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IMPLICATIONS OF PRODUCT SYSTEM ARCHITECTURE ON DESIGN SUSTAINABILITY

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ABSTRACT

Product system architecture defines the foundations, components, and configuration upon which a design is conceived and can have major impacts upon design sustainability. Relatively little work has been done to fully understand the implications. A first step toward the goal of improving our understanding is to better quantify the attributes of product system architecture. For example, modular architectures may be beneficial from a sustainability perspective, whereas integral architecture may be better for performance. Using interaction graphs and the mathematics of graph theory, metrics for evaluating product system architecture are proposed to quantify and make design trade-offs. These metrics are developed from information derived from the geometric design domain based upon part connectivity. With an understanding of product system architecture, it is envisioned that experienced or student system designers can be taught to make more informed decisions resulting in systems that holistically consider configuration design trade-offs, thus filling a gap that is seriously lacking in terms of educating engineering designers of the future.

Keywords: sustainable design, product architecture, education

1 INTRODUCTION, MOTIVATION,

Sustainable design refers to products, processes, and systems that meet the needs of the present without compromising the ability of future generations to meet their own needs. A sustainable design has a life cycle designed for the purposes of furthering its functional life or reclaiming its maximum value for future products, so that minimal waste is generated. Most designs exhibit a combination of modular and integral architectures; and there exists possible arrangements (i.e., system designs) defined as a product architecture that may be more sustainable. Popular design methods such as Design for Assembly [1] tend to encourage designers to integrate more functions into fewer parts in the interest of improving performance and reducing cost. There are inherent conflicts between the broad economic and environmental impacts that drive the need for modular product architecture versus design practices that often result in integral architectures.

2 BACKGROUND

Computer-aided design (CAD) systems focus exclusively on the geometric domain and do not provide a convenient format or the tools for assessing product architecture. Here we describe tools that can represent product architecture in the form of two-dimensional interaction graphs. These graphs display the arrangement of parts and their interfaces to other parts in an assembly, and they are useful for designers because they offer a display of the complexity and arrangement of a design. This is not apparent when viewing assemblies in a three-dimensional space, as is the case with solid modelers. Interaction graphs allow the designer to visualize the extent of design integration. Using graph theory tools and analysis, a designer can identify connections that are candidates for deletion and categorize the "base" part. Aligning the base part to the primary product functions can become an important strategic consideration with regard to technological obsolesce and design sustainability. Cycles in designs that inhibit modularity can be targeted for elimination based on joint strength, part connectivity, material type, relative motion, functional specifications, and other life cycle attributes.

Designing for modularity is becoming an important concept to product designers because it facilitates changes across a product line and throughout the life cycle of a product family. Companies are always trying to find new areas in their manufacturing process where they can lower cost, improve flexibility, and meet rapidly changing market demands. They are also becoming more aware of their impacts on the environment and customer reactions to their product's life cycle. Alongside the wide variety of components that customers demand, designers are forced to optimize modularity for quick redesign and manufacture cycles, as well as serviceability.

3 REVIEW OF PRIOR WORK

In the 1980's, Boothroyd and Dewhurst [1] popularized the idea of Design for Assembly (DFA) by introducing the concept of parts count reduction as a means for achieving design simplification. In the early 1990's, businesses became interested in reducing inventory for improving product delivery responsiveness, which encouraged researchers to explore ways to configure products in ways that would streamline production, while expanding product variation [2, 3, 4]. Most of this work was directed toward high-level system and product line planning during new product development. Ishii [2] proposed a variety of modularity metrics to improve design for life-cycle engineering. Yassine et al. [4] introduced the "connectivity map" as a matrix based tool to analyze component dependencies on design parameters and objectives. As a foundation for the work presented here, Line [5] and Palmer [6] developed methods to extract part connections from assemblies in solid modeling programs. This paper focuses on metrics and methodologies that can be used by design engineers, in the context of product redesign at the part and assembly level.

4 ARCHITECTURAL ORIENTATIONS

Product architectures are often categorized between the two extremes of integral or modular. Ulrich and Eppinger [7] 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. Figure 1 presents a definition that will be referred to here as architectural orientations. In the cases we have studied, there is usually a combination of both integral and modular orientations. All of the graphs represented in figure 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 can be defined as the base part. It is the part with the most part connections or interactions. An integral architecture means that all parts have physical dependencies with no clearly identifiable base part. Striving towards modular design in a world of rapid product development is a cost effective way of generating robust product families. However, Gershenson [8] notes the lack of practicality in many design-for-modularity methods. Here we propose 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.

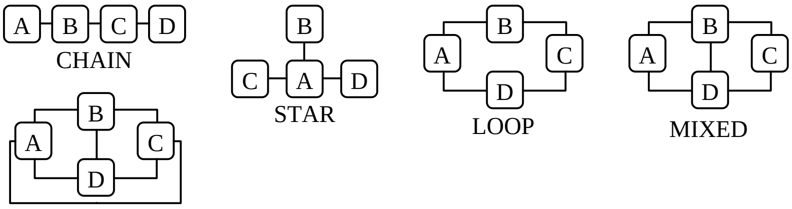

Figure 1 Architectural Orientations – Part Arrangements

5 BASE PART DEFINITION

Steiner [9] suggests maximizing attachment to a base part, while minimizing interfaces with adjoining parts to encourage modular product architecture. Base parts fall into two general categories [10]:

1. Base parts that serve the primary design function need to accommodate the possibility of size variations and are often the most technologically advanced part, hence the need for upgradeability when technology becomes obsolete. They are often locally integral to improve performance and reduce cost, but should be designed to have low joint strength connections to increase modularity.

2. Base parts that primarily serve to provide physical structure should maintain modular interfaces to satellite parts and assemblies to serve as a stable platform for future product generations. They should also avoid congestion associated with too many connections to other functional sub-assemblies, which increases design complexity.

6 GLOBAL MODULARITY AND LOCAL INTEGRATION

Modularity corresponds to flexibility and variation. In contrast, integration corresponds to stability and optimization [3]. Because there is a design trade-off with integral and modular designs, *local integration* **and** *global modularity* should be maximized to achieve the optimal design.

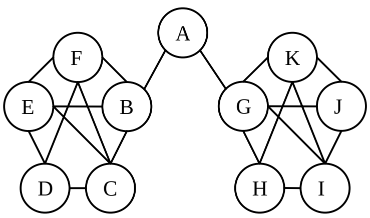

Figure 2a Local Integration and Global Modularity

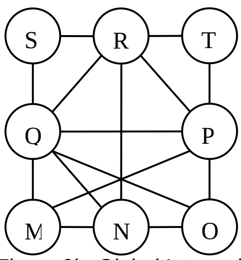

Figure 2b Global Integration

In figure 2a, sub-assemblies B-F and G-K are locally integrated. They are joined to base part “A” by a single connection. This signifies global modularization, and is useful for life-cycle engineering because sub-assemblies B-F and G-K can be readily replaced, serviced, and/or recycled. Figure 2b denotes a global integration scheme in which any change to any part will require a disassembly of several other parts or the possibility of scrapping the design entirely. Furthermore, there is no clear base part in his architecture scheme and it would be difficult to prescribe a functional alignment with any part.

7 ARCHITECTURE METRICS

Using interaction graphs the following metrics can be used to iteratively evaluate architectural design trade-offs.

7.1 Cycle Count

When product architecture is evaluated in terms of connectivity graphs some groups of edges form cycles [11]. The only orientations that do not form these cycles are, by definition, trees. Architectural orientations with many cycles tend to be integral. This is because a single part is connected to more than one other part, reducing the ease to which that part can be serviced, upgraded, and recycled. Eliminating cycles is one approach for improving the “modularity” of an assembly. Graph theory [4, 11, 12] can be used to interpret these connected graphs and give designers a practical way to improve modularity. For a connected graph:

$$\boldsymbol{d = 2 * e} \qquad \text{(Eqn. 1)}$$

$$\boldsymbol{L = e - v + 1} \qquad \text{(Eqn. 2)}$$

Where d is the number of edges incident on all vertices (total degrees of the graph), e the total number of edges (connections), v the total number of vertices (parts), and L is the number of cycles. These parameters can be computed using Palmer’s method [6] of determining the number of parts and connections in a solid model assembly.

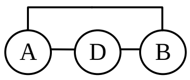

Figure 3a: Integral

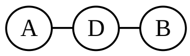

Figure 3b: Modular

In fig. 3a if part D is the base part, then parts B and A creates a cycle because they are connected to each other while still being connected to the base part. Shown in fig. 3b is the acyclic nature of a modular architecture. Removing or modifying part A will not affect part B, and vice-versa. Reducing cycle count increases modularity.

7.2 Adjusted Part Connectivity

Line and Steiner [5] describe adjusted part connectivity (PC_a) as the average number of connections per part in an assembly (where d = total number of degrees (Eqn. 1), v = total number of vertices), normalized at (4) connections per part:

$$PC_a = \frac{(d-2v)+2}{(v^2-3v)+2} \quad , \qquad \text{For v = 3 or 4} \quad \text{or,} \qquad \text{(Eqn. 3)}$$

$$PC_a = \frac{(d-2v)+2}{2v+2} \quad , \qquad \text{For v > 4} \qquad \text{(Eqn. 4)}$$

These equations were developed using graph theory where values of PC_a can vary from 0 to 1 when $\Sigma d/v$ < 4. Values of PC_a close to zero, or at the lower extreme indicate that the architecture is modular, whereas values at the higher extreme indicate an integral architecture. Case studies [10] have shown that a practical integration limit occurs when on average every part has four connections to another part.

7.3 Fundamental Connection Index

Using Boothroyd’s [1] three criteria of relative motion, service, and material, connections rather than parts can be defined as either “fundamental” or “incidental” [13] and analyzed for necessity in design, and if incidental, then depending on the connection strength (joint strength), be seen as a connection with no dependencies. A ratio of the number of fundamental connections over total connections in the assembly can be used to assess how well an assembly is optimized.

7.4 Joint Strength

Reducing the number of cycles to improve modularity ultimately leads to deleting unnecessary edges in a connected graph. A metric that can be used to rank edges for deletion is joint strength that represents the effort required to separate the joint [6]. For example, connections involving integral fasteners with no tools required to separate them will have a low joint strength, whereas in contrast, joints involving a chemical reaction (weld, adhesive, solder, etc.) would be high joint strength.

8 DESIGN FOR SUSTAINABILITY GUIDELINES

Design methodologies tend to be adopted by engineers when they help to improve products based upon accepted design guidelines. The success of design methodologies is based upon underlying design guidelines that can be readily taught and learned. For the methodologies and metrics proposed in this paper, we propose the following design guidelines to optimize modularity and design for sustainability:

1. Maximize attachment to base parts, while minimizing interfaces with adjoining parts for modular product architecture.
2. Strategically identify the base part a product platform for future upgradeability
3. Maximize local integration and global modularity to improve recycle-ability, serviceability, and upgrade.
4. Reduce part connections and cycles to increase modularity
5. Minimize part connectivity to reduce complexity and high congestion of connections per part
6. Eliminate or minimize incidental connections and maximize fundamental connections
7. Reduce joint strength when possible for improved modularity

These guidelines in conjunction with the methods previously described, can serve as a foundation for the introduction of sustainability concepts in undergraduate design courses. Our initial experience with students indicates that at the very least, the methods encourage students to factor sustainability into the context of design. As with most design methods, students, as well as practicing engineers, will need to be encouraged to be creative and deal with the typical ambiguities involved with design. We see reverse engineering case studies by students as an excellent approach to optimize this methodology within the current design process.

9 CONCLUSIONS AND FUTURE WORK

In this paper, we have presented a first step toward developing a practical design for sustainability (DFS) methodology. Much work remains to integrate the design guidelines and proposed metrics with existing CAD technology and ultimately to validate the proposed system with case studies. In future work, we propose to define a utility function that can be used by students and designers to measure how well products satisfy design sustainability objectives and guidelines. DFS utility function attributes will include manufacturability, modularity, reliability, recycle-ability, and logistics. In each area, attributes will be defined to provide tangible inputs for the utility function. Interaction graphs will be used as product architecture models to reverse engineer and conduct sensitivity analysis on design iterations. If we are successful, our DFS methodology will provide insight and design guidance.

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