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IS IT SUSTAINABLE? A CONCEPTUAL EXPOSITION OF SUSTAINABILITY IN TECHNICAL ARTEFACTS

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Abstract

Design is increasingly viewed as a key driver of global sustainability improvement. Accordingly, a range of sustainability-oriented design approaches have emerged over the past decades, all sharing the same high-level goal: the delivery of sustainable artefacts. Developing a shared vision of sustainability is positioned as a crucial first step in sustainability-oriented design processes; however, there is a lack of clarity regarding what the terms sustainable and sustainability fundamentally mean when applied to technical artefacts. To address these issues, we present a conceptual exposition of sustainability, beginning with three fundamental theoretical viewpoints on the concept and translating these to engineering design. Using the first generic model of systems sustainability (the S-Cycle) and an industrial case study, we then explain the basic constitution of sustainability of technical artefacts and discuss goals and metrics for sustainability-oriented engineering design. Some implications of the work for future research are briefly discussed, highlighting that sustainable design is not inherently 'good' and should therefore be conducted with caution and responsibility.

Keywords: Sustainability, Design theory, Ecodesign, Sustainable design, Value

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1 INTRODUCTION

Design may be broadly described as a form of socio-technical change, defined by Jones (1991, p.32) as "the fitting of products and systems to newly emerging forms of society." Socio-technical change is argued to be fundamentally necessary for achieving a more sustainable society, and accordingly, design is increasingly positioned as a key driver of global sustainability improvement efforts (Spangenberg et al., 2010; Tischner and Charter, 2001). A range of environmental, economic, and social considerations have been integrated into design philosophy over the past 30 years, leading to the emergence of several sustainability-oriented design approaches including design for environment, ecodesign, environmentally conscious design, clean design, green design, design for sustainability, sustainable design, etc. (Chapman, 2011). Whilst these approaches were originated by different groups during different time periods and motivated by different values and perspectives, they may all be considered to share a common high-level goal: the delivery of sustainable artefacts.

Several authors argue that the lack of a clear and unified understanding of sustainability among stakeholders in a particular context often renders sustainability improvement efforts ineffectual. To address this issue in design, Waage (2007) suggests that a sustainability-oriented design process should begin one step prior to the identification of needs and desires by answering the question, 'what is sustainability?' and developing a shared vision among stakeholders. However, a clear explanation of what is fundamentally meant by *sustainability* when applied to the design artefact appears to be largely absent from the literature. For instance, consider the following definition of a sustainable design solution provided by Charter and Tischner (2001, p.17): "Sustainable solutions are products, services, hybrids or system changes that minimise negative and maximise positive sustainability impacts - economic, environmental, social, and ethical - throughout and beyond the life-cycle of existing products or solutions, while fulfilling acceptable societal demands/needs." A "sustainable solution" is defined in terms of "sustainability impacts" of a particular quality, but the meaning of "sustainability" *per se* in this context remains unclear. They also discuss the contribution made by "sustainable products" to a "sustainable society" and the overarching processes of "sustainable development" and "sustainable production and consumption," but again, do not define what "sustainable" means. Several other authors may be seen apply *sustainable* and *sustainability* in the design literature without explicating what the terms mean fundamentally (e.g. Alfaris et al., 2010; Chiu and Chu, 2012; Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010). Several authors outline criteria that a technical artefact should meet in order to be sustainable (e.g. Fiksel, 2003; Mayyas et al., 2012; Stasinopoulos et al., 2009), but again, do not explicitly define *sustainable* and *sustainability* in this context.

Hannon and Callaghan (2011, p.878) argue that "the diffusion and popularity of the term *sustainability* with relatively little corresponding rigorous and grounded conceptualization may have created confusion over the basic concepts of sustainability." They suggest that this has resulted in a "sustainability fog" for organisations and practitioners that makes it difficult to develop a clear and unified view of sustainability among stakeholders. Towards addressing this issue, this paper presents a conceptual exposition of sustainability in the context of technical artefacts, beginning with three fundamental theoretical viewpoints on the concept and demonstrating how these translate to engineering design (Section 2). Using the first generic model of systems sustainability (the S-Cycle) and an industrial case study, we then explain the basic constitution of sustainability of technical artefacts and discuss goals and metrics for sustainability-oriented engineering design (Section 3). A brief discussion of the work and key conclusions are provided in Section 4.

2 THEORETICAL VIEWPOINTS ON SUSTAINABILITY

Sustainability improvement has been framed as a wicked problem, if not "*the* wicked problem for design in the twenty-first century" (Wahl and Baxter, 2008, p.75). This implies that *sustainability* may not be conceptualised in a singular, objective fashion and that different definitions may legitimately co-exist (Kajikawa, 2008). This is supported by Vos (2007, p.334), who argues that definitions emphasising "one or another part of the core idea of sustainability will be necessary in different contexts, and as social and environmental conditions evolve." One of the first formal definitions of sustainability may be found in the seminal Bruntland report (WCED, 1987, p.41), where the concept is applied to the overarching socio-economic development process and conceptualised as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Thirty years on, hundreds of sustainability definitions may now be identified in the literature, including the multifarious definitions of sustainable products, artefacts, solutions, etc. introduced in Section 1 as well as conceptions originating in other contexts such as agriculture, business, forestry, and urban planning (e.g. see Table 1).

At first glance, the broad range of sustainability conceptions identifiable in the literature may appear to be fairly disparate. It seems unlikely that commonalities would exist between areas as diverse as urban planning, agriculture, and business. However, Bell and Morse (2008, p.5) argue that when applied in different contexts, the term sustainable "refers to much the same, although the detail can be quite different." They discuss sustainability "in a generic sense," noting that their observations could be applied "to anything that has sustainable as an adjective." This suggests that while sustainability may be defined in different ways, the concept can be interpreted and understood from a common theoretical basis. This is supported to some extent by Vos (2007, p.335), who suggests that virtually "all definitions of sustainability share core elements." In this respect, Hay et al. (2014) report a broadly scoped inductive literature review aiming to develop generic models of systems sustainability. This work may be seen to highlight three fundamental theoretical viewpoints on sustainability, which can be briefly summarised as follows:

- **V1: lexical definitions of sustainability.** Lexically, the term *sustainability* may be etymologically derived from the Latin verb "sustenere" meaning "to uphold" (Rametsteiner et al., 2011). In the most literal sense, sustainability means *the ability to sustain something over time* (Kajikawa, 2008). Authors seeking a deeper understanding have conducted lexical examinations of the word, with three further perspectives emerging prominently from the literature: (i) *the ability to maintain something* (Lele and Norgaard, 1996; Marcuse, 1998); (ii) *the ability to be maintained by something* (Chapman, 2011); and (iii) *the ability to continue something* (Chapman, 2011; Dempsey et al., 2011; Shearman, 1990).
- **V2: sustainability objectives.** It may be seen that lexical sustainability definitions are general - they refer to sustaining something, without indicating what that thing is or how long it is to be sustained for. To develop more concrete conceptions of sustainability, humans must decide *what is to be sustained* and *for how long* (Lele and Norgaard, 1996; Vos, 2007). In other words, they must specify their sustainability objectives. Objectives identifiable in the literature are defined in terms of a finite or indefinite timescale, and focus on multifarious entities including (Table 1): an action, activity, or process; the functioning of both artefacts and natural systems; the life and diversity of organisms and species; the outcomes of socio-economic development; performance metrics; properties and attributes; resources; and a state or situation (Hay et al., 2014).
- **V3: the basic constitution of sustainability.** A final and arguably more fundamental viewpoint on sustainability is its basic constitution, i.e. what it fundamentally *is*. The lexical definitions outlined above seem to unequivocally convey that sustainability constitutes *an ability*. That is, the ability to sustain is fundamentally an ability in the same manner as the ability to drive a car, the ability to read, and the ability to write (although these are qualitatively different abilities). However, three alternative interpretations may be seen to emerge from the literature, namely sustainability as: (i) *a process of change* (Voinov, 2007; Wahl and Baxter, 2008); (ii) *a property or attribute of an entity* (Bodini, 2012; Conway, 1986; Wahl and Baxter, 2008); and (iii) *a particular state of an entity* (Goerner et al., 2009; Spangenberg, 2011).

As conveyed in Figure 1 and Table 1, conceptions of sustainability originating in different contexts can be characterised in terms of these three viewpoints. Thus, the viewpoints may be considered to describe fundamental conceptual elements of sustainability, providing a consistent basis for interpretation and explanation regardless of context. How, then, do they translate to engineering design and technical artefacts?

Firstly, the lexical meaning of sustainability (V1) appears to be straightforward in any context: as highlighted by Voinov (2007, p.489), all sustainability definitions fundamentally "talk about maintenance, sustenance, continuity of a certain resource, system, condition, relationship." All of these terms - sustain, maintain, and continue - may be viewed as essentially synonymous, in engineering design and beyond. Consequently, Shearman (1990) argues that it is not the lexical meaning of sustainability that should be disputed, but rather the implicative meaning arising from the term when applied in different contexts. That is, the meaning conveyed by sustainability objectives (V2) - our answers to the question, "what should we sustain and for how long?" Whilst sustaining society indefinitely may be viewed as the ultimate sustainability objective for humans, precisely what kind of society is a matter for considerable debate. In this respect, several authors argue that what we choose to sustain over time depends upon what we *value* (Chapman, 2011; Kajikawa, 2008; Lele and Norgaard, 1996), something that can vary considerably between people. For instance, consider the range of stakeholders that may be involved in the design process. A manager might place considerable value on sustaining the economic performance of their organisation, perhaps out of loyalty or owing to their own career goals (economic sustainability, corporate sustainability). In contrast, a designer may place greater value on satisfying human needs and therefore be more concerned with sustaining wellbeing (sustinable development), or perhaps the relationship between product and user (sustainable product design). A production engineer is likely to be concerned with the efficiency of manufacturing operations, and may therefore wish to sustain a particular level of energy consumption or resource productivity (sustainable manufacturing, sustainable production). Owing to the prevalence of issues such as resource depletion and global warming in the news, consumers are increasingly concerned with the ecological impacts of production and consumption and may therefore value sustaining the natural environment for future generations (environmental sustainability). Matters are further complicated by conflicts among these objectives, e.g. sustaining the relationship between product and user for longer may negatively impact upon sales and in turn, organisational economic performance. These interactions are formalised in frameworks such as the three pillars of sustainable development (Dawson et al., 2010) and the triple bottom line (Fiksel, 2003), which emphasise the intertwined nature of environmental, economic, and social sustainability objectives and the need for a systems perspective on sustainability improvement. Further value judgements must be made regarding the length of time over which to sustain something - e.g. if we choose to sustain non-renewable resource stocks by designing their consumption out of products, do we continue doing this for fifty years, five hundred years, or indefinitely? To some extent, this depends on the value that present humans determine the needs of future humans to have relative to their own.

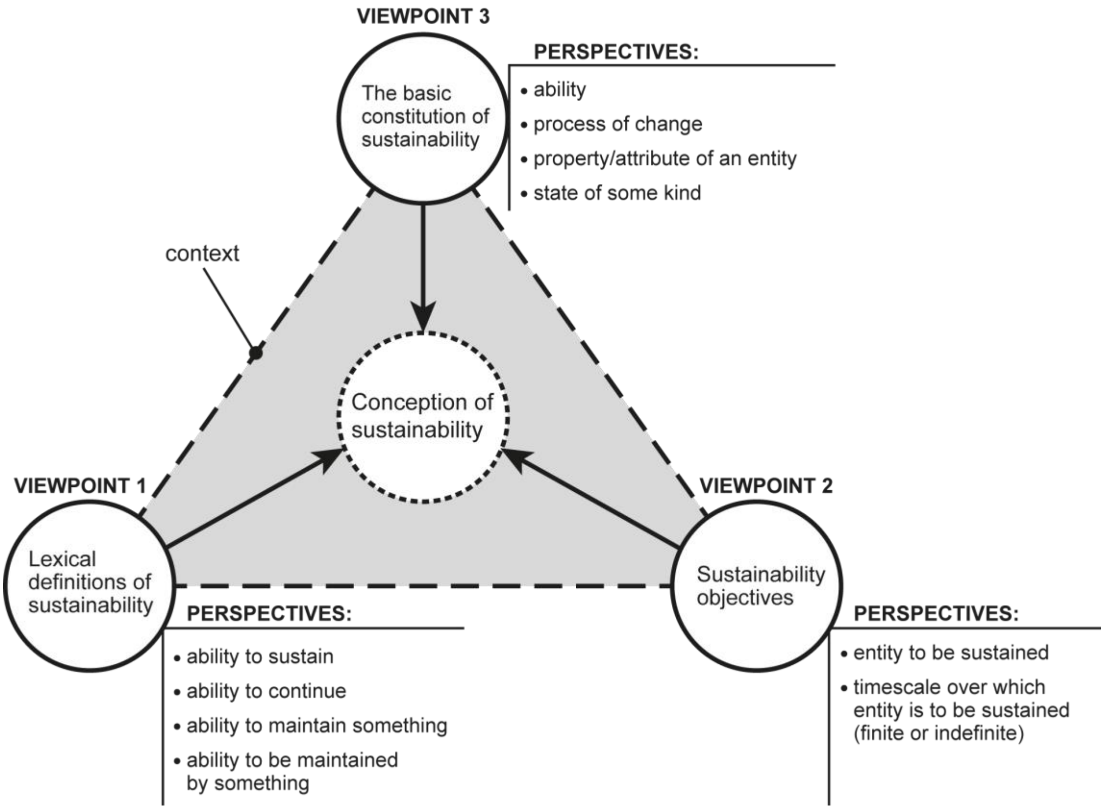

Figure 1. Theoretical viewpoints on the sustainability concept

It may be seen from the above that differences in perspectives on the meaning of the term *sustainability* arise largely from differences in the worldviews, motivations, and values of people. Whilst such differences can be difficult to resolve, they are nonetheless a key characteristic of all wicked problems and relatively easy to comprehend in terms of their implications for sustainability-oriented design. It could also be argued that the ability to work in diverse teams towards common goals is an integral part of design generally, as is the ability to satisfy a range of consumers with different worldviews and values. In contrast, differences in perspectives on the constitution of sustainability (V3) - that is, what sustainability fundamentally *is* - are suggstive of a lack of clarity at a basic conceptual level. An ability, a process of change, a property/attribute, and a state all appear to constitute different things, and it is not clear what these interpretations mean when applied to technical artefacts in engineering design. For instance, if sustainability is indeed a process of change, what is a sustainable artefact and how can it be attained? These issues are explored in depth in Section 3 below.

Table 1. Major sustainability conceptions identifiable in the literature classified with respect to the three theoretical viewpoints

Conception	Entity	Time period	Lexical def.	Constitution	Source
Agricultural sustainability	Performance metrics	Indefinite	Maintain	Ability; Property	Conway, 1986
Corporate sustainability	Action, activity, or process	Indefinite	Continue	Ability	Dyllick and Hockerts, 2002
Environmental sustainability	Function	Indefinite	Continue; Maintain	Ability	Ekins et al., 2003
Global sustainability	Not clear	Indefinite	Not clear	Process of change; Property	Wahl and Baxter, 2008
	State or situation	Indefinite	Not clear	State	Spangenberg, 2011
Maximum sustainable yield	Performance metrics	Finite	Continue	Ability	Gaichas, 2008
Regional sustainability	Outcomes of socio-economic activity	Indefinite	Continue; Maintain	Ability	Wackernagel and Yount, 1998
Strong sustainability	Resources	Indefinite	Maintain	Ability	Costanza and Daly, 1992
Sustainability of community	Function; Whole systems	Indefinite	Continue	Ability	Dempsey et al., 2011
Sustainable agriculture	Action, activity, or process	Indefinite	Continue	Ability	Tilman et al., 2002
Sustainable development	Action, activity, or process	Indefinite	Continue	Ability	WCED, 1987
Urban sustainability	State or situation	Indefinite	Continue	State	Maclaren, 1996
Weak sustainability	Resources	Indefinite	Maintain	Ability	Costanza and Daly, 1992

3 THE BASIC CONSTITUTION OF SUSTAINABILITY OF TECHNICAL ARTEFACTS

We propose that greater clarity on the basic constitution of sustainability may be obtained by considering the nature of *ability* as typically defined in the engineering design and systems engineering literature. Here, an ability may be described as *a property of an artefact*, that is manifested to humans as behaviour that produces certain effects (Hubka and Eder, 1988; Wang et al., 2008). Thus, improving an artefact's ability in a particular dimension involves *a process of change* with respect to its behaviour; furthermore, the behaviour that manifests the ability may be interpreted as a kind of *state of an artefact*. Therefore, rather than referring to fundamentally different things, the range of perspectives associated with V3 in Section 2 may be considered to illuminate different aspects of the basic constitution of sustainability of technical artefacts.

In the following sub-sections, we illustrate the different facets of sustainability outlined above using the S-Cycle model (Figure 2), originally proposed in a general systems context by Hay et al. (2014) to describe system behaviour from a sustainability perspective. We applied the S-Cycle to a ship's cooling system in two case studies conducted at a major British design and manufacturing organisation, referred to as Company X throughout this paper. The case studies were conducted independently by one of the authors and a postgraduate Master's student. Each study was conducted for different purposes as part of a broader research project, but both involved applying the S-Cycle to interpret artefact sustainability during the design process. The case study results are not the focus of this paper, but relevant findings are briefly referred to for illustrative purposes and to support the different aspects of the S-Cycle model below.

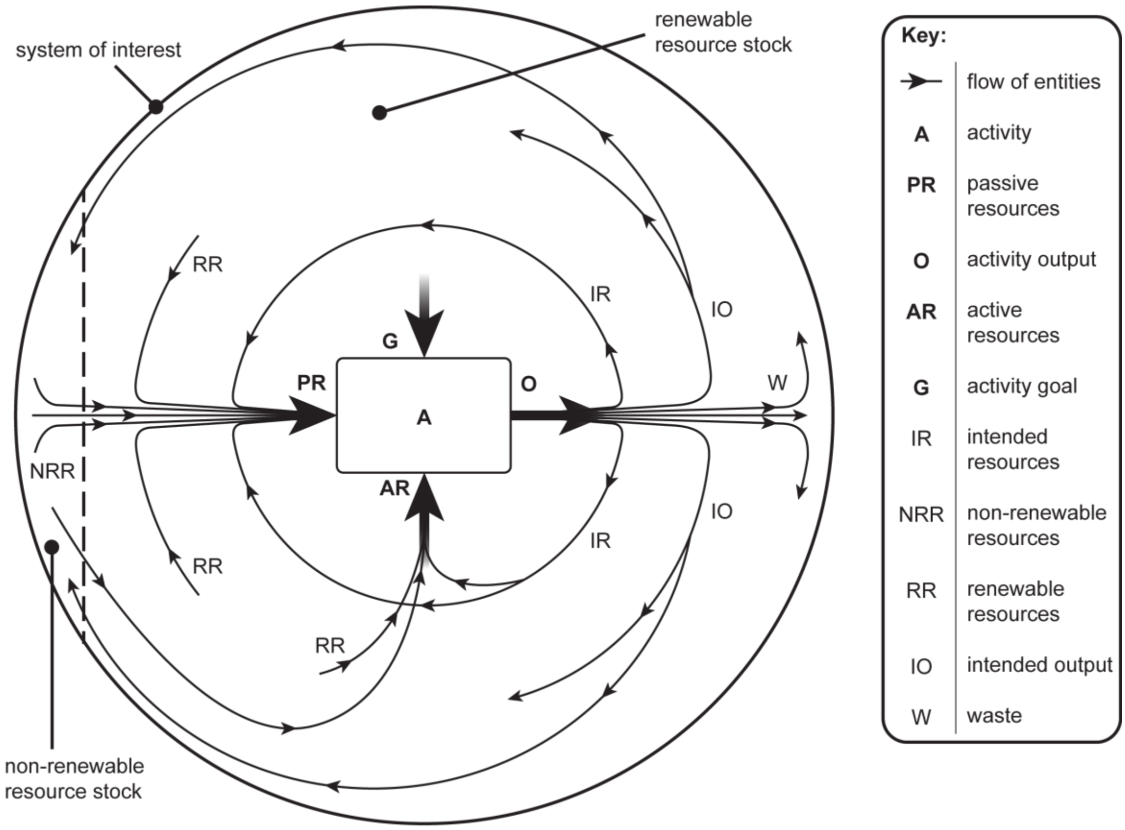

Figure 2. The S-Cycle model (Hay et al., 2014)

3.1 Artefact behaviour for sustainability

The basic behaviour of a technical artefact may be described as the transformation of materials, energy, and information from an input state to some desired output state (Hubka and Eder, 1988). We shall focus primarily upon material and energetic flows in this paper, aligning with the broader sustainability literature where technical artefacts are classed as a type of manufactured capital: systems designed and built by humans in order to transform materials and energy into goods, services, and intangible socio-economic outcomes e.g. living standards, health, and well-being (Meadows, 1998). In the S-Cycle model (Figure 2), the transformative behaviour of an artefact is represented as an activity, defined as a goal-directed action where active resources (human users and artefact components) use passive resources (materials and energy) to produce an output (processed materials and energy) that meets the activity goal.

As discussed previously, sustainability may be considered to be manifested as a particular behavioural state of an artefact. The S-Cycle conveys four aspects of a technical artefact's behaviour that appear to contribute to this state, with the required performance in each dimension specified by sustainability goals and metrics (discussed in Section 3.3). These are, with examples from the case study system:

1. Use of renewable and non-renewable resources, ultimately originating from stocks within the wider Earth system. For example, the cooling system uses oil (non-renewable) and seawater (renewable) to lubricate and cool its internal compressors, respectively.

2. Production of intended output, i.e. an output that is intended to either contribute to resource stocks in the Earth system or be used directly by other artefacts. The primary intended output of the cooling system may be interpreted as cooling power, or a flow of coolant.
3. Production of waste, i.e. the fraction of an artefact's output that is intended neither as useful output nor resources and as such, has no utility to the artefact (although it may be used as a resource by other artefacts). Waste produced by the cooling system included heat losses from compressors and losses of coolant and refrigerant via material leaks.
4. Production of intended resources, i.e. an output intended to be used as a passive or active resource by the artefact itself. As an example, in the cooling system is oil extracted from the refrigerant flow and reinjected to the compressor crankcase for reuse as a lubricant.

3.2 Artefact sustainability as a system property

Another interpretation of sustainability highlighted above is as a property of an artefact. Firstly considering the idealised situation of an artefact operating in isolation from other artefacts, it may be stated that sustainability is a property of that artefact's components, relationships, inputs and outputs, and supporting stocks. However, in reality, artefacts operating in the Earth system are connected to a multitude of other artificial and natural entities via system relationships, e.g. material and energetic flows (Bodini, 2012). This has two key implications: (i) sustainability is typically an emergent property of a particular system of interest comprised of multiple artefacts and natural entities; and (ii) whether or not an artefact can be interpreted as *sustainable* depends upon the system of interest it is interpreted within (Hay et al., 2014).

To illustrate the above: whilst Company X did convey ecological concerns, they were also interested in the sustainability of their cooling system within the system of an operational ship as opposed to the whole Earth system (primarily for financial reasons). This fundamentally alters the stocks that the cooling system activity is considered to be connected to, and in turn the way that it's behaviour is interpreted from a sustainability perspective. For example, in Section 3.1 it was stated that the oil used to lubricate the compressors is a non-renewable resource. In the context of the whole Earth system, this is true - lubricating oil is derived from crude oil, which originates from stocks that do not regenerate significantly along anthropological timescales. However, if we change the system of interest to be an operational ship, oil may be interpreted as a renewable resource because it is replenished through maintenance activities at sea and on the shore. The rate of oil consumption is still relevant, but from an economic/strategic perspective. System boundaries and the emergent nature of sustainability present a particular issue in the design of large-scale, complex technical systems (Alfaris et al., 2010).

3.3 Influencing artefact behaviour towards sustainability

Finally, as discussed in the introduction to this section, sustainability may also be interpreted as a process of change. However, rather than sustainability of a technical artefact *per se*, it seems that this interpretation refers to the process of influencing an artefact's behaviour towards a sustainable state. The performance required to achieve this state is defined in sustainability goals focusing on the aspects of behaviour described in Section 3.1, and measured using sustainability performance metrics. To influence an artefact's behaviour towards sustainability, a designer defines sustainability goals, changes aspects of the design governed by these goals, and measures or estimates the resulting performance (Stasinopoulos et al., 2009). These goals must of course be balanced against the traditional considerations of product design and development and the customer/user's requirements (Hoffenson et al., 2014; Hoffenson et al., 2015).

Sustainability goals relate closely to the sustainability objectives explicitly or implicitly defined for an artefact (Section 2), and specify a future level of performance that the originator considers can or should be sustained over time (Hay et al., 2014). For instance, if a design team wishes to sustain natural resources, they may define goals to minimise the level of resource consumption over an artefact's life cycle. An artefact may be interpreted as sustainable if its performance meets the criteria specified in sustainability goals over the required time period, i.e. has demonstrated the behaviour required for sustainability. It should be highlighted that sustainability goals may be defined from (i) a physical perspective, i.e. considering what levels of performance *can* be sustained over time, and (ii) a moral/ethical perspective, i.e. considering what levels of performance *should* be sustained over time. For example, the consumption of non-renewable resource stocks at current levels likely *can* be sustained over the next few decades or so; however, it may be argued that this level of consumption *should not* be sustained as it degrades the environment and denies future generations access to the same resource stocks as present generations. Sustainability metrics specify measures that will provide information on whether the required level of performance has been achieved in relation to sustainability goals (Meadows, 1998; Stasinopoulos et al., 2009). Performance assessment is a key activity in sustainability improvement and accordingly, a broad range of assessment methods for technical artefacts may be identified in the sustainability-oriented design literature (Gagnon et al., 2012). A full discussion on this topic is beyond the scope of this paper; however, interested readers are referred to Hay et al. (in press) for an in-depth treatment of different approaches and key issues associated with defining and selecting metrics.

The relationship between sustainability objectives, goals, and metrics is illustrated in Table 2, which provides an overview of those defined for the case study cooling system. These have been generalised where necessary for confidentiality purposes.

Table 2. Objectives, goals, and metrics defined for the case study cooling system

Sustainability objective	**Sustainability goal**	**Sustainability metric**	**Relevant behaviour**
Sustain natural systems and stocks	Minimise use of refrigerant and diesel-derived electricity	Coefficient of performance, defined as ratio of cooling capacity to compressor shaft power.	Resource consumption & intended output production
		Environmental impact index, defined as a function of (i) global warming potentials and (ii) consumption rates of refrigerant and diesel.	
Sustain economic performance of cooling system and wider ship	Minimise cost of cooling	Cost index, defined as a function of (i) costs and consumption rates of diesel, oil, and refrigerant; and (ii) other running costs.	Resource consumption
	Minimise production of oil and refrigerant losses	Oil losses, defined as volume of oil lost per kilowatt-hour of cooling produced.	Waste production
		Refrigerant losses, defined as volume of refrigerant lost per kilowatt-hour of cooling produced.	

4 DISCUSSION AND CONCLUSION

In Section 1, we suggested that there is a lack of clarity regarding the meaning of the terms *sustainable* and *sustainability* in the context of technical artefacts, which in turn makes it difficult to develop a clear and unified vision of sustainability during sustainability-oriented engineering design. To provide greater clarity in this respect, we have elaborated three fundamental theoretical viewpoints on sustainability, translated these to engineering design, and explicated the basic constitution of sustainability of technical artefacts using the S-Cycle model. Based on the exposition presented in Sections 2 and 3, it may be concluded that when applied to technical artefacts, *sustainability* may be interpreted as follows: *an artefact's ability to sustain/maintain/continue something valuable over time, which is a property of the artefact and an emergent property of the wider system it operates within, and is manifested to humans as artefact behaviour meeting sustainability performance criteria in four dimensions: resource use, intended output production, intended resource production, and waste production.* An artefact may be interpreted as *sustainable* if it has *demonstrated the behaviour required to sustain the chosen entity over the chosen time period*, i.e. if its performance meets certain criteria (specified in sustainability goals).

Chapman (2011, p.172) suggests that in sustainability-oriented design, considerable time is wasted "attempting to define whether what you do is design for environment, ecodesign, sustainable design, design for sustainability, low-impact design, green design, clean design, and so on, and so on." He suggests that the "way in which we both discuss and name our practice […] needs resolving, and fast." It seems to us that "what you do" as a designer in a sustainability-oriented design process is defined largely by your sustainability objectives, i.e. what you (or more likely, your team, or your organisation, or perhaps even customers and legislative bodies) consider valuable enough to sustain over time. Although the goals and metrics may differ from conventional engineering design, it does not seem that the process of designing an artefact to satisfy these goals should be significantly different, although there is perhaps a greater emphasis on evaluation and performance assessment. Thus, it seems that the different branches of sustainability-oriented design philosophy highlighted by Chapman (2011) are likely to share considerable commonalities. One way to advance the field may therefore be to halt its subdivision into more and more specialised niches, and find ways to make the range of underlying sustainability objectives and goals more explicit.

Over forty years ago, Victor Papanek (1972, p.57) called for the development of a particular kind of "social and moral responsibility" in design, suggesting that designers are responsible for "nearly all of our environmental mistakes." As the work reported herein highlights, sustainability-oriented design is not inherently 'good' - its 'goodness' depends entirely upon the values of the designers and stakeholders involved. Thus, the need for social and moral responsibility in design remains just as pertinent today, if not moreso given the increasing complexity of the problems design is expected to tackle.

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