Integration of Sustainability Into Early Design Through the Function Impact Matrix

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The issue of environmental sustainability, which is unprecedented in both magnitude and complexity, presents one of the biggest challenges faced by modern society. Design engineers can make significant contributions by incorporating environmental awareness into product and process development. It is critical that engineers make a paradigm shift in product design from centering on cost and performance to balancing economic, environmental, and societal considerations. Although there have been quite a few designs for environment (or ecodesign) tools developed, so far, these tools have only achieved limited industrial penetration. The present-day methods are either too qualitative to offer concrete solutions and not effective for designers with limited experience or too quantitative, costly, and time consuming. Thus, current ecodesign tools cannot be implemented during the early design phases. This paper develops a novel, semiquantitative ecodesign methodology that is targeted specifically toward the early stages of the design process. The new methodology is a combination of environmental life cycle assessment and visual tools such as quality function deployment, functional-component matrix, and Pugh chart. Since the early design process is function-oriented, a new visual tool called the function impact matrix has been developed to correlate environmental impacts with product function. Redesign of office staplers for reduced carbon footprint has been selected as a case study to demonstrate the use of the proposed approach. Life cycle assessment results confirm that the new stapler design generated using this methodology promotes improved environmental performance. [DOI: 10.1115/1.4001890]

Keywords: ecodesign, visual tool, life cycle assessment, function impact matrix

1 Introduction

This paper aims at developing a novel design methodology that balances available qualitative and quantitative data, and seamlessly integrates environmental sustainability considerations into the early design process. The issue of environmental sustainability, which is unprecedented in both magnitude and complexity, presents one of the biggest challenges faced by modern society [1]. Population growth and increase in quality of life have dramatically augmented worldwide emissions and energy consumption [2]. Design engineers can make significant contributions to this issue by designing products and processes that satisfy societal needs while minimizing the associated environmental consequences. Decisions made at the initial product design phase determine the environmental and economic impacts of future decisions [3]. Therefore, it is critical that engineers adopt a design paradigm shift from a focus on cost and performance to a balance of economic, environmental, and societal considerations, as well as from a transformation from end-of-pipe remediation to proactive design and process planning [4–7]. However, designing environmentally friendly products is by no means an easy task. Engineered products, such as living organisms, interact with the environment through energy and material flows at every stage of the life cycle from raw materials extraction and acquisition, manufacturing, transportation and distribution, use and maintenance, reuse and recycle, all the way through to disposal and waste management [8]. Due to the complexities associated with a product's life cycle, incorporating environmental sustainability into design consideration requires additional tools.

As pointed out by Pugh, "the wrong choice of concept in a given design situation can rarely, if ever, be recouped by brilliant detail design" [9]. This is also expected to be the case for environmentally friendly design. Up until now, design methods such as quality function deployment (QFD), functional-component analysis, and Pugh chart have gained prominence in the product design community as a means of developing better products [10]. Unfortunately, the decisions based on these tools typically rely on experience, intuition, or at best, a few simplified calculations [11]. As a result, design decisions are viewed with skepticism due to their subjectivity. When environmental performance is considered as a design factor, these tools fail since only very limited amount of experience and knowledge have been accumulated and usually a "life cycle" perspective is missing [12,13]. The lack of effective ecodesign tools has therefore made sustainability an after-thought and not a critical parameter in the design process. As pointed out in a recent editorial published in ASME's *Journal of Mechanical Design*, only 15 entries were found in the ASME digital library in a search for "sustainable design" or "environmentally conscious design" [4].

Product design and development relating to improved environmental performance have many expressions, including design for environment, ecological design, environmental design, environmentally conscious design, environmentally responsible design, socially responsible design, sustainable product design, sustainable product development, green design, and life cycle design [14]. Ecodesign is used throughout this paper to represent all these efforts. During the past decade, quite a few ecodesign tools have been developed. However, these tools are either overly qualitative or subjective, requiring the designer to have extensive experience or are quantitatively complex and not able to be applied during early design when product specifications are unknown [15,16].

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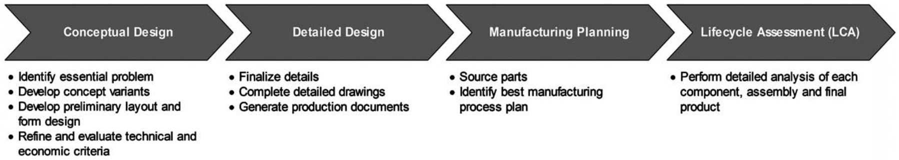


Fig. 1 Existing pipeline for estimating environmental impact during product realization

Moreover, these tools are usually not well integrated into traditional design methods and thus have achieved very limited penetration into industry [17,18].

In this paper, a novel ecodesign methodology will be developed, which is a combination of life cycle assessment (LCA) and commonly used design tools (i.e., quality function deployment, functional-component matrix and Pugh chart). This methodology will be used to formulate a novel visual design tool called the function impact matrix, which will be demonstrated using an office stapler redesign case study.

2 Background and Related Work

Designers invariably use imagery to generate new form combinations [19]. Hence, visual thinking is an integral part of design engineering. During the past ten years, numerous visual tools for ecodesign have been developed. In fact, ISO-TR 14062 [20] suggests the use of some 30 various tools. These tools can be generally classified into three categories: (1) tools based on checklists, (2) tools based on LCA, and (3) tools based on QFD [12].

2.1 Tools Based on LCA. The LCA method was developed to identify environmental consequences of a product or process throughout each of its life cycle stages. LCA provides a holistic approach and therefore presents an accurate estimation of the environmental trade-offs of products. The method was standardized by ISO in 1997 and updated in 2006 [21,22]. So far, LCA has been the most objective tool available for generating environmental profiles of products. However, LCA requires detailed product design information, which makes it unsuitable for use in the early design process [23]. Furthermore, novel products cannot be assessed using traditional LCA since information from reference products (previous generation or competitors) is not available. Additionally, a fully comprehensive LCA is very costly and time consuming and sometimes not affordable for smaller companies. There have been some efforts to address these issues by developing simplified or streamlined LCA for screening purposes. However, these methods tend to ignore environmental impacts from certain life cycle stages, material/energy flows, or impact categories [24,25]. To what level the fidelity can be maintained remains largely unaddressed. Another serious obstacle associated with applying LCA based tools during early design lies in the fact that LCA is inherently not design-oriented. LCA was developed to analyze environmental impacts of product structure, not the environmental costs associated with product functions based on customer requirements. Figure 1 shows how LCA is traditionally used in product development.

2.2 Tools Based on Checklists. These qualitative tools are the easiest to implement and are among the most prevalent in industry, especially among small and medium size companies [26]. A common feature of these tools is the checklist, a set of items used for assessing a product from the environmental perspective over its entire life cycle. These questions, for example, can be asked: "Is less energy consumed during the use phase of the product than other life cycle stages?" or "Are less toxic materials used in the product?" [14]. These tools have been developed particularly for the early stages of the product development process. Compared with LCA based tools, these tools are much more subjective. Their proper use requires extensive experience and knowledge. And it is challenging for even the most experienced designers to recognize and understand complex trade-offs between different life cycle stages or different environmental impact categories. Moreover, these tools usually do not provide designers with quantitative engineering/environmental objectives and can rarely offer concrete solutions.

2.3 Tools Based on QFD. The objectives of a traditional QFD are to convert customers' needs into engineering characteristics and to improve product quality. By introducing environmental impacts throughout a product's life cycle into QFDs as new customer needs, a novel set of ecodesign tools have been developed. These include quality function deployment for the environment, green quality function deployment, and house of ecology [15,26]. In general, application of these tools starts from collecting both customer and environmental requirements and developing correlations between these requirements and quality characteristics. A functional analysis is then performed to identify correlations between quality characteristics and engineering characteristics (including structure or components) as well as key redesign opportunities from both an environmental and traditional perspective. Tools based on QFD are significantly different from LCA based tools as the focus lies in the product specification development stage. One serious drawback of these QFD based tools (similar to traditional QFD) is that the development of correlations between environmental needs and engineering characteristics is fully based on designers' experience. The correlations developed are often based on knowledge from the field of traditional environmental engineering without consideration of the entire product life cycle.

Among these three types of ecodesign tools, QFD based tools are the most suitable for early product development when specifications are being established and concepts generated. Recent efforts in developing ecodesign tools have focused on the integration of LCA within QFD with the goal of determining more objective design targets [15]. However, there is a critical missing link in these approaches, which leaves the inherent drawback of QFD left unaddressed. Although LCA results are used to develop voices for the environment and corresponding weightings, they fail to develop relationships between environment-related requirements and engineering characteristics, as shown in Fig. 2.

3 Methodology Development

The novel ecodesign methodology proposed here is the projection of life cycle assessment data to support the use of visual tools during the early design stage. Since almost all new designs are a novel combination of existing concepts, the knowledge needed can be collected through product tear-down and benchmarking. During tear-down, the designers identify the structure, behavior, and functions of similar products [27]. To understand the structure and behavior of functions within a product, it is essential to gather design requirements from one or more of the stakeholders involved.

It should be noted that one or more of the stakeholders could identify requirements with regard to environmental sustainability. Designers have expressed concerns that they are unable to obtain information on the relative environmental attractiveness of a potential material or process selection [28]. Design engineers must evaluate whether these requirements should be integrated into the design. It is expected that these requirements will change con-

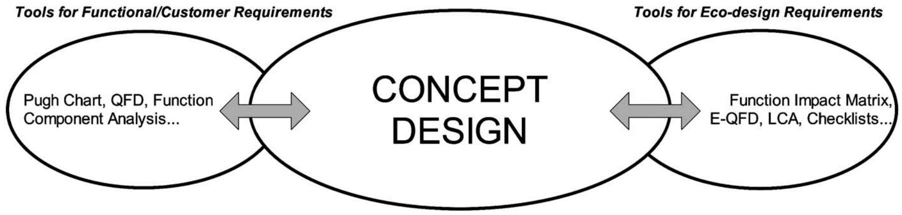


Fig. 2 Integration of ecodesign and existing design tools for concept design

straints and objectives associated with design concepts but the functions should be kept unchanged as long as the environmental requirements remain realistic. Environmental impacts of a product through its entire life cycle can be thought of as a set of new constraints or objectives. Therefore, it is critical to have relationships or mappings developed between functions/behaviors/structures of the product and its environmental impacts. One feasible way to develop such relationships is to conduct LCA with similar products on the market.

For the *i*th benchmark product, its environmental impact in category j can be described as

$$E_{i,j} = \sum_k \left(M_{i,j,k} + \sum_m P_{i,j,k,m} \right) + U_{i,j} \tag{1}$$

where $M_{i,j,k}$ is the environmental impact of category j associated with component k due to material, $P_{i,j,k,m}$ is the environmental impact of category j associated with component k due to the mth manufacturing step, and $U_{i,j}$ is the environmental impact of category j during the use of the product. The decision to include end-of-life and transportation is heavily dependent on the product under consideration. If needed, Eq. (1) can be modified to include impacts from end-of-life disposal ($D_{i,j}$) and transportation ($T_{i,j}$).

QFD has become a widely accepted method for engineering design in industry. The main component of the QFD method, house of quality (HoQ), is very flexible and it can capture the various aspects of working knowledge. The most popular version of HoQ relates to customer requirements for engineering characteristics. In other words, technical requirements are related to design attributes. This is a critical step in the early design process, falling in line with the stakeholders' development of the requirements. When environmental issues are incorporated into customer requirements, the LCA results of similar products can be analyzed to relate the engineering characteristics to environmental performance. For example, if global warming is a concern expressed by a stakeholder, life cycle greenhouse gas emission in terms of kilogram CO_2 equivalent should be selected as an engineering specification. Calculations obtained from LCA could serve as benchmarks for the new designs.

To facilitate design concept development, function decomposition is usually conducted. The describing function without its respective implementation does not support the design process sufficiently. Specifically, function decomposition cannot be performed meaningfully without relating function to structure or form. Knowledge about function is often visualized in hierarchical or procedural function structure diagrams such as the function-component matrix. In a case where one component contributes to more than one function, percentages will need to be assigned to each of the functions involved. That is,

$$FC = [\alpha_{k,n}] \tag{2}$$

and

$$\sum_n \alpha_{k,n} = 100\% \tag{3}$$

where $\alpha_{k,n}$ is the percentage contribution of component k toward function n. Similarly, impacts due to the use of the product can also be distributed by assigning percentages to each function. The challenge lies in interpolating the environmental impact of existing products with the goal of designing an environmentally friendly product. This is indeed possible because (1) products are designed to perform a certain function, (2) products achieve functionality by means of their structure and behavior (use) [29], and (3) environmental impacts are computed using structure and usage information. Therefore, a correlation that connects functional information to environmental impact data through the structure of an existing product can be identified. It is, therefore, possible to estimate the environmental impact of each function, albeit for existing products. Extrapolating the impact to functions of the current design provides a means to (1) rank functions in terms of their environmental impact and (2) estimate a baseline impact that the new design aims to improve. The new visual tool proposed is called the function impact matrix (FIM). The FIM uses information from the function-component matrix to distribute life cycle environmental impacts across product functions. The main goal of the FIM is to identify the importance level of each function and determine the functions, which should be re-examined to obtain a better design from an environmental perspective. The simplest way to derive the function impact matrix is by combining Eqs. (1) and (2):

$$FI = [\beta_{i,j,n}] = \left[\left\{ \sum_k \left(M_{i,j,k} + \sum_m P_{i,j,k,m} \right) \cdot \alpha_{k,n} \right\} + U_{i,j} \cdot \gamma_n \right] \tag{4}$$

where $\beta_{i,j,n}$ is the environmental impact of category j due to function n for benchmark product i and γ_n is the percentage of function n that contributes to overall product functionality, thus, the total material and energy consumption during the use phase of the product. For example, if a product includes a motor to perform a specific function, the environmental impact associated with powering the motor will carry some percentage (γ_n) of the total impact during the product's use phase. In general, γ_n allows the designer to trace functions back to a component level from a use phase perspective while $\alpha_{k,n}$ indicates the percentage distribution of each component to a given function during all other significant phases (material extraction, manufacturing) of a product's life cycle.

It should be noted that the addition of environmentally based requirements and characteristics complicates the technical correlation matrix and the interrelationship matrix of the house of quality and cannot interpolate environmental data for each function of a product. However, this issue can be partially solved using the novel function impact matrix. It should also be noted that the development of these correlations is very likely to be case specific and should take the entire product life cycle into consideration. The quality and quantity of materials used to meet design requirements during the use phase must be considered. Usually, the LCA results of similar products can provide information about challenging correlations.

The function impact matrix can also be extended to concept generation and selection using the Pugh chart in which working principles from other products can be assessed in the new design. If a new concept lacks functional similarities with other products, the function-impact approach cannot be used directly. However, if

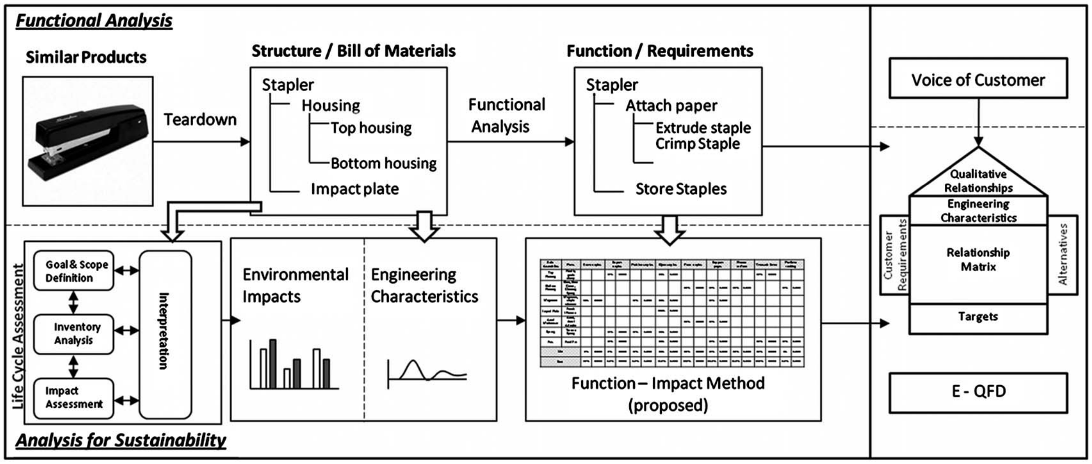


Fig. 3 Approach to integrate LCA into early design through the use of visual tools

it is known that the new mechanism is actually "borrowed" from a different product by suitably choosing the structural boundary of the existing product and after appropriate scaling, the function impact matrix can estimate the impact of the new mechanism.

To summarize, in order to use the methodology for product development, LCA must first be conducted on market leading designs of several consumer products (e.g., staplers, coffee makers, barbecue (BBQ) grills). The environmental impacts will then be distributed to product functions to establish function-impact correlations, which will be used to support conceptual design and concept selection. To validate this methodology, LCA could be conducted on each detailed design. An overview of the proposed approach using an office stapler as an example is illustrated in Fig. 3. The details of the stapler case study are provided in the following section.

4 Case Study

To demonstrate the proposed methodology, a redesign of a regular-sized office stapler was conducted with the goal of reducing environmental impact. Most staplers available on the market today consist of a magazine to hold the staples, an extruder to push the staple through a pile of papers, an anvil on the bottom plate to crimp the ends of the staple pin, and housing to hold all of these parts together. These staplers are made of different materials such as plastic and metal. Recently, a new type of stapler called "Power Ease™" has been developed [30], which stores the energy applied by the user and then releases it on impulse to "shoot" the staple into this paper. This new type of stapler is easier to use and can significantly reduce the chance of staple jamming. In this paper, three staplers have been selected as benchmarks, i.e., one with almost all the components made of metal, one with many components made of plastic and one of the "Power Ease" type. It is also assumed that all staplers have a service life of five years and staple 3000 documents during their lifetime.

A survey was conducted to collect design requirements from stakeholders of office staplers. In this study, the survey was limited to students, staff/secretaries, and designers. The main requirements in order of importance were easy to use, jamming free, inexpensive, durable, maintenance free, light weight, able to use staples of different leg lengths, and able to staple documents up to 20 pages. Environmental considerations were added to the requirements with carbon footprint representing all the potential environmental impacts associated with the stapler life cycle. Other impact categories can also be considered if desired.

Next, the three staplers were torn down to develop an extensive bill of materials. For every component in the bill of materials, the manufacturing processes used to fabricate the component are also listed. Table 1 shows the bill of materials for one of the benchmark staplers, i.e., the "plastic" one. Based on the bill of materials and manufacturing process information, LCA was performed for all the benchmark staplers using SIMAPRO 7.1 [31] and ECOINVENT 2.0 [32]. SIMAPRO 7.1 and ECOINVENT 2.0 are state-of-the-art software tools for LCA and environmental performance evaluation. For a LCA study, environmental impacts are usually classified into categories such as land use, human health effects, ecotoxicity, and climate change. In this study, only climate change was considered given the current overwhelming concern and greenhouse gas (GHG) emission in the unit of kilogram CO_2 equivalent was used as the indicator for climate change. GHG emissions due to transportation were ignored since the three staplers under investigation were of similar weight and, compared with manufacturing stage contribution from transportation, are usually negligible. Also, the end-of-life disposal of the staplers was excluded since negligible GHG emissions were expected. Taking into account the end-of-life scenario of an individual stapler might increase the accuracy of the overall GHG emissions. However, in this study, the main motivation for conducting an LCA was to compare the GHG emissions of the three staplers. Therefore, excluding this data would not have any significant effect on the results. For the use phase, it was assumed that the staplers of the Power Ease™ type were jam-free while the other two staplers had a jamming probability of 20%. A summary of life cycle global warming potential in terms of kilogram CO_2 equivalent for each subassembly and life cycle stages for all three staples is provided in Table 2. Of the three staplers, the Power Ease™ type had the highest carbon footprint over its life cycle. Although it seems that the use phase

Table 1 Bill of materials for a stapler

Part Name	Material	Manuf. process	Wt. (g)
Handle	Plastic (HDPE)	Injection molding	37.5
Base	Aluminum	Die casting	180.8
Anvil	Low-carbon steel	Blanking and punching	13.9
Anvil actuator	Aluminum	Die casting	0.9
Clearing Spring	ASTM Steel	Blanking and bending	9
Rivet	Low-carbon steel	Forging	0.25
Base cover	Rubber (synthetic)	Molding	20.7
Magazine	Low-carbon steel	Blanking and plating	52.8
Staple advance	Low-carbon steel	Blanking and plating	2.5
Guide clamp	Low-carbon steel	Blanking and plating	31.7
Tension spring	Spring steel	Wire drawing	1.9
Pivot pin	Low alloy Steel	Blanking and plating	2
Punch/hammer	Low-carbon steel	Blanking and plating	3.2

Table 2 Life cycle carbon footprint (in kilogram CO_2 equivalent) of three benchmark staplers

	Subassemblies	Plastic stapler	Metal stapler	Power Ease™ stapler
Production stage	Top housing	0.22	0.41	1.06
	Bottom housing	0.66	0.50	0.43
	Magazine	0.18	0.32	0.22
	Impact plate	0.012	0.02	0.004
	Anvil mechanism	0.055	0.04	0.014
	Spring	0.002	0.04	0.001
	Pins	0.04	0.01	0.005
	Use phase	0.86	0.86	0.69
	Total	2.02	2.19	2.42

contributed significantly to the life cycle environmental GHG emissions due to the consumption of staples, especially for the plastic one (43%), it was revealed that the production stage dominates the GHG emissions. The Power Ease™ stapler offered a jam-free system, which would result in less consumption of staples compared with the staplers with 20% jamming rates. However, even with the lower consumption of staples during use, the actual saving on carbon footprint of the Power Ease™ stapler during the use phase was relatively small. This suggests that being jam-free is a feature desired by customers but it may not be significant from an environmental standpoint. To distribute environmental impacts among functions, the function-component matrix must first be developed. The major functions provided by the stapler components in order to render stapling including store staples, import staples (or load staples into compartment), position staples to the front of the housing, eject staples into a paper stack, form staples around the paper stack, support pages within the jaws of the stapler, protect external surface while stapling, transmit force from outer housing to contact area, and allow stapler to tack a poster to a wall. To facilitate carbon footprint distribution, components are assigned percentages based on their contributions to each function. For example, the stapler magazine contributes mainly to storing the staples but also contributes to supporting pages, as well as positioning and ejecting staples. Therefore, 60% is assigned to staple storage, 20% to support pages, and 10% each is assigned to both position staples and eject staples. Table 3 shows the function impact matrix developed for the plastic stapler. Similar analysis was performed for the other two staplers and the average impact of a particular function was obtained. Although the actual impact of a particular function for a new stapler would differ from this value, it nevertheless provides a baseline needed for decision making. The average impact of each function is depicted in Table 3.

As seen in Fig. 4, three functions, i.e., transmit force, eject staples, and form staples, all contribute to nearly 50% of the car-

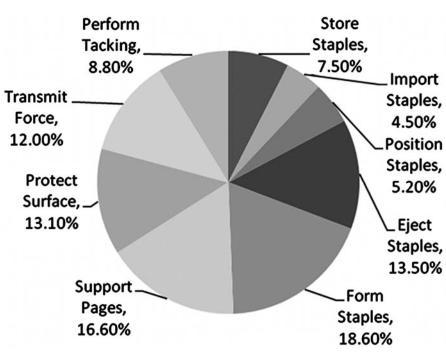


Fig. 4 Average contribution of each function to the overall carbon footprint of the stapler

Table 3 Function impact matrix for estimating the impact of individual functions through means of the structure information

Subassemblies	Parts	Store staples		Import staples		Position staples		Eject staples		Form staples		Support pages		Protect surface		Transmit force		Perform tracking	
Top housing	Handle, guide clamp			20%	0.0440			30%	0.0660							50%	0.1100		
Bottom housing	Base, base cover, clearing spring									30%	0.1982	30%	0.1980	20%	0.1321			20%	0.1321
Magazine	Magazine, staple advance	60%	0.1074			10%	0.0179	10%	0.0179			20%	0.0358						
Impact plate	Punch/hammer							100%	0.0120										
Anvil mechanism	Anvil, anvil actuator									90%	0.0448	10%	0.0102						
Spring	Torsion spring			60%	0.0013	30%	0.0007	10%	0.0002										
Pins	Pivot pin			20%	0.0015			20%	0.0015			20%	0.0015			20%	0.0015	20%	0.0015
Use		5%	0.0430	5%	0.0430	10%	0.0860	20%	0.1720	15%	0.1290	10%	0.0860	15%	0.1290	15%	0.1290	5%	0.0430
Sum		7.5%	0.1504	4.5%	0.0898	5.2%	0.1046	13.5%	0.2696	18.6%	0.3720	16.6%	0.3315	13.1%	0.2611	12.0%	0.2405	8.8%	0.1766

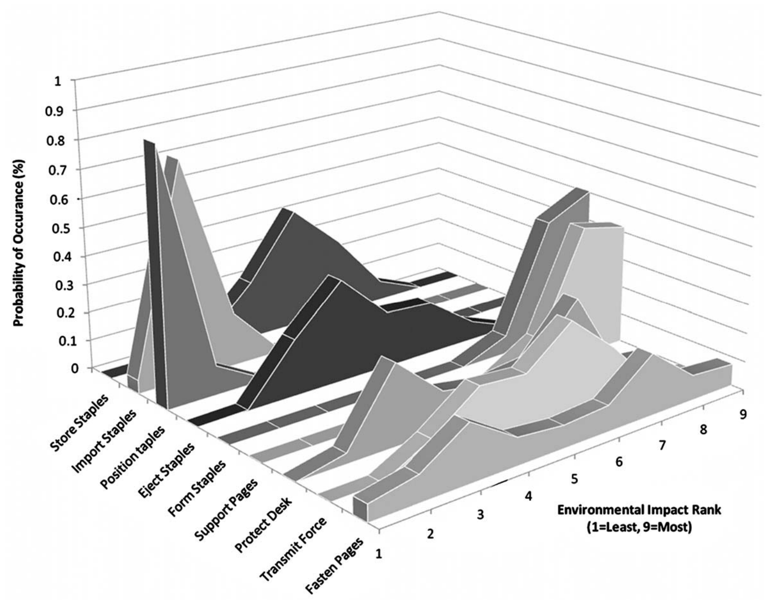


Fig. 5 Histogram of variation analysis for component-function sharing percentages

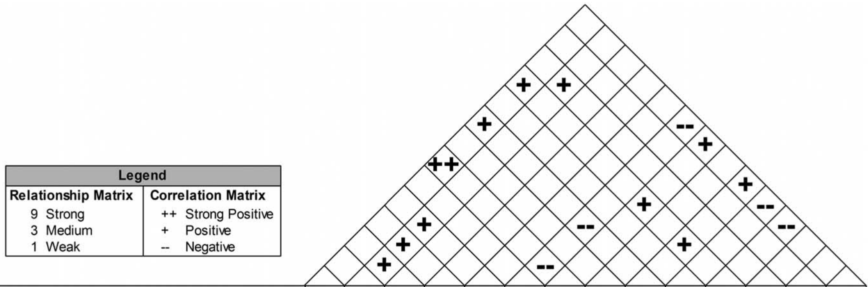
bon footprint of a stapler. This is expected since these three functions together provide the most important functionality of the stapler, i.e., stapling a document. However, it is surprising to see that the function, "support pages," also contributes significantly to the overall environmental impact when compared with other minor functions. According to Table 3, four subassemblies, i.e., bottom housing, pivot pins, anvil mechanism, and magazine, are involved in providing the "support pages" function. By conducting sensitivity analysis on this function, it was found that this is mainly due to the metal (either low-carbon steel or aluminum) used in the bottom housing. Therefore, it is possible to redesign the bottom housing in order to reduce the carbon footprint.

Assigning percentages based on the contributions of the subassemblies to functions carries uncertainties due to the subjective nature, which justifies a sensitivity analysis. Here, the chosen function-component percentages varied around the mean percentage by +/−10% from the selected percentages seen in the FIM (Table 3) following a uniform distribution. One hundred thousand iterations were performed using these combinations of component-function percentages for each iteration, the environmental impacts of the functions were ranked from 1 to 9 in which "1" represents the function with the least environmental impact and "9," the most. Figure 5 illustrates the histogram for each function and the frequency of each rank across all iterations. As seen in the graph, the functions, "support pages" and "form staples," dominate the top two rankings. In fact, in 98% of the runs, support pages achieved at least rank 7. The analysis shows that if the designer is within 10% of the estimates of the function percentage, the same functional areas for redesign will be exposed. In this case, the bottom housing, which contributes significantly to the support pages, is verified as a component to be redesigned in order to reduce the total environmental impact. The variation in function sharing percentages by 10%, in this case, does not change the overall outlook of the FIM because the environmental impacts depend on the material and manufacturing process of the subassemblies themselves.

By combining function-component and function-impact analysis, a QFD that includes both the voice of the customer and the voice of the environment can be developed, as shown in Fig. 6. The target for carbon footprint associated with stapler production is set to be 1 kg CO_2 equivalent, which represents a 10% reduction from the benchmark products with the smallest carbon footprint. Actually, 0.8 kg CO_2 is achieved when summing up the minimum amount of carbon footprint corresponding to each stapler function (use phase contribution excluded) out of the three benchmark staplers. It should be noted that both the requirements and the engineering characteristics with regard to carbon footprint are more or less correlated with other requirements and engineering characteristics. These correlations can be established by conducting additional sensitivity analysis on the LCA results.

Previous discussion on the function impact matrix has revealed that the function support pages contributes 15–20% of the total carbon footprint of staplers and the bottom housing should be an area of focus when redesigning a stapler for reduced carbon footprint. Given the fact that the bottom housing is exposed to force in the vertical direction, the current plate design in all three staplers may not be an efficient one. Also, LCA results suggest that from a carbon footprint standpoint, plastic is the most environmentally friendly, followed by steel and aluminum. The plastic stapler, most notably the bottom housing, is redesigned using CATIA™ V5R19 and Fig. 7 gives a 3D rendering of the new stapler as well as the new bottom housing. The new bottom housing is mainly made of plastic with the anvil supported by a steel frame, which is oriented to sustain the vertical stapling force.

Finite element analysis was used to confirm that the redesign does not change major stress flows. In other redesign situations, the designer should ensure that new modes of failure do not arise and that functional performance is not affected throughout its useful life. This can be achieved by utilizing the "design of shape" of the parts after changing their material. For example, in the present case, the base of the stapler has been changed from metal to plastic, which may cause the base to wear because of contact with the metal. However, since plastics can easily be formed into various shapes, the designer can develop the plastic-steel interface in a manner such that no new failure modes in the redesign would be introduced. For this purpose, the material and shape selection in design concepts can be utilized. Also, how the redesign for the environment affects the functional performance of a product has yet to be completely understood. This topic will be addressed in future work. Table 4 lists the bill of materials of the new design. An LCA is performed and the carbon footprint is found to be 0.95 kg CO_2 equivalent, which confirms that the new stapler is indeed more environmentally friendly.



Row #	Customer Requirements (CR's) / Quality Charateristics (QC's)	Customer Importance (1=Least, 5=Most)	Force to staple (N)	Weight (g)	Length (cm)	Width (cm)	Height (cm)	Stapling Success (%)	Max pages can be stapled (pages)	Min staple leg length (mm)	Max staple leg length (mm)	Life Span (yrs)	Failure rate over life (%)	Cost ($)	Staple reload time (s)	GHG emissions (kg CO2 equivalent)	New Design	Benchmark 1: Plastic	Benchmark 2: Metal	Benchmark 3: PowerEase
	Column #		1	2	3	4	5	6	7	8	9	10	11	12	13	14	Competitive Analysis (1=Best, 4=Worst)			
	Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)		▼	▼	▼	▼	▼	▲	▲	▼	▲	▲	▼	▼	▼	▼				
1	Easy to use	5	9	3	3	3	3	9							3		2	2	2	1
2	Lightweight	3		9	1	1	1									3	1	2	3	4
3	Jam free	3	3					9	9		3			3		9	2	2	2	1
4	Durable	5	3	3				1	3		1	9	9			3	1	1	1	2
5	Can use staples of different sizes	3	1					1	3	9	9					1	1	1	1	1
6	Can be used for thick paper stacks	4	3					3	9		3					1	2	2	2	1
7	Low cost	4										1	1	9			1	2	3	4
8	Low carbon footprint	5						3				3	3			9	1	2	3	4
	Target or Limit Value		20	350	15	2	5	80	20	3	7	5	0.10	20	10	1				
	Difficulty of Accomplishment (0-10)		3	2	3	1	1	1	2	3	6	2	4	5	1	6				
	Weight / Importance		262.5	193.8	56.3	56.3	56.3	334.4	271.9	84.4	165.6	200.0	200.0	140.6	46.9	321.9				
	Relative Weight		11.0	8.1	2.4	2.4	2.4	14.0	11.4	3.5	6.9	8.4	8.4	5.9	2.0	13.5				

Fig. 6 QFD includes both voice of customers and voice of environment

5 Conclusions

In this paper, a novel ecodesign methodology is proposed for supporting early design through visual tools. A new visual tool, called the function impact matrix, which uses information from the function-component matrix to distribute environmental impacts across functions performed by the product, is then developed. This new visual tool is critical since the early design process is generally function focused.

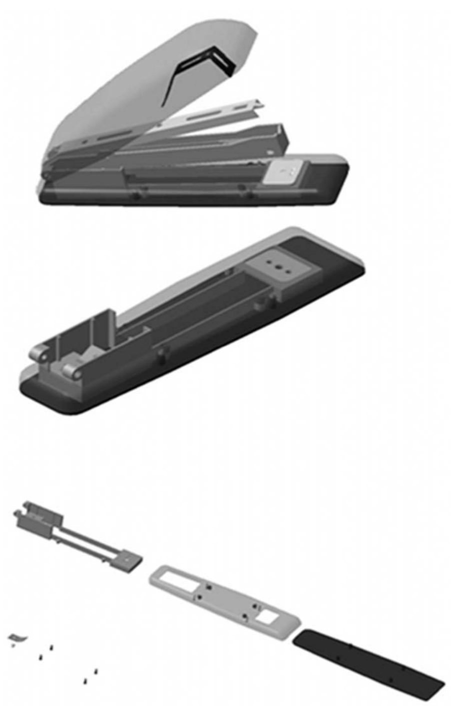


Fig. 7 3D drawings of the new stapler design with the new bottom housing highlighted

Additionally, most new designs are actually novel combinations of existing functions/concepts in already released products'. Combined with traditional function-component matrices, the LCA results and function impact matrix are used to update the QFD to include a voice for the environment. This novel approach is demonstrated in this paper through the redesign of a regular office stapler in order to reduce carbon footprint. A plastic stapler with redesigned bottom housing is proposed. LCA suggests that the new design can achieve at least a 20% reduction in carbon footprint when compared with benchmark products. Furthermore, the case study showed that function-impact may reveal functions that contribute disproportionally to the overall environmental impacts, thus, suggesting areas for improvement. This is different from the traditional design approach, where the focus is usually on the

Table 4 Bill of materials for new stapler design

Part name	Material	Manuf. process	Wt. (g)
Handle	Plastic	Injection molding	35
Base	Plastic	Injection molding	45
Anvil	Low-carbon steel	Blanking and punching	11
Anvil actuator	Aluminum	Die casting	1
Anvil supporter	Low-carbon steel	Blanking and punching	90
Clearing spring	ASTM Steel	Blanking and bending	9
Rivet	Low-carbon steel	Forging	0.3
Base cover	Rubber	Molding	20
Magazine	Low-carbon steel	Blanking and plating	55
Staple advance	Low-carbon steel	Blanking and plating	4
Guide clamp	Low-carbon steel	Blanking and plating	28
Tension spring	Spring Steel	Wire drawing	2
Pivot pin	Low alloy Steel	Blanking and plating	2
Punch/hammer	Low-carbon steel	Blanking and plating	3

structure that delivers a certain function.

It should be noted that there are uncertainties associated with any LCA result. The issue of how uncertainties affect new designs needs to be addressed in future work. Also, tools need to be developed to handle trade-offs when more than one environmental impact category is considered. The effects of redesign for lowering environmental impact on product function and architecture will be considered. Moreover, for the methodology to achieve widespread application, it is necessary to integrate the approach into the current design process so that minimal effort will be required from designers.

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