanced solution; (4) Seek engagement from all stakeholders; (5) Be sure you know the needs and wants; (6) Plan and manage effectively; (7) Give sustainability the benefit of any doubt; (8) If polluters must pollute, then they must pay as well; (9) Adopt a holistic, "cradle to grave" approach; (10) Do things right, having decided on the right thing to do; (11) Beware cost reductions that masquerade as value engineering, and (12) Practice what you preach".

The IPENZ principles are well developed, covering three main areas: environmental, equity, and systems approaches. They are weak on economic and societal sides, however. The RAE principles are short but very instructive for practicing engineers.

5.3. Sustainable Engineering Principles

Sustainable engineering (SE) does not harm the environment, nor does it exploit resources that belong to future generations [53]. The NAL Thesaurus [54] defines it as "the design, commercialization and use of processes and products that are feasible and economical while reducing the generation of pollution at the source and minimizing the risk to human health and the environment". It includes all the three SD pillars. Kauffman and Lee [55] edited a handbook of SE with 66 chapters and 1285 pages written by academic researchers as well as practitioners. They brought new engineering approaches to sustainable production, and innovative operational practices.

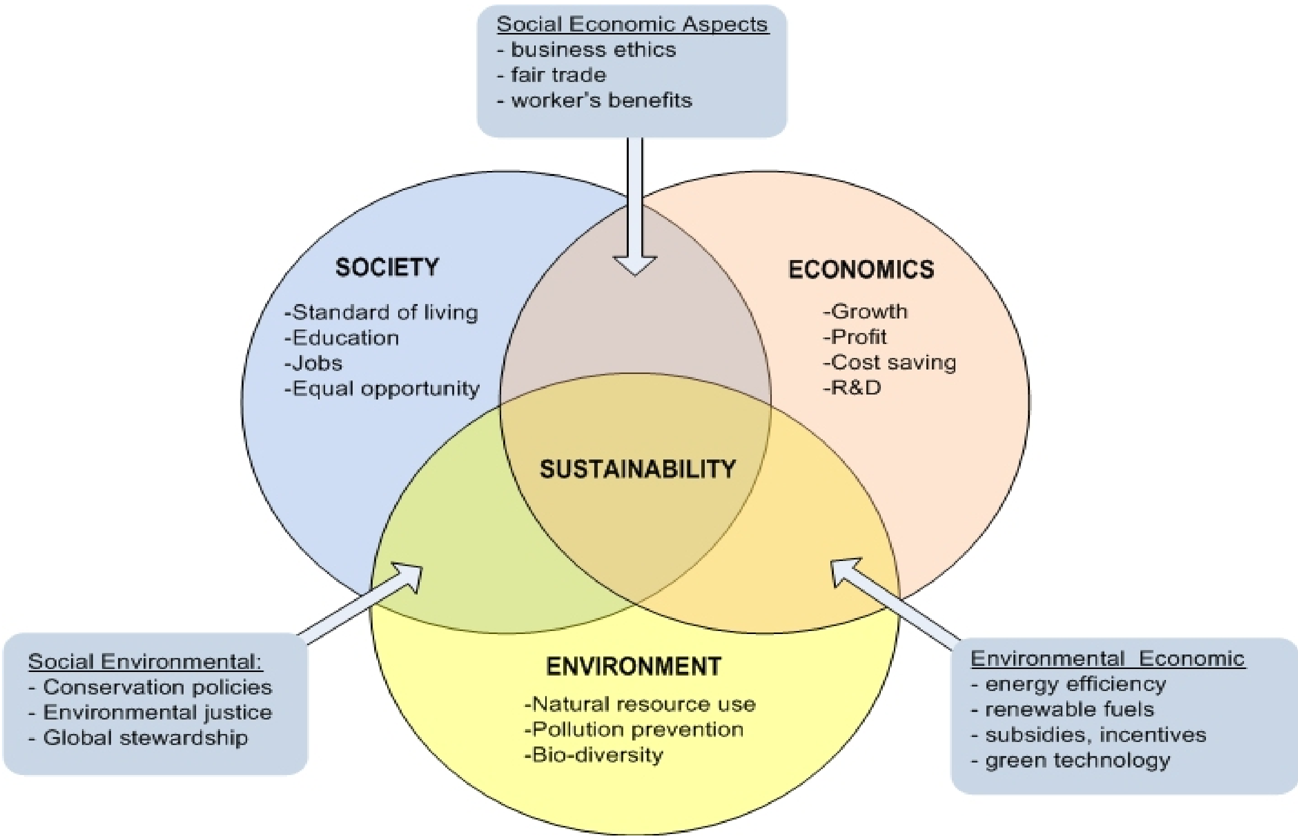

Figure 2. Interplay of the environmental, economic, and social aspects of sustainable development (Mark Fedkin [23]; adopted from the University of Michigan Sustainability Assessment [56]).

The advantages of SE in comparison with traditional green engineering are the following [23]:

- SE considers the whole system in which the product, process or services are used.
- It deals not only with technical but also with non-technical issues in synergy.
- It is designed to solve problems for the distant future, not just for the immediate period.
- As well as the local context, it considers the global one, too.

- It deals with political, ethical, and societal issues by interacting with experts in other disciplines.

Sustainable engineering principles can be shown by a triangle, having environmental, social, and economic pillars as the corners. Figure 2 presents all the tree pillars in the form of spheres, with their most important constituents listed. The environmental aspects include the use of natural resources, pollution prevention, biodiversity, and ecological health. The social aspects include standards of living, the availability of education and jobs, and equal opportunities for all members of society. The economic factors are drivers for growth, profit, reducing costs, investments into research and development, etc. Interaction of the social and economic spheres result in the formulation of combined social–economic aspects. Those are, e.g., business ethics, fair trade, and worker's benefits. The combination of economic and environmental interests facilitates increasing energy efficiency, the development of renewable fuels, green technologies, and creation of special incentives and subsidies for environmentally sound businesses. The intersection of social and environmental spheres leads to the creation of conservation and environmental protection policies, establishment of environmental justice, and global stewardship for the sustainable use of natural resources.

The diagram in Figure 3 presents a consolidated framework for sustainable engineering principles, which are in part adopted from the work of Gagnon et al. [57] and from the green engineering principles established by Sandestin Conference (Abraham and Nguyen, 2003). Gagnon et al. presented sets of principles that are most relevant to sustainable engineering. Based on general sustainable development principles and on specific engineering ones, they proposed a set of fifteen sustainable engineering principles, organized in a triangle. The principles that are closer to the extremities of the triangle are one-dimensional. Those on the sides are bi-dimensional; they have a stronger connection with the angle they are closer to. Three-dimensional principles are in the middle of the triangle; each of them being situated according to their links with the angles. These principles can serve as guidelines in a specific engineering project.

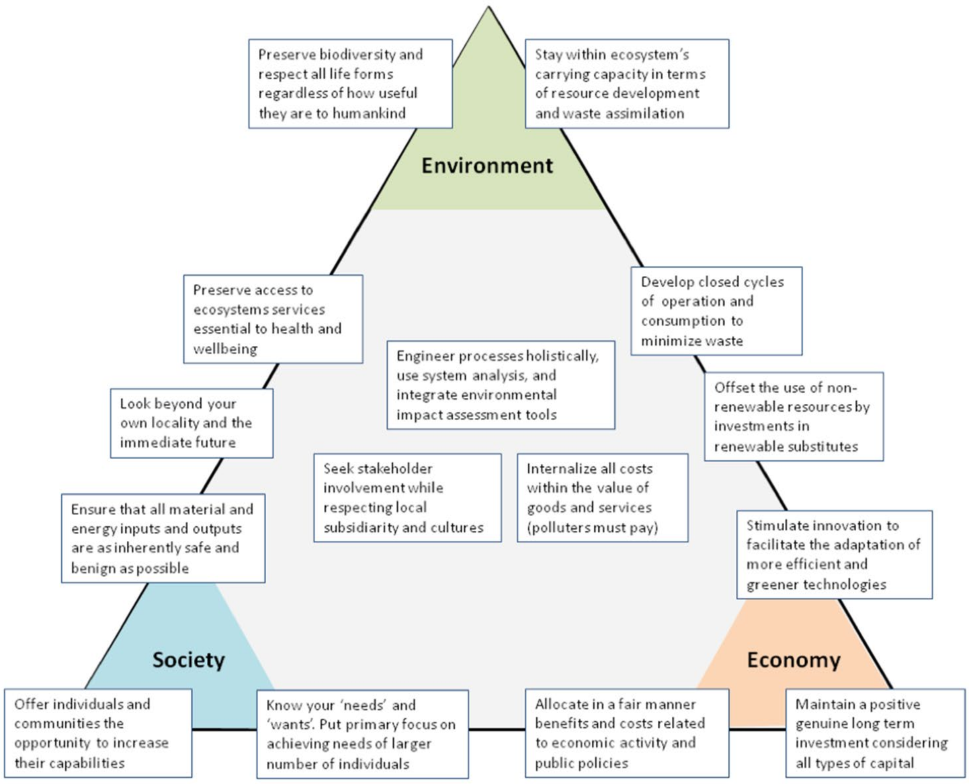

Figure 3. Classification of sustainable engineering principles versus environmental, social, and economic criteria.

Rosen [58] cited "5 key requirements for engineering sustainability: (1) sustainable resources, (2) sustainable processes, (3) increased efficiency, (4) reduced environmental impact when applying LCA, and (5) fulfilment of other aspects of sustainability: economic affordability, equity, meeting increased resource demand, safety, community involvement and social acceptability, human needs, appropriate land use, aesthetics, lifestyles, and population".

All the three approaches described above are close to the modern understanding of SE. However, they do not mention circular economy and zero waste system, which is broader and deeper than just recycling—see the Circular Economy System Diagram [59]. Moreover, human capital, social responsibility, and annual reporting are not presented as societal and 3D components, respectively. Cost-Benefit Analysis using LCA is important, too. The precautionary approach has been well known for three decades, but it is not included in the existing SE principles. Therefore, it seems reasonable to update the SE Principles.

6. Updated Sustainable Engineering Principles

Sustainable engineering (SE) principles need an update to include the present state of the art in human knowledge. Table 5 presents the missing principals in the individual SE sets studied. The updated 12 principles have been synthesized using the literature review in Sections 2–4, especially the above-described principles of sustainable development, SD [33], new trends, recent developments, and personal experience in the SD area. The SDGs have been respected, too. As well as the omissions mentioned in the last paragraph, more rapid climate change than expected, critical raw materials break out, pollution (especially plastics) spread, and acceleration of species extinction are suggested to modify the outdated principles. Increasing inequalities, extreme human wealth distribution, advantage of profits against the common good, the fraction of decent jobs reduction, etc. require changes in the behavior of engineers. They are expected to mitigate the negative consequences of human development and present a solid ground for long-term changes in engineering design. Sustainable engineering principles are an important vehicle towards sustainable development.

Environmental, social, and economic pillars are of equal importance to the future. Therefore, the updated principles (the connections with the SDG numbers are shown in parentheses) include:

A. Tridimensional principles
   1. Holistic approach, systems thinking and management (SDG 16)
   2. Precautionary and preventive approaches (SDG 13)
   3. Annual sustainability reporting using GRI (SDG 4)

B. Environmental principles
   4. Circular economy, waste minimization, sustainability hierarchies (SDG 13)
   5. Efficient use of resources, and increased share of renewables (SDGs 6, 7)
   6. Sustainable consumption and production (SDG 12)

C. Social principles
   7. Equalities within and between generations (SDGs 5, 10)
   8. Engagement of communities and all stakeholders (SDG 11)
   9. Corporate social responsibility and decent work (SDGs 1–3, 8)

D. Economic principles
   10. Human capital, innovations, and creativity (SDGs 4, 9)
   11. Cost–benefit analysis using Life Cycle Assessment (SDGs 3, 13)
   12. Internalizing externalities—polluters must pay (SDG 13)

Table 5. Comparing the updated Sustainable Engineering Principles (SEP) with the ones described in Section 4.

Updated Sustainable Engineering Principles	Green Engineering	Eco-Efficiency Analysis	Sandestin Principles	SD Triangle Figure 2	Sustainable Engineering Principles, Figure 3	Sustainable Principles and Practices IPEN2	RAE Principles of Engineering for SD
Tridimensional principles							
Holistic approach and system thinking			holistic approach	environmental stewardship, environmental justice	holistic process, use system analysis	use holistic systems-based approach	holistic approach
Reporting						prudent risk management	do things right
Environmental principles							
Sustainable consumption and production	minimum resource use, output pull, durability	environmental fingerprint	minimum resource depletion	resource use, pollution prevention, biodiversity	Biodiversity, know the needs and wants	minimum use of resources and risks, integrity	know the needs and wants
Circular economy, waste minimization, waste, and energy hierarchies	recycling, reuse, design for recycling, waste prevention		waste prevention	green technology	closed cycles	within environmental capacity, minimum waste	
Efficiency, renewable resources	maximum resource and time efficiency, renewable resources		ecosystems conservation	energy efficiency, renewable fuels		min energy and material intensity, renewable sources	
Precautionary and preventive approach	non-hazardous in/outputs, no over-capacity		safe and benign inputs	conservation policies	eco-carrying capacity, safe and benign input	minimum hazardous materials, needs-based	look beyond locality and near future
Societal principles							
Equity within, between generations				equal opportunity		equal access to choices	
Communities, all stakeholder's engagement		societal weighing	respect local cond., engage all stakeholders	living standard, jobs	stakeholder interests beyond your	consult and consider directly affected stakeholders	engage all stakeholders, balanced solutions
Social responsibility, CSR, decent work				business ethics, fair trade	health and well-being	no disadvantage for future generations	practice what you preach
Human capital, creativity, and innovations			improve, innovate, invent	education, workers' benefit, R&D	stimulate innovations in greener technologies		innovate and be creative
Economic principles							
Cost–benefit analysis when applying LCA		total costs, eco-efficiency analysis, LCA	LC thinking	growth, cost saving, profit	allocate benefits and costs	reduce unsustainable practices to zero	beware cost reduction masquerade
Internalizing externalities, polluters pay				subsidies, incentives	internalize all costs—PMP		polluters must pay

Table 5 compares the updated SE Principles with those obtained from the descriptions in Section 4. Although it is difficult to find the adequate location of each principle, each of the sets is evidently missing at least two or more of the updated principles.

7. Discussion

To accelerate the transition to equitable, sustainable, livable, post-fossil carbon societies [60], we need to do today more than yesterday and tomorrow more than today.

Scientists, engineers, policy makers, institutions, and NGOs have shown new and improved ways to a sustainable future. They need to be included in the different sets of sustainability principles. The engineering ones will include the SDGs. Although some of them are old, others are not and have to be included in the standard list of SE principles: innovation, decent work, responsible consumption, and peace present some examples of them. International and national organizations are developing new and improved approaches to sustainable development, which will be accompanied by SE activities. The pace is speeding up and, therefore, the SE Principles must be broad enough to encompass new methods and tools into everyday practice.

7.1. The Tridimensional Principles

The Holistic approach considers a global view, the Planet, instead of a local one. It is concerned with assumptions, knowledge, methods, and implications of various disciplines treating them as an integrated whole, or system. Systems thinking is about how things interact with one another; it must be differentiated from systematic (analytical, or synthetic) thinking. Environmental management using ISO 14000 family standards on LCA, and EU Environmental Management and Audit Scheme (EMAS) helps organizations (a) minimize environmental impacts of their operations (e.g., processes); (b) comply with applicable laws, regulations, and other environmentally oriented requirements; (c) apply continuous improvement approach. ISO 14000, LCA, standardizes a technique to assess environmental impacts associated with all the stages of a product's life, from raw material extraction through material processing, manufacturing, distribution, use, repair and maintenance, disposal, and recycling.

Precautionary principle requires the prevention of actions whose consequences are uncertain and/or potentially dangerous. It was first proposed in the Rio declaration. Humans will avoid or diminish activities that may lead to morally unacceptable harm to the environment or humans—to human life or health—serious and effectively irreversible actions that are inequitable to present or future generations, or do not respect the human rights of persons involved [61]. The judgement of plausibility should be grounded in scientific analysis. The principle, proposed as a guideline in environmental decision making has four central components: (1) taking preventive action in the case of uncertainty, (2) shifting the burden of proof to the proponent of an activity, (3) exploring a wide range of alternatives to potentially harmful actions, and (4) increasing public participation in decision making.

The EU definition of the precautionary principle applies where scientific evidence is insufficient, inconclusive, and preliminary scientific evaluation indicates that there are reasonable grounds of concern that the potentially dangerous effects on the environment, human, animal, or plant health may be inconsistent with the high level of protection chosen by the EU [62]. Examples of harm are environmental hazards (climate change and global warming, species extinction, effluents, acute pollution), public and human health hazards (diseases, toxic chemicals, carcinogenic substances, hazardous waste, radiation) of chemical, physical, biological, or psychosocial origins.

The Global Reporting Initiative, GRI [63] is an international organization that "helps businesses, governments and other organizations understand and communicate their impacts on issues such as climate change, human rights and corruption". "A sustainability report published by a company or organization is about the economic, environmental and social impacts caused by its everyday activities including its values and governance model and demonstrates the link between its strategy and its commitment to a sustainable global economy". Sustainability reporting can help organizations to "measure, understand and communicate their economic, environmental, social, and governance performance, and then set goals, and manage change more effectively". An annual sustainability report is the "key platform for communicating sustainability performance and impacts—whether positive or negative". GRI guidelines include (a) the required general standard disclosures, and (b) specific standard disclosures with three categories: economic, environmental, and social, each with several aspects. Each aspect has several descriptions and/or indicators.

7.2. The Environmental Principles

The closed loop or circular economy (CE) model [59] has emerged from the discipline of industrial ecology (described in Section 2). It presents a transition from a linear, "take-make-waste" or "cradle to grave" production system, to a circular, or "cradle to cradle", "waste is food", biomimicry, "blue economy", and "whole system thinking". It has been used as an exemplar [20] to apply the metaphor of natural systems to the production of goods in the industrial economy. CE includes eco-design, sustainable supply, and responsible consumption. The Zero waste ideal leads to waste minimization and better utilization of resources (materials and energy). It requires separation of wastes and their collection and uses all the 12 Rs (rethink, reform, refuse, reduce, reuse, re-gift, repair, refurbish, remanufacture, repurpose, recycle, and recover) to mimic the rules in the biosphere. When using waste, it is important to use it for the highest possible level of hierarchy (Figure 4).

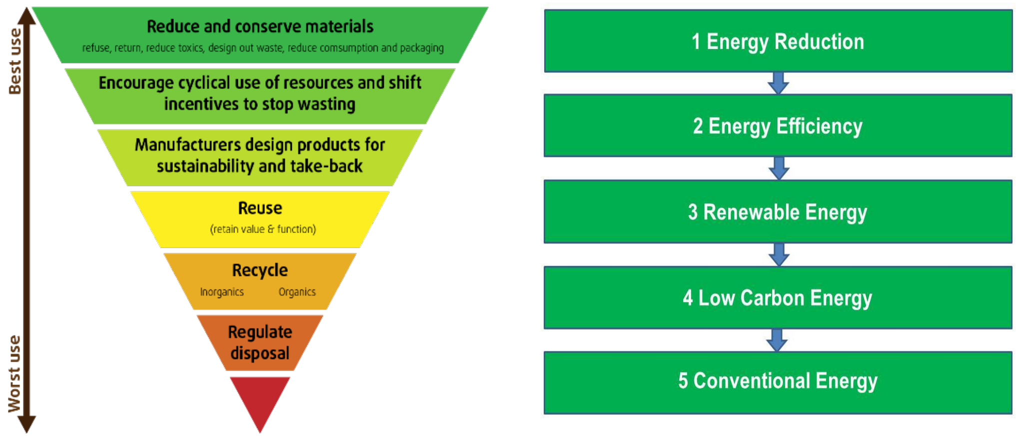

Figure 4. Two possible sustainability hierarchies.

Sustainability hierarchy considers, e.g., natural resource conservation and protection as the top priority, followed by manufacturing efficiency, product quality, judicious product selection, product repair and restoration, resource reuse, resource recycling, energy recovery, waste treatment, waste disposal, and pollution at the bottom [64]. The waste management hierarchy considers waste prevention as the highest priority, followed by waste minimization, resource reuse, and resource recycling, energy recovery, waste treatment, and waste disposal as the lowest preference. A similar approach to the energy hierarchy has energy reduction/saving (leaner) at the top, followed by energy efficiency (keener), renewable (greener) energy, low carbon, and other emissions (cleaner), and conventional (meaner) energy at the bottom.

The resources are finite, and the EU has already identified 30 critical raw materials [65]. China is the biggest producer of them. Several other countries are dominant suppliers of specific raw materials, e.g., USA (beryllium) and Brazil (niobium). A circular economy enables them to be reused but it requires a suitable eco-design. Respecting health and safety rules and including the use of materials that accumulate in the environment (e.g., greenhouse gases) are of great importance for the future climate stability. In the case of energy, cascading is used, e.g., by the closest temperature differences (pinch technology) or distance, by recycling.

Resource efficiency requires use of the Earth's limited resources in a sustainable way while minimising impacts on the environment. It allows us to create more output and to deliver greater value with less input. Resources include materials, water and energy, capital, and finance (money), human capital (staff, employees, unemployed or migrated individuals), etc. Renewables are renewable energy sources (solar, hydro, wind, biomass, biofuel, biogas, geothermal, tidal, and wave energy) as well as material ones (water, air, soil, plants, animals, and humans, agricultural, aqua-cultural, and forestry products—food, biomass, timber, paper, cotton and wool, bioplastics, and bio-chemicals).

Examples from industry, sustainable cities and communities, universities, schools, etc., demonstrate that the proposed principles can be put into practice bringing substantial improvements. Let us consider, for example, achievements of the European chemical industry in the period 1990–2019 [66]: total greenhouse gas (GHG) emissions fell by −54% (–154 Mt/a), GHG intensity (GHGs per unit of production) by −54%, and GHG emissions per energy production by −47%. While chemical production increased by +47%, specific energy consumption decreased by −47%, showing that decoupling of the two is viable.

Sustainable consumption and production (SCP) was identified as one of the three overarching objectives of, and essential requirements for, sustainable development: "Fundamental changes in the way societies produce and consume are indispensable for achieving global sustainable development with the developed countries taking the lead and with all countries benefiting from the process. Poverty eradication, changing unsustainable patterns of production and consumption, and protecting and managing the natural resource base of economic and social development are essential requirements" [67]. SCP is included in the SDGs under No 12: "SCP is about promoting resource and energy efficiency, sustainable infrastructure, and providing access to basic services, green and decent jobs, and a better quality of life for all. Its implementation helps to achieve overall development plans, reduce future economic, environmental, and social costs, strengthen economic competitiveness, and reduce poverty".

7.3. The Societal Principles

Intergenerational equity is a concept that humans "hold the natural environment of our planet in common with other species, other people, and with past, present and future generations" [68]. The present generation includes children, youth, adults, and seniors. They inherited the Earth from previous generations and must pass it on to future generations in good condition. The continued depletion of natural resources in the past diminishes their opportunities in the future. National debt is an example of intergenerational inequity, as future generations will suffer paying it off. Intra-generational equity must ensure equal opportunities and equal access to choices for all customers and employees, irrespective of gender, sexuality, race, nationality, or religion.

Stakeholder engagement means that the public has the right to participate in decision making. Engineers must respect public opinions in project outcomes [69]. Engagement of communities and all stakeholders in projects for the developing world has been explained in Section 3. It is important to achieve the triple bottom line, and it relates to both the corporate social responsibility and the GRI. The ISO 9000 standard series on quality management systems helps organizations to meet the customers' and other stakeholders' needs as well as other requirements related to a product (e.g., quality control).

Social/societal responsibility (SR) is a self-evaluation tool for companies regarding their impact on society [70]. SR is an ethical framework for individual engineers and scientists, too [71]. The word "social" refers to "having to do with human beings living together as a group in a situation in which their dealings with one another affect their common welfare" [72]. The definition of the word "societal" is more restrictive but is roughly included within the wider definition of "social"; it is defined as "of or pertaining to society". "Social/societal responsibility" regards new technologies, which can be found in responsible innovation, and it originates from technology assessment. Technology Assessment emerged in the 1970s to reduce the (negative) side effects of new technologies (motivated by the pollution caused by the growing industrial system).

Social responsibility relates to all citizens, while corporate social responsibility (CSR) refers to companies taking responsibility for their impact on society. The European Commission [73] believes that "CSR is important for the sustainability, competitiveness, and innovation of EU enterprises and the EU economy. It brings benefits for risk management, cost savings, access to capital, customer relationships, and human resource management". The Commission promotes CSR in the EU and encourages enterprises to adhere to international guidelines and principles. "CSR policy functions as a self-regulatory mechanism whereby a business monitors and ensures its active compliance with the spirit of the law, ethical standards and national or international norms" [70].

ISO 26000 voluntary standard (Guidance on social responsibility) helps to integrate social responsibility into company's values and practices; it includes seven key principles: "accountability, transparency, ethical behaviour, respect for stakeholder interests, respect for the rule of law, respect for international norms of behaviour, and respect for human rights". Every user of ISO 26000 should also consider its seven core subjects: "organizational governance, human rights, labour practices, environment, fair operation practices, consumer issues, and community involvement and development".

Decent work has been defined by the United Nations Economic and Social Council [74] as employment that "respects the fundamental rights of the human person as well as the rights of workers in terms of conditions of work safety and remuneration". It respects "the physical and mental integrity of the worker in the exercise of his/her employment". According to the International Labour Organization [75], "decent work involves opportunities for work that are productive and deliver a fair income, security in the workplace and social protection for families". It offers "better prospects for personal development and social integration, freedom for people to express their concerns, organize and participate in the decisions that affect their lives, and equality of opportunity and treatment for all women and men." Health and safety are constituent elements of workplace security.

7.4. The Economic Principles

Human capital (HC) includes social and economic components—the former was dealt with in SR and decent work, the latter is regarded here. It includes personal competences, knowledge, skills, know-how, expertise, habits, and social attributes such as creativity and mobility. Employees need permanent, long-life education, and training. HC consists of attracting talents, innovators, and experts while developing the knowledge and skills of employees by using lifelong learning. It needs good relations between the employees and relaxed relations of workers with management. HC increases productivity, added value, and a company's profit.

Innovation is a joint product of human capital and creativity. "The capacity to innovate is seen to be a function of a region's ability to attract human capital and to provide low barriers to entry for talented and creative people of all backgrounds" [76]. Research, technical development, and innovations are indispensable organizational forms of exploiting human capital. Responsible research and innovation (RRI) require high ethical standards and gender equality in research. Policymakers' responsibility for avoiding the harmful effects of innovation belongs to the social principle.

"Open innovation was defined as the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively" [77]. When using open innovation, boundaries of the organisation become permeable and that allows combining the company resources with the external co-operators. Open innovation is a potential answer to tap into creativity and knowledge outside an organisation. It exploits a creative power of users, communities, and customers to co-develop new products, services, and processes. Innovation is a joint product of human capital and creativity. "The capacity to innovate is seen to be a function of a region's ability to attract human capital and to provide low barriers to entry for talented and creative people of all backgrounds" [76].

"Creativity is the capability or act of conceiving something original or unusual while innovation is the implementation of something new" [78]. Creativity brings new ideas—inventions. Invention must be distinguished from innovation, which is the realization of an invention. Nowadays, all employees should be creative, and companies must take care to stimulate their inventions and develop them into innovations.

Two of the most popular decision support tools today are Cost–Benefit Analysis (CBA) and Life Cycle Assessment (LCA). These two tools provide the decision makers with different information. The CBA objective is to maximize overall utility to society, whereas the LCA aims at minimizing harmful impacts on the environment. Since the methodologies are answering different questions, they should not be considered as competing but rather as complementary tools. The LCA and CBA are decision support tools and not decision-making tools because they provide information that normally needs to be complemented with legal, social, economic, or technical information before decisions are made.

The CBA evaluates the expenses and advantages of a product, process or system, project, policy, or program to society, e.g., implementing a given waste policy or building a treatment facility. If the net benefit is positive, the project will, as a rule, be implemented. A clear advantage of the CBA is that the result is expressed in a well-known measure, money.

The LCA considers the impacts of a product, process, or service on the environment during its whole lifetime, from raw material extraction and energy consumption to waste and emissions and to product disposal. Its result is the life cycle inventory, LCI [79]. Life cycle costing (LCC) or life cycle cost analysis (LCCA) is used to minimize the total cost of a product, service, or system during its life span. Eco-efficiency analysis considers the economic and life cycle environmental effects of a product or process; different scenarios can be conducted [47]. The LCA is based on ISO 14000 family standards

The polluter pays principle (PPP) requires the firm or consumer to pay the total social cost (both private and external), rather than just the private cost [80]. The EU member states are expected to promote this principle and "internalize the externalities". An externality is a cost (e.g., pollution) or benefit (e.g., public health) caused by an external party; it can be positive or negative. Governments can pose a tax to the producer of the externality and thereby internalize its cost. Companies can include the cost or benefit of the externality into the product price.

8. Conclusions

Climate change is following the "hysteresis" effect [81]. Since the preindustrial era, the temperature has grown slowly because of increased greenhouse gas (GHG) emissions, speeding up exponentially later to approach a new equilibrium state. If we want to lower the temperatures just to the preindustrial level, the hysteresis curve will require GHGs to be lowered to below the concentrations in the preindustrial era; by lowering them to the preindustrial level, the temperatures will not fall to the historical level. The same kind of speeding up is taking place in the societal area—since the mid nineteen seventies, the neoliberal economy has increased the inequality gap, which has speeded up in the last few decades, and during the last crisis has reached a state where 1% of the richest individuals possess the same value of wealth as the poorest half of the world's population.

Engineers have a special, crucial role in these circumstances. They must reverse the hysteresis curve of human development. They must halt the increasing GHG emissions and then lower them to slow down the climate change. They also need to design processes, products, and services to adapt to and mitigate the changing environment. By applying life cycle thinking, resource efficiency, and waste minimization, engineers are expected to develop a circular economy and prevent resource and species extinction. By using renewable sources and internalizing environmental costs, they can improve economic sustainability. Sustainable consumption and production are very much depending on the design and operation of engineers.

Engineers have an important influence on the increased quantity and quality of decent, green jobs. They can design for a better life and more equality instead of designing for higher profit. They can participate in stakeholder engagement, increased consumer awareness, and respect their true needs. Fostering a lifelong education of employees, developing their creativity and innovativeness, and enacting corporate social responsibility and professional ethics, they can bring about a just, social, and equal society.

An overview of sustainability, sustainable design, and sustainable design principles has been presented. Twelve principles of sustainable engineering have been proposed in the form of 12 updated sustainable engineering principles, and each one explained. They enable designers and engineers to improve their process, product, and service designs, and optimize resource (re)use. The principles will require constant updating, which is the primary duty of engineers themselves and their associations. This paper is one of the many steps on this path and it can stimulate other colleagues to keep developing sustainable design, engineering, and operations in their everyday work.

Environmental principles respect the ecosystem's carrying capacity and preserve the biodiversity. The Holistic approach considers a global view, the Planet, instead of a local one. Holistic approaches are concerned with the assumptions, knowledge, methods, and implications of various disciplines and treat them as an integrated whole or system. Systems thinking is about how things interact with one another; it must be differentiated from systematic (analytical or synthetic) thinking. The LCA is used to assess environmental impacts associated with all the stages of a product's life from raw material extraction through the materials' processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

The updated societal principles speak in favor of improved equalities including the distribution of wealth. An increased number and quality of decent and green jobs is of utmost importance. True needs in the value chain and the well-being of consumers will be respected. Awareness raising and education level, justice in human development, and respect to ethics will be improved. The industry of arms and wars will be limited and controlled globally. "Sustainable consumption needs products and services that have a minimal impact on the environment enabling future generations to meet their needs. Sustainable production as the creation of goods and services using processes and systems shall be safe and healthful for workers, communities, and consumers".

Regarding the economic principles, precautionary thinking will be respected, and the polluter pays imperative will improve existing consumption patterns. Quality control and annual reporting need to include all the three sustainability pillars. Resource productivity will be increased, while processes, products, and services are optimized. Employees represent human capital, which will be supported, lifelong education enabled, and their creativity maintained at the highest possible level. Profits are important for sustainable future development of businesses, but they will not be regarded as a target by themselves.

International reports from IPCC, EEA, etc., show an increasingly worrying situation—new approaches are required. Therefore, sustainable engineering principles must be adapted constantly to these changes to keep sustainable design at the forefront of the changes for improved future sustainability.

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