Overlooked Role of Technology in the Sustainability Movement: A Pedagogical Framework for Engineering Education and Research

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The term "sustainability" has acquired an all-encompassing ambiguous aura, given that it touches on all facets of human endeavor. This paper, meant to provide a pedagogical framework for engineering education, starts by pointing out that since technology is an important and fundamental driver of current human development and inextricably interwoven into the societal fabric, the discourse on sustainability and sustainable development should evolve beyond its environmental and social origins. One should explicitly recognize the importance of technology in profundly shaping the discourse and not simply view it as an enabler of meeting preset equipment and system performance targets. In order to fragment the monolithic implied by the term "sustainability," a categorization is then suggested ranging from individual products to wicked/complex adaptive systems as a fundamental level of separation. Subsequently, it is argued that the objective analysis of the multidimensional-spatial-temporal nature of sustainability, meant for the assessment of actionable design alternatives and for tracking the status of implemented measures, requires the definition of a small set of quantifiable umbrella capabilities and sub-attributes. The need to identify direct or surrogate parameters/variables and performance measures/metrics which characterize these sub-attributes is then discussed and mapped onto the application categories. Weighting and aggregating these sub-attributes to quantify the umbrella attributes necessarily introduce normative/aspirational preferences/biases of the various stakeholders, and this issue is also discussed. Finally, the two prevalent sustainability assessment frameworks, namely, the structure-based and the performance-based, are reviewed in terms of strengths and weaknesses and illustrative publications cited, and it is urged that more research be undertaken to synthesize these somewhat disparate approaches in dealing with natural, social, economic, political, and technological systems and organizations.
[DOI: 10.1115/1.4046852]

Keywords: sustainability, sustainability metrics, technology and sustainability, sustainability assessments, sustainable engineering pedagogy

1 Introduction

1.1 Background. This is the age of the Anthropocene, i.e., an age where human activity is resulting in measurable and observable changes (often adversely), and at an increasing/alarming rate, to the earth's ecosystems [1]. There is the realization, even anxiety, that the current economic development pathways adopted by mankind cannot be maintained for long (i.e., are not sustainable) and are likely to lead to a self-inflicted collapse or decline. Hence, without (much?) compromising our rate of development—usually taken to be "economic progress" though some argue, rightly so, the need to reconsider this interpretation; for example, Randers [2]—can actionable pathways be identified, as against simple aspirational mantras, that will serve as a guide to transitions for our future and to those of future generations? This has been the topic of innumerable papers and conversations in recent decades under the broad theme of *sustainable development* (SD). In fact, SD itself is controversial even if one excludes its impact on the environment since it is driven by a kaleidoscopic world order and conflicting normative/aspirational visions of humankind's collective future at odds with the morality and psychic development of modern humankind.

1.2 Objectives. The published literature abounds with books, reports, video clips, technical papers, and popular articles on sustainability along with aspects related to SD.[1] The huge mass of the multi-disciplinary literature on SD is confusing to students and to researchers new to this field especially since it has been borrowed/amalgamated from numerous disciplines and applications with their unique vocabulary, terminology, concepts, fundamental principles, disciplinary preferences and biases, and differing analysis frameworks/methodologies. The objectives of this paper are to emphasize the key and often disruptive role of technology in the sustainability dialog and to frame the sustainability discourse in terms of techno-centric pedagogy useful for both engineering students and professionals. For SD efforts to lead to actionable and effective measures and outcomes, objective analysis and assessment based on quantification as against normative and aspirational considerations are necessary. This paper will first provide an overview of the numerous interpretations of sustainability and SD proposed in the published literature, followed by succinct definitions of these terms. A categorization will be suggested of different engineered and natural products/systems covering the range from individual products to integrated wicked systems (i.e., systems whose design

Manuscript received July 9, 2019; final manuscript received April 1, 2020; published online April 8, 2020. Assoc. Editor: Monem Beitelmal.

[1]Having a word for something important helps spread awareness, but too broad a use of the term tends to trivialize its importance.

and operation are subject to conflicting views as expressed by different stakeholders). Next, this paper will propose and define quantifiable umbrella capabilities and secondary attributes as relevant to this classification, followed by a discussion of how to identify these attributes by direct or by surrogate metrics and some of the dilemma/pitfalls of doing so. For example, weighting and aggregating these sub-attributes to quantify the umbrella attributes necessarily introduce normative/aspirational preferences/biases of the various stakeholders. Finally, a literature review of pertinent studies relevant to the two sustainability assessment frameworks (namely, the structure-based and the performance-based) will be followed by a discussion of their strengths and deficiencies and the status of the current state of SD assessments.

2 Influence of Technology

During the age of the Anthropocene, the difference between "natural," "built or engineered," and "human or social" systems (such as economic, finance, political, cultural, religious, etc.) has become blurred. Engineered products and systems require human intervention, and so are fundamentally different from natural ecosystems/organisms in terms of how they are created and operated (a caveat is that when exposed to wicked complexity, they evolve in unpredictable and even unwanted ways). Given that technology is an important, fundamental, and often disruptive driver of current human development (while fueling consumerism) and inextricably interwoven into our societal fabric, the discourse on sustainability should exceed its environmental and social origins and explicitly recognize and give due importance to the impact of technology as well. Often, the enormous transformative/disruptive power of technology is not channeled properly and even misused (the disruptions caused by social media, for example), thereby exacerbating the current situation. The image of "sustainability" as consisting of three social and ethical/moral codes of conduct or *teleological normative dictums* (the imagery of an edifice supported by the three pillars is intentionally avoided)—minimize ecological impact, maintain human flourishing,[2] and assure intra- and inter-generational social equity—does not seem to recognize the role of technological innovations/advances in fundamentally shaping/altering the SD pathways (in reality, aspects in addition to technology ought to also be considered, such as "cultural diversity,"[3] but these are overlooked for now).

The dictum of maintaining ecological balance is non-controversial to most humans—though what is meant by "balance" is subject to individual interpretation. That of "increasing human flourishing" is of course viewed as desirable even though assumed (mistakenly) to be synonymous to economic growth and material prosperity. Finally, that of "striving for social equity" is morally/ethically desirable even though it is at odds with current development patterns (and, may even be, a hidden form of cultural imperialism). In fact, "social equity" is interpreted differently even in western cultures—the *libertarian* view, prevalent in the U.S., is taken as "equality of opportunity," while in Europe, the *egalitarian* view is taken as "equality of outcome" [1]. Vis-à-vis technology on the other hand, it is not even known whether a particular evolving technology is good or bad in terms of sustainability.

As an example of how technology is changing core assumptions of the sustainability discourse, consider the technologies currently under development which may result in significant extensions of human life, with a high quality of life until the end. For example, metformin (a drug being tested by the U.S. Federal Drug Agency) has the potential to contribute to longer, healthier lives for individuals around the world. Together with a number of other research initiatives, such advances have led some doctors and scientists to believe that the first people who will live to about 150 years or more with a high quality of life have already been born. There are other near-horizon technological developments (sometimes driving and sometimes driven by social expectations and desires) which can profoundly and fundamentally impact human society: artificial intelligence, nuclear fusion, cyborgs, etc. Technology is not "*the*" determinant of sustainability or of SD, but it is certainly an intrinsic and influential part of it, and generally ignored (some even attribute present societal ills to it!); this is so because the people who talk about sustainability focus on the three dictums only while not recognizing the impact which technology has on all three of them. Unlike the other three, technology is not a dictum; its role in shaping the future of SD is ever-changing and likely to be always very murky. For example, no one seeing the original railroad would have predicted its effects, from co-evolving communication networks (train networks needed the telegraph) to creating modern time keeping (before railroads, there were no standardized time zones, or indeed standardized times at all), and to changing the corporate scale (from almost entirely local to monopolies and trusts to national and international). Thus, this paper urges that the sustainability community ought to become much more adept at understanding technological evolution and its implications for earth and social systems.

[2]This is, perhaps, a term more representative of the intent than "economic progress".

[3]Further, the role of politics in the sustainability discourse is recognized as important by most people, but inter-governmental attempts to shape SD have been mixed at best.

3 Discussion on Definitions

3.1 Different Views. What, then, is *sustainability*? There are literally dozens of definitions of sustainability partly because it is a highly normative concept, partly because it is multidimensional and multi-disciplinary, and partly because it involves different spatial and temporal scales. The underlying (and perhaps, unavoidable) issue is that concepts or terminology borrowed or adopted from multiple non-technical disciplines lead to confusing or even divergent interpretations to technically trained engineers. One well-known generic definition is the "ability to provide for the needs of the world's current population without damaging the ability of future generations to provide for themselves. When a process is sustainable, it can be carried out over and over without negative environmental effects or impossibly high costs to anyone involved" [3]. This implies that a sustainable society is one that can "persist over generations, one that is far-seeing enough, flexible enough, and wise enough not to undermine either its physical or its social system of support" [4]. Another view: sustainability is an analytical framework to support discourse related to decision-making or performance assessment of an existing system, and guide action [5]. Some have even stated that it is a mistake to view sustainability as a goal or end state, but it is rather a characteristic of a dynamic evolving system [6]. Broader definitions of sustainability and its science are more relevant, and some of these are provided by Sala et al. [7]:

(a) an advanced form of the complex system analysis aimed at enhancing the understanding of the coupled human-environment conditions through advanced analytical-descriptive tools;
(b) embodies the scientific possibility of transcending the reductionist analyses of the traditional sciences by means of a holistic approach to problem-solving, based on a systemic design and mapping of contemporary long-range phenomena, in both the economic and social domains and in environmental, political, and ecological areas;
(c) a solution-oriented discipline that studies the complex relationship between nature and humankind, conciliating the scientific and social reference paradigms, and covering multi temporal and spatial scales. The discipline implies a holistic approach.

A common view is that "unsustainability" is the symptom of the persistent problems faced by society. Unfortunately, symptoms are often the focus of the actionable pathways, while the root cause is not addressed. One example among many pressing issues is to view climate change as a symptom rather than as an outcome of our unsustainable way of life (increasing rate of energy consumption, adverse environmental impact of fossil fuels during extraction and burning, etc.). While technological solutions alone cannot usually solve such problems, there is the need for multi-disciplinary thinking and practice, broadly studied under the theme of SD. It is equally true that it is impossible to implement SD in the real world without a deep understanding of technology and built systems and the potential for major changes in infrastructure, resource flows, and conversion pathways that technology can support. Fiksel [6] and others point out that though numerous corporations have adopted the concept of SD, the same companies "have found it difficult to translate broad goals and policies into day-to-day decision-making." A pragmatic and limited approach, even if suffering from too much pragmatism and too much narrowness, may still be preferable to trying to achieve a *grand* synthesis of all man-made and natural systems. This is where engineers and technologists have an important role to play in the SD discourse since they often tend to bring in the elements of pragmatism/non-ambiguity, unbiased thinking (as against activism), and structured problem-solving.

One of the guiding principles of SD is the "precautionary principle" which advocates that in the face of significant environmental risk, lack of scientific certainty should *not* be used as a pretext to delay cost-effective action [8]. How this approach enhances traditional risk-based approaches by considering a wider range of emerging issues in the sustainability discourse (primarily by dealing with vulnerabilities whose effects cannot be easily quantified) is discussed by Sterling [9] in terms of regulatory concerns of different renewable energy technologies. Note that this interpretation of the precautionary principle is different from those who use it as an anti-technological anti-modernist viewpoint, suggesting that the development of any significant new technology should be halted till humans acquire the necessary understanding and wisdom to chart their future. This line of argument in support of the so-called *risk of zeal* is somewhat fallacious since no person or institution can understand the implications of a powerful technology before it is actually introduced into society (as history has consistently shown).

de Vries [10] takes a much broader view of the role of SD, namely as an "ethical guiding principle and leading aspiration of humankind in the 21st century, not unlike socialism in the late 1900s. Such principles and aspirations need not necessarily be defined very precisely to be effective."

Sustainability science, the new transdisciplinary academic structure and discovery process, seeks to understand the fundamental character of the dynamic interactions between nature and society both spatially (local to global) as well as temporally (near, intermediate, and long-term) and on society's capacity to guide these interactions along sustainable trajectories [11]. Its scope ought not to be largely academic, ideological, and aspirational, nor limited to normative principles (like those suggested by [12]) but should provide the basis of pragmatic thinking by encouraging certain types of research and analysis. This utilitarian objective ought to allow actionable insights/assessments (through indices/metrics and frameworks/methodologies) on the current state, alternative measures to enhance SD, and track progress toward the SD goal.

The scientific maturity of a theory or science, apart from its ability to explain phenomena retrospectively, can be gauged by its *falsifiability*, i.e., by its testable propositions and predictions. For example, the credibility of Einstein's General Theory of Relativity was enhanced by its ability to correctly predict the amount of gravitational bending of light during an eclipse. In that respect, sustainability science has yet to reach the status of a science and arguably lags other evolving so-called scientific fields such as economics, medicine, and social sciences. In fact, sustainability science, by directly including a highly normative and aspirational term "sustainability" in its very title, pretty much announces that it is not a science in the traditional sense. Bell and Morse [13] go further: " politicians have created a storm by picking on the word sustainability which was intended to be the marker and driving force for the global development effort, and that the very holistic and anthropocentric essence of sustainability continues to elude our attempts at objective analysis and assessment."

3.2 Proposed Definitions. In summary, the following pragmatic definitions are proposed in an attempt to dispel some of the prevailing confusion[4]:

(a) Sustainability—desire for "perpetual" existence by humankind (i.e., inter-generational) is a teleological concept, currently predicated on three social and ethical dictums: maintain ecological balance, increase human flourishing, and strive for social equity, all the while recognizing the underlying and pervasive impact of technology.[5]
(b) SD—planned actions needed to maintain a desired dynamic pathway/condition by constantly fine-tuning a short-term trajectory as circumstances vary over time. Stated differently, it is a process or journey toward the "sustainability" telos with normative, aspirational, and moral recipes spiced with emergent pervasive technological innovations (desirable or otherwise). It has to represent much more than "simply an analytical approach to environmental auditing or improving business accountability but also encompass our values and beliefs and ascribing meaning to such activities" [14].
(c) Sustainable science—the academic discipline seeking to define/develop a set of fundamental principles/methodologies which will allow understanding the fundamental character, both spatially and temporally, of the dynamic interactions between nature, society, and technology in order to guide SD. Unfortunately, the current status of sustainability science remains but a rough (and even naïve) scaffolding of a science.

4 Categorization

4.1 Application Categories. Let us start with the definition of a system. *Systems* are a set of interacting, interdependent synergetic parts/components linked together by exchanges of energy, matter, and/or information for a specific purpose, which are dynamic, i.e., change with time, and usually have hybrid goals. One way to categorize them is as follows: (a) natural, (b) engineered, (c) societal/cultural, and (d) institutional/governance. Note that category (c) involves adhoc social groups with common or differing views/desires/aspirations that are not necessarily satisfied by the political and economic constraints influencing category (d). In turn, engineered systems can be separated into (i) *hard* technological (such as power grid, water distribution, telecommunication, agricultural, etc.) and (ii) *soft*, such as the internet-based banking and finance services which do not involve physical materials, i.e., no bricks and mortar. Finally, such technological engineered systems can be studied in isolation (this is the traditional educational approach), or as interlinked with other engineering systems, or further integrated with social and governance systems.

Infrastructure systems (IS) are a special type of systems that provide commodities and services essential to enable, sustain, and enhance societal living conditions. In prehistoric times, IS were largely natural since the very small numbers of humans with no mechanization relied on nature for all their needs. The human-ecosystem interface was intrinsically coupled. On the other hand, modern day man has created numerous engineered systems, which are also coupled with natural systems at some location but often these couplings are remote, and outside the awareness of

[4]These definitions are of course subject to revision depending on (hopefully) future Delphi-like consensus reached by multi-disciplinary stakeholders.
[5]Technology is not teleological but has its own identity irrespective of sustainability or SD.

Table 1 Techno-centric categories of engineered products and systems

	Category	Description
1	Individual inert products	Knife, chair, solar photovoltaic module, etc.
2	Production process/conversion	Different pathways/processes, i.e., electricity generation, cement-making, aluminum production, etc.
3	Complex and isolated products or systems	Automobile, aircraft, ships, satellite, etc.
4	Supply chain practices	Green and labor equity considerations as promoted by numerous companies
5	Single functionality IS with/without different mix of technologies	Green buildings, distributed and centralized electric generation (by coal, nuclear, natural gas, solar, etc.)
6	Multi-functional coupled/interlinked engineered IS	Engineering networks; power, water, food, transportation, communication, etc.
7	Integrated wicked IS or CASs	Communities and regions which explicitly *integrate* engineering and natural systems with often conflicting stakeholder aspirations and desires

most humans unless a breakdown occurs (such as a massive grid failure). In addition, there is the issue of population size; the hunter-gatherer lifestyle could support only a few million people while currently there are over 7.8 billion individuals. Hence, IS ought to inherently include almost all types of modern-day natural and engineering systems and institutions.

Table 1 is a first attempt to categorize the wide variety of engineered products and technological systems to which sustainable thinking can be applied to as relevant to an engineer. The design of the products in each of the categories involves different considerations in terms of technical complexity, access to repair, interaction with other systems, ability to make autonomous decisions, etc. but also in the degree to which differing stakeholder opinions (or wicked complexity) play a role in their design and operation. Note that this proposal at categorizing engineering products and technological systems is bound to be revised in the future as consensus emerges across multiple stakeholders.

4.2 Complex Adaptive Systems.

No one wishes to make their life or the society they live in needlessly more complicated. Increasing complexity is an unwanted byproduct of the current societal development path, and it appears in most human-made systems (engineering, social, financial, governance, etc.). A complex system is one in which large networks of components with no central control and simple rules of operation give rise to (somewhat) unpredictable collective behavior, sophisticated information processing, and adaptation via learning or evolution [15]. This has, in turn, spawned the study of *complex adaptive systems* (CAS) which are at the intersection of engineering, management, earth and social sciences. The study of CAS is concerned with an expanded set of problems addressed by engineers; products expanding into systems which in turn became larger in scale and inter-twined with social and governance [16]. As an example, a car has mechanical components (say, pistons) that are coupled into complicated mechanical systems (the engine) that are in turn built into larger systems (the car), that in turn requires a whole set of coupled IS (roads, gas stations, and oil wells) which then, because people are the final users, morphs into a societal and quite wicked system.

Inherent in this way of thinking is the realization that technology defined narrowly in the traditional manner cannot solve our current problems; solutions need a strong technological basis but also need to involve various aspects of social sciences, management, policy, etc. The premise is that as CAS become more integrated, blended, and operationalized, they are likely to promote SD. Whether this is a good assumption is yet to be determined since two very different frameworks are involved. SD is a highly normative concept leading to a particular teleological endpoint. CAS including technological systems, are evolutionary: that is, they reflect an immediate internal and external system state, and they have no teleological end state to which they tend toward. Moreover, complex systems are nowadays being integrated in many ways, and there is no indication that the world is moving toward a more "sustainable" endpoint.

The confluence of these various systems has led to greater efficiency, value, and productivity gains but usually at the expense of an increase in complexity and fragility (at least, this is the widely held current belief). The complexity arises from many different sources, including:

(a) physical complexity—the number of inter-connections and their architecture (different types of engineering IS such as power, water, transportation, telecommunication);
(b) control of multi-functionality services;
(c) intertwining of engineering, earth, social, governance systems;
(d) the increasing effect of wicked complexity; and
(e) temporal changes in governance oversight and changing values and expectations of society.

The complexity leads to highly non-linear overall system behavior, sensitivity to small changes (tipping points), enhanced overall system fragility, and lowered resilience. Thus, of the various categories shown in Table 1, CAS are the most difficult to tackle. The differing (often conflicting) opinions of the stakeholders and the inability to both properly define the objectives or acquire complete information on operational needs and system/environmental/societal constraints result in optimal solutions remaining elusive. Different sets of tools are needed; for example, satisficing analysis approaches rather than optimization methods.

5 Umbrella and Secondary Attributes of Sustainability

5.1 Umbrella Capabilities.

Let us focus on CAS (or wicked IS) which are at the apex of the categorization scheme proposed. They have evolved into an integrated class of systems characterized by a high degree of technical complexity, social intricacy and elaborate processes aimed at fulfilling important functions in society, and which can adapt or evolve to changing needs and stresses over time [16]. Common examples of CAS are those which serve communities, cities, and regions. The various life cycle properties of CAS (where the full range of secondary attributes come into play) have been well described by de Weck et al. [16] who calls them "ilities"; this approach and terminology are retained to a great extent but with some changes in classification, nomenclature, and attribute description. *Sustainability* of such systems, in its most holistic sense, involves three partly inter-related capabilities (Fig. 1), namely

(i) *Functional,* which is an attribute concerned with the continuation of operation while meeting accepted standards of resource use, efficiency, cost, environmental impact, safety, reliability under *normal*, or as-designed operation of the system;
(ii) *Resilience,* which is an attribute related to the coping and recovery behaviors of a system when subjected to short-lived *extreme* external shocks often leading to partial or complete failure; and
(iii) *Longevity,* which generally involves (a) the continuous assessment over time of both functionality and resilience attributes and (b) the adaptation of the system under *incipient* natural change (such as climate change), gradual shifts in policy and governance pressures/attitudes, and socio-economic and cultural changes/evolution.

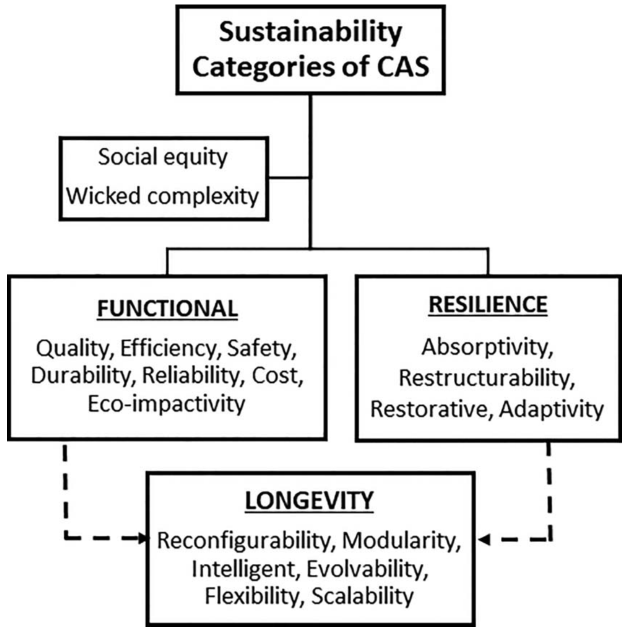

Fig. 1 The three umbrella capabilities and associated sub-attributes of *sustainability* as applied to CAS. The social or human element (i.e., wicked complexity) is pervasive in all three umbrella categories. Largely adapted from de Weck et al. [16] with some modifications.

Note that the longevity capability is placed under the other two umbrella capabilities (see Fig. 1) to reflect the fact that one is dealing with different temporal scales. While the first two capabilities relate to the current status of the existing system (or over the short-term time horizon), the longevity capability would apply to the medium- and long-term temporal time scales (inter-generational).

5.2 Description of Categories and Sub-Attributes

5.2.1 Functional Umbrella. The "functional" category is meant to capture the following objective: the system is designed, operated, and maintained during normal operation so that it meets its functional objective in a cost-effective, reliable, and safe manner while consuming minimum resources and having little environmental impact. A description of the various sub-attributes relevant to the "functional" umbrella category is assembled in Table 2.

Table 2 Description of sub-attributes of the functional umbrella capability

	Sub-attribute	Description
1	Quality	System is able to achieve its basic function in the way intended and designed
2	Efficiency	System has high ratio of functional performance compared to resources consumed (such as energy, water, etc.)
3	Safety	System designed to avoid injury to people should accidents occur while not incurring unacceptable physical losses
4	Durability	System is able to deliver specified level of functionality for a specified length of time
5	Reliability	System or components will function as intended over a specified life time (at a pre-determined probability level)
6	Cost	System has been designed and is operated in a cost-effective manner (say, following the traditional LCC method)
7	Eco-impactivity	System has been designed and operated within allowable or minimal ecological impact (say, following the LCA method)

The functional attribute has historically been the one most studied in engineering, and numerous sophisticated methodologies and tools have been developed involving detailed engineering models of components and their control and the simulation of whole systems for design or operation. Sub-attributes (2) and (7) implicitly include the current social awareness of *green design and operation*. This entails the design, commercialization, and use of cost-effective engineering solutions that require minimal resource use in energy, water, and materials [17]. Such solutions minimize the use of dwindling energy and material resources to meet existing needs while also minimizing the adverse impact of their wastes on the natural environment and on human health and well-being. Industry has generally been good at satisfying customer needs while improving system efficiency but much less adept at identifying some of the long-term consequences on the environment and on how best to marshal existing natural resources.

A well-known example of combining traditional design practices with the emerging eco-impactivity attribute is Leadership in Energy and Environmental Design (LEED) developed by the U.S. Green Building Council [18]. It is a voluntary program meant to motivate customers to recognize the value of green building designs. All LEED programs award certification on a numerical scale extending up to 110 by assigning different points to seven specific design groups which include traditional one such as energy use efficiency, indoor air quality, water use, etc. along with others such as sustainability of site, material and resource use, recyclability, etc.

Life cycle costing (LCC) is a traditional well-accepted design method meant to address the "cost" criteria. Life cycle analysis (LCA) is a methodology which has been extensively researched in the last few decades and has reached a certain maturity level although it still involves inherently uncertain and difficult-to-quantify considerations. This is well illustrated by the *streamlined LCA* methodology proposed in the early 1990s for environmentally responsible product assessment such as different makes of automobiles [17].

Moslehi and Reddy [19,20] illustrate the use of LCC and LCA to assess the operation of an integrated energy system (traditional sources plus solar system and combined heat and power plant) for a large university campus using monitored disaggregated hourly data for a whole year and to evaluate different design alternatives. Halasah et al. [21] evaluated different options to supply photovoltaic electricity to a whole region in the Middle East. They used annual performance simulations coupled with LCA to compare field versus roof-mounted systems for different types of solar cell technologies.

5.2.2 Resilience Umbrella. Resilience is the coping and recovery behavior under severe short-term shocks on the system leading to partial or complete failure. Secondary attributes involve

(i) *Absorptivity*: the ability to withstand external shocks and to continue delivering the needed functional services (similar to *robustness* and the opposite of *vulnerability*);
(ii) *Restructurability*: the ability of a system to be flexible under partial failure such that it restructure itself in order to meet as much system functionality as possible;
(iii) *Restorative*: the ability to return to the original state of functioning after partial or total failure, within acceptable time-periods and incurred penalties; and
(iv) *Adaptivity*: the ability to learn from adversity experienced from past undesirable events and to make necessary modifications in order to withstand similar future events in the near future.

Resilience has become a major mainstream societal issue in recent times, and this important topic is addressed more fully in a subsequent paper [22].

5.2.3 Longevity Umbrella. The "longevity" category is meant to capture the following objective: be able to preserve, modify, adapt, and enhance system functionality under *incipient changes* due to natural/social/cultural/technical change/stress over the medium to long-term future. A description of the various sub-attributes relevant to the "functional" umbrella category is assembled in Table 3.

This umbrella attribute is the aspect of sustainability whereby decisions made now ought not to adversely impact future generations. Traditionally, the term "adaptive" is widely used for this capability. However, one can argue that "adaptive" is an attribute that should appear in all three categories. The word "adaptive" conjures up Darwin's theory of natural selection without "divine intervention." Pure engineered systems (i.e., those with little or no social wicked complexity) do not evolve or adapt organically like do ecosystems or organisms; they need some external agent identifying the need, and then making the necessary changes—humans are the "divinity"! For example, operators often intervene and make small changes/improvements to systems during normal operation whenever they become aware of problematic issues (many systems have recursive learning algorithms embedded in their control software but that allows only limited adaptation and versatility), and designers modify future system designs to improve/enhance resilience as lessons are learnt from past adverse events. So, the use of the word "longevity" to the third umbrella capability is preferred to denote that the fact that the system designer should consider alternative configurations, including material choices and operational practices which can satisfy additional sets of environmental, societal, and political constraints likely to arise in the future (inter-generational time frames)—perhaps the most obvious being climate change.

The framework considered most appropriate to study the longevity element is system dynamic modeling (SDM) formulated by Forrester [23,24], which led to the concept of *systems thinking*. SDM models are relatively simple *macro* models of individual components and interactions meant to provide indications of mega-trends over decades of the system behavior and impacts as it evolves over time under certain presumed conditions/assumptions at the start of the analysis period. It is said to provide insights into *leverage points* (places in the systems where a small change could lead to large shifts/changes in system behavior) and into avoiding *policy resistance*, i.e., improper interventions which may unintentionally exacerbate rather than alleviate likely problems. SDM has had a large impact on the scientific and governance psyche of sustainability scientists since temporal scenario models on how man-induced activities can adversely impact the future "world" behavior suggest human collapse in the near/intermediate future [4,25]. However, it has been pointed out that the approach does not properly allow/consider (i) for wicked complexity, (ii) for the feedbacks that a functional economy provides as one commodity gets relatively more expensive compared to others [26], nor (iii) for evolutions in technological trajectories which respond to immediate conditions or to needs with no larger teleological purpose or end.

Table 3 Description of sub-attributes of the longevity umbrella capability

	Sub-attribute	Description
1	Reconfigurability	Ability to engage in new functionality (swiss knife)
2	Modularity	Components can be designed, operated, or changed independently of each other
3	Intelligent	Be able to learn from past behavior and adapt to incipient changes
4	Evolvability	Ability to efficiently change as new requirements, needs, and constraints emerge over time
5	Flexibility	Ability of a system to undergo changes with relative ease
6	Scalability	Ability to increase size of system while maintaining performance and functionality.

Though SDM may indicate general trends, it is faulted on its inability to capture component-level dynamics properly even with input from experts. Since CASs have numerous interlinked/interactive elements/sub-systems with time-variant feedback loops and delays with difficult to predict temporal and spatial volatility, SDM may yield misleading results. Moreover, there is the challenge of capturing the linkages between engineering aspects and environmental issues, economic development, social and cultural needs, policy, and regulations. Finally, extensive data are required to calibrate the parameters and functions and, therefore, can be validated only at the conceptual level [27]. The above factors make the problem of predicting CAS behavior and its influence on society and the environment very complex and uncertain if extrapolated temporally. Despite this, SDM has had some success in business-corporation planning and management [28], and this approach warrants further investigation and adaptation to engineering processes and IS.

5.3 Linkages Between Application Categories and Umbrella Categories. Not all the umbrella and sub-attributes map onto all the techno-centric application categories proposed earlier. Table 4 is an attempt to point out these inter-connections and also identify which of the different application categories would qualify as CAS which, by definition, involves a certain degree of social wicked complexity.

6 Indicators and Metrics

6.1 Data Types. Let us start with an analogy between the sustainability of a system and the personality of a person. Someone wishing to improve his personality would identify different desirable traits (generosity, even temper, politeness, etc.), evaluate their status based on perceived/actual performance, and strive to improve these traits one by one if found wanting. Just the desire to improve his overall "personality" would not translate into a meaningful and actionable course of action.

Similarly, characterizing the state of a system or of the environment by studying attributes/traits would require making use of different types of observations or data. These types of data will have to be consolidated into one single (or a few) metric(s) for which quantification is necessary (how this is done is discussed below). This process would allow engineers and scientists to (a) evaluate different designs of engineered products and systems, (b) rate alternative production paths, (c) evaluate alternative policies meant to achieve certain goals, and (d) monitor progress towards that goal. Ideally, one or a set of orthogonal metrics ought to capture the essence of each of the various sustainability attributes. It should be recognized that the concept of sustainability is highly normative, and so several associated data may appear relevant and objective on the surface without being so. A data-indicator, for example, that looks at "years of schooling for girls" embeds highly normative cultural assumptions that are strong in the secular West but just as strongly disputed in many African, Islamic, and Confucian cultures.

One can distinguish between different data types (this nomenclature, however, is not uniformly adopted in the literature):

(i) *Nominal indicators* which are descriptive measures or characteristics or qualities with no rank order (such as male/female or yes/no);
(ii) *Ordinal indicators* which are descriptive measures or characteristics which can be converted into categorical numbers whose magnitude is relative over an *arbitrary* min-max scale (such as children/young/middle-aged/old or little/medium/large or happy/neutral/sad), or a percentile based on the relative scale of a sample group;
(iii) *Numerical variables* which are direct observations/measurements of the input and output quantities of a system;

Table 4 Applicability matrix of different engineering application categories and sustainability umbrella categories

Application categories (examples)		Sustainability umbrella categories: Functional	Resilience	Longevity	Complex adaptive systems?	Comments
1	Individual inert products (knife and telephone)	Y	N	N	N	Purely engg focus, reliability analysis applies
2	Production processes/conversion (cement-making and electric generation)	Y	F	Y	N	Largely engg focus
3	Isolated engineered systems (automobile, jetliner and cruise ship)	Y	F	F	F	Primarily engg focus, reliability and risk analysis apply
4	Supply chains	F	Y	Y	Y	Primarily business management focus with some amount of social considerations
5	Single functionality systems (electric grid)	Y	Y	Y	F	Primarily technical considerations
6	Coupled/interlinked engg IS (power + water + transport)	Y	Y	Y	Y	Important engg focus with governance oversight and important social considerations
7	Integrated wicked IS (serving communities, cities, and regions)	Y	Y	Y	Y	Social and governance aspects as important (if not more) as engg considerations

Note*:* Many categories have some measure of wicked complexity inherent in them while the magnitude generally increases with higher category; *Y—applicable, N—marginal, F—fuzzy.*

examples are monitored system performance data (such as energy or matter flowrates) or publicly available historic records (such as population, demographics, or income levels) or generated from process/system simulations;

(iv) *Numerical indices* or *figures-of-merit* which are absolute quantitative numbers or ratios determined from the basic system variables or from scientific principles, say the thermodynamic 1st and 2nd law efficiencies; and

(v) *Metrics or scores* which are aggregated/composite numbers determined from weighting one or more of the above types of data. Of all of these types, metrics are most likely to rely on often unstated but powerful normative assumptions.

Thus, observations based on descriptive measures (such as types (i) and (ii) above) are usually designated as attributes, while those based on numerical characteristics (types (iii) and (iv)) are referred to as variables or numerical indices. Often, one may not be able to directly identify, quantify, or measure attributes, and suitable proxy or surrogate data types must be used which are weighted and consolidated into composite metrics (type (v)) which can suggest actionable information. These are generically referred to as *SD indicators* or SDI.

It is very unlikely that a single metric/score characterizing the system will be satisfactory to all stakeholders involved in the decision-making process because of the subjective and value-laden assignment of the weights of the SDI used to determine the aggregate score. The first step in reducing such subjectivity is to collect the appropriate data and opinions from a sufficient number of stakeholders, provided they meet specific requirements. For example, in a particular context, there may be objective reasons for assuming a greater weight for the environmental dimension than the social one, which in turn may be greater than the economic ones. Another way to reduce subjectivity is to take into account the opinions of all stakeholders and perform stochastic simulations (e.g., Monte Carlo) assuming different probability distributions for the estimation of the indicators and different sets of weights, for instance, each one with a specific probability. Desirable traits of SDI adapted from numerous references (i.e., [13,16,29]) are assembled in Table 5.

6.2 Sustainability Assessment Frameworks. Historically, SDI and sustainability assessments were focused primarily on environmental and social issues at an enterprise, community or regional scale. For example, flow indicators such as substance/material flow analysis and energy analyses can be used to assess various types of regional-scale system efficiencies or intensities (which characterize the inefficiencies or the residuals, i.e., amounts rejected to the environment). Ness et al. [30] suggest three main categories of sustainability assessment frameworks which have been reduced to two as follows:

(a) *Structure-based assessment methods* focus on the structure and general characteristics of the system and generally tend to be qualitative or semi-quantitative, i.e., systems are evaluated/scored using public data (such as census data) and results of surveys and questions categorized by pre-identified attributes (subjective data). They provide insights into the structure (or make-up) and general characteristics of the system from a social and human-centric perspective.

(b) *Performance-based assessment methods* aim to evaluate system attributes from the functional response of the system, either based on numeric variables or numeric indices. These indices could be based on historic system performance data or from mathematical simulations of system operation. This approach is considered by many as holding the promise of providing better specificity and precision. However, there has been a certain amount of skepticism by sustainable policy and decision makers toward such

Table 5 Desirable traits of sustainable development indicators[a]

Indicator	Description of trait
Relevant	Must be a suitable proxy measure for the objective of the SD effort
Parsimonious	Small set of non-overlapping (or orthogonal) important measures, too many indicators tend to confuse
Definable	Simple to understand and easily communicated even to non-experts, not overly complex
Measurable	Can be assessed in terms of obvious value to the public and decision makers, should not be value-laden, numeric data usually desirable
Actionable	Must be useful and be of strategic value in terms of identifying practical steps/actions meant to attain an objective
Economical	Cost effective in acquiring necessary data on which to quantify and to track progress
Durable	Should have long-term relevance
Transferable and scalable	Adaptable at regional, state, or local levels

[a]Several authors include "inter-generational" as a desirable trait. However, more than others, this metric is subject to arbitrary quantification (who knows what the preferences of future generations will be, for example?) and is also in clear conflict with the established human cognitive bias which favors the present and discounts the effect on future generations.

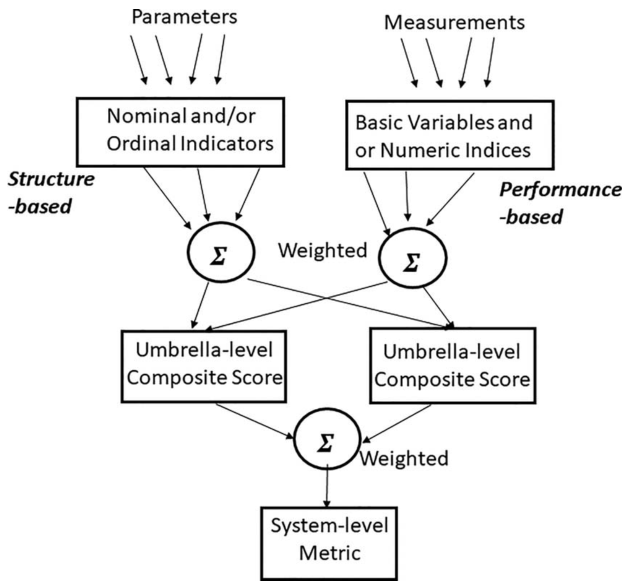

Fig. 2 Schematic representing a hierarchical relationship between data types (parameters and measurements), indicators and indices, weighted and aggregated composite scores at the umbrella-level, and system level metrics for the two sustainability assessment frameworks (structure- and performance-based)

> methods dismissing them as often too narrow in technical complexity (*unable to bridge the gap between the problem modeled and the model of the problem* [31]), and unable to realistically treat the soft/qualitative attributes of the problem which defy quantification.

Both these frameworks allow evaluations/assessments to be done at three different levels: (i) non-aggregated: those that rely on broad categories impacting sustainability and proceed by identifying separate indicators for each umbrella category; (ii) aggregated at the umbrella category level: those that go a step further and perform an analysis which converts the indicators/indices into a weighted and aggregated score characterizing the state of a specific umbrella category; and (iii) aggregated at the system level: those that go even further and combine the category scores into a composite weighted metric applicable to the whole system. This process is shown schematically in Fig. 2.

Current sustainability assessments tend to be primarily structure-based partly because of the socio-environmental origins of the sustainibility movement. Such assessments are generally deemed more suited for a preliminary evaluation since they are holistic, allow tacit knowledge to be included in the methodology, and are usually simpler to undertake (at least, on face value). However, the drawbacks are that such evaluations tend often to be superficial, largely subjective and the veracity of the holistic result suspect. This situation parallels the one faced by the qualitative risk analysis as compared to the quantitative approach. The several limitations of the quantitative risk analysis methodology have been stated in several publications (see, for example, [32]); and these apply to performance-based sustainability assessments as well. The scientific opinion of risk analysists is that the limitations of the quantitative risk analysis should not be taken as a deterrent to developing such methods but be viewed as issues to be diligently addressed and overcome in the future. The two sustainability assessment frameworks should be considered as complementary, each providing a specific type of insights into different types of attributes. While the structure-based assessment can suggest whether the necessary data needed for attribute evaluation have been included or not, the performance-based approaches are, in theory, able to determine the magnitude of the performance indices (such as figure of merit or efficiency) of the system vis-à-vis this attribute. Combining the strengths of the two approaches ought to be an active area of research.

7 Illustrative Literature Review

A few published studies germane to the discussion above are presented, especially pertinent to national/regional scales and to energy infrastructure systems. This is not meant to be a detailed literature review but, rather, to be illustrative of the diversity to be found in the literature and how these align/differ from what is proposed in this paper. It must be pointed out that the authors of these publications use slightly different terminology, nor do they adopt the same type of umbrella categories and sub-attributes viewpoint delineation proposed in this paper.

7.1 Examples of Non-aggregated Indicators and Indices. An example of non-aggregated indicators at the national level is given by Vera et al. [33]. The United Nations Commission on Sustainable Development (UNCSD) was created to carry out the priorities of the 1992 UN Rio Conference. In 2001, a set of 58 national indicators were identified which have not been integrated or aggregated in any way. Several member countries submit reports which include social (water quality level, national education level, population growth, etc.), environmental, economic (per capita GDP, etc.), and institutional monitoring mechanisms.

Shane and Graedel [34] proposed ten categories of non-aggregated indicators applicable to the urban environment, each of which was evaluated as low, medium, or high according to some determined level of environmental efficiency for the following: air quality, water, solids waste, transportation, energy, resource use, population (and land use), urban ecology, livability, and general environmental management.

Schwarz et al. [35] proposed a set of five basic indices of sustainability, namely material intensity, energy intensity, water consumption, toxic emissions, and pollutant emissions useful to chemical manufacturing companies to assess their production processes. They also suggest that company managers can evaluate their production process against their peers (benchmarking), evaluate alternative process changes, and track the impact of implemented ones over time.

Cohen et al. [36] developed a set of non-aggregated indicators to characterize sustainability meant primarily for "organizational management of the physical resources with a small dose of social concerns and desires." The premise was that "sustainability is simply the latest step in the past century's evolution of the field of organizational management." They compiled a database of 557 indicators gleaned from sustainability reports issues by corporations, municipalities, and nonprofit organizations. Categories included (i) *Environmental metrics* such as energy, emissions, water, materials, and effluents (*Energy*—clear winner in the sheer number of metrics); (ii) *Social metrics* such as private sector and public sector; and (iii) *Governance metrics* (transparency, corruption, equality, and fairness). Though of practical and immediate utility to companies intending to present a more socially responsible image, it can be argued that sustainability in its essence ought to be much more than physical/environmental resource auditing.

Ayres [37] proposed a slightly more quantifiable approach involving six criteria for "perfect sustainability" for *ecology at the national level*. He viewed perfect sustainability as requiring stabilization, i.e., no further net increase in (i) climatic—atmospheric greenhouse gas concentrations, (ii) acidity in rainfall, (iii) toxicity—accumulation of long-lived halogenated chemicals in soils or sediments, (iv) agriculture—withdrawals for non-replenishing aquifers in arid regions, (v) agriculture—loss of topsoil (i.e., erosion or desertification), and (vi) nutrient cycle—loss of such biological resources as wetlands or old-growth forests. These criteria are actually figure-of-merit indices based on measured quantities such as ratio of electricity generation by primary inputs to electricity generation which would indicate efficiency in power generation. However, though a link to the sustainability of such measures exists, the link is quite tenuous.

7.2 Examples of Aggregated Indicators and Metrics. Several studies on aggregated indicators can be found in the published literature. Integration requires a multi-criteria decision-making approach involving several additional steps (see Fig. 2) which are somewhat arbitrary (normalization of individual indices within each category, weighting them to determine a single index per category, aggregating them, explicit treatment of uncertainties, and fuzziness). The various ways of performing the above steps are discussed in several papers, for example Liu [38] with the aim of developing general sustainability aggregated indices for renewable energy systems. At a country level, Lammers and Gilbert [39] proposed a set of environmental pressure indicators which consists of 60 indicators in total (10 indicators in six different policy fields pertaining to different environmental aspects) from which a single composite metric can be determined to assess the environmental conditions in different EU countries.

Hadian and Madani [40] used a structure-based approach to evaluate the "greenness" of 15 different energy sources (10 renewable and five nonrenewable) in terms of climate change, energy security with minimum unintended consequences and secondary effects. They evaluated the secondary impacts on natural resources of different energy sources in terms of carbon, water and land footprints, and cost. These qualities were normalized and aggregated in a multi-criterion framework in conjunction with a Monte Carlo method to handle uncertainty; they were able to determine a single aggregate number called the *relative aggregate footprint* of energy supply alternatives. Another framework is that proposed by Santayo-Castelazo and Azapagic [41] for evaluating the sustainability of different types of energy systems in general, which was then applied to evaluate different electricity supply systems based on 17 criteria as relevant to Mexico projected outwards till 2050.

Cartelle Barros et al. [42] proposed a similar framework for the sustainability assessment of energy generation from conventional and renewable power plants. They were able to calculate a single global sustainability index for each type of the power plant based on a combination of environmental, social, and economic requirements. The life cycle of the plant is broken up into different stages (in this case, five). Pertinent indicators were identified for each requirement (environmental, social, and economic); these are mixed, i.e., some are continuous and some categorical. Next, relevant indicators were assigned to each of the stages. Rather than a simple normalization, indicators are converted into different dimensionless (between 0 and 1) value functions which could be nonlinear. Next, weights were introduced for different indicators and summed allowed a composite score for each requirement, and finally a single global sustainability index was deduced by weighting the composite scores. This assessment framework parallels the streamlined LCA analysis described by Graedel and Allenby [17] for environmentally responsible product assessment such as automobiles. Even at this lower level, the resulting score/metric is highly normative and subjective. This is because the single metric has to merge very different kinds of considerations such as toxicity, safety and health, ecological impacts, climate impacts, water impacts, and so forth which are assigned different importance weights by different stakeholders.

7.3 Sustainable Development Frameworks for Complex Adaptive Systems. The above studies really only pertain to the "functionality" umbrella category of specific processes or to engineering/ecological/business practices which are narrower in scope than CAS. On the other end, the full scope of how the concept of sustainability is to be translated into practice, i.e., operationalized, comes into play at the global level. A less challenging intermediary spatial scale relates to CAS projects at the community level. An elaboration of indicators to SD planning and implementation to this level requires several additional aspects.

Sahely et al. [29] proposed an assessment and decision-making framework for urban IS consisting of a list of generic sustainability criteria/indicators based on four interaction and feedback mechanisms between engineering and surrounding environmental (energy use, material flows, etc.), economic and social systems, and sub-criteria for different IS (buildings, transportation, and water supply) and illustrated the assessment framework for the urban water system in the city of Toronto, Canada. The framework consisted of three steps: (i) problem definition, (ii) inventory analysis, mostly based on data collection and analysis, and (iii) impact assessment and decision analysis. They acknowledge the subjective nature of the impact analysis and argue that engineers can make a major contribution here in terms rational decision-making by bringing their domain knowledge and analytical skills to bear. They also suggest that their framework should be integrated into a *decision support tool* for urban infrastructures.

Bell and Morse [13] argue that each sustainability project has unique elements and so a blueprint or top-down approach is not advisable. Rather a *participatory approach*, referred to as *systemic sustainability analysis (SSA)*, is proposed whereby: (i) first, the problem is deconstructed with active participation from various stakeholders involving negotiation between differing views, (ii) the analysis scope, objectives, and constraints (including financial ones) are formulated and modeled, (iii) a number of satisficing solution sets rather than an optimal one are identified, (iv) the analysis results are converted into sustainability indicators which reflect the collective vision of the group (v) which are then communicated to different stakeholders, and (vi) the final consensus reached collaboratively in an iterative manner. The involvement of a technical person in all stages of a IS project is important while he/she would play a decisive role in steps (ii)–(iv) and a key role in steps (v) and (vi). A contextualized example of SSA, namely the *Imagine methodology,* is also described which is relevant to coastal zone management in the Mediterranean and communities in the UK. It is clear that the generic SSA approach is really suitable for CAS system projects (with inherently strong social element) rather than for purely interlinked engineering systems.

A similar argument is made by de Vries [10] who states that a single indicator for SD will never be satisfactory due to different stakeholder perspective, and so an interdisciplinary approach is warranted, which he calls *SDI System (SDIS).* This involves defining the outcome correctly while considering different stakeholder views, keeping the approach balanced in terms of social, environmental, and engineering aspects, properly defining system boundaries and constraints, keeping the models/analysis transparent while reaching a compromise, and most importantly viewing it as an ongoing process.

8 Status of Sustainability Assessments

The field of sustainability assessment of IS is yet to mature; more research and development is needed before such assessments can provide tangible and pragmatic value to designers, operators, and planners. Selecting proper inputs and analyses methodologies are critical, and so is involvement and collaboration of multi-disciplinary teams with domain-specific expertise. It is important to recognize some limitations of the current approach to sustainability metrics and their use in assessments and in field projects.

An example in point is the application of the concept of "maximum sustainable yield (MSY)" which has a seemingly sound analytical basis to determine harvesting rates of fisheries; this is perhaps as simple as it gets in terms of metrics! Bell and Morse [13] discuss the dangers of operationalizing the narrow definition of this concept to the management of a single species and give several reasons for not doing so. They point out that Peruvian anchovy fishery collapsed in 1972 even when the harvesting rate was under the MSY. On the other hand, a dramatic explosion of cod fish stocks occurred in the North Sea in 1997 even when the fishing levels were kept at MSY levels. Despite these instances, according to Morse and Bell, the MSY concept is still useful as a benchmark but should not be used for the practical management of renewable resources.

There is a more fundamental issue separating the rhetoric from the reality. The basic premise behind metrics or indicators is that if one cannot measure something, how can one know that progress is being made? Bell and Morse [13] raise the following concerns: *Is measuring "sustainability" a futile exercise? Are we simply measuring aspects of sustainability which can be measured while leaving those which cannot be? Are we caught in a circularity dilemma—sustainability becomes defined by the parameters that can be measured rather than the other way around!* In fact, there is yet an even more fundamental issue. Sustainability is, and always will be, a highly normative and subjective discipline; as such even the scientific approach (starting with collecting data) is informed and validated by the normative structure within which those data are analyzed, interpreted, and operationalized. This might be especially important as more and more scientists argue that activism is a necessary part of science, especially in environmental and sustainability domains. All participants in a sustainability dialog will necessarily be biased by their own normative perspectives and academic/professional training/experience, but engineers, as problem solvers, must strive to treat their normative beliefs as simply part of the system that must be managed. If their participation and contributions are to be recognized and valued by other stakeholders, engineers need to be able to identity and include the normative postures (often unconscious) of other stakeholders into their quantitative analysis frameworks, develop the ability to communicate their results to non-engineers in a manner meaningful to the latter, be open minded to their feedback, and be willing to modify their analyses iteratively.

9 Summary

This paper started by discussing and defining terms such as sustainability, SD, and sustainability science and discussed their respective scopes. It was stated that sustainability is a teleological socially inspired construct, largely idealized and based on normative and value considerations with little association to the real world. Part of the reason is that different segments of society in different countries hold different values and beliefs based on local conditions and historic context (except for some global issues such as climate change or plastic pollution of oceans). Therefore, it is not surprising that given such a kaleidoscopic nature of our collective future, SD (and sustainable science) still remains "both ideological and immature and has neither the breadth nor the profundity of the traditions that, to an extent, it supersedes" [14]. An important argument made in this paper is that the discourse on sustainability and SD should exceed its environmental and social origins and recognize the predominant role of technology. Technology should shape the sustainability dialogue at a fundamental level given the increasing techno-centric perception of the world[6] and its impact on social views, interactions, and expectations, and not simply be viewed as an enabler to meet preset equipment and system performance goals. In order to provide a means of objective analysis and assessment, this paper has:

(i) proposed a framework which involves categorization of different application areas covering the range from individual products to integrated systems and discussed relevance to commonly used terms such as wicked complexity and complex and adaptive systems; this serves to identify the specific role of the engineer with other disciplines;
(ii) defined umbrella capabilities and secondary attributes of sustainability which better serve to fragment the all-encompassing term "sustainability" into sub-attributes which can be evaluated individually;
(iii) provided a discussion on the need to identify direct or surrogate metrics to these attributes and pointed out some of their current limitations; and
(iv) discussed strengths and deficiencies of assessment metrics and methods/tools for better communication with stakeholders with different educational backgrounds and views. Finally, it is cautioned that relying too much on indices may be more reassuring in theory than it is in practice (and may suffer from hindsight bias), given that the concept of sustainability is a multidimensional normative construct.

This paper has framed the sustainability discourse in terms of techno-centric pedagogy useful for both engineering students and professionals. SD is a concept meant to be operationalized (i.e., lead to actionable and effective measures to be identified and implemented), while pedagogy lives in the world of ideas and tries to give them an analytical reality often confused for concrete representations. Despite this, the various techno-centric aspects covered in this paper will be useful for engineering instruction and comprehension, for formulating future research directions, and for highlighting the important role of the engineer in the sustainability movement.

[6]The satellite photo of earth rise over the moon or that of the night lights of different geographical regions of the earth.

Acknowledgment

The umbrella and secondary attribute approach and many of the definitions have been adopted from de Weck et al. [16]. Constructive comments from anonymous reviewers led to a rewrite of the earlier manuscript resulting in an improved paper.

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