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Promoting effectiveness in sustainable design

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Abstract

Sustainable design of engineered products and systems is fantastically challenging. Think up a technology that protects the environment and perhaps a business model cannot be developed for it. Think up a business model for the technology that resonates with the market and consumers use so much of the technology that Earth would have been better without it. In the meantime the landscape is constantly shifting due to transient regulations, technology potential, and knowledge about anthropogenic impacts on Earth. This presentation focuses on the effectiveness of sustainable design and emphasizes the need to simultaneously evaluate market success, environmental impact, and meeting societal needs under regulatory constraints. The paper provides framework approaches to concept generation and design validation that facilitate the evaluation of design sustainability. The presentation that will accompany this paper will discuss research case studies from the University of Michigan and evaluate them against these frameworks as illustrative examples.

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1. Introduction

As an instrument of sustainable development [1], *sustainable design* should significantly contribute to meeting the needs of today without compromising the ability of future generations to meet their needs. As such sustainable design serves a system larger than itself, arriving at an artifact that balances the private interests of the firm and engineering functionality against broader environmental, economic, and societal considerations. It follows that the effectiveness of a sustainable design should be evaluated against at least the following criteria: (a) *does the design make significant progress toward an unmet and important environmental or social challenge (Section 2)?* (b) *is there potential for the design to lead to undesirable consequences in its lifecycle that overshadow the environmental/social benefits (Section 3)?* (c) *is the design likely to be adopted and self-sustaining in the market (Section 4)?* (d) *is the design itself so likely to succeed economically that, due to rebound effects, planetary or social systems will be worse off because of the design (Section 5)?* It can be argued that if any one of these criteria are not met, the design will not contribute to sustainable development and therefore should not be forwarded as sustainability progress. This paper will discuss these questions, as well as drivers and evaluation models for sustainable design. The presentation associated with this paper will briefly review these principles and apply them to research case studies from the Environmental and Sustainable Technologies Laboratory at the University of Michigan.

2. Targeting Significant Sustainability Challenges

There is no shortage of significant challenges to the environment and society that are impacted by engineering design. For example impacts at the global scale include climate and ocean acidity due to greenhouse gas emissions, disruption of the nitrogen and phosphorous cycles, overconsumption of scarce resources, and losses in biodiversity. Regional impacts include air pollution, water pollution, water accessibility, exposure to toxic and nuclear materials and land degradation. Negative social impacts may occur inside the workplace (e.g., such as exposure to harmful substances or repetitive injuries), in the community served by the business (e.g., corruption), in the operations upstream in the life cycle (e.g., acquisition of

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conflict materials), or in the operations downstream in the life cycle (e.g., burning electronics to recover metals in open fires). These impacts relate to sustainability in that they harm people directly (i.e., reduce the lifespan or quality of life) or they degrade the ecosystems, social systems, or and resources that society depends on today and in perpetuity.

It is easy to connect just about any engineering project to these impacts, and therefore it is easy for any project claiming an improvement in one of these areas to call itself "sustainable". But, for example, is a 10% reduction in the electricity consumption of a factory "sustainable factory management", or is it just good engineering with the potential to pay itself off during the lifetime of the factory? In other words should we, in this example, be labeling design improvements as progress towards sustainability if such progress should have occurred anyway if the system were designed originally with energy costs in mind? Sustainability by its nature must be relevant to human survival (either humans as individuals or as a society). Designs claiming to aid sustainability must be held to this standard both in dimension and in magnitude of improvement.

The transition from unsustainability to sustainability is fundamentally transformative. Therefore effective sustainable designs should also be transformative, matching their proportional improvements with the scale of transformation required in the particular sustainability dimension they are addressing. For instance, given the need to reduce greenhouse gas emissions globally by approximately 80% before 2050 to avoid dangerous anthropogenic interference, perhaps "sustainable" reductions in electricity consumption by the factory should be measured against an absolute 80% total (not a normalized quantity) reduction in greenhouse gases. Or perhaps the measure should be greater than 80% given the need for developing countries to have room to grow their carbon footprints prior to ultimate reductions. Although where to draw the line of magnitude is arguable, the principle of getting the dimension correct as well as the magnitude approximately correct is unassailable. Indeed, reducing electricity consumption by 80% does not reduce greenhouse gas emissions at all if the factory were already powered by renewable energy. The world has plenty of energy available to fuel humanity, the problem is the specific pollution and resource depletion caused by energy use. Thus the analysis target dimension and rough magnitude (e.g., "factor 5" or "factor 10") must both be set appropriately. This has been recently discussed in [2].

Claims of "sustainable product design" abound that are based on spurious dimensions. Vehicles capable of burning ethanol in the United States rarely use ethanol, and when they do the ethanol comes from corn. The net greenhouse gas emissions are roughly the same from corn based ethanol as gasoline, air emissions are roughly equivalent, and it has been claimed that corn prices were negatively impacted with real economic harm posed to people in developing countries [3]. The cell phone housing that is biodegradable and capable of yielding sunflowers is an interesting end-of-life outcome for the phone but may give someone the itch to end the phone's life early for the satisfaction of planting the casing [4]. Extending the life of the phone and avoiding another purchase of the phone would have much more beneficial environmental impact than the biodegradable housing. In Section 5 we will label claims of sustainable design associated with such concepts as "traps". Biodegradable cell phone housings would be better suited for replacement or protective covers [5] than as an important sustainability attribute of a new cell phone.

The process of evaluating whether a technology is likely to be addressing a significant sustainability challenge is best left to practitioners of life cycle assessment. The technology need not be without environmental or social impact of its own but it must have important benefits that far outweigh the costs in lesser important dimensions. The challenge of measuring sustainability in a life cycle sense during the design stage is discussed in the next section.

3. Evaluating Life Cycle Impacts during Design

After sustainability dimensions and targets are established, specialized tools are needed at the product design level to estimate the anticipated environmental and social profile associated with different design options. Such tools are particularly important since designers would suffer in their work if taxed by the need to impact assessments from scratch for each design option. Existing sustainable design tools are used for the following purposes: 1) to create awareness about potential environmental impacts and possible mitigating design strategies (e.g., checklists, guidelines, and case studies), 2) to provide the ability to rank or score the environmental performance of a product with respect to a limited number of environmental aspects (e.g., toolboxes or advisor software tools), or 3) to facilitate a life cycle assessment (LCA).

With the large number of guidelines found in typical checklists, it is almost certain that they will conflict, either with each other or with other performance attributes of the design. To resolve conflicts between different sustainable design guidelines and to support innovation, a number of application-specific software tools have been developed in the electronics and automotive sectors. Application-specific software tools have both the advantage and disadvantage of requiring less information than a full life cycle assessment. These tools allow design options to be quickly ranked and therefore help provide justification for specific design decisions taken to reduce environmental impact. On the other hand, they tend to lack the transparency of full LCAs and do not normally capture the environmental characteristics of the supply chain, which can be significant (e.g., integrated circuits). Software tools are also unlikely to fully account for situational factors in production, use, and disposal. For instance, it has been suggested that per capita consumption in North America causes roughly the same per capita disease burden due to particulate matter in China due to production activity as the disease burden in China caused by total per capita consumption in China itself [6]. Whether the magnitude turns out to be true or not, database approaches have difficulty connecting specific design and manufacturing decisions with economic supply chain and local environmental impacts.

LCA-based methods are generally considered to provide the most comprehensive and reliable product evaluations, although they are intended for existing activities and are therefore difficult to use in the creative design process. Tools such as EDIP LCV, Umberto, Simapro, TEAM, and GaBi intend to overcome the challenges by providing: 1) open frameworks for life cycle inventory development, 2) a database of

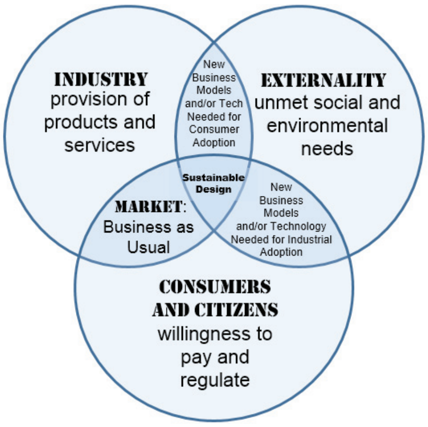

Fig. 1. Framework model of sustainable design effectiveness.

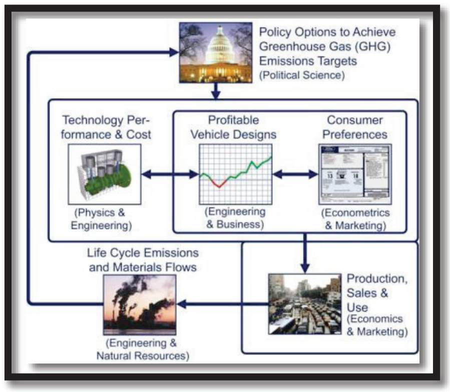

Fig. 2. Framework model for evaluating emissions in context of consequential life cycle assessment with market driven design.

representative materials and process inventories, and 3) impact assessment frameworks for comparing design options. While their inventory methods and data presentations are useful and similar, their impact assessment methodologies can vary significantly and may conflict markedly. Utilization of impact scoring methods is often inconclusive and inaccurate, and a decision based on any single scoring metric taken in isolation will only serve to propagate the assumptions used for characterization, normalization, and valuation in that method. Such complications have led to a provision in ISO 14042 which discourages the use of weighted impact scores for comparative assertions. The EcoAudit method avoids some of these considerations by focusing on CO2 and energy consumption only.

There is a growing interest in utilizing the results of life cycle inventory data more directly in sustainable design activities. For instance the EU Energy Related Products (ErP) directive distinguishes between actual product *environmental impacts* (e.g., climate change, forest degradation due to acid rain, ozone depletion, eutrophication, etc.) and product *environmental aspects* which are stressors leading to those impacts (e.g., emissions of greenhouse gases, emissions of acid substances, emissions of substances disturbing the oxygen balance, emission of substances affecting stratospheric ozone, etc.) [7]. ErP shows strong preference for the regulation of environmental aspects rather than impacts. This is because the environmental aspects are more easily measured and controlled by the producer through design (whereas impacts depend on additional factors such as locality, time, and user choices), they can be measured consistently, and they are more transparent in interpretation.

The danger with a focus on environmental aspects is that summary analyses usually treat all emissions as if they occur at one (non-defined) place and all at the same time. This challenges interpretation and may be misleading. As a result there is a need for enhanced working relationships between practitioners of (industrial) ecology, environmental studies, public health, and life cycle engineering as discussed in [8].

4. Sustainable Design Adoption Models

Figure 1 illustrates a framework model for evaluating the potential sustainability of an engineering design. The triple bottom line is represented somewhat differently than the typical triangle of economy, environment, and society. The economic dimension is captured as a nexus of industrial activity (upper left) and consumer activity (bottom center). The intersection of these domains represents today's market systems which are known to treat the environmental and social sustainability challenges as externalities. These externalities are represented as unmet social and environmental needs (upper right). The process of eliminating these externalities in today's economy is represented as the union of all three circles which is labeled as sustainable design.

Designers inspired by sustainability often start first with the goal of addressing a social or environmental externality but too often are too focused on this goal while neglecting the need for an appropriate business model so that industry has appropriate incentive to deliver the technology to the market. For instance, car sharing did not just require technology for booking vehicles and unlocking them; it required a business model, relationships, and infrastructure that created a profitable enterprise. Profit naturally requires that the consumer is willing to pay the price that would be required for market introduction of the new system. If the market will not adopt a technology due to its inherent characteristics or the absence of a viable business model, another choice is for the technology to be introduced through regulation, a process which is more common at the industrial scale (e.g., air pollution control equipment or hazardous materials restrictions) than at the consumer level (e.g., phase out of incandescent light bulbs).

Figure 1 provides a first check as to the potential for a design to contribute to sustainable development, useful at the earliest conceptual design stages, but it is by no means comprehensive. Even when a company can profit, a consumer is willing to pay, and an unmet sustainability needs is met, there may be barriers to the diffusion of sustainability technologies. In the pollution prevention sector these barriers are described in depth by Lindsey in [9] and include organizational issues such as early-adopter attitudes, discount rates, opportunity costs, trialability, observability, and perceived complexity. In the automotive sector such barriers have been observed in the relatively slow adoption of hybrid vehicles, despite the fact that such vehicles often pay themselves back over their lifetime.

Figure 2 provides a detailed model to evaluate the potential for addressing environmental sustainability through engineering design. This model is more appropriate once a detailed design and prototype is created. With information such as bill of materials, manufacturing costs/methods, and consumer willingness to pay, the series of cause-effect chains that trace the path by which policies and technology designs affect environmental impacts can be evaluated. For example, automotive fuel economy standards directly impact producer design decisions by requiring automotive firms to meet a prescribed fuel economy requirement. This regulation alters the choices producers make regarding vehicle pricing and design features, such as engine power and powertrain control systems. Together with consumer preferences, these design and pricing decisions change the mix of vehicles on the road and have a direct bearing on climate sustainability. These changes in vehicle designs and sales in turn affect downstream processes, such as consumer decisions concerning how much to drive, and upstream processes, such as the amount of produced steel and aluminum. As a result, the environmental emissions, wastes, and resource use associated with the lifecycles of these vehicles will change.

In [10] the approach outlined in Figure 2 was introduced as consequential life cycle assessment with market driven design (cLCA-MDD). The technique was applied to the evaluation of new car design in response to changes to the U.S. Corporate Average Fuel Economy Standards for vehicles in [11], a study which was referenced by the Department of Transportation and Environmental Protection Agency during the rulemaking process. While Figure 2 is specific to vehicle design in accordance with the example above, the framework concept linking policy, engineering design, market factors, and environmental emissions is general to technical product design.

Most evaluations of the sustainability of an engineering design will fall between the simplicity of Fig. 1 and the complexity of Fig. 2. The commonality between the two frameworks is that Life Cycle Assessment is taken as an outcome of market decisions in a consequential sense rather than as a detached, after-the-fact, analysis. Indeed, an environmental sustainability assessment is incomplete without an assessment of potential market drivers for adoption as discussed in Section 5.

5. Market Factors Influencing Sustainable Design Efficacy

In the ideal situation, sustainable design decisions would spontaneously self-assemble in the marketplace. For this to happen, sustainable design would need to create more business value than could be captured by designs that are not sustainable. But how can sustainable design add value for companies? Here we define three categories of value created by sustainable design: adding positive value, eliminating negative value, and creating negative value for competitor firms. Each of these categories is discussed below.

5.1. Adding positive market value

Inspiring Innovation. Sustainable design need not be considered an additional constraint for producers, especially if the sustainability perspective can encourage the designer to search a previously unexplored region of the design space, leading to a breakthrough design. Examples of environmentally inspired breakthrough innovations include hybrid powertrain systems for automobiles, novel production facilities and methods and advanced renewable electricity generation systems.

Increasing Market Share or Consumer Willingness to Pay. According to [13], only about a small fraction of US consumers will consistently pay more for products perceived as being environmentally friendly. These customers tend to exist in niche markets, such as the organic food market, which has recently been growing in the US.

Development of New Markets for Environmentally Conscious Products. This route to capturing environmental market value is pursued by the discipline of industrial ecology [14], where resource cycling is investigated with the aim of converting waste from one product or process into an input for another industrial activity. The idea is to simultaneously create market opportunities while addressing significant environmental problems. Towards this end, economically successful examples of recycling and remanufacturing are on the rise. One report from the 1990s claimed that the US remanufacturing industry exceeds $53 billion per year in annual revenue and employs almost a half million individuals spanning 46 major product categories [15]. However, due care must be taken in evaluating the environmental characteristics of reused or remanufactured products, since such products need not be environmentally superior to manufacturing new products.

5.2. Removing negative market value

Reducing Production Costs. The pollution prevention literature is replete with examples describing how the redesign of manufacturing processes has inspired simultaneous reductions in production costs and pollution. Some of the most common examples exist in the Green Chemistry literature, where large cost savings in chemical and pharmaceutical manufacturing have been observed. As one example, Dow Chemical claims to have reduced emissions of targeted substances by 43% and the amount of targeted wastes by 37%, primarily through green chemistry innovations. In this case alone, a one-time investment of $3.1 million is now saving the company $5.4 million per year [16]. Other profitable pollution prevention examples come from diverse areas such as membrane filtration recycling of industrial fluids [17-18], novel metal finishing technologies [19-20], and alternative integrated circuit production methods [21-22].

Minimizing Regulatory Losses and Avoiding Litigation. Pollution prevention investments by US companies are small relative to investments made toward compliance with EPA regulations, which amounted to 2.1% of GDP in 1990 (approx. $241 billion in 2003 dollars) [23]. While it has been estimated that $1 invested in complying with EPA regulations returns $10 to $100 in terms of ecological and health benefits [24], it is widely accepted that current US regulations fail to address pressing sustainable design issues such as excessive resource consumption (e.g., petroleum), the proliferation of toxics in the environment (e.g., the disposal of electronic waste), and the accumulation of greenhouse gases (e.g., CO2) in the atmosphere. With respect to each of these issues, the US is lagging in sustainable design policy drivers relative to Europe and Japan, both of which have been more progressive in eco-design oriented legislation.

Minimizing Damage to Public Image. Since the development of the Toxic Release Inventory in the U.S., public reporting of environmental emissions has driven many companies to reduce the amount of pollution they produce. Moreover, companies such as Exxon, Union Carbide, and Nike learned the hard way that public image related to environmental and corporate social responsibility (CSR) issues can directly affect profitability. Now such issues are a key component of public image management for large companies across a wide range of industries ranging from oil and chemical production, to consumer electronics, to the automotive industry. In fact, the need for accountability and visibility with respect to environmental and social sustainability has been an influential driving force for CSR initiatives [25].

5.3. Increasing negative market value for competitors

Strategic Utilization of Legislation for Competitive Advantage. Sustainable design can create negative value for competitor organizations when it facilitates the development of government policies that favor organizations in a relatively strong sustainable design position. For example, at the time of debate over the Montreal Protocol, DuPont and ICI were major producers of ozone-destroying chlorofluorocarbons (CFCs) and held patents on costly CFC substitutes. While initially resistant, DuPont and ICI eventually supported the Montreal Protocol, which served to increase the value of the companies' proprietary technologies. For similar reasons, it has been occasionally observed that larger companies, with a greater capacity to manage sustainability issues, are more supportive of stringent health and environmental protection than smaller and/or environmentally weaker companies.

Strategic Utilization of Product Attributes for Competitive Advantage. Changing the system of societal valuation by altering consumer perception and education regarding the sustainability attributes of products can create opportunities for profit. For instance, in the early days of hybrid technology (between January 2003 and January 2004), US sales of the Toyota Prius increased by 82% as consumers became more comfortable with the technology. Toyota not only profited from the increased sales, but also from the sales of hybrid technology patent rights to Ford and Nissan [26,27]. More generally, this concept is beginning to take hold as indicated by growing attention being paid to programs, such as the Eco-Label program in the EU and the Swedish Environmental Products Declaration program, that are predicated on the notion that eco-friendly attributes can be used strategically by corporations to gain competitive advantage. A recent article by Hoffman et al. explores the more recent developments regarding the use of Industrial Ecology as a source of competitive advantage [28].

5.4. Sustainable Design Traps and Triumphs

To start a discussion regarding the sustainability of a specific design it can be useful to discuss the idea of traps vs. triumphs. The idea of labeling traps vs. triumphs follows from the observation that products pushed and marketed as environmentally sustainable may have marginal or no impact on sustainable development (e.g., corn-based ethanol vehicles in the USA or biodegradable cell phone housings) while products that have had massive sustainability implications (e.g., flat panel displays, LED lamps) are rarely pushed as sustainable products and do not owe their success to being pushed as sustainable products. Rather they were inexpensive replacements to incumbent designs with more desirable attributes. While it is easy to define a trap, defining a triumph is harder. Candidate triumphs such as flat panel displays and LED lamps, that have excellent *relative* environmental characteristics and are transformational by nature, may suffer from overly successful adoption rates with the potential to swamp out any gains the products make on a per-unit basis. Traps, trade-offs, and triumphs are defined and discussed briefly below. Attaching such labels to a product necessarily requires an analysis from a global systems view.

Trap. Traps are products that are marketed as sustainable for economic success, but are not sustainable. They fail in at least one of the questions (a-d) identified in Section 1. Typically they have no environmental merit or only reduce environmental burden in an unimportant dimension. Products sold as recyclable without recycling infrastructure, or products which focus on renewable materials while ignoring electronics content might fall in such a category. Manufacturing methods sold as sustainable but enable more cost-effective production of polluting products might also fall in this category.

Trade-Off. Products that are not clearly traps or triumphs might be called “trade-offs”. Such products might advance sustainability in some important dimensions but not work against sustainability in other important dimensions. For instance, a product might reduce greenhouse gas emissions but increase water consumption and nutrient loadings to water. Alternatively, a product might have excellent environmental characteristics but it cannot succeed in the market place without a change in consumer interest (e.g., a willingness to pay) or regulation which drives the product into practice. After a change of regulation, there is a possibility that the product becomes a triumph (e.g., catalytic converters for vehicles). Fracking technology might also fit this category as having important climate benefits in the short-term but also having potential negative climate effects long-term as well as impacts on human health and water pollution.

Triumph. A product is environmentally, socially, and economically successful. Such products may not ever be mentioned as being sustainable because they have attributes that make them market-ready. For instance, LED lights are hardy and controllable whereas incandescent lights are fragile, heat generating, and cumbersome. “Product-triumphs” are characterized by the fact that new environmental impacts are unimportant relative to the gains. However examples such as LED lights are subject to rebound effects that might ultimately make them “Market-traps”. For instance, it has been predicted that the adoption of LED lights due to their low cost and potential for ubiquity will increase the overall use of lighting such that the overall impacts of lighting on greenhouse gas emissions relative to the status quo will be negative [29]. Flat panel displays are now so common in televisions and computer monitors, and have permitted increases in display sizes as well, that the overall impact of flat panel displays may be higher than previously observed from CRT monitors and televisions as whole. The CRT case study is detailed in articles such as [30] and [31].

Product-triumphs can be subject to Market-traps just as Product-traps can be subject to Market-triumphs. However simultaneous Product-triumphs and Market-triumphs do exist. The domain of remanufacturing, for example, has notable examples of bringing old product to current environmental standards while greatly reducing the costs (and therefore diffusivity) of environmental improvements. Products such as seatbelts and airbags with excellent social sustainability characteristics are clear candidates as triumphs. Products such living buildings [32] and cogenerators, with excellent environmental sustainability characteristics, might become sustainable design triumphs as they become more mainstream.

6. Conclusions

Sustainable design is hard. Achieving success requires a market oriented approach that can fail due to its own success. Despite the challenges it is important to try, with the potential aid of regulatory change helping to increase adoption rates. Critical questions and criteria must be addressed before using the label "sustainable" within an engineering context (Section 1). The criteria must be focused on key sustainability challenges (Section 2) and backed up with design tools that can facilitate evaluation of progress towards sustainability challenges (Section 3). Environmental and social progress must be evaluated next to market factors (Section 4) within which drivers are needed to diffuse products into real-world use (Section 5) with the hope of the products not becoming so successful that they wipe out the gains relative to the products and systems which they replace

Acknowledgements

Sections 3 and 5.1-5.3 come from [33] with minor updates.

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