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ARE MODULAR PRODUCTS LARGER THAN INTEGRAL PRODUCTS?

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ABSTRACT

Modularity, the use of structurally independent building blocks (modules), has become a common strategy in many companies due to its numerous economical benefits. One of the disadvantages mentioned with modularity is the possible larger size of the modular products compared to their integral counterparts. For example, modular products are claimed to be larger and heavier due to the space and weight taken by the additional interfaces not needed in integral products. There is, however, no quantitative investigation whether modular design leads to larger or heavier products. We will, in this paper, show the relationship of product size and the degree of modularity. We use two pre-existing modularity metrics to measure the modularity of the products and a packaging factor to measure the use of space in the product. We investigated the relationship of product's degree of modularity and its Packaging Factor in a case study of four product pairs of similar function: cellular phone & desk phone, laptop computer & desktop computer, walkman & boom box cassette player, portable CD player & standalone CD player. We found that modular products use space less efficiently than their integral counterparts. In general, the modular products were also larger, but the larger size was not necessary for the functionality of the products. We therefore conclude that modular products do not have to be larger than integral products and thus the size should not be a reason not to pursue modularity if the other benefits of modularity are sought after.

Keywords: Modularity, Product Architecture

1 INTRODUCTION

Modularity and integrality refer to the interconnectivity of components within a product. Modularity, the use of structurally independent building blocks (modules)[1,2], has become a common strategy in many companies due to its numerous economical benefits. These benefits include savings due to economies of scale, faster development time due to design reuse, and ease of product variety by use of interchangeable modules [3,4]. One of the disadvantages mentioned with modularity is the possible larger size of the modular products compared to their integral counterparts [5,6].

In order to define a product as modular or integral it is important to understand what properties these titles denote, and what this means to the various methods of quantifying these apparently ambiguous titles. It is also important to discuss what the relevance of such information is and how it is applicable to product architecture.

A product which is referred to as integral has many connections between different components which interact in a multitude of ways [4]. An example of an integral product is the Apple I-Pod video/MP3 player. This palm-sized device has the capabilities to organize, play, and store your personal music and video library onto the same unit. Most physical products are integral to some degree. The opposite of integral is modular. A product that is very modular is one which has many interchangeable parts and very few connections between distinctly separate modules. Similar to integrality, the property of modularity is something that all products possess to some extent. An example of a modular product is the Personal Computer (PC). Every component of a PC, with the exception of the motherboard, has the ability to be interchanged and removed with relative ease.

Products of any variety may be analyzed to determine their density, or how efficiently they use the volume they occupy. A repeatable methodology and a metric Packaging Factor (PF) was developed in order to quantify this characteristic of physical products. Packaging Factor is a previously unexplored facet of product architecture and thus receives much attention to methodology and its results with reference to the results from other methods of quantifying modularity such as the metric developed by Guo & Gershenson [7]. The Packaging Factor of different products can be compared to each other which may or may not lead to conclusions regarding Packaging Factors relevance as well as other methods reliability. Packaging Factor, if determined to be indicative of a product's modularity, could be used to further classify products by modularity and aid in the determination of whether or not modularity is inherently beneficial.

The primary goal of this research is to determine whether or not modular products are larger than integral products. In order to be able to measure the size and space used by the products' components, a novel metric, Packaging Factor, was developed. Utilizing the Packaging Factor allows us to quantify the way modular and integral products use the volume that the product occupies. Another goal of this research is to determine a repeatable way of calculating the Packaging Factor for a product, and establish the relevance to modularity and the implications of such data. In Section 2.2 Packaging Factor, the experimentally derived methodology for determining the ratio of 'used space' within a product to the total space it occupies, is discussed in detail and is revisited for critique in section 4 Discussion.

1.1 Product Architecture

Product architecture is the mapping of product function to the completed product form [8]. A well designed product encompasses well structured product architecture, to the point where every component has a very detailed function and does not contain needless components. Reducing the amount of components leads to an overall integral product. An integral product has a very high function-to-component ratio, which means that the product is able to perform many different functions using the same components in different ways. This approach is opposite to the idea of modularity, where modular products have many components that correspond to a specific function that the product fulfils. Often times, one design method is chosen over the other even though the advantages of applying either method to a certain product are not fully realized.

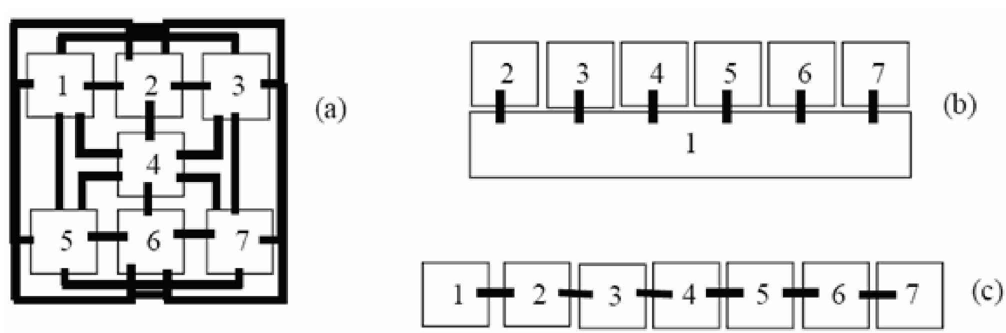

Figure 1 – Generic product structures of a fully integral (a), bus-modular (b), and modular system (c)

Products can be described as having characteristics of an integral, bus-modular, or modular architecture. The product structures in *Figure 1* [9] illustrate these ideas clearly. The bus modular system contains a main 'motherboard' type element where separate physical elements can be attached and detached to the main bus easily. An example of a bus modular system would be a desktop PC motherboard. The video card, ethernet card, and sound card are all separate physical elements which are 'loosely' connected to the motherboard and do not necessarily connect with each other. The structures in *Figure 1*, mainly the integral and modular structures, shall be referenced and made comparisons against in order to determine the structure type of the product under consideration.

1.2. Benefits and Disadvantages of Modularity or Integrality

Modularity often means using the same module in multiple products enabling a large variety of products while using more common component types than if the different products did not share common modules. This can bring scale and scope advantages such as reduced capital requirements as well as economies in parts sourcing and manufacturing [1,3].

Modules are also helpful in design re-use since already designed modules with well defined interfaces can be used again in other designs [11,12]. This applies to software products as well as hardware. Design (module) re-use can lead to reduced cycle time, which in turn results in e.g. increased revenue due to increased market penetration as a result of being first to market, success in time sensitive markets, and shorter time to market increases accuracy of meeting emerging customer needs. Further, product change, upgrade, and variety can potentially be achieved by replacing one or more modules in a system without other changes to the overall product, or product platform [4]. In addition, a well defined module, in terms of simple interfaces, can ease project management due to decoupling of tasks, enabling parallel development, and providing design freedom within a module. Further, modular design can also bring benefits at the end of a product's lifecycle - as a means to ease the disassembly and recycling of the product [13].

Modularity can also have disadvantages, and an integral architecture may then be preferred. Whitney [6] argues this especially in the case of high power mechanical products, as opposed to low power information processing products. A more modular product is likely to be larger, heavier, slower, and less energy efficient. Also side effects are harder to control. This argument is supported also by Cutherell [10] who mentions an example of a modular heavier car being less fuel efficient. In his work, Whitney [6] compares complex electro-mechanical-optical products to large chips designed with VSLI (very-large-scale-integration), which can be considered fully modular. Mechanical parts have a "multi-function character" partly due to basic physics (material contains also energy, rotating axle transmits shear loads and rotational energy) and partly due to "design economy". Whitney also points out that the interfaces (in high power systems) require substantial space and weight and they must be custom-designed for each application. Also, Benini and de Micheli [5] discuss the same issue. According to them power optimization is especially important in low power, high performance systems, such as cellular phones.

2 METHODS

We investigated the relationship of product's degree of modularity using two pre-existing modularity metrics and its packaging factor, both of which will be described below. We used the three metrics in a case study of four product pairs of similar function: cellular phone[1] & desk phone[2], laptop computer[3] & desktop computer[4], walkman[5] & boom box cassette player[6], portable CD player[7] & standalone CD player[8].

2.1 Modularity Metrics

We use two pre-existing modularity metrics to measure the modularity of the products and a packaging factor to measure the use of space in the product. The first metric is the functions to components ratio (See Eq. 1).

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[1] OKI, 1998
[2] Sony, IT-B3, 1996
[3] Dell Inspiron 3800, 2000
[4] Dell Dimension Series Pentium II, 1999
[5] Sony WM-EX110, 1995
[6] Toshiba RT-100S (80's)
[7] Philips Powersaving 45ESP3 (2000's)
[8] Onkyo DX-702, 1991

$$M_1 = \frac{n_{functions}}{n_{components}} \quad (1)$$

$n_{functions}$ is the number of functions in the product
$n_{components}$ is the number of components in the product

This is based on the notion that a modular product has close to a one-to-one mapping from functions to components, whereas in the case of an integral product, multiple functions are realized by few modules. We disassemble each product to obtain the number of components. The number of functions is determined using a functional decomposition approach described in detail in [8]

The second modularity metric (See Eq. 2) used in this study was developed by Guo and Gershenson [7]. The metric is based on the definition of a module, where a module is tightly connected within a module and loosely connected to the rest of the system.

$$M_2 = \frac{\sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k} \sum_{j=n_k}^{m_k} R_{ij}}{(m_k - n_k + 1)^2} - \sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k} \left(\sum_{j=1}^{n_k - 1} R_{ij} + \sum_{j=m_k+1}^{N} R_{ij} \right)}{(m_k - n_k + 1)(N - m_k + n_k - 1)}}{M} \quad (2)$$

where
n_k is index of the first component in k^{th} module
m_k is index of the last component in the k^{th} module
M is total number of modules in the product
N is total number of components in the product
R_{ij} is the value of the i^{th} row and j^{th} column element in the “modularity” matrix.

This metric can be applied to component-to-component matrix as explained in [7]. The number of components and modules is based on the disassembly of each product.

These metrics use a slightly different definition of a module or modular product architecture, but since the connectivity between and within modules is directly the connectivity of the product’s functions, the metrics result in similar results. Two metrics is, however, used to not limit the study to only a single view of modularity.

2.2 Packaging Factor

Packaging Factor (See Eq. 3), as developed here, is defined as the ratio of the interior volume used by a product divided by the total volume a product occupies, thus quantifying how well a product utilizes its volume.

$$PF = \frac{V_{used}}{V_{total}} \quad (3)$$

V_{used} is the interior volume used by the product
V_{total} is the total volume a product occupies

This value is derived from the products geometry. Packaging Factor, if determined to be indicative of a product’s modularity, could be used to further classify products by modularity and aid in the determination of whether or not modularity is inherently beneficial.

The Packaging Factor is a numerical value which gives the observer a representation of the unused volume within the product. A limitation to the method is that it involves the use of a commercial moulding material[9] which is realistically usable for measuring of unused volume only when a

[9] *Crayola Model Magic*

relatively small product is being studied. Products with a large interior volume require separate methods to determine the 'unused' space within the product. Methodologies for both cases were developed and are described in the following sections.

2.2.1 The spill over method

The spill over method is used to determine a volume by displacement. As seen in Figure 2 an object is inserted into a container which is at a slight angle for accuracy. The container is filled with water so that a single drop would displace water over the brim. This container is placed on a metal rack which has enough structure to support the container of water and can also allow displaced water to pass through, which is supported by legs. Beneath the rack is a collection tray for capturing the displaced water for measurement.

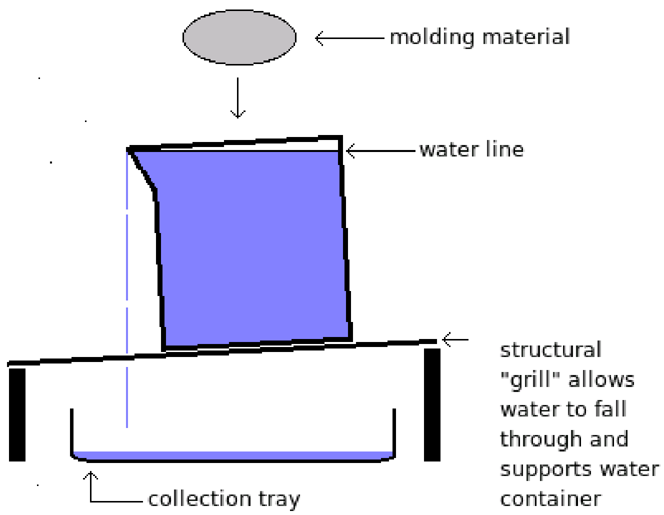

Figure 2. Spillover method experimental setup

2.2.2 Methodology for Determining Packaging Factor

The methodology for determining the packaging factor of a certain product can change depending on the size and geometry of the product. Creating and developing methods for accurately obtaining the volumes of products of different sizes was an important aspect of the research.

Products of relatively smaller sizes (portable CD-Player, portable cassette player, cell phone, desktop phone) were able to make use of one of the methodologies that was developed to measure the two necessary volumes of the product in order to obtain the packaging factor value. Products with difficult to measure exterior geometries had to be sealed with a zip-loc bag with known volume, and was then submerged into a completely full container of water. An example of a product that falls into such a category is the miniature engine used for remote controlled RC vehicles shown in *Figure 3.*

Figure 3. NEO-16ST engine manufactured by Megatech

The amount of water that was displaced over the edge of the container was captured by another container. The volume of water in the 2nd container was measured and was recorded. This measured volume was the exterior volume of the product.

To determine the total used interior volume of the smaller products, the moulding material was used to determine the amount of 'dead space' within the product. The product's cover was opened and the moulding material was placed into every visibly open area inside the product. The cover(s) was then pressed together and the excess moulding material was forced out of the product. The excess material was removed, and the product was then opened and the amount of material that remained in the product was removed and its volume was recorded using the spill over method. This 'dead space' measurement was subtracted from the exterior volume of the product to obtain the amount of interior space that was occupied by the product itself. The packaging factor of a relatively smaller product can then be calculated.

The methodology for developing the packing factor for relatively larger products (PC tower, Laptop, standalone CD player, standalone cassette player) differs on two accounts. The spill over method no longer is useful because the product cannot fit inside the container holding the water, and the moulding material (in most cases) is not useful because the 'dead space' within the product is too large and would require more moulding material than was purchased. The exterior volume of these larger products was found by measuring the length, height and width with a measuring tape capable of measuring millimetres. The total used interior space was measured by a variety of methods depending on the objects within the product. Integrated circuit boards were covered with the moulding material in order to create a uniform object that could be measured with the measuring tape. The volume of the removed moulding material was subtracted from the initial volume measurement in order to give the volume of the circuit board. Objects of uniform geometry were measured using the measuring tape to accurately determine the volume. The total of the used interior space of the product was taken and was divided by the total exterior volume to determine the packaging factor.

3 RESULTS

The packaging factor is categorically larger for the smaller product of the pair of similar products (Table 1). This is logical as the same or similar functions must fit into a tighter space. For example, the packaging factor for the cell phone was 0.90 whereas the same value for the larger desk phone was 0.61. Results are similar in all product pairs. The desktop and laptop computers have the most pronounced difference in their Packaging Factor values.

The two metrics for modularity correlate well with one another except for one product pair – the walkman and the cassette player. We do not have enough data to fully confirm why these metrics do not give similar results, but it is likely to do with the different interpretations of modularity behind the metrics, as discussed in a recent literature review [12], for example.

Comparing the two modularity metrics to the calculated Packaging Factor, we notice, that in general, the more modular the product is, the smaller the packaging factor (Table 1). This suggests that modular products use space less efficiently than integral products. In other words, modular products have more empty space.

Table 1. Modularity indices for all 8 products

	Functions-to-components ratio	Guo & Gerhenson (0-1, 1 most modular)	Packaging Factor
Cellular phone	4.67	0.57	0.90
Desk phone	4.07	0.59	0.61
Laptop computer	6.00	0.55	0.90
Desktop computer	4.43	0.68	0.18
Walkman	*1.85*	0.15	0.63
Cassette player	*2.22*	0.20	0.33
Portable CD Player	1.87	0.42	0.76
Standalone CD Player	1.21	0.43	0.19

4 DISCUSSION

It can be seen through the three modularity quantification methods that modular products use more space than their more integral counterparts. The functions-to-components ratio as well as the Guo and Gershenson [7] metric each show that the smallest of each product pair is more integral. In each one of these cases the packaging factor shows a higher value for the more integral product. This means that the more integral products use less space, and better utilize the volume they occupy.

We find that although each product, that was determined more modular of the product pair using the modularity metrics, was larger than the other that was determined more integral, there was no evidence suggesting that that had to be the case. The Packaging factor reveals that the larger size of the modular product is due to the inefficient use of space in the product. Modular product does not have to be larger than an integral product of the same functionality.

This result is significant in product design. Products, while in the design phase, must adhere to current product standards in order for those products to be marketable. An important design criterion when developing a standalone CD player is to ensure that it will fit well with other audio equipment. Generally, the standalone CD player is one of many components to a stereo sound system, and if a component does not stack well, then it will be difficult to implement into the system. Therefore, there is a standard geometry within the stereo component market which developers must adhere to in order for their product to be profitable. Specifically in regard to the standalone CD player, the amount of components and hardware necessary to play a CD takes up far less volume then the standard geometry for the component of the sound system. This fact must be taken into account when looking at the packaging factor results because the amount of 'unused space' within the product is now not a matter of necessity for the product to fulfil its function, but more a matter of conforming to the market standards. In this case the research shows that there may be an alternative to such a bulky module for a task that is performed by a relatively small device (walkman). For instance the standalone CD player is held to its width component but in more advanced design could be made very thin, which is a desirable marketing feature. This solution would allow the designer and manufacturer to benefit from the products reusable modules without sacrificing the attractive smaller size of the CD-player.

It is important to note that the three metrics cited are new and are not mature enough to have established tolerances, or ranges of reasonable values. The values from the Guo & Gershenson metric are in this case paid careful attention to due to their very similar values with regard to the phones and CD players. With further data and experience with the different metrics, it will be determined what range of values actually constitute modularity and what change of values between products constitutes an appreciable difference. This is also true of the packaging factor, but is less critical in these cases for the reasons that the packaging factor was only used to show that the product assumed to be more integral actually has less wasted space relative to the product assumed to be more modular. The functions to components ratio, also requires further investigation because of some inconsistent data.

As seen in the results section Table 1, the walkman has a functions to components ratio of 1.85 and the cassette player has a ratio of 2.22. This does not correlate to the integrality of the products and is contrary to the assumption. In order for the functions to components ratio to be indicative of a product pair's level of modularity, the two products must have the same number of functions. The strategy of functions to components ratio therefore requires more in depth and repeated iterations in the future to assure its practicality as a method of quantifying modularity.

The data calculated suggested opposite conclusions from what was expected for modularity for the functions to components ratio in case of the walkman and the CD player. This could be due to several reasons. First and foremost, is it possible that the walkman is more modular than the cassette player and the assumption is incorrect? Secondly what is the degree of detail that functions are taken to and similarly what level of detail is taken with the component list. In an extreme case let us suppose a great deal of detail went into the function structure, but the components were only defined as far as what could easily be disassembled. This number would probably be very high and completely incomparable to a product which was analysed using different standards even if it were done by the same researcher. This visits the plausibility of relative differences between two products to discuss 'relative modularity'. Could the 'relative modularity' or relative function component ratio's of product sets be compared, leading to conclusive information? The functions to components ratio is also not telling at all to what the actual size of a product may be. The recent developments of nano-tube construction have lead to increasingly smaller product design, and this new generation of products are remarkably smaller, but their functions to components ratio could remain the same if a product was replicated and scaled down.

Recalling that the Packaging Factor is a measure of the volume used by a product by the total volume a product occupies, it is seen that every tested product's modular counterpart has a smaller value. This shows that modular products don't necessarily need to be so large, because the unused space is unnecessary in many situations. A more rigorous planning of space usage could result in smaller products without sacrificing products degree of modularity. We therefore conclude, based on the investigation of eight products, that modular product do not have to be larger than integral products and thus the size should not be a reason for designers not to pursue modularity if the other benefits of modularity are sought after.

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