Sustainable Design Engineering and Science: Selected Challenges and Case Studies

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1. INTRODUCTION

As an instrument of sustainable development, *sustainable design* intends to conceive of products, processes, and services that meet the needs of society while striking a balance between economic and environmental interests [1]. By definition, the benefits of sustainable design are publicly shared, and to achieve them individual designers must place their decisions into a context larger than any single company, and even larger than the society or generation within which the design functions. It is therefore difficult to define sustainable design in an operational sense, and thus sustainable design is easy to ignore, especially in the fast paced and competitive process of bringing design artifacts to market. Complicating sustainable design further is the fact that environmental impacts depend on the consequences of specific stressors, rather than on which product or process causes the stressor (e.g., the atmosphere is indifferent to a kg of CO_2 saved by changing the design of a refrigerator versus changing the design of a television). Due to these characteristics, sustainable design requires consistent and well-coordinated implementation to be achieved in a meaningful way.

Given the challenge of coordinating the complex trade-offs between economic, societal, and environmental factors influenced by design, it can be expected that governments interested in operationalizing sustainable development will begin to directly legislate the feasible space of options available to designers. This has been the approach in the EU, where the last few years alone have seen the proliferation of Directives on Waste Electric and Electronic Equipment (WEEE) [2], Restrictions on Hazardous Substances (RoHS) [3], and End of Life Vehicles (ELVs) [4]. For instance, according RoHS, new electrical and electronic equipment cannot contain lead, mercury, or cadmium after July 1, 2006, *except* for listed applications (e.g., leaded glass in CRTs) where substitution via design changes or materials is technically or scientifically impracticable, or where their substitution would cause environmental, health, and/or consumer safety impacts larger than their use [3]. Such regulations attempt to level the competitive playing field for environmental improvement, and to reduce the need for companies to make subjective and isolated judgments regarding the sustainability of design decisions.

While prescriptive environmental Directives such as RoHS and WEEE intend to simplify sustainable design, they do not necessarily achieve its objectives. For example, eliminating a toxic substance from a product, such as mercury from fluorescent lamps, might lead to greater use of incandescent lamps that consume more energy, which on balance could have a negative impact on the environment [4]. In industrial cleaning machines, reduced use of detergents might typically lead to increased water temperature and hence higher energy consumption, which on balance could have a negative impact on the environment [4]. In the design of fuel cell vehicles, selecting materials on the basis of recyclability could ultimately lead to vehicles of larger mass, and consequently increased emissions associated with hydrogen production, which on balance could have a negative impact on the environment [5].

The need to coherently resolve such trade-offs among environmental attributes, and between environmental attributes and product performance, provides the rationale for the European Commission's (EC) recent proposal for a framework Directive to set *eco-design* requirements for energy-using products. Eco-design is the focus as it is estimated that over 80% of all product-related environmental impacts are determined during the product design stage [4]. With government entities now targeting the design process, it is becoming imperative that companies and their designers understand the environmental and economic implications of their design options. Moreover, the impending consideration of such eco-design legislation will require companies to become actively engaged in the broader development of environmental product policy, not as a matter of environmental altruism, but as a matter of maintaining competitive position.

Against this backdrop, it is an interesting and perhaps ironic observation to note that those who apply knowledge of science toward fulfilling society's needs through technological invention and selection (e.g., engineers and designers) rarely have a quantitative understanding about society's preferences, business decisions, economics, and the environmental impact of technological decisions. In other words, it is rare for engineers and designers to have the ability to systematically address the trade-offs inherent to sustainability. Unfortunately, this is more than just an educational shortcoming. At present, there is a clear need for a comprehensive body of knowledge and quantitative approaches that integrate engineering, economic, societal, and environmental science models towards a holistic definition of sustainable design.

For the purposes of this text, we define **design** as *a creative decision-making process that aims to find an optimal balance of trade-offs in the production of a product or service that best satisfies customer and other stakeholder preferences*. The artifact can be a product, manufacturing process, or service, with typical trade-offs including those between performance characteristics (e.g., light weight vs. high strength), manufacturing capability, cost, safety, time-to-market, degree of customization, and the often-contradictory preferences of different stakeholders. In our view, **sustainable design** only adds specific focus to design: *design, with particular attention paid to life-cycle trade-offs between functional performance, economic success, and the establishment of healthy social and environmental systems*. In other words, sustainable design is a consideration of the balance between public and private interests in the course of satisfying customer and other direct stakeholder interests.

In this chapter, we focus on the following challenges to sustainable design:

1. Understanding Incentives and Inhibitors to Sustainable Design (Section 2)
2. Establishing Targets, Metrics, and Strategies for Sustainable Design (Section 3)
3. Accounting for Variability in Product-User Interactions (Sections 3, 4)
4. Evaluating Alternative Technologies for Sustainability Characteristics (Section 4)
5. Estimating the Market Value of Sustainable Design Attributes (Section 5)
6. Developing Market-Conscious Policies to Encourage Sustainable Design (Section 5)

Fig.1 serves as a framework for organizing these challenges in a manner that suggests a flow of abstract societal values regarding sustainability into products and services with economic, environmental, and societal consequences. Various influences are listed in one of

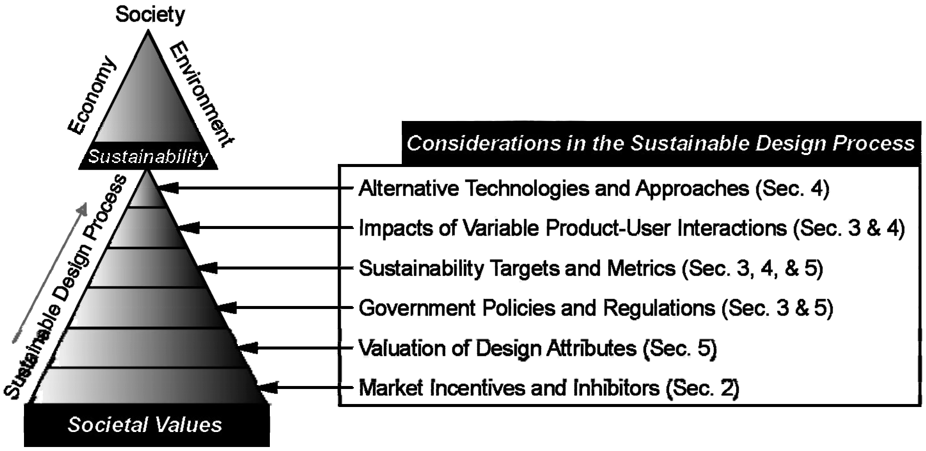


Fig. 1. Framework for conceptualizing sustainable design challenges described in this chapter

many possible progressions from values to artifact, including the designer's perceptions of technical and environmental alternatives (Challenges 2, 3, and 4) and the implementation of societal values as regulatory and market variables (Challenges 5 and 6). Influenced by the designer's perceptions, and against the backdrop of current market conditions, the company will optimize its design decisions and set them into action, thus affecting the balance of factors in the sustainability triangle.

In this chapter, we begin by providing an overview of business incentives and inhibitors to sustainable design (Section 2). This is followed by a brief review of sustainable design processes and metrics (Section 3). In these introductory sections, we focus primarily on environmental aspects of sustainable design, although issues of corporate social responsibility and trade-offs between societal and environmental variables are mentioned. The introductory sections are followed by two case studies which highlight specific trade-offs that arise in sustainable design applications. The first case study (Section 4) provides an overview of economic, environmental, and societal aspects of mobile telephone production, use, and remanufacturing. The second case study (Section 5) provides a quantitative methodology for the evaluation of sustainable design policies related to automotive fuel efficiency. The two case studies are starkly different in approach. While the first takes a high-level and empirical view of existing mobile phone design and remanufacturing activities, the second takes a mathematical approach toward modeling the impacts of environmental policy options on engineering design. By presenting both case studies in this chapter, we contrast the strengths and weaknesses of these approaches as they apply to sustainable design.

2. SELECTED INCENTIVES AND INHIBITORS TO SUSTAINABLE DESIGN

2.1. Incentives for Sustainable Design

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 not considered 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.

2.1.1. 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 (e.g., [6]), and advanced renewable electricity generation systems (e.g., [7]).

Increasing Market Share or Consumer Willingness to Pay. According to [8], only about 15% of US consumers will consistently pay more (up to approximately 22% 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 by 25% per year in the US [9]. Similar examples are currently difficult to find in North America.

Development of New Markets for Environmentally Conscious Products. This route to capturing environmental market value is exemplified by the discipline of industrial ecology [10], where resource cycling is investigated with the aim of converting waste from one product or process into an input for another industrial activity. This simultaneously creates market opportunities while addressing significant environmental problems. Towards this end, economically successful examples of recycling and remanufacturing are on the rise. In fact, one report has estimated 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 [11]. 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 (see Section 4).

2.1.2. 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 [12]. 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 [13]. Other profitable pollution prevention examples come from diverse areas such as membrane filtration recycling of industrial fluids [14-15], novel metal finishing technologies [16,17], and alternative integrated circuit production methods [18,19].

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) [20]. While it has been estimated that $1 invested in complying with EPA regulations returns $10 to $100 in terms of ecological and health benefits [21], 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., CO_2) 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, 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 [8]. In fact, the need for accountability and visibility with respect to CSR issues has been an influential driving force behind corporate backing for initiatives such as the United Nations Global Compact program [22].

2.1.3. 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 [23]. 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, 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 [24,25]. 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 [26] and the Swedish Environmental Products Declaration program [27], that are predicated on the notion that eco-friendly attributes can be used strategically by corporations to gain competitive advantage.

2.2. Inhibitors to Sustainable Design

Numerous factors can serve to overcome the incentives listed above, precluding the manifestation of sustainable design. While some barriers are technological, many of the greatest challenges are products of the economic system itself [28]. Perhaps most importantly, sustainable design characteristically requires one firm or entity to pay its costs, while the benefits are widely shared. Since the designer’s traditional stakeholders receive only a small fraction, and in some cases none, of the benefits of sustainable design, deciding who and how much to pay for sustainable design is a complex endeavor.

For example, private preferences that individual US consumers have for larger vehicle size and faster acceleration are well captured in the market, while public preferences that the same individuals may have for greater environmental protection, human health, and sustainability are not as easily captured. Since any individual is both a private player in the market and a member of society, inherent conflicts of interest exist that must be resolved in a fair and equitable manner. Incorporation of public value in the marketplace is usually achieved by direct incentives or regulations imposed by elected government officials (e.g.,

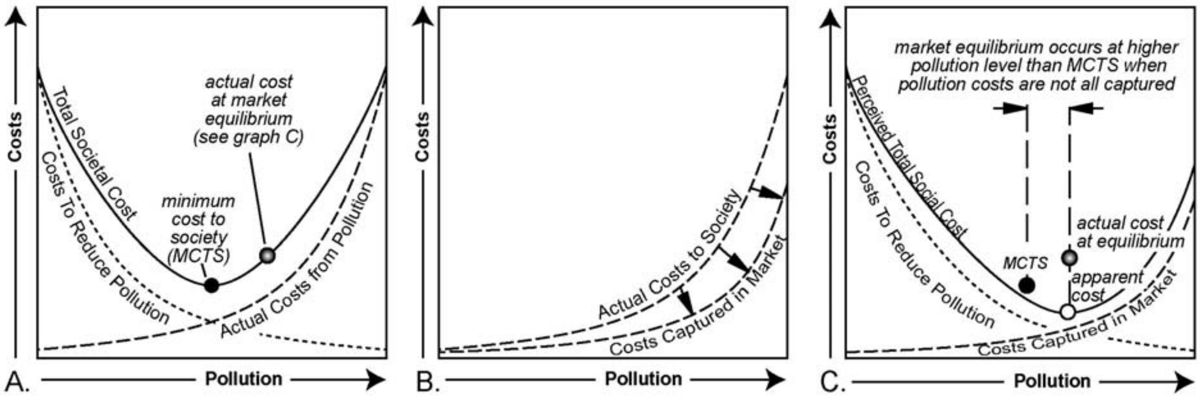


Fig. 2. a) Pollution level at minimum total cost to society; b) undervaluation of pollution costs to society; c) Resultant level of pollution observed at equilibrium when pollution costs are undervalued.

through tightened CAFE standards), with some government policies being more economically efficient than others (see Section 5). Naturally, such decisions extend beyond trade-offs between environmental protection and performance into issues of vehicle safety, production cost, dependence on foreign oil, and consumer preference. A committee of the National Academy of Sciences recently concluded that such trade-offs can only rightly reside with elected officials, and that the trade-offs themselves are inherently difficult to quantify [29].

The example of automobile costs and benefits also makes clear that at points of optimum economic efficiency, where total costs to society are minimized [28], some pollution and resource consumption still exists. As suggested by Fig. 2a, the benefits associated with sustainable design (e.g., reduced pollution) have diminishing returns and increasing costs, such that when the point of minimum total social costs is reached, dollars invested in pollution prevention are best spent in other arenas where the marginal “benefit” to the environment (as valued by society) exceeds the marginal costs to society. While quantifying the costs of sustainable design is relatively straight forward, it is extremely difficult to quantify the benefits. The undervaluation of benefits skews the optimum point in Fig. 2 towards excess pollution. Quantifying the benefits of sustainability has been a growing topic of interest in the field of natural resource and environmental economics. While much progress has been made toward this end in the field of contingent valuation and behavior methods, the limitations of the methods are also now well-established [28]. Moreover, even if the benefits could be quantified precisely, the fact remains that while individuals pay the costs to achieve sustainable design, they only receive a small fraction of the benefit [30].

Beyond trade-offs between public and private value, a number of other inhibitors to sustainable design are inherent to the US economic system. Such inhibitors that have been discussed in the literature include: technology and infrastructure cycle times that are either too fast (e.g., electronic equipment) or too slow (e.g., manufacturing facilities) [15,31], emphasis on short-term profits driven by quarterly reporting cycles [32], financial structures biased against prevention-based investments [33], difficulties valuing non-financial assets [28], financial discounting [34], and lost opportunity costs related to sustainability investments [21]. While these are significant inhibitors to sustainable design, they are not insurmountable. As recent EU Directives are demonstrating, barriers to sustainable design can be removed through government actions requiring businesses to adhere to design targets.

3. TARGETS, METRICS, AND STRATEGIES FOR SUSTAINABLE DESIGN

The basic challenge of sustainable design can be summarized by the old business management adage: "if you do not measure it, you do not manage it". Ultimately, governments bear the bulk of responsibility for managing sustainable design, and recent EU Directives on RoHS, WEEE, and ELVs are a reflection of this responsibility. The EU approach to the management of sustainable design is conceptually similar to Fig. 3.

Fig. 3 is an idealized approach to establishing quantitative sustainable design targets. The approach has a scientific component in that life cycle impact assessment is utilized for quantifying environmental impact magnitudes and uncertainties as inputs to a political decision-making process. Government then facilitates a discussion among stakeholders, industry, and the general public towards establishing sustainability objectives for society as a whole. It is these sustainability objectives for society that are to be met by establishing tangible design targets for specific products. Partitioning society's overall objectives into sustainability targets for specific product categories is a total cost minimization problem (Fig. 2) which must account for performance, societal, economic, and environmental aspects of the products to be regulated. In the words of the European Commission [4], simultaneous consideration of these factors is needed to assure that proposed sustainability targets do not result in "unacceptable loss of performance or utilities to customers". Once established, a competitive environment must be created where companies can pursue these sustainable design targets without fear of economic loss, as discussed in Section 5.

3.1. Targets, Metrics, and Processes for Sustainable Design

After product targets for sustainability are developed, specialized tools are needed at the product design level to predict the environmental stressor profile associated with different design options and to compare them with established targets. Such tools are particularly important since designers would suffer in their work if taxed by the need to generate stressor profiles 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 perform a life cycle assessment (LCA).

The 2003 Sandestin Conference on Green Engineering, in addition to several other initiatives, has led to the development of useful principles that serve as a starting point for sustainable design [35,36]. From here, experience-based checklists and guidelines are often developed by companies, in most cases pointing out what not to do or suggesting how sustainability principles can be specifically utilized in a given application. Sustainable design guidelines and checklists are currently in widespread use throughout the consumer electronics, appliance, and automotive sectors of the economy (e.g., [37-39]). Some examples of guideline-based and case study resources tailored to specific life cycle stages include: material selection (e.g., [9,40]), assembly and disassembly (e.g., [41-43]), packaging and transport (e.g., [44]), recycling (e.g., [41, 45]), and remanufacturing (e.g., [46-48]).

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. Typical conflicts may arise for example between mass and recyclability (e.g., using polymers versus metals in automotive applications), reusability and energy consumption (e.g., reusing an old refrigerator versus producing a new energy-efficient one), and between toxic chemical

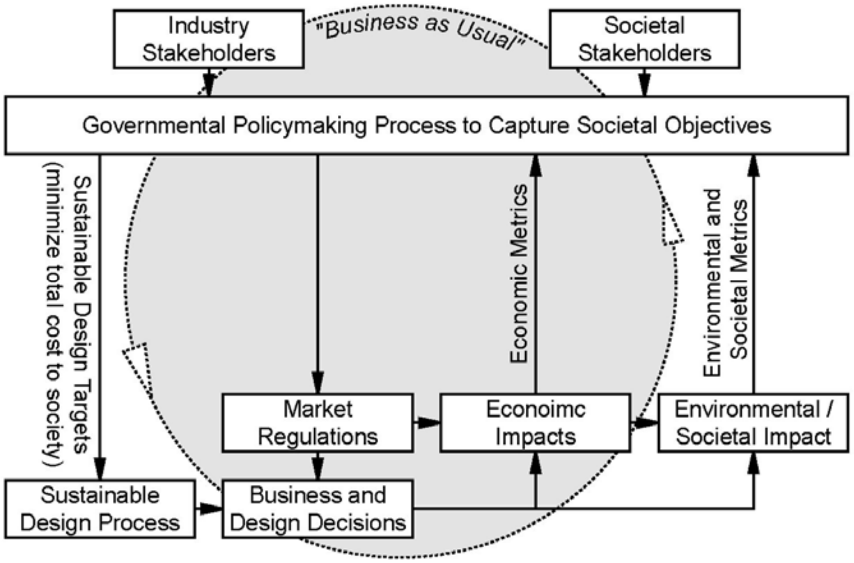


Fig. 3. Overview of high-level considerations in the development of sustainable design targets

use and energy consumption (e.g., using mercury-containing compact fluorescent lamps versus incandescent lamps). Without a significant amount of experience or investigation, and in the absence of product-specific sustainable design targets established by government, it is difficult to know which guideline is most applicable to the current situation. For instance, it has been suggested that the EU Directive on ELVs is currently biasing design options away from high-strength, low-weight composite materials, even though this may not be optimal from the life cycle design perspective.

To resolve conflicts between different sustainable design guidelines and to support innovation, a number of application-specific software tools have been developed. For instance, Motorola has developed a Green Design Advisor that stores information regarding component recyclability along with disassembly information in order to calculate the maximum degree to which products can be recycled [49]. A similar, but more general End-of-Life Design Advisor has also been developed at Stanford University [50]. Such software tools are now widely reported in the consumer electronics sector, where further developments have extended beyond end-of-life considerations into the assessment of product and process materials toxicity and energy intensity (e.g., [51]).

Application-specific software tools such as these have both the advantage and disadvantage of requiring less information than a full life cycle assessment (for details on LCA methodology, see [52]). These tools allow design options to be quickly ranked and have demonstrated the ability to inspire respectable eco-design solutions [53]. 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 rather significant (e.g., in the case of integrated circuits). Application-specific software tools are also unlikely to account for situational factors in production, use, and disposal.

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. Since a properly conducted LCA can take several months to perform and cost tens of thousands of dollars even for a relatively simple product, a number of software tools have been developed that contain representative environmental emission and resource consumption quantities for typical engineering materials

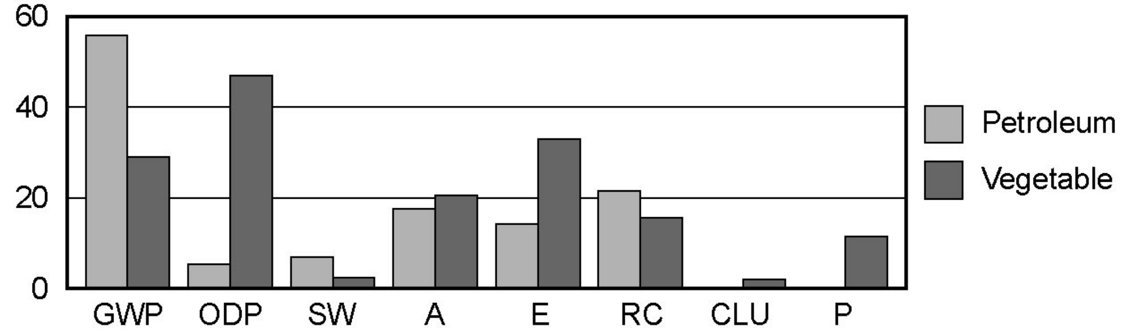


Fig. 4. Comparison of life cycle inventories for the production of 2000 kg of vegetable vs. petroleum metalworking fluid. GWP: Global Warming Potential (10kg CO_2); ODP: Ozone Depletion Potential (mg CFC11); A: Acidification (kg SO_2); E: Energy Consumption (gigajoules); SW: Solid Waste (kg); RC: Resource Consumption (100 kg); CLU: Cultivated Land Use ($1000m^2$); P: Pesticides (g)

and manufacturing processes. Some of the most commonly used tools in the design of consumer products include EDIP LCV [54], Umberto [55], Simapro [56], TEAM [57], and GaBi [58]. These software packages generally contain three components: 1) open frameworks for life cycle inventory development, 2) a database of representative materials and process inventories, and 3) impact assessment frameworks for comparing design options.

While the inventory methods and data presentations are fairly similar across existing software packages, the impact assessment methodologies can vary significantly. As an example of these differences, the Eco-Indicator 99 (hierarchist) and EDIP methods were compared in the production of vegetable versus petroleum based metalworking fluids (MWFs) [59]. Resource consumption and emissions associated with the production of both MWFs (2000 kg each) were assembled into an inventory, which is provided in Fig. 4 in terms of aggregated equivalent inventory categories. Fig. 4 shows that the vegetable-based MWF is superior in some categories, while the petroleum-based MWF is superior in others. Since the goal of impact analysis is to resolve such differences, Fig. 5 shows the conversion of the inventory into single score environmental impact results using the Eco-Indicator 99 and EDIP assessment methodologies. According to the Eco-Indicator 99 methodology, the bio-based MWF is superior to the petroleum-based MWF, resulting in a score 60% lower, while the EDIP analysis indicates that the petroleum-based MWF is superior, with a score 57% lower. Several categories comprise the key differences in the single score results from these two methods. In the EDIP analysis, pesticides used in the production of the vegetable based MWF account for a significant portion of the final score due to their chronic and acute toxicity in water. It is the weighting of pesticide impacts (relative to the weighting of petroleum

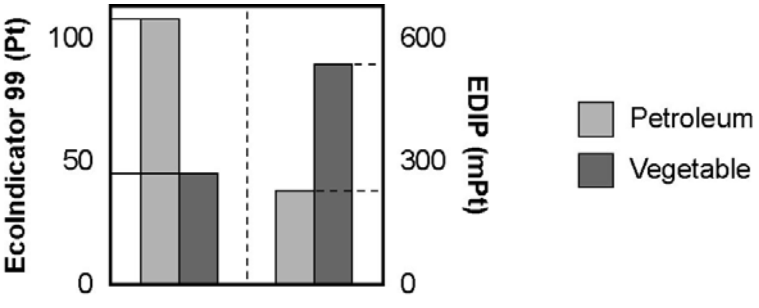


Fig. 5. A comparison of life cycle impact scoring results for the production of 2000kg of vegetable vs. petroleum metalworking fluid using the EDIP and Eco-Indicator 99 methodologies.

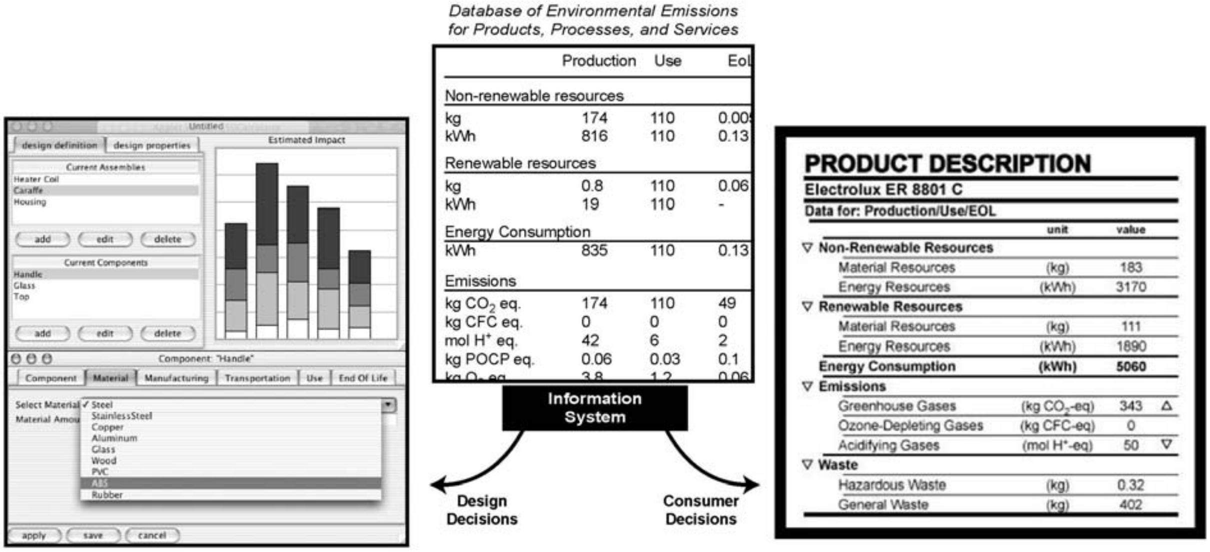
consumption) that shifts the final outcome from favoring bio-based MWFs to favoring petroleum-based MWFs when using the EDIP methodology. Utilization of impact scoring methods is therefore inconclusive in this application, and a decision based on any single scoring metric taken in isolation will only serve to propagate the assumptions used for characterization, normalization, and valuation in that method.

Such issues of interpretation, situationality, and appropriateness associated with environmental impact metrics complicate their use in design applications and run counter to their intention to allow the designer to utilize such metrics comfortably without developing expertise in environmental science. Such complications have also led to a provision in ISO 14042 which discourages the use of weighted impact scores for comparative assertions [60]. Therefore, there is a growing interest in utilizing the results of life cycle inventory data more directly in sustainable design activities. For instance, the Swedish Environmental Management Council has promoted the development and distribution of standardized Environmental Product Declarations (EPDs) [27]. The EPD approach establishes product-specific requirements for selected product groups, as well as harmonized rules for LCA data collection, calculation, and presentation of the results. The EPD metrics are typically expressed within equivalent emission categories, similar to Fig. 4. EPD metrics typically include greenhouse gas emissions, ozone depletion potential, acid rain forming potential, etc. Taking such product declarations one step further, the EPA has suggested displaying such metrics in the form of a “nutrition label” (Fig. 6) which provides a familiar aesthetic for consumers [61, 62]. Fig. 6 also illustrates how such an environmental inventory database could be used during design to evaluate evolving product concepts.

With respect to the establishment of quantitative sustainable design targets, the proposed EuP framework similarly 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.) [4]. The proposal, which intends to harmonize environmental regulation impacting the eco-design of energy using products across the EU, has stated a 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. Also, for small and medium enterprises with fewer resources, the prediction of environmental impacts may not be feasible, while the measurement of environmental aspects is relatively straightforward.

3.2. Research Opportunities Related to Establishing Sustainable Design Targets

The goal of setting product-level targets and metrics for sustainable design through a process such as Fig. 3 presents a number of opportunities for quantitative research, especially in the areas of industrial ecology, LCA, economic impact analysis, and product performance modeling. With respect to LCA, inventory and impact profiles for different product categories are required, including their supply chains. For example, the inventory profile of the supply chain is particularly important for the case of integrated circuits that are utilized in consumer electronics [63]; however little product-specific information is available in the public domain regarding their environmental profile, as discussed in Section 4.



Database of Environmental Emissions for Products, Processes, and Services

	Production	Use	Eo
Non-renewable resources			
kg	174	110	0.00
kWh	816	110	0.13
Renewable resources			
kg	0.8	110	0.06
kWh	19	110	-
Energy Consumption			
kWh	835	110	0.13
Emissions			
kg CO_2 eq.	174	110	49
kg CFC eq.	0	0	0
mol H^+ eq.	42	6	2
kg POCP eq.	0.06	0.03	0.1

PRODUCT DESCRIPTION

Electrolux ER 8801 C

Data for: Production/Use/EOL

	unit	value	
▽ **Non-Renewable Resources**			
Material Resources	(kg)	183	
Energy Resources	(kWh)	3170	
▽ **Renewable Resources**			
Material Resources	(kg)	111	
Energy Resources	(kWh)	1890	
Energy Consumption	**(kWh)**	**5060**	
▽ **Emissions**			
Greenhouse Gases	(kg CO_2-eq)	343	△
Ozone-Depleting Gases	(kg CFC-eq)	0	
Acidifying Gases	(mol H^+-eq)	50	▽
▽ **Waste**			
Hazardous Waste	(kg)	0.32	
General Waste	(kg)	402	

Fig. 6. Conceptual use of environmental inventory databases to support design and consumer decisions

With respect to environmental impact assessment, it can be assumed that the *selection* of product-level environmental aspects to be targeted by EuP will be based on life cycle impact analyses performed across product sectors, as suggested by Fig. 3. Ongoing research towards establishing cause-and-effect relationships between environmental stressors and impacts, including geographic, temporal, and statistical uncertainty information, will be particularly helpful in establishing these targets. Such issues have recently been raised in the context of developing the TRACI life cycle impact assessment method [64].

Quantitatively modeling the relationship between eco-design options, performance, cost, environmental emissions, and resource consumption is an issue for engineering research. This begins with the quantitative prediction of environmental emissions and resource consumption as a function of design variables. As a simple example, consider the case of modeling the electricity consumption of a refrigerator/freezer. Design variables include the volume of the refrigerator/freezer, its configuration (e.g., side-by-side, top over bottom, etc.), insulation type and thickness, compressor characteristics, evaporator/condenser characteristics, etc. Using basic heat transfer equations, material data (e.g., for insulation), and a limited number of calibration experiments to estimate the efficiency of heat rejection systems, it is relatively straightforward to predict the steady-state electricity consumption of different design options as they would be reported (for instance) on the EnergyGuide label utilized in the US. A modeling approach is therefore useful for sustainable design, as it can permit the calculation of eco-efficiency (e.g., cost per unit of environmental emission reduction) associated with different design options.

Typically, the ability to model steady-state or standardized operational performance (e.g., EnergyGuide ratings) is sufficient for comparison of the relative environmental impacts of two designs. However, there are instances where the ability to model subtle and/or dynamic behavior of the product is also useful in the sustainable design process. For instance, the electricity consumption of a refrigerator/freezer may actually be up to 30% higher than predicted from the EnergyGuide label due to factors in-use that would not be captured from steady-state engineering models [65]. In the case of the refrigerator/freezer, losses associated with opening and closing the door usually account for 5 to 10 percent of the total life cycle energy consumption of the refrigerator [65]. The ability to predict the effectiveness of design measures intending to reduce losses from the door opening and shutting would require models and assumptions related to the convective replacement of cold air in the refrigerator with warm, humid air from the kitchen, using non-steady state calculations. While such advanced design modeling intending to reduce a 5-10% loss may not seem worthwhile, depending on the product, such design efforts can reduce the overall environmental impact of the industry significantly. In fact, reducing energy consumption of all US refrigerators by just 1% would save approximately $140 million dollars in energy costs and 1.5 million tons of carbon released to the atmosphere each year [66]. This carbon savings would exceed the average carbon emission per nation per year on the African continent [67]. The point is that modeling subtle, second-order impacts of design decisions on environmental performance can be important for products with a relatively large environmental impact, and that are in widespread use.

The refrigerator case also demonstrates that while basic engineering modeling can be useful to reveal the *relative* environmental impact of one product versus another, rather advanced modeling may be needed to reveal the *absolute* impact of eco-design changes on the environment. These absolute impacts may have particular relevance to policymaking. For example, the EPA is currently considering for the first time in two decades changing the way it reports standard automotive fuel efficiency to better reflect real-world performance [68]. In filing a petition to the EPA, the Bluewater Network (San Francisco, CA) argued that real-world gas mileage can be up to 1/3 lower than calculated using EPA's current test methods, even though these EPA estimates are already adjusted downward 22% for highway and 10% for city. They believe that "more accurate estimates of fuel economy would benefit both consumers and those involved in setting national energy policy" [69]. In short, while current fuel economy estimates provided by EPA are useful in selecting one vehicle over another on a relative scale, they may understate the actual magnitude of fuel consumption, and by consequence, they may also understate the benefits of sustainable design strategies for the automobile.

As discussed above, quantitative modeling of technological performance and emissions can allow design options to be compared with sustainable design targets at the product concept level. Once this capability is achieved, it is necessary for sustainable design to be seamlessly integrated into traditional design processes. For example, research in [70] describes the integration of environmental variables and targets into an engineering design process using a quality function deployment approach. Within such a framework, it becomes possible to evaluate trade-offs between cost, functional performance, and environmental emissions. While it has been shown that such trade-offs can be established on a quantitative basis, a quantitative prediction of how sustainable design attributes might impact market performance is much harder to achieve in the analysis, and has not traditionally been considered as part of the design process.

Section 5 describes how mathematical models of consumer preference can be utilized within a decision-making framework to understand the relationship between sustainable design attributes and market performance. As a lead-up to this theoretical treatment, the next section describes empirical observations of sustainability attributes for the case of mobile phone production, use, and remanufacturing. The case study emphasizes the complexity associated with simultaneously balancing the economic, environmental, and societal implications of technological decisions, as well as the challenge of developing metrics for sustainable design.

4. CASE STUDY: SUSTAINABILITY CHARACTERISTICS OF MOBILE PHONES[1]

In 2002, Original Equipment Manufacturers (OEMs) sold over 420 million mobile telephones worldwide [71]. By 2005, it has been estimated that the number of discarded mobile phones will grow to more than 500 million [72], providing the stockpile necessary for the continued acceleration of mobile phone reuse and remanufacturing (or "re-marketing") activites. Currently, third party re-marketers of mobile phones are making significant profits from reselling mobile phones in emerging markets. *But is remanufacturing of mobile phones consistent with the goals of sustainable design?*

This section describes the synthesis of empirical research related to the economic, environmental, and societal aspects of mobile phone production, use, reuse, and remanufacturing. The research on economic and societal aspects is largely literature based, while also including significant input from personal communications with parties currently engaged in remarketing mobile phones. The research on environmental aspects is largely LCA based, drawing from direct observation of mobile phone production and remanufacturing activities, as well as the literature.

4.1. Economic Characteristics of Mobile Phone Reuse and Remanufacturing

Mobile phone reuse and remanufacturing is currently economically attractive for a variety of reasons. First, mobile phones are, in advanced markets, not purely technological objects but trendy or stylistic objects, leading to rapid disposal rates and a large supply pool of functionally reusable phones. Currently, only third party "remarketers" are involved with the reuse-oriented treatment of obsolete phones, serving a market estimated to represent less than 1% of the annual OEM market share [74,75]. A scan of clearinghouse websites such as Ebay also indicates a large but informal activity in discarded mobile phone re-sale. According to a major mobile phone re-marketer in the US, 2003 sales of discarded mobile phones were expected to reach 4 million. For that company, processing of discarded mobile phones follows Fig. 7, with about a 90/10 distribution between direct phone re-sale and remanufacturing operations for the over 300 phone models claimed to be profitable to resell.

At first, handset OEMs may consider third party remarketing as a threat to their market share. However, taking into account that the majority of remarketed handset users are first-time customers, originally not able to afford to mobile telephony, but tending to change to new handsets later on, market shares could be expected to increase in medium-term. In fact it has been shown in [76] that flourishing second-hand sales can lead to accelerated sales of virgin product. Obviously, remanufacturing conducted by handset OEMs themselves carries the potential for increased process efficiency relative to the operations of third parties, due to reduced technical and logistical barriers. Especially for the European market, where WEEE makes handset OEMs responsible for take-back and end-of-life treatment of phones by 2006, reuse and remanufacturing with OEM participation would have economic and technological advantages.

Driving the growth of remanufacturing operations is an increasing demand for mobile communication, especially in emerging markets (EMs). Despite their low purchasing power, sales of mobile phones (both new and reused) are growing rapidly. At present, the majority of

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[1] The results described in this section are derived from research conducted between the Technical University Berlin (TUB) and The University of Michigan (UM). The TUB participants included Professor Guenther Seliger, Ph.D. Candidates Bahadir Basdere and Marco Zettl, and M.S. graduate Aviroot Prasitnarit. The UM participants included Professor Steven J. Skerlos, Ph.D. pre-candidate W. Ross Morrow, and M.S. graduate Aaron Hula.

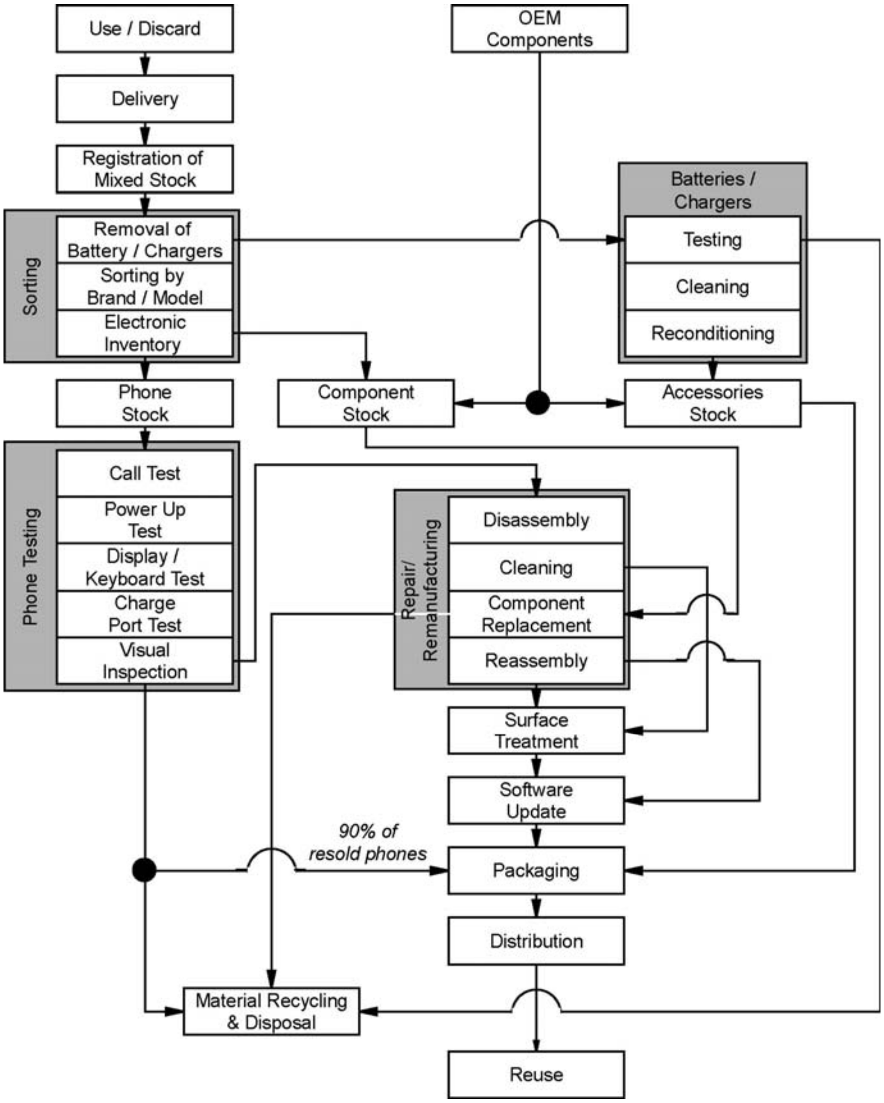

Fig. 7. Remanufacturing process flow diagram for the organizational re-marketing of discarded phones

remarketed phones are distributed to EMs in Africa and South America. Distributing these mobile phones in developed markets (DMs) would offer some potential for profits also, although the bulk of sales currently exist in EMs. Interestingly, it has been found that the attractiveness of the second-hand mobile phone market is rising in DMs, especially in European countries such as Germany. Supported by recent changes in legislation, such as the new warranty law which grants customers a one to two year warranty for used products purchased, there is impending competition of remarketed mobile phones with new ones, creating real, albeit slight, competition for OEM market share.

4.2 Environmental Characteristics of Mobile Phone Production and Reuse

It is widely known that mobile phones have a potentially hazardous end-of-life (EoL) profile: landfilled or incinerated mobile phones create the potential for environmental release of heavy metals or halocarbon materials from batteries, printed wiring boards (PWBs), liquid crystal displays, plastic housings, wiring, etc. Over the past few years, OEMs have been particularly active in pursuing environmental improvements, which has resulted in a number of life-cycle investigations related to mobile phones. For example, the Ericsson 2001

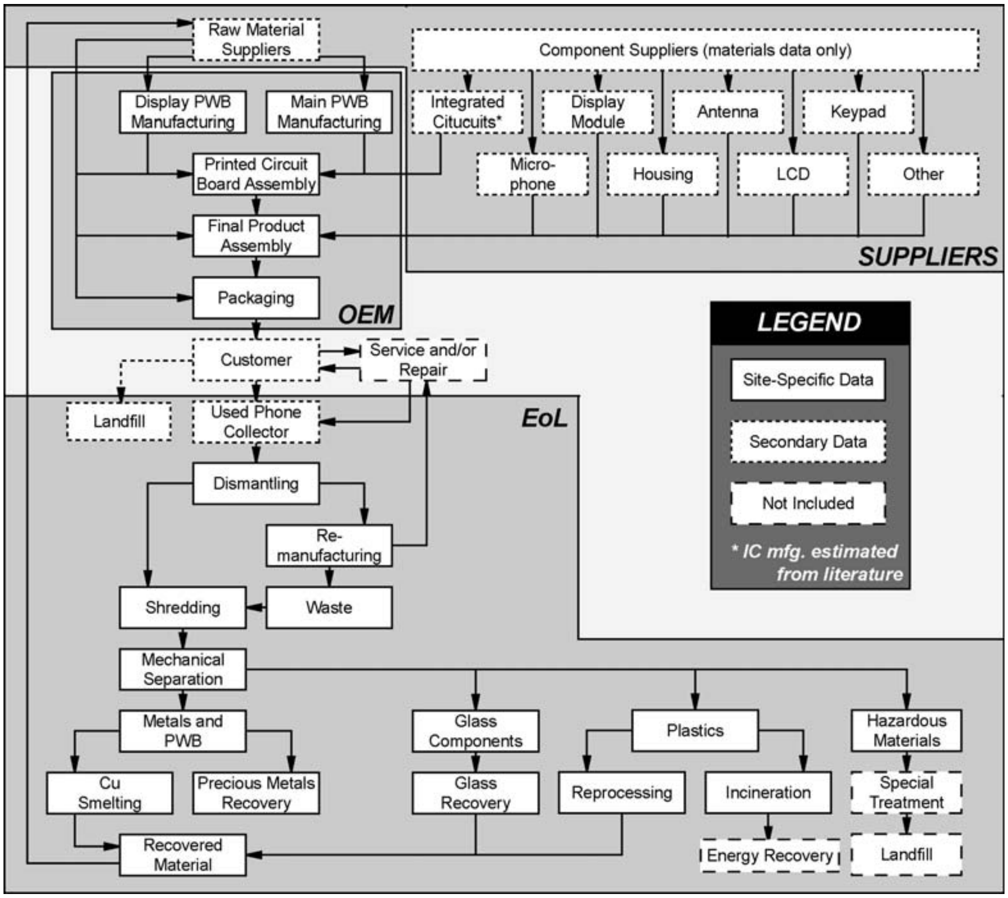

Fig. 8. Boundaries considered in mobile phone life cycle inventory of [79].

Sustainability Report claims that mobile phone production accounted for 10% of CO_2 releases for the company that year [77]. In [78], an LCA of the Phillips Fizz and Genie phones suggests that the manufacturing stage accounts for 77 - 79 % of the phones' life cycle environmental impact, as assessed using the Eco-Indicator 95 method.

Useful cross comparisons of publicly reported mobile phone LCAs such as these are not possible, not only due to different reporting units, but also due to the use of differing LCA boundary scopes, inventory categories, or use of aggregated impact metrics. For instance, while the Ericsson life cycle assessment included overhead activities such as travel and commuting, they did not include integrated circuit (IC) manufacturing [77]. IC manufacturing was explicitly included in the Philips study [78]. For mobile phones, such scope variations can be of particular importance, especially with respect to the inclusion of IC components. This is due to the large quantity of energy and emissions necessary to produce ICs [63], as well as the number of ICs utilized per phone (which can exceed 40).

4.2.1. Emissions Inventory: Mobile phone production

Prasitnarit (2003) describes an LCA of a mobile phone with the scope definition shown in Fig. 8. Total emissions and energy use over material acquisition, manufacturing, use, and EoL stages were estimated using a mixture of database information (primarily for material acquisition and EoL phases) and direct process measurement (primarily for manufacturing and use phases). The life cycle inventory of over 400 materials was included in the material acquisition phase. Only a small number of low concentration metals and chemicals in the

Table 1
Profiles of charger use as modeled in [80].

Profile	Charger Use Behavior
1	Charger always left in wall socket
2	Charger left in the socket while phone is charging overnight; removed during day
3	Charger is left in socket only for amount of time needed to recharge the battery

phone were not included [79]. In the investigation, the manufacturing process energy and emissions were directly measured. This included manufacturing of the display printed wiring board (PWB), the main PWB, chip shooting and placing, reflow, screen printing, assembly, and testing. IC-related energy and emissions were not directly measured, but were taken from the literature.

The results of the investigation showed that mobile phone production accounts for almost all of the non-energy related emissions in the life cycle. It was also found that the ICs, display module, and main PWB accounted for nearly three-quarters of the energy consumed in the production phase. Not including IC manufacturing, the production stage itself consumed approximately 250 MJ of energy, which was over two times the amount of energy consumed by the normal use of the mobile phone estimated over two years.

4.2.2. Emissions Inventory: Mobile phone use and remanufacturing

Use Phase. In [80], a model was developed to help understand the effect of mobile phone user habits on energy consumption. The model considered efficiency losses during charging, as well as in-call and standby power consumption. Table 1 lists the three representative use scenarios that were considered. As observed in Fig. 9, significant variation in energy consumption (expressed as CO_2 emissions in different electricity grid situations) arises due to variation in user behavior. Although this variation is large, even in the worst case the use phase energy consumption per year is below 20% of the energy consumed during phone production (without including ICs). Further, a "typical" charger profile (e.g., Profile #2) over one year has the same energy consumption as the production of only six of the "typical" ICs investigated in [73]. For reference, the phone considered in [78] had approximately 40 ICs.

Remanufacturing and Redistribution. Apart from a relatively small quantity of emissions from cleaning operations and packaging, emissions from remanufacturing processes and distribution are almost entirely associated with energy consumption associated with the use of electricity. In the remanufacturing operations listed in Fig. 7, the top three energy consuming activities are: sorting (driving a conveyor belt), battery testing and reconditioning (e.g., using a Cadex® C7000 series analyzer), and software updating (standard PC usage). The total amount of process energy consumption per remanufactured phone has been estimated to be between 0.8 and 1.6 MJ, with the variation almost completely dependent on the method and amount of battery testing and reconditioning, as over 90% of energy consumption during remanufacturing occurs in the testing, charging, and reconditioning of batteries [31].

After remanufacturing, shipping the restored mobile phones to emerging markets is typically accomplished by air transport owing to large distances (ranging from 5,000 – 13,000 km), relatively small volumes, and the urgency of transactions (due to volatility in the second-hand market). Especially for remanufacturing, this air transportation represents a dominant energy consumption and emissions activity. For example, the estimates presented in Table 2

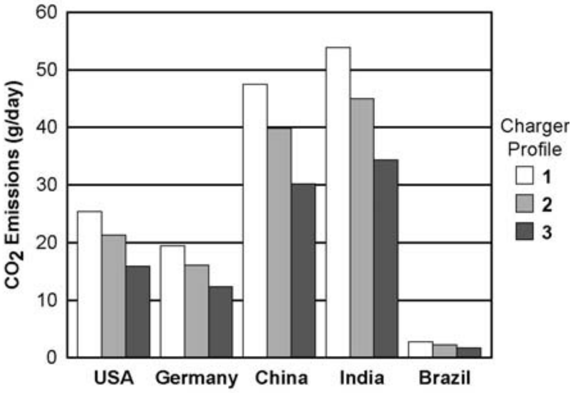

Fig. 9. CO_2 emissions per year for reused phone with different charging and electricity grid profiles

are based on an assumed mobile phone mass of 100 g, and a CO_2 release of 1110 g/ton*km for air travel according to [81]. It is seen that distribution to EMs can release an amount of CO_2 that is at least an order of magnitude higher than the remanufacturing process, but still insignificant relative to the production phase.

Once a mobile phone is resold, the environmental impact of its "second life" is likely to be greater than the impact of its "first life". In EMs such as those in South America, Central Asia, and Africa, there is not typically an infrastructure to properly handle toxic battery and circuit board materials that remain after the phones are discarded. Moreover, since remanufactured batteries generally hold less charge than new batteries (80 – 100 % of original capacity), higher energy consumption per unit service will occur in the second life. The associated environmental emissions may be compounded further where power generation and distribution systems of EMs are relatively inefficient and/or more dependent on polluting energy-generation technologies than in developed markets (DMs).

Consideration of electricity grid technology leads to Fig. 9, which highlights such situational factors among different use-profiles of remanufactured mobile phones (transmission line losses not included in the analysis). For instance, Fig. 9 shows that India and China are likely to have among the highest CO_2 emissions for remanufactured mobile phones on a per day basis. Brazil, on the other hand, has the lowest proportion of CO_2 emissions since most of its electricity is generated from hydroelectric sources. For Brazil, reduced environmental impacts due to less CO_2 release are traded off against the environmental impacts associated with the use of large amounts of hydroelectric power.

Another situational issue to be considered with the diffusion of remanufactured mobile phones to EMs is the heightened pressure that this creates for base stations and a supply chain for both auxiliary and replacement components. Compared to a remanufactured mobile phone sold in a market closer to purchase saturation, a mobile phone sold in an EM would create a disproportionately higher demand for new base stations and supply chains. In other words, a mobile phone in a DM generally creates less "infrastructure demand" than one in an EM.

Table 2
CO_2 release for air transportation between New York and target markets overseas [12].

EM	Distance	CO_2 Released	Percent of Remfg.	Equivalent Use Duration
	(km)	(g)	(%)	(days)
Bombay	12536	1400	1140	31
Rio de Janeiro	7757	900	740	360

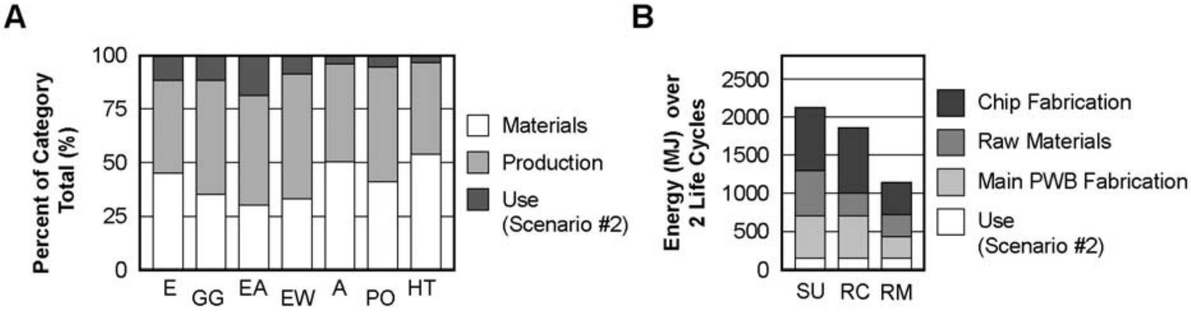

Fig. 10. (a) Relative contribution of life cycle stages for the mobile phone in [78]. E: energy consumption (MJ); GG: greenhouse gas emissions (kg CO_2 equivalent); EA: emissions to air (kg dichlorobenzene [DCB] equivalent); EW: emissions to water (kg DCB equivalent); A: total acidification potential (kg SO_2 equivalent); PO: total photochemical oxidant creation potential (kg ethane equivalent); HT: human toxicity potential (kg DCB equivalent). (b) Energy consumption comparison for two mobile phones under single use and disposal (SU), recycling (RC), and remanufacturing (RM) scenarios

4.2.3. Emissions Inventory: Summary

Fig. 10a illustrates a summary inventory profile for the mobile phone of [79], highlighting relative contributions of each life cycle stage. Fig. 10b compares the production, use, and EoL energy consumption for two of these phones under the following three scenarios: 1) both phones are manufactured and disposed at landfill without recycling or remanufacturing, 2) both phones are manufactured and completely recycled (even though 100% recycling is neither economically nor technically feasible), and 3) one phone is manufactured as-new, and the other identical phone is restored as-new from a discarded phone of the same model. Perhaps unsurprisingly, it is evident from Fig. 10b that a remanufacturing pathway has by far the least energy consumption. This is because the remanufacturing pathway, unlike recycling, avoids repeating manufacturing steps with characteristically high energy consumption and environmental emissions.

While these results are encouraging for remanufacturing, it should be noted that reduced environmental impact is only achieved if the remanufactured phone replaces the production of a new one. However, the vast majority of remanufactured mobile phone customers are first-time users in EMs, for whom the low cost of the remanufactured mobile phones serves as a conduit for entry into the market. Consequently, new use-phase, transportation, and end-of-life environmental impacts are created by remanufacturing where they did not exist before, adding to the overall environmental impact of the mobile phone industry. *The mobile phone example therefore highlights a disconnect between realizing the narrow goal of remanufacturing, and achieving the broader goal of lowering global environmental impact in the context of sustainability*. Currently, in the case of mobile phones, remanufacturing is creating new users and is increasing environmental impact without significantly reducing the production of new phones. Since the environmental impact of the cell phone industry is currently increasing due to the cell phone remanufacturing activity, it must be asked whether cell phone remanufacturing is consistent with the goals of sustainable design. For this reason, the societal dimension of cell phone remanufacturing is explored in Section 4.3.

4.3. Societal Characteristics of Mobile Phone Use in EMs

The importance of telephony as a requisite for economic development is well established. In fact, telephony has been described as a basic human need, which is implied by the fact that the function of the telephone (two-way conversation over distance) has not changed over the past 100 years [82]. In addition, it is widely recognized that modern economic development can only occur if there is a communications infrastructure to support it. Telecommunication is a critical part of a modern economy, along with a steady supply of electricity to power factories, good roads, rail systems, ports, and a steady financial system that can support the supply chain [83]. For this reason, and due to the close relationship between telecommunications, information systems, democracy, education, and job creation, the United Nations has placed a high priority on expanding communications systems within the poorest countries, such as those in Africa [84]. Although 80 percent of mobile phones are currently found in the more developed nations, the 1990s saw the number of subscribers in EMs grow faster than anywhere else [84]. The rapid expansion of mobile phone use in EMs is largely due to the fact that a mobile phone network can be up and running much more quickly and inexpensively than a fixed one.

4.3.1. Anecdotal evidence of mobile phone benefits in EMs

There exist a number of examples which highlight the role of mobile phones in improving lives for individuals living in EMs. For example, groups of small farmers in remote areas of Côte d'Ivoire share mobile phones so that they can follow hourly fluctuations in coffee and cocoa prices. This means that they can choose the moment to sell their crops when world prices are most advantageous to them. A few years ago, they could only have found out about market trends by applying to an office in the capital, Abidjan. Even then their deal-making was based on information from buyers, which was not always reliable [85].

A study conducted by Bayes (2001) observed the effects of mobile phones on rural villages in Bangladesh [86]. Bayes' study found that the introduction of mobile phone services led to improved law enforcement, communication during natural disasters, and the ability to call doctors for health-related information. In addition, the phones helped families keep in touch with relatives living far away, strengthening family bonds. The study also described positive effects of mobile phones with respect to the empowerment of women, and suggested that the services from mobile phones can most greatly benefit poor members of the community. These examples, while not discussing the potential negative impacts of mobile phones on developing societies, provide some of the context and justification for their rapid diffusion into developing countries.

4.3.2. Quantitative metrics of mobile phone societal impacts

Although the incorporation of economic and environmental metrics with metrics for societal development has been recognized as a critical need in sustainability evaluation and life cycle assessment [87,88], quantifying the benefits of expanding mobile phone utilization in EMs remains difficult. Thus far, societal indicators have not been incorporated into decision-making frameworks because, even more so than environmental metrics, societal impact metrics are subjective, confounded with other causal variables, and situation-dependent [88]. However, it is also generally agreed that subjective indicators are needed in societal policymaking because objective indicators only provide part of the information needed to understand the decision context [89].

To quantify if and to what extent expanded mobile phone use might foster accelerated societal development, one can begin by analyzing the statistics of the United Nations

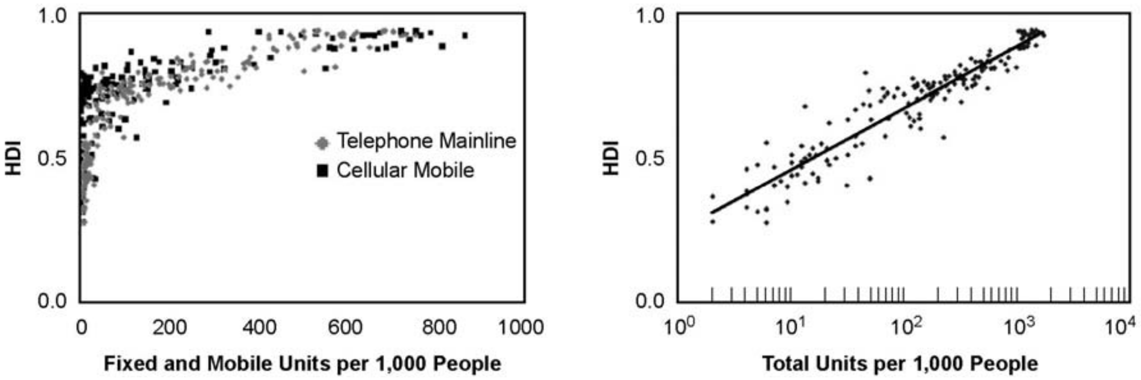

Fig. 11. (a) Human Development Index (HDI) vs. number of mobile/fixed line phones per 1000 people based on data from [90]. (b) Semi-log plot of HDI versus total teledensity based on [89].

Development Programme (UNDP). The annual UNDP Human Development Report provides measurements of various indicators of progress in specific categories under six main areas. Under the category of "Technology: Diffusion and Creation" there are estimates of the number of fixed telephone lines and mobile subscribers per 1000 people for numerous countries that can be cross-compared with the human development index (HDI) reported by the UNDP. Such an analysis shows that countries rated with a "high" HDI (e.g., Sweden, USA, Singapore) had an average of 556 fixed telephone lines and 487 mobile users per 1000 people, while countries with a "low" HDI (e.g., Nigeria, Ethiopia, Bangladesh) had an average of 8 telephone lines and 3 mobile users per 1000 people. The effect of telephony on development is not explored in the report, but the correlation between telephone access and development can be clearly seen [90].

A plot of HDI versus number of fixed and mobile phone users per 1000 people is shown in Fig. 11 [90]. A logarithmic-type relationship can be seen: lower teledensity exists in countries with lower HDIs, and higher teledensities in countries with higher HDIs. The slope of this curve decreases significantly as teledensity increases. Put simply, expanding phone access in less developed countries has a higher positive correlation with HDI than expanding phone access in more developed countries, which has little correlation with HDI.

4.3.3. Situational differences in the ethics of pollution

For cases such as cell telephone remanufacturing where net environmental impact is increasing, but where societal development benefits exist, it seems appropriate to factor-in the potential for increased HDI (or other similar-intending metrics) in the context evaluating sustainability. For instance, the global warming potential (GWP) associated with providing 50MJ of electricity to power a mobile phone in an EM for a year might be compared with the equivalent GWP of an activity that might be less correlated with increasing HDI (e.g., watching a high-end, 190W flat screen television for 73 hours). Is one GWP emission more appropriate or acceptable than the other? If so, how can such ethical metrics be built into LCA frameworks? Moreover, what are the ethical implications of making discarded mobile phones available to countries not able to handle the waste, and who have not been offered technical assistance or financial aid in this regard?

As yet, the state of the art is unprepared to discuss such questions quantitatively in the context of sustainable engineering. Discussion of such issues has recently begun to appear in the literature (e.g., [91]), and will be important to consider with respect to decision-making for sustainable development. Correlative analysis between HDI and expanded use and consumption can help in such analyses, but naturally these analyses need to be accompanied by research aimed at understanding if such correlations between expanded access to telephony (e.g., through expansion of mobile phone use) and HDI are truly causal in nature.

In summary, with respect to the balance of sustainability factors, the recent growth of mobile phone reuse and remanufacturing is a case where the economic and societal benefits are positive, while the short-term environmental impact is negative due to increased energy consumption and the potential for toxics release at EoL associated with the currently observed flux of second-hand mobile phones toward developing countries. Although growing concern over the latter issue is being voiced in the press [72], it remains to be seen whether developed countries exporting discarded electronics will take steps to limit the EoL impact of electronic waste in developing countries. Even if such action were to be taken, a new discussion would begin regarding how to minimize toxics release from electronic waste at minimum cost to contributing governments and international organizations. In short, the question would turn to one of maximizing the "eco-efficiency" of the environmentally targeted intervention.

5. CASE STUDY: ECO-EFFICIENCY, PUBLIC POLICY, & VEHICLE DESIGN[2]

The core concept of eco-efficiency is to maximize the societal and environmental benefits of a design decision or policy, while minimizing its economic cost and negative impact on individual consumer preferences. The need for developing eco-efficient government policies arises when 1) the economic drivers described in Section 2 are not strong enough to achieve the self-assembly of environmentally conscious actions in the marketplace (e.g., environmentally conscious disposal of electronic waste), or 2) if a societal decision-making process such as described in Section 3 concludes that the environmental or societal consequences of a particular activity are too large to be considered acceptable (e.g., the consumption of gasoline by automobiles). In this section, we consider two basic questions related to the eco-efficiency of government policies: 1) What are the impacts of environmentally conscious policy alternatives on engineering design and business decisions, and 2) how can the relative eco-efficiencies of sustainable design policies be quantified? To highlight how such questions can be addressed from a mathematical modeling perspective, we consider the case of automotive fuel economy and emissions.

In recent years, the environmental burden created by automotive emissions has been increasing in the United States due to falling average fuel economy and an increase in total vehicle miles traveled [92]. Reversing this trend will require a balance between reducing vehicle emissions, meeting consumer mobility demands and preferences, and minimizing added vehicle costs (since alternatives to gasoline engines, such as diesel, hybrid, fuel cell, and electric systems are currently more expensive to manufacture than traditional gasoline systems). Government policies can provide incentives to bring these alternative choices into the market, but the problem of quantifying the impact of specific government policies on engineering design and business decisions is as yet not well-studied.

In the development by Michalek et al. [93] that is summarized in this section, the paradigm of Fig. 12 is applied to quantify the impact of fuel economy and emission policies on design decisions of competing automotive companies. The links between engineering and

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[2] This section summarizes research conducted as part of the Antilium project (http://antilum.umich.edu) at The University of Michigan. The research was performed by Postdoctoral Research Fellow Jeremy Michalek and Professors Panos Y. Papalambros and Steven J. Skerlos. The research is described in detail in Michalek et al., 2004 [93].

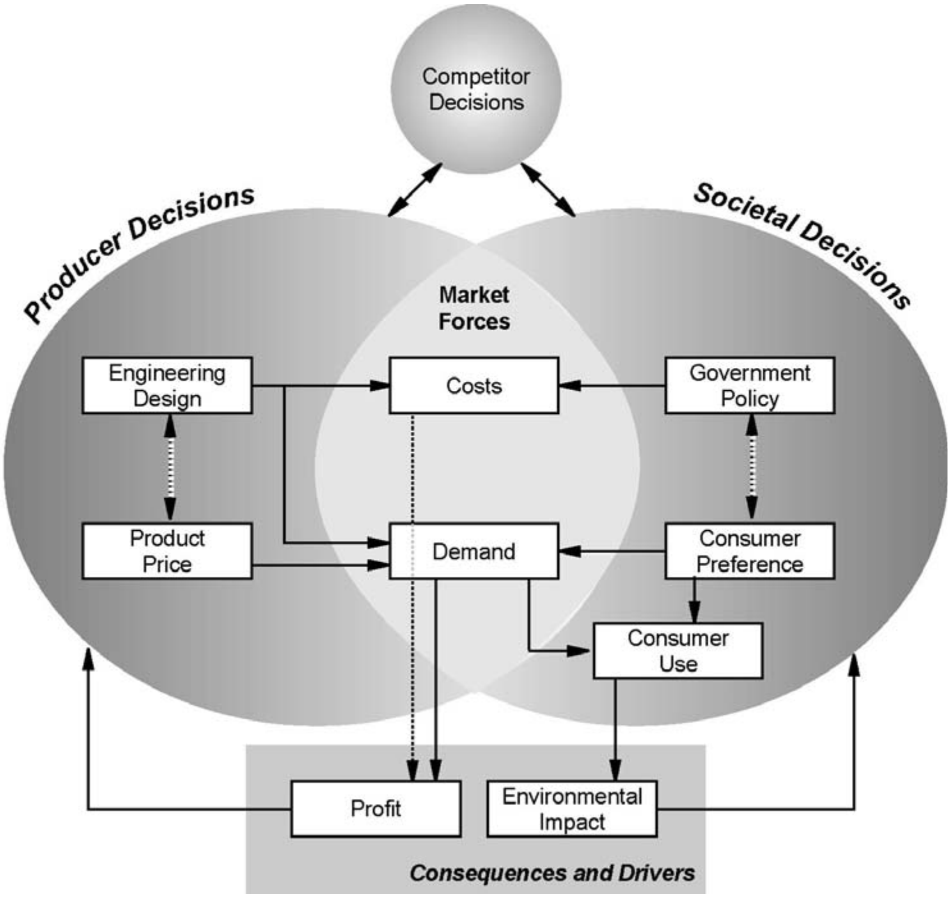

Fig. 12. Conceptual model of the interaction between producer, consumer, and public policy decisions in the market, along with their relationship to engineering design and environmental impact.

business decisions, including models of cost and demand, are at the core of the investigation. Each of these considerations is represented by a separate analysis model, and their interactions are captured within an integrated design decision model. By performing a series of optimization routines with respect to the local perspective of each producer, one can explore the effects that vehicle emission policies have on consumers, manufacturers, and the design decisions that a particular policy encourages.

Section 5.1 provides a conceptual overview of a basic modeling paradigm which intends to capture all of these factors within the context of a market simulation. Section 5.2 discusses specific mathematical models that were developed to analyze the impact of environmental policies on design decisions, with particular attention paid to the strengths and weaknesses of individual models used in the market simulation. Section 5.3 reviews the results of the modeling approach and provides a discussion regarding the calculation of eco-efficiency.

5.1. Quantitative Models of Economic and Environmental Design Characteristics

Fig. 12 illustrates the interplay of engineering design decisions, cost drivers, demand forces, and government policy in determining the environmental impact of a consumer product. Ultimately, the engineering design determines the overall cost and environmental characteristics of the product, as well as the extent to which consumers demand the product. In addition, business decisions such as price and production volume have a major influence on both the costs and revenue generated by a specific design. Government policy, as mentioned in Section 3, also plays a role in influencing design by restricting the feasible space of options and by changing producer cost structures through penalties and incentives.

Consumer preference is the key driver for the revenue generated by a specific design, while also playing a major role in determining environmental impact through the way in which products are used. In the automobile case, variability in environmental impact caused by consumers arises mostly due to differences in fuel economy during highway versus city driving, as well as distances traveled. Auxiliary functions such as the use of air conditioning also have a substantial, but situational, influence on automotive fuel consumption and emissions.

Although Fig. 12 is intuitive and conceptually simple, the development of a meaningful model for the system at an appropriate level of detail is complex. For some of the sub-models, such as the calculation of manufacturing cost, the model forms can be simple, but necessary data to support them may be difficult to obtain. In other cases, such as the modeling of demand, commonly utilized model forms may be straightforward, yet lacking of a cause-and-effect meaning, particularly when based on observed choice data from the market. Moreover, preference for a specific product is not only a function of performance characteristics, which vary in relative importance to consumers over time, but also of price, which is perceived differently as a function of time-dependent economic conditions. Also, data for demand models as a function of the product characteristics relevant for a specific study can be difficult to find and expensive to collect, and due to the dynamics of consumer preference as a social phenomenon, such models are difficult to validate in the traditional scientific sense, since the market cannot be manipulated in the context of a controlled experiment. In the case of environmental and health impact, inventory data may be lacking, and the impacts of specific factors may be so confounded by other variables that casual relationships may require decades to establish.

Predicting vehicle performance characteristics such as acceleration, fuel economy, and emissions as a function of detailed vehicle design decisions is also challenging. Vehicle performance must be considered during sustainable design, as it is a key parameter in influencing consumer preference that, in turn, determines which products are bought and how they are used. While the complex chemistry of combustion can be modeled from fundamental scientific principles, such models are too complicated to be run over a full driving cycle and may not be able to capture heterogeneities in temperature, pressure, and airflow in the engine that have a major influence on the quantity and nature of vehicle emissions. Empirical measurements of automotive emissions are widely available, but are only useful to engineering design when put into a model context as a function of design variables.

The next section describes how the separate analysis models of Fig. 12 can be developed and integrated within the context of game theory towards an analysis of how government fuel economy policies impact engineering design decisions in a competitive market. We consider that each producing firm chooses engineering design decisions, production volume, and selling price for each vehicle in its product line with the aim of maximizing profit. We also consider that the engineering design decisions of each producer not only impact the decisions of competitors, but the decisions of competitors also impact the decisions of the producer. Furthermore, government penalties are imposed on specific vehicles proportional to the quantity of emissions produced or fuel economy attained. Individual consumers in the market choose among alternatives by maximizing benefit (utility) to themselves, considering their own preferences as captured in the model. By considering the self-interested decisions of producers and consumers in the market, based upon real observations of the marketplace, the potential success of environmentally conscious policymaking can be evaluated.

5.2 Overview of Specific Analysis Models and Optimization Framework

5.2.1. Profit model

To start, each producer k decides on a set of products $\mathcal{J}_k$ to produce including design decisions, prices, and production volumes. Specification of the design topology τ_j (engine type, diesel or gasoline) and design variables $\mathbf{x}_j$ (engine size and final drive ratio) determine the product characteristics $\mathbf{z}_j$ (fuel consumption and acceleration) that are observed by the consumer. Vehicle topology τ_j, design variables x_j, and production volume V_j of each product in $\mathcal{J}_k$ together determine the total cost c_k to producer k. Consumers make purchasing choices among the set of all products $\mathcal{J}=\bigcup_k \mathcal{J}_k$ based on the product characteristics $\mathbf{z}_j$ and price p_j of each product, resulting in an overall demand q_j for each product j calculated by the demand model. Each producer k attempts to maximize its profit Π_k (defined as revenue minus cost) by making the best possible design, pricing, and production decisions according to Eq. 1:

$$\begin{aligned}&\text{maximize } \Pi_k = \left(\sum_{j\in\mathcal{J}_k} q_j p_j\right) - c_k \\ &\text{with respect to } \left\{\tau_j, \mathbf{x}_j, p_j\right\} \forall j \in \mathcal{J}_k \\ &\text{subject to engineering constraints}\end{aligned} \tag{1}$$

5.2.2. Engineering performance model

In the Michalek et al. (2004) study, the scope is limited to the small vehicle market segment and the following variables: 1) engine type τ, either a gasoline or diesel, 2) engine size x_1, taken as a scaling of the baseline engine size ranging from 0.75 to 1.50, and 3) the final drive ratio x_2, taken in the range of 0.2 to 1.3. Each producer in the market selects the engine type, the engine size, and the final drive ratio on the basis of profit maximization. Using the engineering model ADVISOR [94], these producer decisions are mapped to product characteristics $\mathbf{z}$, upon which consumer purchasing decisions are based. In this case, it is assumed that the relevant performance criteria $\mathbf{z}$ consist of the vehicle gas mileage z_1 (in mpg) and the time for the vehicle to accelerate from 0 to 60 mph z_2 (in seconds). It is also assumed that vehicles only differ by engine design: Specifically, the default small car vehicle parameters in ADVISOR are used in all simulations (based on the 1994 Saturn SL1), and only the engine variables $\{\tau, x_1, x_2\}$ are changed. The EPA Federal Test Procedure (FTP-75) driving cycle is used to compute the performance and fuel economy characteristics for all vehicle simulations.

5.2.3. Consumer demand model

The consumer demand model is based on discrete choice analysis (DCA), which presumes that consumers make purchasing decisions on the basis of the *utility* value of each product option. Utility u is measured in terms of an observable deterministic component v, which is taken to be a function of the product characteristics $\{z_1, z_2\}$, and a stochastic error component ε. The probability P_j of choosing a particular product j from the set $\mathcal{J}$ is calculated as the probability that product j has a higher utility value than all alternatives,

$$P_j = \Pr\left(v_j + \varepsilon_j \geq v_{j'} + \varepsilon_{j'}; \forall j' \in \mathcal{J}\right) \tag{2}$$

Various probabilistic choice models follow the DCA approach, including the widely used logit [95] and probit [96] models. The logit model, which was originally developed by

McFadden to study transportation choices, is utilized here and has been used extensively in the marketing literature. Only recently have logit models begun to be applied to engineering design problems [97].

The logit model assumes that the unobserved error component of utility ε is independently and identically distributed for each alternative, and that ε follows the double exponential distribution (i.e., $\Pr[\varepsilon < \alpha] = \exp[-\exp(-\alpha)]$). Assuming the double exponential distribution for ε terms in Eq. 2, the probability P_j of choosing alternative j from the set $\mathcal{J}$ takes the form,

$$P_j = \frac{e^{v_j}}{\sum\limits_{j' \in \mathcal{J}} e^{v_{j'}}}, \tag{3}$$

where each utility function v_j depends on the characteristics $\mathbf{z}_j$ and the price p_j of design j. Given a functional form for $v_j(\mathbf{z}_j,p_j)$ and observed choice data, a model fitting procedure is performed to arrive at $v_j(\mathbf{z}_j,p_j)$. Given the empirical nature of $v_j(\mathbf{z}_j,p_j)$, the model must be developed and interpreted carefully.

In the Michalek et al. (2004) investigation, the utility model developed by Boyd and Mellman is used [98]. This model, originally developed using vehicle purchase data from 1977, was found to be the best logit model available in the public literature that included engineering design variables and an appropriate level of detail for the study. Although several other variables are included in the demand model (e.g., vehicle style, noise, and reliability), these variables are assumed equal across vehicles in the Michalek et al. (2004) investigation [93]. The utility equation developed by Boyd and Mellman is,

$$v_j = \beta_1 p_j + \beta_2 \left(\frac{100}{z_{1j}} \right) + \beta_3 \left(\frac{60}{z_{2j}} \right), \tag{4}$$

where β_1=-2.86·10^{-4}, β_2=-0.339, β_3=0.375, p_j is the price of vehicle j, z_{1j} is the gas mileage of vehicle j in mpg, and z_{2j} is the 0-60 mph acceleration time of vehicle j in seconds [98].

In [92], Eq. 4 is applied to the small car sub-market (assumed population s to be 1.57 million people based on [99]), with the recognition that this could introduce error since the equation was developed based on the entire car market. Using the logit model, the demand q_j for product j is,

$$q_j = sP_j = s\frac{e^{v_j}}{\sum\limits_{j' \in \mathcal{J}} e^{v_{j'}}}, \tag{5}$$

where v_j is defined by Eq. 4.

While the Boyd and Mellman demand model is adequate for a preliminary analysis, it does introduce several sources of error that highlight the need for additional research:

- The model is fit to purchase data from 1977-1978.
- The model utilizes purchase data only: Consumers who choose not to purchase vehicles were not studied. Thus, the model can only predict *which* vehicles consumers will purchase, not *whether* they will purchase. The size of the purchasing population is treated as fixed, independent of vehicle prices (i.e., there is no outside good).
- The model is an aggregate model, and therefore it does not account for different segments or consumer groups.

- The use of the logit model carries with it a property called *independence from irrelevant alternatives* (IIA), which implies that as one product's market share increases, the shares of all competitors are reduced in equal proportion [100]. For example, a model with the IIA property might predict that BMW competes as equally with Mercedes as with Chevrolet. In reality, different vehicles attract different kinds of consumers, and competition is not equal. In this investigation, predictive limitations of the IIA property were mitigated since the model is applied only to the small car market (a relatively homogeneous market) rather than to the entire spectrum of vehicles.

5.2.4. Cost model

The total cost to manufacture a vehicle c^{P} is considered to be the sum of two parts: the investment cost to set up the production line c^{I} and the variable cost per vehicle produced c^{V}. The variable cost is composed of the engine cost c^{E} and the cost to manufacture the rest of the vehicle c^{B}, so that $c^{\mathrm{V}} = c^{\mathrm{B}} + c^{\mathrm{E}}$. The cost to manufacture q units of a vehicle with engine type τ and design variables $\mathbf{x}$ is then calculated as:

$$c^{\mathrm{P}}(\tau,\mathbf{x}) = c^{\mathrm{I}} + qc^{\mathrm{V}}(\tau,\mathbf{x}) = c^{\mathrm{I}} + q\left(c^{\mathrm{B}} + c^{\mathrm{E}}(\tau,\mathbf{x})\right) \quad (6)$$

In Eq. 6, it is assumed that c^{B} = \$7500 and c^{I} = \$550 million per vehicle design. c^{B} is estimated based on data for the Ford Taurus [101], and c^{I} is based on an average of two new product lines described in the literature [102]. c^{E} is determined based on regression of established engine cost data for diesel (compression ignition) and gasoline (spark ignition) engines. Finally, the total cost to producer k is calculated as the sum of the production cost of each vehicle in k's product line and the regulatory cost c^{R}:

$$c_k = \left(\sum_{j \in \mathcal{J}_k} c_j^{\mathrm{P}}\right) + c_k^{\mathrm{R}} \quad (7)$$

.

5.2.5. Environmental policy models

Three specific producer penalty scenarios are considered here: CAFE (corporate average fuel economy) standards, a hypothetical use-phase CO_2 emission tax, and a hypothetical quota system for producing a minimum percentage of diesel vehicles. To start, the current CAFE standard for cars (z_{CAFE} = 27.5 mpg) is used, and two different penalty charges are explored. The first penalty charge is the current standard: ρ = \$55 per vehicle per mpg under the limit, and the second is a hypothetical double-penalty scenario. The total regulation cost c^{R} incurred by design j is therefore $\rho q_j(z_{\mathrm{CAFE}} - z_{1j})$, where ρ is the penalty, q_j is the number of vehicles of type j that are sold, and z_{1j} is the fuel economy of vehicle j. In this investigation only a single market segment is utilized even though CAFE applies to all passenger vehicle markets in which the producer operates.

A CO_2 valuation study from the literature [103] is utilized to estimate the economic cost to society associated with environmental damage caused by the release of a ton of carbon dioxide in the use-phase. A CO_2 tax per vehicle sold is calculated as $\upsilon d\alpha_M/z_1$, where υ is the dollar valuation of a ton of CO_2, d is the number of miles traveled in the vehicle's lifetime, α_M is the number of tons of CO_2 produced by combusting a gallon of fuel, and z_1 is the fuel economy of the vehicle. For this investigation, it is assumed that d = 150,000 miles, α_M is $9.94\cdot10^{-3}$ tons CO_2 per gallon for gasoline or $9.21\cdot10^{-3}$ tons CO_2 per gallon for diesel fuel, and υ is taken from [103] to range from \$2/ton to \$23/ton, with a median estimation of \$14/ton.

A quota regulation was also modeled to force alternative fuel vehicles into the market, as was attempted for electric vehicles in the California market [104]. Here, the quota policy is to levy a large penalty cost for violation of a minimum diesel to gasoline engine ratio quota. For the quota case, the regulation cost is modeled as:

$$c_k^{\mathrm{R}} = \max\left(0,\ \rho\left(q_k^{\mathrm{SI}} - \left(1-\phi\right)\left(q_k^{\mathrm{SI}} + q_k^{\mathrm{CI}}\right)\right)\right), \tag{8}$$

where ρ is the penalty per vehicle over quota (\$1000), ϕ is the minimum diesel percentage required by the quota (here, ϕ =0.40), $q^{\mathrm{SI}}{}_k$ is the total number of gasoline engines sold by producer *k*, and $q^{\mathrm{CI}}{}_k$ is the total number of diesel engines sold by producer *k*.

5.2.6. Simulated oligopoly competition.

Substituting Eqs. 2-8 into Eq. 1 yields the following profit objective for each producer:

$$\Pi_k = \left(\sum_{j\in\mathcal{J}_k} q_j p_j\right) - c_k = \left(\sum_{j\in\mathcal{J}_k} q_j\left(p_j - c_j^{\mathrm{V}}\right) - c^{\mathrm{I}}\right) - c_k^{\mathrm{R}}. \tag{9}$$

To account for competition in the design of vehicles subject to government regulations, game theory is used to find the market (Nash) equilibrium among competing producers. In game theory, a set of actions is in Nash equilibrium if, for each producer $k = 1,2,...,K$, given the actions of its rivals, the producer cannot increase its own profit by choosing an action other than its equilibrium action [105]. It is assumed that this market equilibrium point can provide a reasonable prediction of which designs manufacturers are driven to produce under various regulation scenarios, even though Nash equilibrium does not model preemptive competitive strategies by producers. In order to find the Nash equilibrium point for a set of *K* producers, the decision variables of each producer *k* are optimized to maximize the profit of that producer Π_k while holding the decisions of all other producers constant. This process is then iterated, optimizing all producers $k = 1,2,...,K$ in sequence until convergence, yielding the Nash equilibrium for *K* producers, where *K* is set to the largest value that yields positive profit for the producers. Additional details can be found in [93].

5.3. Results and Discussion

The results of the investigation are summarized in Table 3. For each regulation scenario, Table 3 lists the maximum number of producers *K* that yield a positive-profit Nash equilibrium and the market share per producer. Due to the use of an aggregate demand model, each producer makes the same decisions (i.e., produces the same designs) at market equilibrium, so Table 3 summarizes the decision variables, product characteristics, costs, and profits for a typical producer in each scenario.

It is found at equilibrium that each producer manufactures only a single design rather than a product line (except in the quota case) due to competition and the existence of substantial investment cost. This result may have been caused by factors such as neglecting the possibility of commonality among designs, and the use of an aggregate model for demand that ignores consumer heterogeneity. Table 3 also indicates that producers accrue equal profits in all regulation scenarios (except the quota case), and all incurred costs are passed to the consumers at equilibrium. This is because the demand model assumes a fixed car-buying population (there is no option not to buy) and does not consider the utility of outside goods.

Table 3
Model predictions yielded by market simulation under various policy scenarios

		Regulation Type							
		None	CO_2 Tax			CAFE	sCAFE	Quota	
			Low	Med.	High				
No. Producers (-)	K	10	10	10	10	10	10	5	
Market share (%)	q/s	10	10	10	10	10	10	11.9	8.1
Engine type (SI/CI)	M	SI	SI	SI	SI	SI	SI	SI	CI
Engine size (-)	$b_M x_1$	127.9	127.7	114.3	110.3	113.3	88.4	127.9	98.0
FD ratio (-)	x_2	1.28	1.28	1.28	1.27	1.28	1.29	1.28	0.88
Price ($)	p	12,886	13,031	13,719	14,259	13,058	12,772	13,372	16,083
Gas mileage (mpg)	z_1	20.2	20.3	21.8	22.4	22.0	25.5	20.2	29.8
Accel. Time (s)	z_2	7.46	7.46	7.93	8.10	7.97	9.29	7.46	7.84
Investment cost ($) [a]	c_1	550	550	550	550	550	550	550	550
Var. cost/vehicle ($)	c_2	9,001	8,999	8,878	8,844	8, 869	8,670	9,001	11,713
Reg. cost/vehicle ($)	c_R/q	0	147	956	1,530	304	217	0	0
Profit ($) [a]	$\prod$	60.5	60.5	60.5	60.5	60.5	60.5	276	6.5

[a] In millions of dollars.

The Michalek et al. (2004) study lists a number of important caveats that are useful to consider when using observation-based demand models as the basis for sustainable design analysis. For example, the demand model used here (Eq. 5) predicts a preference for vehicles with faster acceleration. Therefore, a vehicle that dramatically sacrifices unmeasured characteristics such as maximum speed for a slight improvement of acceleration time will be preferred according to the model. However, in practice a consumer would observe the unmeasured limitations during a road test, especially if the limitations are extreme. To account for this issue, each optimum vehicle design was tested to ensure the vehicle's ability to follow the standard FTP driving cycle and achieve a speed of at least 110mph on a flat road. All vehicle designs in the study passed this test [93]. The example highlights the importance of thoughtful modeling and of remaining cognizant of the limitations inherent to quantitative modeling approaches when simulating market competition.

5.3.1. Base case

The first case considered in [93] is the no regulation case ($c^R = 0$), which provides a baseline comparison for results obtained under different regulatory policies. In the absence of regulation, the model predicts ten producers in the small car market. Each producer manufactures a single vehicle with the design variables, product characteristics, and costs shown in Table 3. The resulting vehicle has a spark ignition engine with a fuel economy of 20.2 miles per gallon.

5.3.2. CAFE

Table 3 shows that the CAFE standard succeeds in increasing resulting vehicle design fuel economy to 22.0 mpg with roughly a half-second increase in 0-60 acceleration time and a $172 increase in vehicle price. The vehicle production cost drops by $132 per vehicle relative to the baseline case due to the smaller engine size; however, regulation costs are approximately $304 per vehicle. The CAFE standard is not attained at equilibrium because, unlike the real automobile market, the model does not capture intangible costs to companies who do not meet the CAFE standard. According to the model there is significant risk for a company that would attempt to produce a vehicle at 27.5 mpg, since its market share would be captured by more powerful, less fuel efficient competitor vehicles. This is a direct consequence of Eq. 4, which shows that consumers receive more utility from improvements in acceleration than they do from improvements in fuel economy. Making matters worse, for a given powertrain technology there is a negative trade-off between acceleration and fuel economy. In fact, for the gasoline engine favored by producers in the modeling results, a regression between z_1 and z_2 through the optimal designs in Table 3 (an estimate of the Pareto surface) yields,

$$z_2 = az_1^2 + bz_1 + c\,, \tag{10}$$

where a = 0.0159, b=-0.380, and c=8.64 ($R^2 = 0.99$).

Given that Eq. 10 expresses the relationship between fuel economy and acceleration, one can utilize Eq. 4 to calculate the change in vehicle price p that would be necessary to maintain constant utility to the consumer as the fuel economy z_1 is increased:

$$\frac{\partial p}{\partial z_1} = \frac{1}{\beta_1}\left(\frac{100\beta_2}{z_1^2} + \frac{60\beta_3\left(2az_1 + b\right)}{\left(az_1^2 + bz_1 + c\right)^2}\right) \tag{11}$$

Using the baseline engine from the no-regulation scenario as the evaluation point for Eq. 11, it is observed that the producer must *lower* the asking price by $136 per mpg increase in fuel economy to maintain equal utility to the consumer. This result provides a quantified expression of a trend currently observed the US: In many cases higher fuel economy actually brings with it reduced utility to individual consumers, a fact which is consistent with the observation that the average fuel economy of the US fleet is in decline. While a vast number of attributes are not considered in Eq. 11, Table 4 suggests that many desirable attributes, like acceleration, are negatively correlated with fuel economy.

5.3.3. "Strict" CAFE

As shown in Table 3, a fuel economy of 25.5 mpg is achieved by the strict CAFE standard, with a consumer vehicle price $114 less than the baseline case. The 0-60 acceleration time, however, is approximately 1.8 seconds higher. Perhaps surprisingly, this "strict" CAFE policy *reduces* regulatory costs for each producer. The reduction in regulatory costs follows from the fact that under the previous CAFE model (remembering that unmodeled "reputation and image" costs associated with CAFE violations are not captured), it is profitable for manufacturers to violate CAFE and pay the penalty in order to increase market share by selling powerful vehicles. However, when CAFE penalties are increased substantially, producers are forced to meet the standard in order to stay in business. In this case there is little danger of losing significant market share to a competitor who sells more powerful engines because none of the producers can afford to sell such engines; therefore all of the producers design smaller, less expensive engines. As such, the strict CAFE standard serves to remove risks associated with producing more fuel efficient vehicles by increasing the penalty for deviation from the CAFE standard 27.5 mpg. The desired eco-efficient result is achieved. Company profits are unaffected, vehicles are less expensive, and fuel economy is increased. However, as Table 4 indicates, consumers and society at large lose out on benefits associated with the engineering design characteristics that reduce fuel economy (e.g., acceleration). Here we see the trade-off between desirable attributes as perceived by individuals acting in the marketplace and individuals acting as members of society, with preferences for resource conservation, lower air pollution, and reduced life cycle carbon dioxide emissions, as expressed by their support for government regulations on fuel economy.

Table 4
Sample List of desirable automobile features and their relationship to lower fuel efficiency

Desirable Feature for Consumers	***Engineering Solution***	***Impact on Vehicle***
Engine Performance		
Quiet engine compartment	Add padding and deadener	Adds weight, material
Strong engine performance	Robust design, larger engine size	Adds weight, material
Passing power	Robust mounts, larger engine	Adds weight, material
Ride, Handling, and Braking		
Quick, safe braking	Robust brake design	Adds materials
Quiet ride during highway driving	Add padding and deadener	Adds materials
Quiet ride over harsh bumps	Add padding, better shocks	Adds materials
Power steering with minimal effort	Always-on fluid pump	More power, fluids used
Comfort and Convenience		
Front leg/foot room	Move engine, lengthen vehicle	Adds material
Headroom	Taller vehicle	Adds material
Side mirror controls	More electronics	Increased current draw
Well lit gauges and instruments	Add materials	Increased current draw
Ability to watch movies; internet	DVD player, WIFI, Bluetooth	Increased current draw
Navigation system	More electronics	Increased current draw
High-quality and powerful stereo	Powerful amplifier and speakers	Increased current draw
Heated/cooled seats	Add electronics and content	Increased current draw
Adjustable with controls	Add electronics and content	Increased current draw

5.3.4. Use-phase CO_2 emissions tax

It is seen in Table 3 that the use-phase CO_2 emissions tax is a considerably less eco-efficient policy than the CAFE standards. As the tax increases, producers do tend to design smaller, more fuel-efficient engines. However, the low valuation penalty ($2/ton) has little impact on fuel economy relative to the baseline case, with the only notable effect being added regulation costs that are passed on to consumers. The median valuation ($14/ton) has a larger impact, increasing fuel economy by 1.5 mpg, while the high valuation ($22/ton) adds only slight additional improvement in fuel economy relative to the median level (0.6 mpg) at a substantial added regulation cost per vehicle ($540) relative to the median tax level. The results suggest not only that the use-phase CO_2 emissions tax is less eco-efficient than CAFE standards, but that it is also dangerous as a policy approach: In this policy, vehicle prices increase, performance is lower, and fuel economy is increased only marginally. Therefore it would appear that there are no major winners with this policy. Based on these results, the policy might only be expected in practice to lower the demand and sales of vehicles relative to other modes of transportation or market segments not subject to the tax (e.g., in the current CAFE standards, more lax standards exist for light trucks relative to automobiles).

5.3.5. Quota

Although diesel engines have higher fuel economy than gasoline engines for equivalent acceleration performance, the model predicts that they are only manufactured under the quota policy (which bears similarity with the current situation in the US small car market). Additionally, the model predicts that under the quota policy only the minimum number of diesel vehicles is produced to exactly meet the standard. This is due to the higher costs associated with producing diesel engines, and the greater profitability of gasoline engines – prompting producers who are forced to sell diesel engines to also produce as many gasoline engines as allowed.

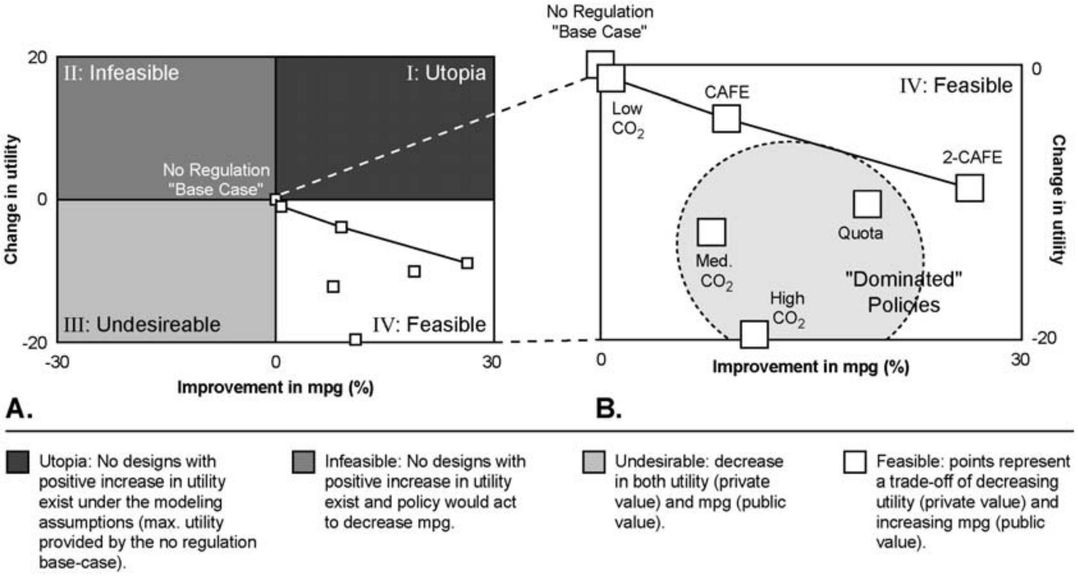

Fig. 13. Change in utility versus percentage change in fuel efficiency relative to baseline no-regulation case. (a) Definition of four quadrants in trade-off analysis. (b) Quadrant IV policies

The diesel engines produced in this scenario have a fuel economy 9.5 mpg higher than the baseline (no regulation) scenario. This is achieved at a substantial increase in diesel vehicle price relative to the baseline spark ignition vehicle ($3197). However, only a small reduction in vehicle acceleration relative to the no regulation case is observed (0.38 seconds). On the other hand, for a 150,000 mile life of the vehicle, the 29.8 mpg diesel vehicle consumes approximately 2400 fewer gallons of fuel, which means that at fuel prices above $1.33 per gallon, the initial cost of the vehicle is recovered over its life (not accounting for time-based discounting). This suggests that the quota policy is a reasonably eco-efficient approach, albeit one that could not spontaneously self-assemble in today's market place. Consistent with these observations, Sullivan et al. (2004) has recently suggested that the increased adoption of diesel engines into US vehicles is worthy of consideration for its potential to economically reduce CO_2 emissions produced by the vehicle fleet [106].

5.3.6. Analysis of eco-efficiency for selected policies

Eco-efficiency in the context of policy evaluation implies that a re-evaluation of the balance between private and public value is occurring with the aim of simultaneously minimizing environmental impact and the costs to society necessary to achieve the reduction in environmental impact. To capture this trade-off, Fig. 13 attempts to illustrate the performance of the individual policies as a function of both their public and their private values. On the vertical axis, the change in utility relative to the no-regulation case is given. Utility as calculated by Eq. 4 is utilized because it captures trade-offs between key attributes in a manner related to private value (although it does not express private value directly). On the horizontal axis, the change in fuel economy resulting from each policy relative to the no-regulation case is given (expressed as percentage). This relative improvement in fuel economy is the core intent of the policy, although like utility, it is not a direct expression of value. Ideally, the public and private value of the specific policies would be estimated directly, in which case plots such as Fig. 13 could provide a direct measure of eco-efficiency that could be compared across applications as necessary for the systematic development of sustainability targets across industries (see Section 3).

In Fig. 13b, the trade-off between public and private value is expressed by the set of non-dominated policies, which are the policies for which no alternative policies achieve higher fuel economy without sacrificing utility or vise versa. Given the definition of the origin as the reference no-regulation case, from which deviations in utility and fuel economy are defined, it is evident that policies in Quadrants II and III, which result in inferior fuel economy, would not be of interest to policymakers. Also, Quadrants I and II contain no feasible designs because the base no-regulation (free market) case results in the design with highest feasible (private) utility. In other words, consumers asked to choose their most preferred design while paying only the cost to manufacture that design will choose the same design as that produced by the unregulated market. Thus, viewing the set of non-dominated policies as a (Pareto) trade-off curve between private and public preferences, we see that the unregulated free market yields an extreme point on this tradeoff curve such that private preferences (utility) are valued exclusively over public preferences (mpg improvement), while non-dominated policy alternatives allow exploration of the best alternative policies as modeled in the investigation. It can be seen in Fig. 13b that the Pareto set of non-dominated policies include the no-regulation case, the low CO_2 taxation case (which is much the same as no-regulation case), the CAFE standard, and the Strict CAFE standard. Depending on the interpretation of "acceptable utility loss to consumers" (recall Section 3), one of these policies would be best under the modeling assumptions and scope of the model.

5.4. Remarks on Policy-Driven EcoDesign and Eco-Efficiency Analysis

This section has described an optimization framework to analyze the impact of fuel economy regulations on the design decisions made by automobile manufacturers from an eco-efficiency perspective. It was observed that government policies are necessary to provide incentives for producers to design alternative fuel vehicles (e.g., diesels) that cost more to produce. Without a regulatory standard, producers cannot afford to make smaller, less expensive, and more fuel efficient engines. Under the modeling assumptions, it is observed that some policies can result in cost savings for all parties (e.g., CAFE) and do not affect profitability within the market segment. On the other hand, certain regulations can also lead to higher costs, diminishing returns, and little environmental improvement (e.g., CO_2 tax).

Such results indicate that the cost-benefit characteristics of policy alternatives can be modeled in a realistic and quantitative way, and that a holistic integration of costs, performance, consumer preference, and competition can facilitate the selection of effective policies, while helping to determine how policy parameters should be set. Additional investigations that combine engineering, marketing, and policy models with models of changing consumer preferences and driving habits could be used to predict trends regarding the diffusion of alternative fuel vehicles into society, possibly avoiding costly investments in products that are unlikely to achieve wide acceptance, and helping to focus resources and incentives toward sustainable design solutions that will make the most impact.

6. SUMMARY AND CONCLUSIONS

The very need for sustainable design research implies that an imbalance exists between private value captured in the marketplace and its consequential impacts on societal and environmental systems. It also implies an imbalance between the incentives and inhibitors to sustainable design outlined in this chapter (Section 2). Specifically, the chapter has discussed six challenges to sustainable design for which academic research, performed in conjunction with industrial partners and governments, could have a major impact:

1. Understanding Incentives and Inhibitors to Sustainable Design
2. Establishing Targets, Metrics, and Strategies for Sustainable Design
3. Understanding Variability in Product-User Interactions
4. Evaluating Alternative Technologies for Sustainability Characteristics
5. Estimating the Market Value of Sustainable Design Attributes
6. Developing Market-Conscious Policies to Encourage Sustainable Design

When sustainable designs do not spontaneously self-assemble in the marketplace, corrective action is generally left as the responsibility of governments, who can either 1) create market conditions that allow sustainable designs to proliferate on their own, 2) restrict the feasible space of options available to designers, or 3) establish tangible sustainable design targets with which individual products must comply. Each of these approaches requires a profound understanding of the relationship between engineering design options, market costs and revenues, available alternative technologies, and societal and environmental impacts. Research needs in these areas have been outlined in Section 3.

Once sustainable design is defined in the context of a specific product, it is necessary to develop tools that facilitate the seamless incorporation of sustainability metrics into the design process. The development of appropriate metrics, and the establishment of trade-offs with other cost and performance aspects of the design were underlying themes of the case studies presented in this chapter. The first case study (Section 4) provided an overview of economic, environmental, and societal factors related to mobile telephone production, use, and remanufacturing. Empirical observations of current activities revealed the complexity associated with sustainability assessment, as well as the critical importance of considering the specific circumstances and drivers surrounding individual products, activities, or services that are being evaluated.

The second case study (Section 5) provided a quantitative framework for the evaluation of sustainable design policies related to automotive fuel economy. This case study demonstrated the possibility of capturing market forces, technology realities, and environmental considerations within a model suitable for policy evaluation. The complexity and data challenges involved with developing viable quantitative models were demonstrated. The necessary simplifications required in the model development made the conclusions most valuable in terms of their trends, and the realistic nature of these trends suggest that the mathematical approach developed here would be helpful to consider during the development of policies intending to encourage sustainable design.

We conclude this chapter by recalling from Fig. 1 the perspective of design as a flow from abstract societal values to products and services with impacts on the sustainability triangle. This flow is, at its root, influenced by the knowledge base of society as a whole. As evidenced by the change in attitude towards safety design over the past century, ethical systems are evolutionary in nature and can impact design processes positively. A similar change of heart and practice is needed in the sustainability realm. However, quantitatively measuring the sustainability of products, processes, and services is a very difficult task and will remain a primary focus of sustainable science and engineering for years to come. As the field matures, it will be necessary for researchers and practitioners alike to provide education to the general public, as well as to engineers, designers, and policymakers, in order to create the conditions necessary for sustainable design to flourish.

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