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Quantifying Sustainability through Reverse Engineering: A Multi-Disciplinary Senior Capstone Experience*

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Many senior engineering capstone projects focus on an open-ended design experience, often ignoring the concept of design sustainability. In contrast, the work reported on in this paper describes a multi-disciplinary engineering team that was given the opportunity to research detailed design factors that contribute to sustainable designs. This paper focuses on the reverse engineering and comparison of design sustainability of four consumer inkjet printers using given design metrics that influence sustainability. Some metrics were open to modification, using these case studies and prior research as an empirical benchmark. The capstone team established a teardown and assessment procedure to standardize the reverse engineering process, the apparent antithesis of their pre-conceived notions for the course (students generally think 'to design' is 'to construct'). In a clear effort to convey the current opportunities in designing for sustainability, the students were able to draw insight from the design comparison of a discontinued printer model (manufactured in 2001) with those currently on the market. While one would intuitively expect the older model to rank lower on a sustainability scale, students also theorized opportunities pertaining to both form and functional improvements in sustainability for all printers involved. Using specific design attributes that have proven implications on design complexity, and therefore design [1], the capstone team has developed a database tool to classify and score consumer products.

Keywords: capstone design; sustainability metrics; product architecture; reverse engineering

1. INTRODUCTION

DESIGN EDUCATION is an incongruous element within the engineering curriculum. Literature has argued the differences between traditional engineering problems (i.e. 'textbook problems') and the open-ended nature of real-world design problems [2]. However, many well-known design authors remain committed to structuring the design process in clear, systematic steps with the aid of many analytic and visual tools [3].

The past twenty years of research has evolved more design guidelines [4, 5], principles [6, 7], and 'best' practices applicable at every stage of an artifact's life cycle, the science of design is now a multi-disciplinary venture.

It is not the goal of the guideline-focused literature to constrain the creative design track, but rather to serve as the starting gates, checkpoints, and finish line assessments. The emerging field of Design for Sustainability has naturally experienced an infusion of guidelines from energy and material-related fields. For example, Royal Philips Electronics has adopted the Eco-Vision program top-down in their organization, to communicate the environmental details (energy consumption, weight reduction, packaging and transport, environmentally relevant substances, and recyclability) of its designs to its stakeholders and customers [8]. In the material domain, vehicle industry leaders BMW, Volkswagen, Daimler, Porsche, Opel, and Ford have established a joint International Material Data System (IMDS) to maintain and archive all material data used for their products [9].

However, within any given design process, current guidelines describe in limited amounts or ignore intrinsic design data existing within the geometric domain of the design, which could add insight into design choices that drive sustainability. Therefore, we, as instructors, offered a problem-based learning experience to seven senior multi-disciplinary design students, which served the following academic objectives:

1. Introduce the current state of sustainability motives in consumer products.
2. Use a case-study to test the assertion that product architecture plays an essential role in the life cycle of a product, and that its effect can be quantified and used by engineers (or in this case, student-engineers) as a comparison and improvement technique against similar functioning products.
3. Sustainability is an inherent multi-disciplinary venture, thereby awarding this team comprised of (4) different engineering majors a chance to reflect how design choices affect products across engineering disciplines.

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1.1 The task

The above educational objectives were transferred to the work statement given to the student team as follows:

1. Reverse engineer (i.e. to completely disassemble, classify, and understand all of the important components *and* their interactions to one another) four consumer products in a fully documented, comparative based case-study.
2. Using knowledge gained from the reverse engineering activity, sustainable guidelines, and architectural measurement methods; identify areas of waste and sustainable practices in the case products, and propose your own design changes to minimize waste.

1.2 The team

Giving undergraduate engineering students a pragmatic method to assess the sustainability of a product's architecture would be a novel task; however, literature describing the role of product architecture in the undergraduate experience is very limited. This new research does not translate well into a structured lecture-based or systematic problem oriented courses. Hence, a multi-disciplinary capstone design course allowed the following areas of flexibility:

1. Multi-disciplinary backgrounds consisting of the following students:
    a. Four (4) Industrial Management (IME).
        i. This major focuses on the design, development, and implementation of complex decision-making systems, along with quantifying and modeling information that can serve decision makers and problem solvers. This major is a perfect match to embark in the reverse engineering process.
    b. One (1) Electrical Engineering (EE).
    c. One (1) Mechanical Engineering (ME).
    d. One (1) Mechanical Engineering/Science & Technology Studies Dual (ME/STS).
        i. The STS Major seeks to understand the influences technology has on society, and vice-versa. This is another valuable point of view in the sustainable design of products.
2. Offer the opportunity to explore certain architectural strategies that a designer could control and/or have a significant impact on sustainability.
3. Offer a hands-on lab approach, similar to many companies' competitive analysis and benchmark testing areas, where competing products are completely disassembled, classified, and compared.

2. QUANTIFYING SUSTAINABILITY

As previously stated, the world of product design has experienced rapid growth in the number of guidelines and metrics applicable to various design process stages.

The Merriam-Webster Dictionary gives the formal meaning of *metric* [10]:

metric (n):	a standard of measurement

Dym et al. focus this definition towards engineering design [11]:

design metric (n):	a scale on which the achievement of a design's objectives can be measured and assessed

Boothroyd [4] and others focused design metrics initially on the assembly process [12], others applied them to quantify product modularity [13] [14], linking this objective to lower retirement costs [15]. Some advances towards eco-design have notably been pushed from the government sector [16] along with the popularity of green initiatives in recent years [17]; industry is beginning to publish the environmental impact data (i.e. metrics) of their products [18]. To stay competitive, companies will measure what matters, and what matters will be measured. Some companies are now offering web-based life cycle assessment (LCA) tools, analysis services [19], and scorecards [20] to clients that wish to quantify life cycle data (e.g. material acquisition, carbon and energy footprints, noxious gas and chemical emissions, land and water impact, etc.) for their products [21]. With increasing green legislative pressures, especially in European nations, Ford of Europe initiated their Product Sustainability Index (PSI) to incorporate life cycle analysis of their vehicles early in their development cycle [18]. Ford's PSI measures eight product attributes over the life cycle of the vehicle, outlined in Table 1. Because of these measures, not only does Ford claim their vehicles improved from an environmental impact standpoint, the company has been publicly awarded by independent and legislative organizations for performing their sustainable analysis over the entire design process.

The traditional design approaches involving optimization of functional requirements and cost have ignored and often competed against sustainable design practices. A perfect case example rests in Table 1, where performance-driven automobile engines of the past were in direct conflict with exterior noise, emissions, and ownership costs. To

Table 1. Ford of Europe PSI Metrics

1. Carbon Dioxide emissions
2. Other gaseous emissions (NOx, VOC)
3. Sustainable (recycled/renewable) material usage by weight
4. Vehicle interior air quality (Allergy tested)
5. Exterior noise impact to the environment (while driving—dB)
6. Safety
7. Mobility (Number of seats/luggage volume)
8. Ownership costs (Price, fuel, maintenance, taxation—residual value)

make an assembly stronger, it may be welded rather than bolted; however, to disassemble this weld is now impossible. It is for this reason that the capstone team was instructed not to focus the majority of their efforts on the functional performance (e.g. yield strength, power consumption, efficiency, energy expended during raw material acquisitions, greenhouse gas (GHG) emissions, etc.), but rather on the form, or architectural (i.e. geometric and material) impact of the design.

3. THE ROLE OF PRODUCT ARCHITECTURE

Product architectures are often categorized between the two extremes of integral or modular. Ulrich and Eppinger define an integral architecture as a complex mapping of function to form with many interactions between component parts, whereas a modular architecture is a one to one mapping of function to form, with relatively few interactions between component parts [22]. Figure 1 presents a visual definition of part arrangements that will be referred to here as architectural orientations.

Product architectural analysis, within the scope of this capstone experience, defines a *part* in the sense that is must exist or have existed separate from other parts, prior to manufacturing, to perform a single function. For example, a motor or a printed circuit board may have tens or hundreds of integral parts (windings, screws, resistors, etc); however, they are each classified as a single part within this methodology. In reality, the designer of a printer will not design internal components of a motor, but rather appropriately match an existing (i.e. 'off-the-shelf') motor to the outlined specifications. A printed circuit board will typically be disassembled as an entire entity and recycled as-is [23]. Likewise, a *module* is defined has a collection (i.e. assembly) of at least two connected parts that perform an overall function. A module will exhibit a higher degree of part connectivity (i.e. integration) within itself, but will be easy to remove from the rest of the artifact. Modular devices may be defined as machines, assemblies, or components that perform a function through a combination of distinct and detachable building blocks [3].

Specifically for mechanical assemblies, sustainable products exhibit both modular and integral architectures; and there exists possible arrangements (i.e. design alternatives) of modular and integral systems within a product's architecture that are more sustainable than others are. Most products incorporate a mixture of integral and modular elements. Functional design requirements (e.g. performance, strength, energy transmission, lower number of parts) may drive designs toward an integral architecture, or increase the number of components [24]. An integral architecture means that all parts have physical dependencies with no clearly identifiable base part.

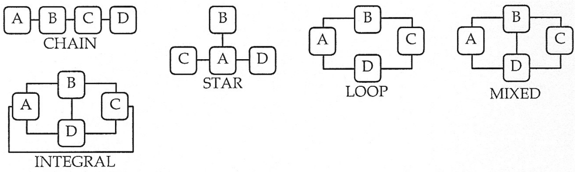


Fig. 1. Architectural orientations: part arrangements.

Morris [25] and Palmer [26] proposed the use of graphs to allow designers to conceptualize assembly architectures that are free from functional constraints in order to give designers freedom to redesign and reorder components without geometric and functional constraints.

All of the graphs represented in Fig. 1. depict *connected* graphs. A graph is connected if every pair of parts (vertices) has at least one connection (edge). A tree is a connected graph that has no cycles. The 'Star' and 'Chain' architecture represent tree configurations. The central part in the star (part 'A') can be defined as the base part. It is the part with the most part connections or interactions [27].

4. CAPSTONE APPLICATIONS

4.1 The products

The team felt comfortable assessing electromechanical consumer inkjet printers. Aside from the availability and price, the components for the most part, are easily identifiable as to their function and material type. Inkjet printers suit architectural studies due to their common functions, shortened technology cycle, shrinking geometric footprint, decreasing weight, moderate part count (less than 200 parts), and present a clear need maintenance (i.e. ink replacement). Sustainable initiatives from companies such as Hewlett-Packard$^{\text{TM}}$ (HP), Lexmark$^{\text{TM}}$, and Epson$^{\text{TM}}$ have become transparent in their products during the past decade. The students were given the following products (Figs 2–5). All products are current models (manufactured est. 2008) with the exception of the HP 960C (manufactured Sept. 2001). Within the last seven years, have architectural design decisions been impacted by external pressure to design for sustainability? If so, can designers use sustainability metrics to drive sustainable product architectures in the future? The answers to these questions were the much sought-after insights the capstone team would hope to understand by semester's end.

4.2 The procedure

In an effort to keep this methodology practical to a design unit (i.e. designer or design team) at any particular point in the design process, classification boundaries must exist.

Parts were classified into modules from visual

Fig. 2. HP D1560.

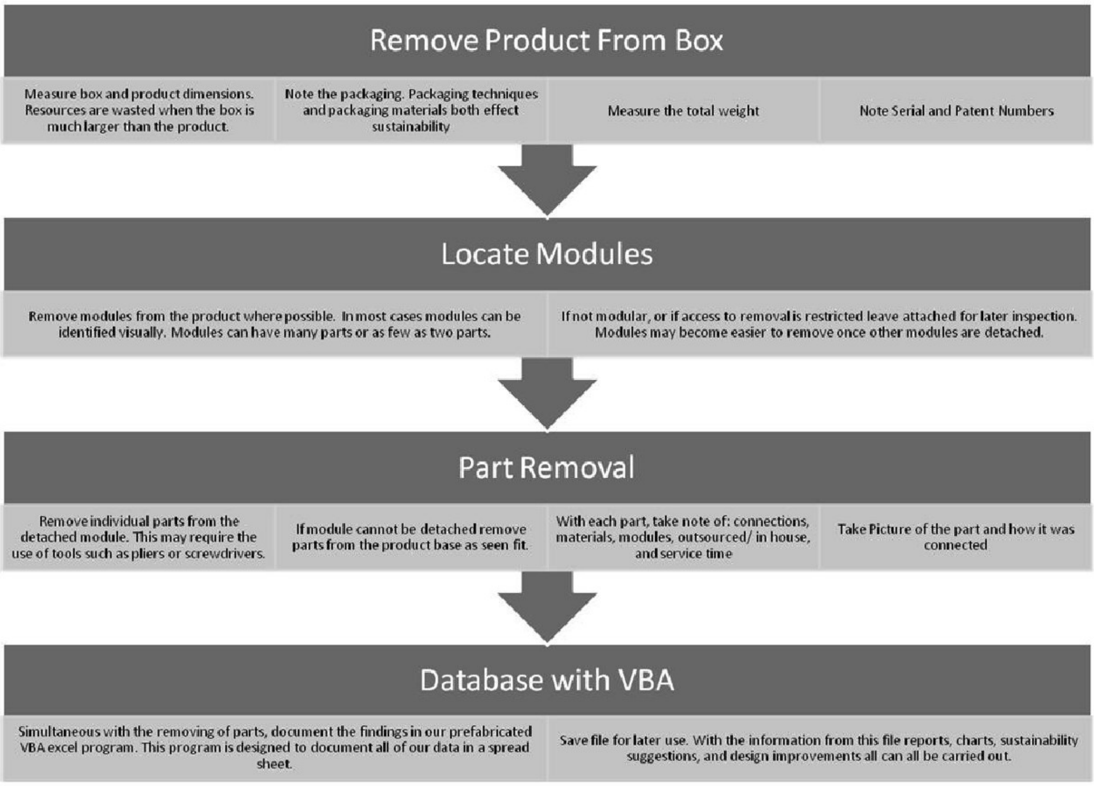
Fig. 3. HP 960C.

Fig. 4. LexMark Z1300.

Fig. 5. Epson C120.

inspection and connectivity analysis to surrounding parts during disassembly.

Much to the delight of the instructor, the team chose to automate the classification (i.e. 'bagging and tagging' of components) of each product part by formulating an original database program. Drawing from the strengths of the IME students, the process of starting with the virgin product, new in box, to the completely disassembled phase is detailed in Fig. 6.



Remove Product From Box

Measure box and product dimensions. Resources are wasted when the box is much larger than the product.

Note the packaging. Packaging techniques and packaging materials both effect sustainability

Measure the total weight

Note Serial and Patent Numbers

Locate Modules

Remove modules from the product where possible. In most cases modules can be identified visually. Modules can have many parts or as few as two parts.

If not modular, or if access to removal is restricted leave attached for later inspection. Modules may become easier to remove once other modules are detached.

Part Removal

Remove individual parts from the detached module. This may require the use of tools such as pliers or screwdrivers.

If module cannot be detached remove parts from the product base as seen fit.

With each part, take note of: connections, materials, modules, outsourced/ in house, and service time

Take Picture of the part and how it was connected

Database with VBA

Simultaneous with the removing of parts, document the findings in our prefabricated VBA excel program. This program is designed to document all of our data in a spread sheet.

Save file for later use. With the information from this file reports, charts, sustainability suggestions, and design improvements all can all be carried out.

Fig. 6. Reverse engineering process.

Table 2. Comparative results

Applied metric	HP 960C	HP D1560	Lexmark Z1300	Epson C120
Part count	143	116	77	121
Total weight (oz.)	208	71.5	84	118
Service time index	5.5	4.8	3.8	5.5
Adjusted part connectivity	0.28	0.47	0.15	0.54
Module count	21	14	7	11
Integration level	41	54	15	61
Unique materials	17	12	15	17
Package volume ratio	0.43	0.52	0.68	0.52
Overall sustainability score	–3.1	–2.2	–2.2	–3.7

Table 3. Architectural metric definitions

Part count	The total number of parts in the system as defined by section IV.D.
Total weight	The measured weight of the total product, due to the material and component choices.
Service time index	This metric quantifies the accessibility (i.e. number of parts requiring removal before accessing a particular part), joint strength [25] [28], and connectivity between parts.
Module count	The number of modules visually or functionally identified. Design for retirement research has identified modularity as a key concept to decrease life cycle costs [29].
Integration level	This metric quantifies the number of cycles in a product's architecture (see section III). A higher cycle count signifies increased part connectivity and overall complexity [30].
Unique materials	This metric quantifies the number of different materials within the product. The use of higher amounts of differing materials increases the difficulty of recyclability.
Package volume ratio	The smallest cube volume of the product/the cube volume of the package, values approaching unity are ideal to minimize wasted space.
Adjusted part connectivity	Line and Steiner [28] describe adjusted part connectivity (PC_a) as the average number of connections per part in an assembly, normalized at (4) connections per part.
Sustainable score	This is the result of the sustainable model given appropriate inputs.

4.3 Model results

The capstone team accumulated the comparative results in Table 2. Some product architectural metrics used are detailed in other literature [25, 28]. After an initial literature study on sustainable designs and product architecture, the team added another metric: *Service Time Index*. Table 3 lists the definitions of the architectural metrics used by the team.

After which, a weighted linear model yielded the objective score given (last row in Table 2). The greater (more positive) the value, the 'better' the product performed in the sustainability assessment. The inconsequential fact that the scores were negative was a result of the specific weighting factors used.

5. DISCUSSION

The purpose of this capstone was to engage students in a problem-based learning experience, while introducing them to another avenue of sustainable design. Using the quantitative data above, the students linked the sustainability of the printers to product architectural design choices. The following list shares some insights:

- Multiple joining methods for the same parts (960C): for example, parts both welded and bolted together; this was not present in current models.
- The HP 960C consisted of more aluminum and steel parts (as seen by the 2 to 1 factor of weight increase in Table 2) than similar functioning plastic pieces in current models. While this would increase sustainability in the material domain from a recyclability perspective, the 960C incurs many more parts due to the lack of integral fasteners and structural integrity necessary to constrain the heavier components.
- A considerable amount of parts in the Epson C120 consisted of polyoxymethylene (POM), used for its wear-resistant and high strength properties, however, its recyclability is rather poor.
- Due to poor geometric design, the HP D1560 package forfeits approximately 45 in.^{3} of space within its cardboard box. If a standard shipping pallet was stacked ten rows high, 20 more printers could be shipped per pallet! Moreover, each brand's package had varying amounts of protective Styrofoam, wasting space and creating more byproducts likely to end up in solid waste streams.
- The Lexmark Z1300 incurs the lowest score due to its lower part count, minimal wasted packaging space, and lower service index. Overall, this printer was the least complex and integrated, and from these case examples, the students concluded this led to higher sustainability.

6. CONCLUSIONS

Reverse engineering an existing product is a necessary first-step to perform any product architectural and sustainability assessment. The multidisciplinary design team became well suited to the inquisitive nature of a tear down and assessment procedure. It could be argued that we, in the academic setting, fail to realize the true intent of some alleged 'unsustainable' design choices discovered during the process, and to a certain degree, the students were not expected to know the functional existence of every part. However, the beauty of analyzing the product's architecture is the freedom from the functional domain. To design the artifact to be less complex architecturally is to enhance sustainability.

Understanding the concept of design trade-offs is necessary for every senior engineering student. At best, a senior capstone project strives to cover this implicitly. For example, to increase print speed, a printer head will move faster, causing ink spillage and waste. While boasting the highest print speed of the printers studied, the Epson C120 spilled a considerable amount of ink, so much that an entire product module (ink tray) had to be designed to accommodate the waste. While the spilled ink was the obvious culprit, by critically evaluating the added geometry, modules, and materials that increase complexity, the team can now offer insight into design choices that may enhance sustainability.

Capstone experiences aim to engage students, to have them become part of the design process, seek their own answers by formulating their own questions. While the ME and EE student were mostly motivated to find functional metrics assessing sustainability (e.g. stepper-motor efficiency, energy consumption, gear backlash), this experience demonstrated to the entire team the important role of material, geometry, part arrangement, and connections (i.e. a design's architecture) towards achieving sustainable design.

Multi-disciplinary reverse engineering endeavors engage students at the very foundations of design work: inquiring into the nature of form and function, confronting their uncertainty about the product, and because the complete system exists, assessing the design from a *system* and *module* perspective—a methodology frequently lacking in mechanical design courses.

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