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A new methodology for evaluating sustainable product design performance with two-stage network data envelopment analysis

Chialin Chen [a,*], Joe Zhu [b,1], Jiun-Yu Yu [c,2], Hamid Noori [d,3]

[a] Queen's School of Business, Queen's University, Kingston, ON, Canada K7L 3N6
[b] School of Business, Worcester Polytechnic Institute, Worcester, MA 01609, USA
[c] Department of Business Administration, National Taiwan University, Taipei, Taiwan, ROC
[d] Laurier School of Business, Wilfrid Laurier University, Waterloo, ON, Canada N2L 3C5

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ABSTRACT

Sustainable product design has been considered as one of the most important practices for achieving sustainability. To improve the environmental performances of a product through product design, however, a firm often needs to deal with some difficult technical trade-offs between traditional and environmental attributes which require new design concepts and engineering specifications. In this paper, we propose a novel use of the two-stage network Data Envelopment Analysis (DEA) to evaluate sustainable product design performances. We conceptualize "design efficiency" as a key measurement of design performance in terms of how well multiple product specifications and attributes are combined in a product design that leads to lower environmental impacts or better environmental performances. A two-stage network DEA model is developed for sustainable design performance evaluation with an "industrial design module" and a "bio design module." To demonstrate the applications of our DEA-based methodology, we use data of key engineering specifications, product attributes, and emissions performances in the vehicle emissions testing database published by the US EPA to evaluate the sustainable design performances of different automobile manufacturers. Our test results show that sustainable design does not need to mean compromise between traditional and environmental attributes. Through addressing the interrelatedness of subsystems in product design, a firm can find the most efficient way to combine product specifications and attributes which leads to lower environmental impacts or better environmental performances. This paper contributes to the existing literature by developing a new research framework for evaluating sustainable design performances as well as by proposing an innovative application of the two-stage network DEA for finding the most eco-efficient way to achieve better environmental performances through product design.

1. Introduction

*In December 2007, the European Commission proposed the introduction of legally-binding fuel efficiency standards for new cars. The proposed law says that CO_2 limits should be differentiated according to the type of car and that the so-called "utility parameter" used to define the targets should be the car's weight. In simple terms the proposal says heavier cars should get easier (higher) CO_2 standards and lighter cars should get tougher (lower) ones (*European Federation for Transport and Environment, 2008*). Similarly, the US Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) are finalizing a set of fleet-wide average CO_2 emission standards where each vehicle has a different CO_2 emissions compliance target depending on its "footprint value" related to the size of the vehicle (*US EPA, 2010*).*

*In the 2008 CTI Symposium on Automotive Transmissions, Robert Lee, Chrysler's vice president of power train engineering whose company's has not introduced any hybrid electric vehicles (HEVs), argued that, while a portion of the car-buying public may try to ride out that storm in HEVs, which now get most of the popular attention in the debate about how to minimize fuel consumption, engineers can still improve the conventional vehicles, too, by scouring them for fuel-wasting losses. "Solving the fuel economy puzzle requires a total-vehicle solution," Lee said, emphasizing the interrelatedness of the various vehicle subsystems (*Design News, 2008*).*

Sustainable product design or, sometimes equivalently, design for the environment (DfE), is considered as one of the most

* Corresponding author. Tel.: +1 613 533 6982.
E-mail addresses: cchen@business.queensu.ca (C. Chen), jzhu@wpi.edu (J. Zhu), jyyu@ntu.edu.tw (J.-Y. Yu), hnoori@wlu.ca (H. Noori).
[1] Tel.: +1 508 831 5467.
[2] Tel.: +886 2 33661041.
[3] Tel.: +1 519 884 0710x2571.

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important practices for achieving sustainability. In recent years, however, there has been a fundamental shift in the ways which sustainable design performances are measured in both the public and private sectors, from emphasizing the absolute environmental performance to the eco-efficient design performance with carefully combined functional and environmental attributes (e.g., vehicle weight and fuel efficiency) in a product design (Ulrich and Eppinger, 2012), as exemplified in the above two cases of applications. In this paper, we conceptualize the novel notion of "design efficiency" for combining multiple subsystems in the design process, and propose a comprehensive research framework based on the two-stage network Data Envelopment Analysis (DEA) for sustainable design performance evaluation. The vehicle emissions testing database published by the US EPA (2009) will be used to demonstrate the applications of our proposed new methodology in both the public sector (for evaluating the sustainable design performances of different vehicle designs by automakers) and private sector (for identifying the most eco-efficient sustainable design choices).

Today sustainable product design has received significant attention from both the public and private sectors worldwide (Graedel and Allenby, 2009; Fiksel, 2009). According to the most recent Green Brand Survey (2010) of 9000 consumers in Australia, Brazil, China, France, Germany, India, the US, and UK, over 60% of consumers want to buy from environmentally responsible companies. While 72% of consumers still consider "offering good value" as an important criterion in making a purchasing decision, 50% of consumers also consider "environmental consciousness" as an important criterion. In response to the strong public interest in sustainable purchasing, various directives and regulations aimed to encourage sustainable design practices have been considered or imposed by governments around the world. For example, in order to reduce greenhouse gas emissions and to achieve national energy independence, US President Barack Obama has recently proposed a new and more stringent Corporate Average Fuel Economy (CAFE) Standard that ultimately requires an average fuel economy standard of 35.5 miles per gallon (MPG) in 2016, a jump from the current average of 25 miles per gallon (Businessweek, 2009). In Europe, the Waste Electrical and Electronic Equipment Directive (WEEE) and Restriction of Hazardous Substances Directive (RoHS), which have gone into effect since 2006 in most EU member states, both require the "producer-polluter" to take the responsibility of processing and recycling electronic equipment when it reaches end-of-life to induce the producer to implement various practices for sustainable design (Lauridsen and Jørgensen, 2010). In China, due to the increasing number of motor vehicles in recent years, the State Environmental Protection Administration is planning to push the date to adopt the Euro IV standard for controlling vehicle emissions earlier in certain urban regions to induce Chinese automakers to make more significant efforts in designing and producing vehicles with low greenhouse gas emissions and carbon footprints (CNTV, 2010).

However, despite the calls and regulatory pressures from the general public and the governments, today's companies have mixed responses regarding the implementation of sustainable design practices. On the one hand, most companies recognize the importance of sustainable design as exemplified by the fact that the websites of most Fortune 500 companies now feature an environmental section with substantial information regarding each company's "commitment" to sustainable design. On the other hands, with only a handful of exceptions, most major companies still adopt a relatively reactive approach to sustainable product design. In the United States and Europe, the new CAFE Standard and the WEEE and RoHS Directives have all encountered rather strong resistance from the industries due to the potential technological and financial difficulties to achieve the required environmental performances. The fact is that, to design a product with improved environmental performance, a company usually needs to deal with some difficult technical trade-offs with new product specifications (Hopkins, 2010). For example, a product made from 100% recycled materials may have poor material consistency and durability (Malloy, 1996; Verhoef et al., 2004). The zero-emission electric vehicles introduced in California in the early 1990s had rather poor traditional performances such as engine power, range, and size. These types of "green" products, which have been shown to have little chance to achieve market success, represent an inefficient use of resources in product design as the excellent environmental performances are combined with (or at the expense of) poor traditional product performances. According to the 2010 *Green Brand Survey*, mentioned previously, "offering good value" is still a predominant criterion for most consumers (72% of respondents) in making a purchasing decision. As a result, the traditional performance measures for sustainable design which mostly focus on the "absolute scale" of environmental performance may not be sufficient to provide the industries with enough incentive to implement the practice of design for the environment as well as to offer consumers with adequate choices of well-functioning products with satisfactory levels of both traditional and environmental performances.

The purpose of the paper is to propose a new methodology with the use of "design efficiency" as a novel measurement of sustainable design performances based on an innovative application of data envelopment analysis, a method which has been widely applied to evaluate the efficiencies of decision-making units (DMUs). We conceptualize "design efficiency" as a key measurement of design performances, and develop a two-stage network DEA model for evaluating the sustainable design performances to find the most efficient way to combine product specifications and attributes to achieve better environmental performances through product design. We also discuss how to use the centralized and non-cooperative game theoretic models to solve for design efficiencies under the simultaneous, proactive, and reactive strategies adopted by firms for sustainable design. To demonstrate the applications of our proposed methodology, we use data of key engineering specifications, product attributes, and emissions performances in the vehicle emissions testing database published by the US Environmental Protection Agency to evaluate the sustainable design performances of different automobile manufacturers.

Our proposed performance measure of design efficiency, which measures how well multiple product specifications and attributes are combined in a product design to achieve better environmental performance, differs significantly from the traditional measures for sustainable design which mostly focus on the absolute scale of environmental performance. For example, if two products which are evenly matched in all the major functionalities (portability, material consistency, durability, etc.) generate different amounts of toxins, the product that generates a lower amount of toxins represents a more efficient design which leads to better environmental performance with the same input resources. Similarly, everything else being equal, if two motor vehicles with different sizes lead to the same level of greenhouse gas emissions, the vehicle with the larger size represents a more efficient design with a better combination of traditional and environmental product attributes. Notice that the use of design efficiency as an additional performance measure for sustainable design does not mean that one should ignore the traditional absolute measures of environmental performances which are often directly tied to the human or ecological impacts of a product. Rather, through better understanding of the design efficiency in sustainable design, a firm may utilize its limited resources in a more efficient way to design a product with better environmental performance, or, conversely, to meet the same environmental standard with a more efficient product design with a better combination of traditional and environmental attributes. Such an efficient sustainable design process would ultimately lead to the more efficient allocation of design resources for a firm as well as better product choices with improved functionalities and environmental performances for consumers.

The remainder of the paper is organized as follows. In Section 2, we review relevant literature. In Section 3, we conceptualize design processes to develop a research framework for measuring design efficiencies based on a two-stage network DEA model. In Section 4, we perform DEA analysis with the vehicle emissions testing database published by US EPA to demonstrate how to use our proposed methodology for evaluating sustainable design performances. Test results are discussed in Section 5, and concluding remarks are in Section 6.

2. Literature review

There exists a growing body of work on sustainable product design and DfE. One stream of the research focuses on micro-economic analyses of different sustainable design practices. Calcott and Walls (2000) compare the effects of different policy instruments that are used to target green design practices. Under a framework with design trade-offs, Chen (2001) analyzes the green product design decisions under different strategic and regulatory settings. With the introduction of recyclability through a technological parameter, Fullerton and Wu (1998) examine the effects of different public policies in a general equilibrium model. Atasu et al. (2008) model consumer's heterogeneous reaction to environmental friendliness through their differential appreciation for a remanufactured product versus a new product. Atasu and Souza (2010) investigate the impact of product recovery on design quality choices. While these papers provide good insights to a number of operational, strategic, and policy issues related to DfE, there has been less sustained work on performance measurement and evaluation for sustainable design.

Another stream of research in sustainable product design and DfE provides practical guidelines for implementing sustainable design practices. Handfield et al. (2001) propose a comprehensive conceptual framework with detailed implementation processes for DfE that connects corporate environmental objectives, design processes, and outcome evaluation. By using the framework of scenario planning, Noori and Chen (2003) propose a methodology for developing breakthrough products with environmental attributes. Fiksel (2009) uses case studies from major corporations to details implementation steps for DfE in the context of product life-cycle management. By using the industrial ecology principles and case studies, Graedel and Allenby (2009) identify a number of practical approaches to green design decisions. Ulrich and Eppinger (2012) discuss how to frame DfE as a material problem to provide incremental design solutions through the product "industrial" life cycle and the natural "bio" life cycle. The quantitative evaluation of sustainable product design performance, however, is an area which has not received much attention. Conway-Schempf and Lave (1999) and Hendrickson et al. (2006) develop an input–output approach for analyzing the life-cycle impact of a product which addresses several shortcomings of the traditional life-cycle assessment. Their approach, however, is primarily focused on the quantification of the environmental impacts of different products as opposed to using operations research techniques such as DEA to identify the efficient frontiers for evaluating and comparing different product designs as in our model.

Data envelopment analysis has been widely used to measure the performance of decision making units (DMUs) in terms of efficiency in combining inputs into outputs (Farrell, 1957; Charnes et al., 1978; Liang et al., 2008). Comprehensive reviews of research in DEA are provided in Emrouznejad et al. (2010) and Cook et al. (2010). Traditionally, DEA has been used in a single-stage model within a "black-box" framework. Such an efficiency measure, however, has limitations to deal with decision-making processes which can be divided into sub-processes or stages, where outputs of one sub-process are inputs to another sub-process. With a network structure, one might expect the decision maker to optimize the efficiencies of multiple sub-processes in a sequential fashion. To incorporate the multi-stage decision-making process into performance measurement, Färe and Grosskopf (1996, 2000) extend Shephard and Färe's (1979) production framework into a network DEA model. Recently, Kao and Hwang (2008) show that the whole-system efficiency can be decomposed into the product of sub-process efficiencies. Liang et al. (2008) further develop two systematic approaches to analyze network efficiency: a game-theoretic non-cooperative approach and a centralized approach, which will be adopted in our model for evaluating the efficiency in sustainable product design.

In recent years, DEA has been increasingly used for performance evaluation in engineering design. Miyashita (2000) applies DEA to develop evaluation criteria to solve the collaborative design problem. Linton (2002) uses DEA to select materials which are efficient for various environmental indices. Farris et al. (2006) present a case study of how DEA is applied to generate objective cross-project comparisons for evaluating the relative performance of engineering design projects. By using DEA as a decision supporting tool, Cariaga et al. (2007) evaluate the degree to which each design alternative satisfies the customer requirements. Lin and Kremer (2010) apply DEA to solve the conceptual design problems and product family design problems. These papers, however, are all based on the standard DEA where the internal structure of a unit under evaluation is not modeled while our model is based on the more complex two-stage network DEA with a well-defined input–output internal structure.

In the literatures of management science and operations management, sustainable operations are commonly modeled as two-stage processes. Fleischmann et al. (1997) propose a framework decomposing the business logistics process into the "forward channel" and "reverse channel," which has been widely adopted in quantitative models of sustainable operations for product recovery and green supply chain management (Dekker et al., 2010). Recently, Ulrich and Eppinger (2012) propose a DfE framework with both the product "industrial" life cycle and natural "bio" life cycle. As in the above-mentioned analytical models for sustainable operations, our two-stage network DEA model allows decision makers to clearly identify the underlying factors and their interactions which lead to different environmental performances/consequences as well as the areas for future improvement. While the focus of the paper is not on DEA model building as our main analysis is largely based on Liang et al. (2008), this paper proposes an innovative application of network DEA in sustainable product design with the following three major contributions. First, we conceptualize "design efficiency" as a key measurement of design performances, and develop a two-stage network DEA framework for evaluating the sustainable design performances to find the most efficient way to combine product specifications and attributes to achieve better environmental performances through product design. Second, we discuss how to use the centralized and non-cooperative game theoretic models to solve for design efficiencies under the simultaneous, proactive, and reactive strategies adopted by firms for sustainable design. Third, we demonstrate the innovative applications of our proposed methodology in both the private and public sectors by using data of key engineering specifications, product attributes, and emissions performances in the vehicle emissions testing database published by the US Environmental Protection Agency to evaluate the sustainable design performances of different automobile manufacturers. According to the authors'

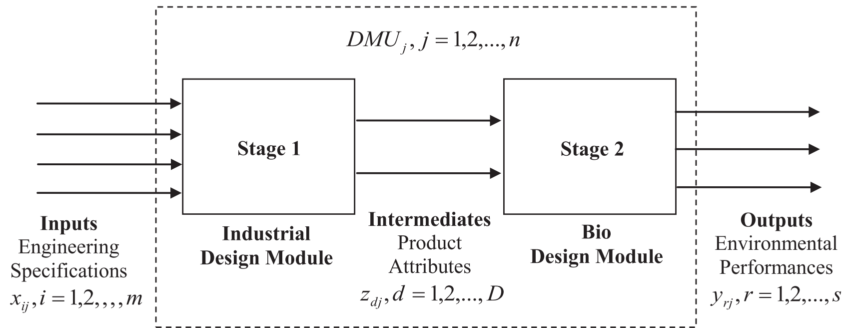

Fig. 1. The network DEA model for sustainable product design.

knowledge, our paper presents the first research work that applies network DEA to develop a comprehensive analytical framework with well-defined internal structure for analyzing the complex decision-making processes for sustainable design, an area which is of crucial importance to the future of human society, with empirical validation. In the section that follows, we will present our analytical framework based on a network DEA model.

3. Research framework

Consistent with the two-stage frameworks commonly used in the existing literatures of sustainable operations and DfE, our proposed network DEA model for sustainable design performance evaluation includes two internal modules: an "industrial design process" and a "bio design process," as illustrated in Fig. 1. Following Liang et al. (2008), we consider a set of n different designs of a particular product as the decision making units (DMUs). Assume that for each product design, denoted by DMU_j ($j = 1,\ldots,n$), there are m relevant engineering specifications as the inputs, denoted by x_{ij} ($i = 1,\ldots,m$), to Stage 1 (industrial design) and D product attributes as outputs, denoted by z_{dj} ($d = 1,\ldots,D$), from that stage. These D outputs (attributes) are also the inputs to Stage 2 (bio design) and will be referred to as intermediate measures. The outputs from Stage 2, denoted by y_{rj} ($r = 1,2,\ldots,s$), are the levels of environmental performances of the product. We can then model the sustainable design problem with a two-stage network DEA model with either the "centralized" (integrated) approach in which efficiencies in both stages are optimized simultaneously or the "non-cooperative" (sequential) approach in which efficiencies in the two stages are optimized sequentially in any given order (Stage 1 first followed by Stage 2, or in the reverse order) (Liang et al., 2008). Notice that using the proposed two-stage model does not require that the industrial design and bio design processes be conducted separately. In fact, the centralized approach allows the simultaneous, joint decision-making for the industrial design and bio design processes concurrently. The major components of the proposed DEA framework are described below.

3.1. Stage 1: industrial design performance

At the first stage, we evaluate the efficiency of the industrial design module, which can be viewed as the standard design process for combining engineering specifications (inputs) into product attributes (outputs). An engineering specification is defined as "a precise description of an engineering characteristic incorporated in a product design" (Ulrich and Eppinger, 2012), and a product attribute is defined as "one of the main physical features of a product as the combination of a number of engineering specifications" (Noori, 1990; Urban and Hauser, 1993). For example, the portability of a handheld music device (product attribute) is determined by the combination of several engineering specifications, such as materials used, battery type, and the size of internal hard drive (or flash memory). The fuel economy of a vehicle (product attribute) is influenced by the combined effects of a number of engineering characteristics such as vehicle horsepower and engine compression ratio. The process of linking engineering characteristics with product attributes at the first stage is analogous to that used in standard methods for product design such as "House of Quality" and "Quality Function Deployment" (Hauser and Clausing, 1988; Urban and Hauser, 1993). The DEA analysis, however, allows us to evaluate the efficiency of resource usage of each product design (DMU) in terms of combining inputs (engineering specifications) into outputs (product attributes) in the industrial design process.

3.2. Stage 2: bio design performance

At Stage 2, we evaluate the efficiency of the bio design module by examining the links between key product attributes and environmental performances/consequences. It is well documented that reducing the environmental impacts of a product through product design usually requires systematic design solutions to address the combined effects and interfaces of multiple product attributes (Hendrickson et al., 2006; Fiksel, 2009). Based on the DfE concept proposed by Ulrich and Eppinger (2012), sustainable design and innovation is fundamentally a "material problem" which often requires redesign and reengineer of a product as well as its supply-chain functions to reduce the amount of toxins, the use of non-renewable resources, and the use of energy. Therefore, reducing the environmental impacts of a product involves not only the environmental attributes but also many of the traditional attributes. For example, if a company wants to reduce the use of virgin materials in a product, it is often necessary to redesign and reengineer the entire product so that it works properly (e.g., with the same material consistency and durability) and looks great without some of the virgin materials used in the original design (Hopkins, 2010). Similarly, to reduce the emissions levels of a vehicle, a company usually needs to deal with the combined effects of a number of traditional and environmental attributes such as the size/weight and the fuel economy. As another example, the exact amount of e-waste generated by a laptop computer is usually influenced by the combined effects of its recyclability and other product attributes such as size, weight, and portability. Therefore, the DEA analysis at the second stage is aimed to evaluate the efficiency of a product design (as a DMU) in combining key attributes to reduce the environmental impacts or to improve the environmental performances of a product.

Depending on data availability, the outputs from the second stage can be either the life-cycle environmental impacts (Hendrickson et al., 2006; Fiksel, 2009) or only one or a few environmental performances or impacts of interest, such as the amounts of e-waste and levels of vehicle emissions. We keep our model general with the understanding that, while reducing the overall life-cycle environmental impacts should be the ultimate goal of sustainable design, the DfE approach with incremental improvements on one or a few environmental performances is usually more executable for most businesses today (Hopkins, 2010). Analyses based on only one or a few environmental performances or impacts of interest can also be parts of or integrated into the more complete environmental assessment under the life-cycle framework.

3.3. Design performance evaluation

We now discuss the performance measures for each two stages (industrial design and bio design) as well as the overall two-stage network model. On the basis of Charnes et al. (1978), the efficiencies of the first and second stages for a DMU_j ($j = 1,2,\ldots,n$) can be calculated as:

$$e_j^1 = \frac{\sum_{d=1}^{D} w_d z_{dj}}{\sum_{i=1}^{m} v_i x_{ij}} \quad \text{and} \quad e_j^2 = \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{d=1}^{D} \tilde{w}_d z_{dj}}, \tag{1}$$

where v_i, w_d, $\tilde{w}_d$, and u_r are unknown non-negative weights to be solved. These ratios are then used in a mathematical programming problem which can be converted into a linear program. It is noted that w_d is set equal to $\tilde{w}_d$ as in Liang et al. (2008).

Two different approaches, termed "centralized" approach and "non-cooperative" (decentralized) approach, can be used to measure the efficiencies of each of the two individual stages as well as the overall two-stage process (Liang et al., 2008). With the centralized approach, the efficiencies of both stages (industrial design and bio design) are evaluated simultaneously to determine a set of optimal weights on the intermediate measures that maximizes the aggregate or global efficiency score in a joint decision-making process. With the decentralized approach based on the leader–follower paradigm of the Stackelberg model, Stage 1 (industrial design) is the leader whose performance (efficiency) is more important and thus optimized first. Then the efficiency of Stage 2 (bio design) as the follower is computed, subject to the requirement that the leader's efficiency remains fixed. Similarly, with the decentralized approach based on the follower–leader paradigm, Stage 2 (bio design) is the leader and optimized first while Stage 1 (industrial design) is the follower. The mathematical program for solving the efficiencies under the centralized approach used in our DEA test is described as follows: For a specific DUM_o, the following linear programming model maximizes the centralized (overall) efficiency as the product of individual efficiencies of the two stages.

$$\begin{aligned} &Max\ e_o^1 \cdot e_o^2 = \frac{\sum_{r=1}^{s} u_r y_{ro}}{\sum_{i=1}^{m} v_i x_{io}} \\ &s.t. \quad e_j^1 \leqslant 1 \quad \text{and} \quad e_j^2 \leqslant 1 \quad \text{and} \quad w_d = \tilde{w}_d. \end{aligned} \tag{2}$$

Model (2) can be converted into the following linear program

$$\begin{aligned} &Max \sum_{r=1}^{s} u_r y_{ro} \\ &s.t. \quad \sum_{r=1}^{s} u_r y_{rj} - \sum_{d=1}^{D} w_d z_{dj} \leqslant 0 \quad j = 1,2,\ldots,n \\ &\qquad \sum_{d=1}^{D} w_d z_{dj} - \sum_{i=1}^{m} v_i x_{ij} \leqslant 0 \quad j = 1,2,\ldots,n \\ &\qquad \sum_{i=1}^{m} v_i x_{io} = 1 \end{aligned} \tag{3}$$

$$w_d \geqslant 0, \quad d = 1,2,\ldots,D; \quad v_i \geqslant 0, \quad i = 1,2,\ldots,m; \\ u_r \geqslant 0, \quad r = 1,2,\ldots,s.$$

We can then obtain the efficiencies for the first and second stages, namely

$$e_o^1 = \frac{\sum_{d=1}^{D} w_d^* z_{do}}{\sum_{i=1}^{m} v_i^* x_{io}} = \sum_{d=1}^{D} w_d^* z_{do} \quad \text{and} \quad e_o^2 = \frac{\sum_{r=1}^{s} u_r^* y_{ro}}{\sum_{d=1}^{D} w_d^* z_{do}}. \tag{4}$$

Similarly, the mathematical programs used under the non-cooperative approach can be established. To obtain the overall efficiency of the two-stage process, let $e_o^{1^*}$ and $e_o^{2^*}$ denote the efficiencies of the first and second stages obtained with the centralized or non-cooperative approach. The overall two-stage efficiency, denoted by $e_o^{\text{all}^*}$, can then be calculated as the product of the individual efficiencies of the two stages (i.e., $e_o^{\text{all}^*} = e_o^{1^*} \times e_o^{2^*}$) regardless of whether the centralized or non-cooperative approach is used, as shown in Liang et al. (2008).

With the solved individual and overall efficiencies from the DEA model, we will be able to compare and evaluate the design performances of different DMUs (product designs), and identify the most efficient way to combine product specifications and attributes to achieve better environmental performances or to reduce environmental impacts through product design. Note that, in a typical DEA model for measuring production efficiency, an efficient DMU is the one that is capable of using the minimum input resources to produce the same levels of outputs or, equivalently, using the same input resources to produce the maximum levels of outputs. Similarly, in our DEA model for measuring sustainable design performances, an efficient DMU (product design) is the one that has the best combination of engineering specifications or product attributes to achieve the same environmental performances (i.e., how well different product specifications and attributes are combined in a product design to achieve the environmental performances) or, equivalently, the DMU (product design) that is capable of using the same levels of product specifications/attributes to achieve the best environmental performances. Notice that, while the models in Kao and Hwang (2008) and Liang et al. (2008) are developed under the assumption of geometric mean of two stages' efficiency scores, additive forms of efficiency decomposition can also be used. For example, Chiou et al. (2010) develop an integrated DEA model where the overall efficiency is defined as a (weighted) average efficiency of two stages under the assumptions of constant and variable returns to scale (CRS and VRS). Chen et al. (2009) discuss the additive efficiency decomposition under both CRS and VRS assumptions when a set of DMU-related weights are used. Our proposed framework can readily be applied to the models proposed in the above studies.

3.4. Strategic implications

The two-stage network DEA model and different solution approaches presented above make it possible to analyze three different sustainable design strategies firms may adopt, namely:

(i) Simultaneous approach: a firm simultaneously optimizes both the industrial and bio design processes, which can be analyzed with the centralized approach of two-stage DEA.
(ii) Reactive approach: a firm optimizes the industrial design process first, and then optimizes the bio design process, which can be analyzed with the decentralized approach of two-stage DEA with Stage 1 (industrial design) as the leader and Stage 2 (bio design) as the follower.
(iii) Proactive approach: a firm optimizes the bio design process first, and then optimizes the industrial design process, which can be analyzed with the decentralized approach with Stage 2 (bio design) as the leader and Stage 1 (industrial design) as the follower.

With the proposed two-stage network DEA model, decision makers would be able to investigate and compare the individual and overall design performances with either the centralized and decentralized approach under different strategies for sustainable product design. It should be noted that, for a product with a simpler, single-stage design process, our analytical framework can be easily modified and reduced to a single-stage DEA model. In the section that follows, we will demonstrate the applications of our analytical model in evaluating the sustainable design performances with vehicle emissions testing data for the automobile industry.

4. Data collection and research procedure

In this section, we use the data of product specifications, attributes, and indices of vehicle emissions performances in the vehicle emissions testing database published by the US EPA (2009) to demonstrate the applications of our model in evaluating sustainable design performances of vehicles introduced in North American in 2009. Since the database only includes data of vehicle specifications, attributes, and emission performance indices which are considered relevant to the emissions tests by the agency as opposed to the complete data sets of vehicle specifications, attributes, and life-cycle environmental performances, the purpose of our analysis is to show how to use our model for evaluating sustainable design performances instead of suggesting the more eco-efficient product designs or assessing the actual design performances of automobile manufacturers. To present our analysis from the problem-solving perspective, we first identify two applications of our DEA tests in the public and private sectors corresponding to the two real-world examples regarding the new performance measures considered by the European Commission and US EPA as well as different design options considered by Chrysler.

Application #1 (public sector): an environmental protection agency has been using the tailpipe emissions levels as the primary measures of environmental performances of different automobile manufacturers for years. However, it has come to the agency's attention in recent years that many consumers do not purchase environmentally-friendly vehicles due to the perception that good environmental performances are usually at the expense of other important vehicle performances such as power and size. As a result, the agency would like to understand the overall "design efficiencies" of different automobile manufacturers in terms of combining engineering specifications and customer attributions in product design to achieve environmental performances as an alternative measure of environmental excellence.

Application #2 (private sector): a major automobile manufacturer is considering investing in developing hybrid electric engine in order to reduce emissions and to improve the environmental performances of its vehicles. However, some of the company's designers and engineers argue that good environmental performances can be achieved with the traditional ICE engine in an eco-efficient way with carefully combined vehicle subsystems. Therefore, the company would like to study and compare its own vehicles as well as other ICE and hybrid vehicles offered by its competitors in terms of the "design efficiency" for achieving environmental performances.

We now demonstrate how to use the proposed two-stage network DEA analysis to solve the problems for the environmental protection agency and private company.

4.1. Data

All new cars and trucks sold in the US must be certified to meet federal emissions standards. This is accomplished by performing laboratory tests on pre-production vehicles by the US EPA or by manufacturers at their own facilities under EPA's supervision. The 2009 database includes the data of 2885 new vehicles tested in the year. For each tested vehicle, the database provides information about the relevant engineering specifications, attributes, and vehicle emissions performances based on separate tests performed on city and highway. Since our purpose is to demonstrate the applications of the proposed model, we only analyze the emissions data based on the city tests. In many cases, multiple vehicles of the same model/option are tested. To analyze the efficiencies of individual vehicle designs, we first sort all the data by each "carline" identified by EPA as one major option of a particular vehicle model. For example, the two-wheel drive (2WD) option and four-wheel drive option (4WD) of Chrysler Grand Cherokee are considered as two different carlines. Similarly, the option with 5-speed manual transmission and the option with automatic transmission of Honda Civic are considered as two different carlines. For some carlines with repetitive data in the database, the average values of engineering specifications, attributes, and emissions levels are calculated whenever applicable. Missing data, however, are quite common in the database. We therefore remove some of the engineering specifications, attributes, and emissions test results with significant portions of missing data. Carlines with missing data are also removed from our analysis, which results in 534 carlines (product designs) used in our analysis with data of cubic inch displacement (cid), rated horsepower (rhp), compression ratio (cmp), axle ratio (axle), equivalent test weight (etw), fuel economy (mpg), hydrocarbon emissions (hc), carbon monoxide emissions (CO), carbon dioxide emissions (CO_2), and nitrogen oxide emissions (no_x). These carlines are introduced by more than 20 different manufacturers including all the major automakers for the North American market such as Chrysler, Ford, General Motors, BMW, Mitsubishi, Mercedes Benz, Honda/Acura, Hyundai, Kia, Nissan/Infiniti, SAAB, Mazda, Toyota/Lexus, Audi/Volkswagen, and Volvo.

4.2. Testing procedure

Our testing procedure follows Liang et al. (2008) for two-stage network DEA with efficiency decomposition. Since we do not have the private information about whether the automobile manufacturers use the simultaneous, proactive or reactive strategy for sustainable design, we only use the centralized approach in our analysis to simultaneously evaluate the efficiencies of both stages to obtain the maximum overall efficiency, which is considered as the more "neutral" measurements of design performances. Our analysis can be easily modified with the decentralized approach if the exact information about the sustainable design strategy (proactive or reactive strategy) used by each manufacturer is available.

With the compiled 2009 vehicle emissions testing database, we consider that each carline forms a DMU as a particular product design with four relevant engineering specifications, namely, cubic inch displacement, rated horsepower, compression ratio, and axle ratio, as the inputs. Two attributes, fuel economy and equivalent test weight, which is commonly used as a surrogate measure of vehicle size (Crandall and Graham, 1989; Chen and Zhang, 2009), are considered as the intermediate measures. The levels of hydrocarbon emissions, carbon monoxide emissions, carbon dioxide emissions, and nitrogen oxide emissions, are considered as the outputs. In DEA, higher levels of outputs usually indicate better performance. Therefore, we treat the outputs by taking the reciprocals of the emission levels. Similarly, we use the reciprocals of cubic inch displacement, rated horsepower, compression ratio, and equivalent test weights in our analysis to fit the DEA use. Notice that the definitions of inputs, intermediates, and outputs in our network DEA analysis are similar to those of engineering characteristics, customer attributes, and product performances for the design process of car doors discussed in the "House of Quality" framework proposed by Hauser and Clausing (1988). In the first stage (industrial design module), the interactions between engineering specifications (cubic inch displacement, rated horsepower, compression ratio, axle ratio) and customer attributes (size/weight and fuel economy) are analyzed. In the second stage (bio design module), the effects of customer attributes on environmental impacts/performances (the emissions of hydrocarbon, carbon monoxide, carbon dioxide, and nitrogen oxide) are analyzed.

It should be noted that one needs to exert caution when dealing with both the ratio and raw data to avoid the situation where they are not properly mixed, but the use of ratio data (fuel economy) in our model does not lead to any of those problematic situations described in Dyson et al. (2001) and Cooper et al. (2007) (e.g., a factor appears on both the input and output sides). Also notice that the list of inputs does not include any human resources due to data availability. Human contribution to product design, such as knowledge and creativity, is usually hard to measure and quantify. While the number of patents is sometimes used as a surrogate to measure human contribution in the existing literature, such information (the number of patents used in each individual vehicle design) is not available in the database or in any other data sources. Another technical issue regarding the centralized approach for solving a two-stage network DEA model is that, while the optimal overall efficiencies for DMUs are unique, the individual efficiencies of the two stages may not be unique. Therefore, we use the procedure proposed in Liang et al. (2008) to check for uniqueness of solved individual efficiencies, which shows that all the efficiency decompositions in our DEA analysis are unique.

5. Research results

By using the data of 534 different carlines (DMUs) introduced in North America in 2009, we perform the DEA test with the procedure discussed in the previous section to obtain the design efficiencies of the two stages as well as the overall (centralized) efficiency. The results of the overall and individual design performances are presented and discussed below.

5.1. Overall performance comparison

Fig. 2 presents the first-stage and second-stage efficiencies of all the carlines tested in our analysis. According to the figure, the first-stage efficiencies of most carlines are higher than the second-stage efficiencies; i.e., the "positions" of most carlines lie below the diagonal line of the diagram. In particular, the first-stage efficiencies of most carlines are higher than 50% (0.5), while the second-stage efficiencies are mostly lower than 50%. This indicates that, while most manufacturers are quite capable of combining engineering specifications to achieve satisfactory levels of vehicle weight (size) and fuel economy with relatively high design efficiencies at the first stage (industrial design), many of them are less capable of utilizing the resulting combinations of vehicle weight and fuel economy to produce good emissions performances with relatively low design efficiencies at the second stage (bio design).

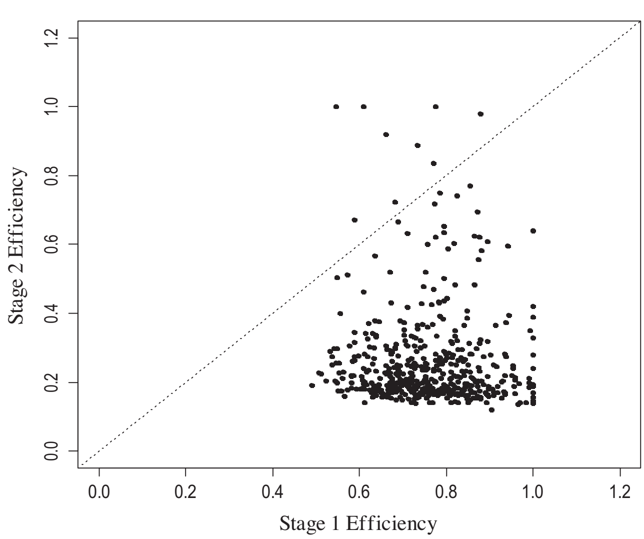

Fig. 2. A comparison of design efficiencies of the two stages (all carlines).

Table 1
A comparison of design efficiencies of selected manufacturers.

	Stage 1 efficiency	Stage 2 efficiency	Overall efficiency
American Company 1	0.7066	0.4269	0.3033
American Company 2	0.7322	0.1990	0.1454
Japanese Company 1	0.7560	0.3048	0.2304
Japanese Company 2	0.7470	0.3577	0.2637
European Company 1	0.7716	0.2375	0.1831
European Company 2	0.7964	0.3752	0.2966

Due to space limitation, we will only present the detailed test data and results of six major companies with disguised names as American Company 1 (AC1), American Company 2 (AC2), Japanese Company 1 (JC1), Japanese Company 2 (JC2), European Company 1 (EC1), and European Company 2 (EC2). Table 1 shows the summary of the average first-stage efficiencies, second-stage efficiencies, and overall (centralized) efficiencies of the six manufacturers. According to the table, AC1 has the highest average overall efficiency. While the average first-stage efficiency (for industrial design) of AC1 is slightly lower than all the other manufacturers, its significantly higher second-stage efficiency (for bio design) not only offsets the relatively lower first-stage efficiency but also leads to the highest average overall efficiency among the six manufacturers. EC2, which has the highest first-stage efficiency but lower second-stage efficiency than AC1, ranks second for the overall efficiency. The two Japanese companies (JC1 and JC2), both with moderate first-stage and second-stage efficiencies, rank third and fourth for the overall efficiency. EC1 and AC2 rank fifth and sixth for the overall efficiency largely because of their significantly lower second-stage efficiencies.

5.2. Individual carline performance comparison

We now present more detailed test data and results for the six automobile manufacturers. Due to space limitation, we will only present the test data and results of 23 selected carlines for each company, including the top three carlines with the highest overall efficiencies as well as twenty other commonly seen carlines as the representative examples. (We only present partial results since one company has more than 100 carlines, and three others have more than 45 carlines listed in the database.) Tables 2–7 show the overall, first-stage, and second-stage efficiencies as well as the data of inputs, intermediate measures, and outputs of the 23 selected carlines of AC1, AC2, JC1, JC2, EC1, and EC2, respectively. We first note that, carline #2 produced by JC1 (Table 4), a compact car which is one of the first hybrid vehicles introduced in North America, justifies its reputation as an environmentally friendly all-around vehicle with the highest overall efficiency (0.86034) among 543 carlines in our test. Although this vehicle does not define the most efficient design in either Stage 1 or Stage 2, its overall efficiency is the highest as a result of the rather high design efficiencies in both the first and second stages (0.87879 and 0.97900). However, not all

Table 2
Data and test results for selected carlines of American Company 1 (AC1).

Carline (DMU)	Overall efficiency	Stage 1 efficiency	Stage 2 efficiency	cid	rhp	cmp	axle	etw	mpg	hc	CO	CO_2	no_x
1	0.18784	0.81114	0.23158	268.31	247.23	9.84	3.31	3923	19.32	0.0216	0.4108	329.77	0.0054
2	0.45475	0.75539	0.60200	140.00	160.00	9.70	4.04	3583	25.83	0.0067	0.1667	343.67	0.0033
3	0.17072	0.80975	0.21083	182.00	217.00	10.00	3.46	3750	22.30	0.0240	0.1800	397.00	0.0100
4	0.64428	0.77061	0.83606	182.00	215.50	10.00	3.46	3938	20.85	0.0075	0.0425	107.50	0.0050
5	0.14839	0.66017	0.22477	281.00	250.00	9.40	3.27	4500	15.50	0.0400	0.5700	485.50	0.0050
6	0.58829	0.78343	0.75091	161.00	205.50	10.00	3.82	3688	25.55	0.0055	0.1450	157.00	0.0050
7	0.56000	0.94118	0.59500	140.00	155.00	9.70	2.00	4250	37.40	0.0080	0.2300	237.00	0.0200
8	0.64000	1.00000	0.64000	140.00	155.00	9.70	2.00	4000	45.20	0.0070	0.1900	196.00	0.0100
9	0.20329	0.58709	0.34627	244.00	210.00	9.70	3.64	5250	16.10	0.0280	0.5300	283.00	0.0050
10	0.14161	0.61661	0.22967	280.00	292.00	9.80	3.55	5250	16.75	0.0260	0.3600	531.50	0.0150
11	0.12445	0.62840	0.19805	330.00	310.00	9.80	3.31	6000	15.27	0.0400	0.7467	522.33	0.0100
12	0.60996	0.60996	1.00000	280.00	262.67	9.40	3.69	5556	16.90	0.0062	0.1333	117.00	0.0011
13	0.15219	0.66414	0.22915	280.00	292.00	9.80	3.55	5000	17.90	0.0260	0.2100	495.00	0.0100
14	0.12534	0.67419	0.18591	330.00	310.00	9.80	3.31	6000	17.10	0.0390	0.9450	517.50	0.0100
15	0.26126	0.73360	0.35613	330.00	310.00	9.80	3.15	5375	17.85	0.0215	0.4450	250.50	0.0050
16	0.60652	0.65939	0.91983	330.00	310.00	9.80	3.53	5900	16.92	0.0132	0.2280	105.00	0.0020
17	0.13448	0.53680	0.25052	330.00	310.00	9.80	3.31	6000	11.60	0.0420	0.3500	532.00	0.0100
18	0.28129	0.60790	0.46272	330.00	310.00	9.80	3.15	5375	12.90	0.0145	0.2350	244.50	0.0050
19	0.54527	0.54527	1.00000	330.00	310.00	9.80	3.53	5900	12.22	0.0070	0.0840	102.80	0.0040
20	0.27440	0.74345	0.36909	140.00	171.00	9.70	4.13	3625	28.30	0.0110	0.2900	314.00	0.0100
21	0.13385	0.69798	0.19177	140.00	171.00	9.70	4.09	3875	23.75	0.0235	0.3350	374.00	0.0100
22	0.14476	0.75513	0.19170	140.00	143.00	9.70	4.01	3594	24.28	0.0225	0.2325	366.75	0.0100
23	0.19589	0.66249	0.29569	244.00	207.00	9.70	3.85	4250	17.60	0.0320	0.5767	334.00	0.0033

Notes: cid = cubic inch displacement, rhp = rated horsepower, cmp = compression ratio, axle = axle ratio, etw = equivalent test weight (lbs), mpg = fuel economy, hc = hydrocarbon emissions, CO = carbon monoxide emissions, CO_2 = carbon dioxide emissions, no_x = nitrogen oxide emissions.

Table 3
Data and test results for selected carlines of American Company 2 (AC2).

Carline (DMU)	Overall efficiency	Stage 1 efficiency	Stage 2 efficiency	cid	rhp	cmp	axle	etw	mpg	hc	CO	CO_2	no_x
1	0.17891	0.87979	0.20335	145.00	175.00	10.40	2.89	3750	27.80	0.0320	0.8700	323.00	0.0100
2	0.15866	0.93311	0.17003	204.00	185.00	9.50	2.48	4000	21.30	0.0365	0.6850	417.00	0.0100
3	0.61158	0.82505	0.74127	231.00	200.00	9.40	3.05	3875	21.80	0.0060	0.2200	406.00	0.0100
4	0.13488	0.71150	0.18957	145.00	163.00	10.40	3.91	4000	23.90	0.0430	1.4900	371.00	0.0100
5	0.13858	0.84916	0.16320	122.00	260.00	9.20	3.73	3375	23.30	0.0410	0.2600	381.00	0.0400
6	0.13728	0.84596	0.16228	122.00	260.00	9.20	3.73	3375	24.30	0.0420	0.4600	367.00	0.0100
7	0.17398	0.91749	0.18962	134.00	148.00	10.00	3.77	3042	31.60	0.0350	1.0467	280.00	0.0100
8	0.13117	0.78808	0.16645	279.00	275.00	10.00	3.11	4250	19.00	0.0420	0.4800	467.00	0.0100
9	0.20414	0.78188	0.26109	237.00	236.00	9.80	2.93	4250	19.63	0.0293	0.8433	405.33	0.0033
10	0.17483	0.86624	0.20182	110.00	138.00	10.50	4.03	3125	31.00	0.0180	0.2950	287.00	0.0150
11	0.19163	0.75497	0.25382	145.00	170.00	10.40	3.63	3875	33.20	0.0450	0.9100	266.00	0.0200
12	0.15308	0.87600	0.17475	218.00	250.00	10.20	2.77	4000	21.40	0.0490	1.1500	404.00	0.0100
13	0.54485	0.87595	0.62201	214.00	211.00	9.80	2.86	3875	22.90	0.0070	0.2500	387.00	0.0100
14	0.16421	0.71933	0.22828	218.00	288.00	11.30	3.16	5000	20.60	0.0240	0.5300	454.00	0.0200
15	0.14055	1.00000	0.14055	376.00	620.00	8.80	3.42	3625	16.80	0.0880	2.6800	532.00	0.0300
16	0.22273	0.72576	0.30689	122.00	210.00	9.50	3.55	4000	23.60	0.0150	0.2000	382.00	0.0200
17	0.11676	0.70534	0.16554	364.00	395.00	10.90	4.10	5000	14.90	0.0460	0.8800	617.00	0.0100
18	0.14756	0.63717	0.23159	325.00	300.00	9.90	4.10	5500	15.80	0.0445	0.9050	559.50	0.0050
19	0.12624	0.55275	0.22839	325.00	320.00	9.90	3.42	6000	12.60	0.0330	0.5600	502.00	0.0100
20	0.10447	0.69831	0.14960	380.00	400.00	10.50	3.42	5500	15.40	0.0930	1.5800	597.00	0.0200
21	0.13421	0.74391	0.18041	325.00	300.00	9.90	3.42	5000	18.40	0.0560	1.5500	464.00	0.0100
22	0.12750	0.69084	0.18456	178.00	190.00	10.00	3.73	4250	21.70	0.0390	1.3100	406.00	0.0100
23	0.16038	0.68752	0.23327	325.00	320.00	9.90	3.08	5250	15.78	0.0280	0.5400	512.50	0.0050

Notes: cid = cubic inch displacement, rhp = rated horsepower, cmp = compression ratio, axle = axle ratio, etw = equivalent test weight (lbs), mpg = fuel economy, hc = hydrocarbon emissions, CO = carbon monoxide emissions, CO_2 = carbon dioxide emissions, no_x = nitrogen oxide emissions.

the hybrid vehicles perform well in our tests. For example, carline #11, a mid-size hybrid car produced by AC2 (Table 3), has a moderate first-stage efficiency (0.75497) but a low second-stage efficiency (0.25382), which leads to a relatively poor overall efficiency (0.19163).

For the two American manufacturers, carlines produced by AC1 perform generally well in the DEA test, as shown in Table 2. In particular, carline #4, a mid-size car powered by an internal combustion engine (ICE), has the highest overall efficiency (0.64428) among all the carlines produced by AC1 with relatively high efficiencies in both Stage 1 and Stage 2 (0.77061 and 0.83606). In addition, carline #8, a hybrid SUV produced by AC1, defines the efficient design of Stage 1 (first-stage efficiency = 1.0000) according to Table 2. In contrast, carlines produced by AC2 generally do not perform well in the DEA test, as shown in Table 3. Carline #3, a mid-size ICE car, and carline #13, a large-size ICE car, are two exceptions with relatively high overall efficiencies (0.61158 and 0.54485).

The two Japanese manufacturers perform moderately well in the DEA test. For JC1, in addition to the hybrid vehicle (carline #2) with the highest overall efficiency among all the carlines in our test, the carline with the second highly overall efficiency (0.55519) among all the vehicles produced by the company is carline #11, a hybrid mid-size car. Besides hybrid vehicles, carline #15, a compact ICE car, has the third highest overall efficiency (0.35105), as shown in Table 4. For JC2, carline #8 and #9, the

Table 4
Data and test results for selected carlines of Japanese Company 1 (JC1).

Carline (DMU)	Overall efficiency	Stage 1 efficiency	Stage 2 efficiency	cid	rhp	cmp	axle	etw	mpg	hc	CO	CO_2	no_x
1	0.34800	0.99321	0.35038	91.00	106.00	10.50	3.98	2625	37.40	0.0128	0.0750	157.83	0.0100
2	0.86034	0.87879	0.97900	91.00	76.00	13.00	4.11	3250	66.60	0.0080	0.0200	131.00	0.0100
3	0.17962	0.86263	0.20822	110.00	132.00	10.00	4.22	3000	34.50	0.0280	0.1950	256.50	0.0200
4	0.16894	0.80805	0.20907	110.00	132.00	10.00	4.28	3188	32.93	0.0303	0.2125	268.00	0.0300
5	0.17780	0.87419	0.20339	110.00	128.00	10.00	4.04	3000	34.10	0.0310	0.3050	257.00	0.0250
6	0.20316	0.78645	0.25833	144.00	157.25	9.80	3.53	3688	26.95	0.0173	0.1525	325.50	0.0200
7	0.16126	0.89756	0.17966	144.00	161.00	9.80	3.49	3250	25.80	0.0245	0.2150	343.00	0.0150
8	0.22169	0.81315	0.27263	211.00	268.00	10.80	3.69	3875	24.50	0.0190	0.1200	360.00	0.0100
9	0.20006	0.78837	0.25376	211.00	272.00	10.80	3.69	4000	23.80	0.0190	0.1700	366.00	0.0100
10	0.30855	0.78489	0.39311	152.00	204.00	12.00	4.10	4000	24.60	0.0225	0.0650	357.00	0.0150
11	0.55519	0.77164	0.71949	211.00	292.00	11.80	3.77	4500	27.90	0.0070	0.0900	313.00	0.0100
12	0.22646	0.83452	0.27136	211.00	303.00	11.80	3.77	4000	23.85	0.0290	0.1200	370.50	0.0200
13	0.15585	0.74966	0.20789	262.00	288.00	10.50	3.77	4250	20.30	0.0240	0.2750	432.00	0.0150
14	0.20747	0.82257	0.25223	281.00	380.00	11.80	2.94	4750	20.20	0.0220	0.1850	433.50	0.0100
15	0.35105	0.93653	0.37484	303.00	416.00	11.80	2.94	4250	19.65	0.0135	0.0950	444.50	0.0100
16	0.22758	0.90872	0.25044	152.00	180.00	10.40	2.74	3750	27.30	0.0190	0.1500	325.00	0.0100
17	0.26889	0.73249	0.36709	211.00	270.00	10.80	3.29	4500	21.10	0.0220	0.0800	414.00	0.0200
18	0.16334	0.71622	0.22806	211.00	270.00	10.80	3.48	4500	22.10	0.0280	0.2100	399.00	0.0200
19	0.17663	0.75144	0.23506	211.00	266.00	10.80	3.08	4500	22.40	0.0350	0.2200	395.00	0.0100
20	0.12941	0.67872	0.19067	241.00	236.00	10.00	3.73	4500	20.40	0.0320	0.3700	432.00	0.0100
21	0.27719	0.54829	0.50555	285.00	276.00	10.00	4.11	6000	17.15	0.0140	0.1000	255.50	0.0100
22	0.20164	0.61910	0.32570	346.00	383.00	10.20	3.91	6500	15.30	0.0200	0.1800	575.00	0.0150
23	0.29616	0.70857	0.41797	346.00	381.00	10.20	4.30	5563	17.35	0.0133	0.1425	380.75	0.0125

Notes: cid = cubic inch displacement, rhp = rated horsepower, cmp = compression ratio, axle = axle ratio, etw = equivalent test weight (lbs), mpg = fuel economy, hc = hydrocarbon emissions, CO = carbon monoxide emissions, CO_2 = carbon dioxide emissions, no_x = nitrogen oxide emissions.

Table 5
Data and test results for selected carlines of Japanese Company 2 (JC2).

Carline (DMU)	Overall efficiency	Stage 1 efficiency	Stage 2 efficiency	cid	rhp	cmp	axle	etw	mpg	hc	CO	CO_2	no_x
1	0.17512	0.87118	0.20101	91.00	117.00	10.40	4.59	2844	35.75	0.0168	0.2450	248.00	0.0100
2	0.35606	0.80159	0.44419	82.00	110.00	10.80	4.94	3125	54.60	0.0080	0.1300	163.00	0.0100
3	0.28454	0.87816	0.32401	114.00	154.50	11.00	4.52	3146	28.77	0.0152	0.2350	169.17	0.0067
4	0.27213	0.75563	0.36014	144.00	185.67	10.50	4.42	3708	26.84	0.0126	0.0944	329.00	0.0189
5	0.21965	0.77588	0.28310	144.00	201.00	11.00	4.60	3750	26.00	0.0175	0.1050	342.50	0.0200
6	0.22902	0.80633	0.28403	212.00	280.00	11.20	4.31	4000	22.60	0.0170	0.1400	393.00	0.0200
7	0.23029	0.79289	0.29044	212.00	271.00	10.00	3.55	3875	20.70	0.0170	0.1000	427.00	0.0200
8	0.51893	0.79411	0.65346	212.00	271.00	10.50	4.31	3938	23.83	0.0068	0.1200	373.50	0.0150
9	0.50382	0.79263	0.63563	212.00	271.00	10.50	4.31	3875	23.70	0.0070	0.1000	373.50	0.0150
10	0.28322	0.76849	0.36854	224.00	305.00	11.20	4.53	4250	21.20	0.0140	0.1100	421.00	0.0100
11	0.23926	0.72280	0.33102	224.00	300.00	11.20	4.53	4500	20.00	0.0190	0.0900	443.00	0.0200
12	0.14689	0.60916	0.24114	140.00	240.00	8.80	4.53	4250	20.90	0.0200	0.3700	426.00	0.0100
13	0.22639	0.70396	0.32159	144.00	166.00	9.70	4.50	3750	25.30	0.0140	0.1200	349.00	0.0200
14	0.20331	0.68125	0.29844	144.00	166.00	9.70	4.50	3875	24.75	0.0155	0.1400	359.00	0.0200
15	0.49248	0.68058	0.72361	144.00	166.00	9.70	4.63	3875	24.00	0.0060	0.3350	369.50	0.0150
16	0.34763	0.66964	0.51913	144.00	166.00	9.70	4.63	3938	23.50	0.0085	0.4100	376.50	0.0150
17	0.23042	0.61961	0.37188	212.00	250.00	10.00	4.53	4750	18.60	0.0160	0.1000	476.00	0.0100
18	0.18837	0.62248	0.30261	212.00	242.50	10.25	4.31	4875	20.45	0.0195	0.1450	435.00	0.0150
19	0.20220	0.65991	0.30640	212.00	250.00	10.50	4.31	4625	20.75	0.0240	0.1100	428.00	0.0250
20	0.24228	0.64456	0.37589	212.00	250.00	10.50	4.31	4750	20.00	0.0180	0.0800	443.00	0.0200
21	0.19412	0.67336	0.28828	224.00	300.00	11.00	4.53	4750	18.90	0.0240	0.1200	469.00	0.0200
22	0.14684	0.89205	0.16461	122.00	197.00	11.00	4.76	3250	25.60	0.0490	0.5900	344.00	0.0300
23	0.13190	0.96410	0.13681	132.00	237.00	11.10	4.95	3125	22.20	0.0470	0.7700	398.00	0.0200

Notes: cid = cubic inch displacement, rhp = rated horsepower, cmp = compression ratio, axle = axle ratio, etw = equivalent test weight (lbs), mpg = fuel economy, hc = hydrocarbon emissions, CO = carbon monoxide emissions, CO_2 = carbon dioxide emissions, no_x = nitrogen oxide emissions.

sedan and coupe versions of a mid-size ICE car, has the highest and second highest overall efficiencies (0.51893 and 0.50382) among all the vehicles produced by the company, and carline #15, a compact ICE SUV, has the third highest overall efficiency (0.49248), as shown in Table 5.

For the two European manufacturers, carlines produced by EC1 perform generally poorly in the DEA test. Carline #4 and carline #5, the sedan and sport-wagon versions of a compact ICE car, have the first and second highest overall efficiencies (0.34554 and 0.32735) among vehicles produced by the company. Carline #14, another compact ICE car, has the third highest overall efficiency (0.30841) according to Table 6. In contrast, carlines produced by EC2 perform generally well in the test. In particular, carline #19, a large-size ICE car, not only defines the efficient design in Stage 2 (second-stage efficiency = 1.0000), but also has the highest overall efficiency (0.77495) among vehicles produced by the company. In addition, carline #20, a compact ICE car, has the second highest overall efficiency (0.65856) and relatively high efficiencies in both Stage 1 and Stage 2 (0.85382 and 0.77131), as shown in Table 7.

Based on the limited test results, we now present a number of interesting observations regarding sustainable product design. Technology innovation for expanding the efficient envelope/frontier, such as the development of hybrid technologies, is an important way for a firm to achieve high design efficiencies, as

Table 6
Data and test results for selected carlines of European Company 1 (EC1).

Carline (DMU)	Overall efficiency	Stage 1 efficiency	Stage 2 efficiency	cid	rhp	cmp	axle	etw	mpg	hc	CO	CO_2	no_x
1	0.16177	0.69116	0.23406	121.00	200.00	9.60	4.08	3958	22.67	0.0195	0.2617	392.67	0.0250
2	0.21183	0.73130	0.28966	121.00	200.00	9.60	4.06	3750	27.45	0.0145	0.4100	323.50	0.0150
3	0.17770	0.82271	0.21600	121.00	200.00	9.60	3.94	3375	26.05	0.0175	0.5750	340.50	0.0100
4	0.34554	0.79332	0.43556	121.00	200.00	9.60	3.94	3500	26.00	0.0090	0.5050	341.00	0.0150
5	0.32735	0.76597	0.42737	121.00	200.00	9.60	3.94	3625	25.85	0.0095	0.5600	343.00	0.0150
6	0.15570	0.84309	0.18468	121.00	200.00	9.60	3.09	3625	26.00	0.0260	0.5200	342.00	0.0200
7	0.18904	0.92927	0.20343	121.00	200.00	10.30	3.14	3375	28.80	0.0235	0.2150	309.00	0.0100
8	0.12596	0.60647	0.20768	254.00	350.00	12.50	4.32	6000	16.20	0.0340	0.4000	546.00	0.0200
9	0.16121	0.66724	0.24160	254.00	350.00	12.50	4.32	5500	15.70	0.0260	0.4100	566.00	0.0200
10	0.14256	0.75904	0.18781	121.00	232.50	9.70	4.42	3563	26.85	0.0290	0.5050	330.50	0.0150
11	0.14234	0.73331	0.19411	121.00	232.50	9.70	4.42	3688	26.70	0.0295	0.4300	331.00	0.0150
12	0.22893	0.74831	0.30593	121.00	200.00	9.60	4.00	3688	26.23	0.0135	0.5475	338.25	0.0150
13	0.13873	0.83151	0.16684	317.00	560.00	12.50	4.06	4000	14.50	0.0450	0.3300	618.50	0.0300
14	0.30841	0.84139	0.36654	195.00	265.00	12.50	3.81	4083	19.12	0.0235	0.1383	206.50	0.0100
15	0.10894	0.90266	0.12068	254.00	420.00	12.50	4.57	4000	15.35	0.0540	1.0500	577.50	0.0250
16	0.33618	0.78173	0.43004	121.00	200.00	9.60	3.14	3875	25.35	0.0125	0.1850	157.00	0.0100
17	0.14296	0.80642	0.17727	254.00	350.00	12.50	3.31	4500	20.10	0.0620	0.3600	443.00	0.0400
18	0.26674	0.85190	0.31311	254.00	354.00	12.50	3.70	4250	17.13	0.0173	0.4300	236.50	0.0100
19	0.14976	0.72198	0.20743	121.00	211.00	9.60	3.09	4250	24.80	0.0280	0.6800	357.00	0.0200
20	0.18805	0.71112	0.26444	121.00	200.00	10.50	3.54	4250	24.40	0.0180	0.4500	364.00	0.0100
21	0.13734	0.79375	0.17303	317.00	429.00	12.50	3.80	4750	17.20	0.0390	0.3300	516.00	0.0300
22	0.15905	0.72147	0.22045	254.00	344.00	11.00	3.66	4500	16.77	0.0240	0.4200	536.67	0.0267
23	0.15799	0.77302	0.20438	366.00	450.00	10.80	3.32	5000	15.90	0.0270	0.9500	555.00	0.0200

Notes: cid = cubic inch displacement, rhp = rated horsepower, cmp = compression ratio, axle = axle ratio, etw = equivalent test weight (lbs), mpg = fuel economy, hc = hydrocarbon emissions, CO = carbon monoxide emissions, CO_2 = carbon dioxide emissions, no_x = nitrogen oxide emissions.

Table 7
Data and test results for selected carlines of European Company 2 (EC2).

Carline (DMU)	Overall efficiency	Stage 1 efficiency	Stage 2 efficiency	cid	rhp	cmp	axle	etw	mpg	hc	CO	CO_2	no_x
1	0.39640	0.82057	0.48308	365.00	528.00	11.30	3.06	4750	14.60	0.0120	0.2500	610.00	0.0100
2	0.54335	0.89347	0.60814	213.00	268.00	10.70	2.82	3938	21.45	0.0075	0.1050	415.00	0.0100
3	0.14423	0.89662	0.16086	333.00	382.00	10.70	2.65	4250	18.00	0.0370	0.3200	496.00	0.0200
4	0.25589	0.81260	0.31490	213.00	268.00	10.50	3.07	4125	20.70	0.0150	0.2450	429.00	0.0100
5	0.18245	0.75571	0.24143	182.00	210.00	16.50	3.45	5500	22.50	0.0350	0.2500	452.00	0.0200
6	0.54032	0.86488	0.62473	379.00	507.00	11.30	2.82	4500	14.75	0.0090	0.1450	604.00	0.0100
7	0.18360	0.83993	0.21860	336.00	510.00	9.00	2.65	4750	14.10	0.0270	0.3700	629.00	0.0300
8	0.24238	0.85602	0.28315	365.00	603.00	9.00	2.65	4750	14.10	0.0220	0.6400	629.00	0.0100
9	0.14901	0.74522	0.19995	379.00	518.00	11.30	3.06	5000	13.80	0.0310	0.6100	643.00	0.0200
10	0.17705	0.79097	0.22383	336.00	510.00	9.00	2.65	5250	13.60	0.0280	0.4400	651.00	0.0400
11	0.21057	0.98959	0.21279	182.00	210.00	16.50	2.65	4250	29.10	0.0955	1.1250	348.00	0.0800
12	0.27448	0.87494	0.31372	183.00	228.00	11.30	3.07	3875	22.30	0.0140	0.2400	399.00	0.0200
13	0.60577	0.87150	0.69509	379.00	503.00	11.30	2.82	4750	15.50	0.0080	0.2000	576.00	0.0100
14	0.20322	0.87494	0.23227	183.00	228.00	11.30	3.07	3875	16.40	0.0230	0.1500	382.00	0.0200
15	0.25124	0.90030	0.27906	213.00	268.00	10.50	2.82	3875	21.30	0.0160	0.2500	417.00	0.0100
16	0.18004	0.77125	0.23345	333.00	382.00	10.70	2.65	5000	17.40	0.0260	0.2100	510.00	0.0200
17	0.48054	0.77398	0.62087	333.00	382.00	10.70	3.07	4500	16.50	0.0100	0.0500	535.00	0.0100
18	0.18584	0.58832	0.31589	213.00	268.00	10.50	3.90	5250	18.40	0.0190	0.2700	480.00	0.0200
19	0.77495	0.77495	1.00000	213.00	268.00	10.70	3.27	4250	20.30	0.0060	0.0200	435.00	0.0100
20	0.65856	0.85382	0.77131	379.00	450.00	11.30	2.82	4250	15.20	0.0070	0.2000	588.00	0.0100
21	0.16170	0.58670	0.27560	213.00	268.00	10.50	3.70	5500	18.20	0.0220	0.5000	485.00	0.0200
22	0.22994	0.95256	0.24139	333.00	382.00	10.70	2.47	4250	18.40	0.0210	0.2200	482.00	0.0200
23	0.45850	0.68762	0.66680	379.00	503.00	11.30	3.45	5500	12.80	0.0100	1.0300	696.00	0.0300

Notes: cid = cubic inch displacement, rhp = rated horsepower, cmp = compression ratio, axle = axle ratio, etw = equivalent test weight (lbs), mpg = fuel economy, hc = hydrocarbon emissions, CO = carbon monoxide emissions, CO_2 = carbon dioxide emissions, no_x = nitrogen oxide emissions.

exemplified by the good industrial and bio design performances of some of the hybrid vehicles (e.g., carline #2 of JC1 and carline #8 of AC1) in our DEA test. However, high design efficiencies can also be achieved through innovative design choices to find the most efficient combination of product specifications and attributes that leads to high environmental performances even in the absence of advanced technologies, as exemplified by those ICE vehicles with high design efficiencies (e.g., carline #4 of AC1 and carline #19 of EC2). In many cases, finding the efficient combinations of product specifications/attributes may sometimes be an even more effective way to achieve higher design efficiencies than expanding the technology envelope/frontier through technology innovation. As shown in our test results, a large-size ICE car (carline #19 of EC2) may define the efficient design for the second stage, while a hybrid vehicle (carline #11 of AC2) may have poor design efficiencies. In fact, the test results suggest that, while the first-stage design efficiencies for industrial design of most carlines are reasonably high, there is still plenty of room for further improvement to enhance the second-stage efficiencies for bio design for most carlines and for most automobile manufacturers.

We now discuss how the proposed methodology can be used to improve decision-making in both the public and private sectors in the two applications presented previously. For Application #1, the comparative results given in Fig. 2 can be used by the environmental protection agency to understand the overall sustainable design efforts by different automakers in both the industrial design process and bio design processes. The performance comparison in Table 1 can also be used to evaluate the design efficiencies of different automakers, and adjust its regulatory approaches or policy instruments (e.g., taxes, subsidies, emissions standards, etc.) accordingly. For Application #2, the test results in Tables 1–7 can be used to benchmark the private company's design efficiencies, to conduct internal and external evaluations of different design options, as well as to identify the more eco-efficient ways to achieve environmental performances. Compared to the results in other DEA models for sustainable design (e.g., Linton, 2002; Liu, 2008; and Lin and Kremer, 2010, which are all based on single-stage DEA), our test results provide a clearer picture of the individual efficiencies of both the industrial design process and bio design process as well as the overall sustainable design efficiency, which allows decision makers to better allocate their design efforts as well as to adjust the private strategies and public policies to induce more eco-efficient product designs.

It is noted that the DEA test can also be done by removing all the hybrid vehicles, but this is not likely to affect the test results because there exist ICE cars that define the efficient designs of Stage 1 and Stage 2, respectively, as the frontier units (e.g., carline #15 of AC2 and carline #19 of EC2). It should also be reiterated that our test results are limited by the assumption of using the centralized approach and by the incomplete product information provided in the database. With complete information of product specifications, attributes, and environmental performances as well as the exact design strategies (simultaneous, proactive, or reactive) adopted by firms, decision makers would be able to accurately assess the design performances through the network DEA model. It should also be noted that the dual model is not studied in the paper. While Kao and Hwang (2008) provide and discuss the dual model in the multiplier form, studying the dual model will not provide additional information related to the efficiency scores. If, however, assurance region (AR) type of information is available (Thompson et al., 1990), one would use the dual model to incorporate these AR constraints. The current paper does not have this type of information available. Thus, we leave this as a future topic for application.

6. Conclusion

In this paper, we propose a new methodology with the use of two-stage network DEA for evaluating sustainable product design performances. We conceptualize design efficiency as a key measurement of design performance, and develop a network DEA model to link key engineering specifications, product attributes, and environmental performances in sustainable design. We also discuss how to use the centralized and decentralized models to analyze the simultaneous, proactive, and reactive approaches adopted by firms for sustainable design. In addition, we use data of engineering specifications, product attributes, and emissions performances in the vehicle emissions testing database to demonstrate the real-world applications of our DEA model for evaluating sustainable design performances in both the public and private sectors. The main message delivered here is that sustainable design does not need to mean compromise between traditional and environmental attributes. Through innovative design decisions for material selection, product reengineering, as well as expanding the technology envelope/frontier, a firm can find the most efficient way to combine product specifications and attributes which leads to better environmental performances. Our DEA-based methodology provides an innovative tool for decision makers to implement the win–win type of product design and innovation strategies for achieving the long-term sustainability of human society.

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