J Intell Manuf (2007) 18:143–157
DOI 10.1007/s10845-007-0007-y

Discovering relationships between modularity and cost

Fang Guo · **John K. Gershenson**

Received: August 2005 / Accepted: February 2006 / Published online: April 2007

Abstract While much has changed in product modularity research in the 18 years since the independence axiom, some basic questions remain unanswered. Perhaps the most fundamental of those questions is whether increasing modularity actually saves money. The goal of the research behind this paper was to clearly define the fundamental relationship between product modularity and product cost. Our previous work in modular product design provided a complete package of a product modularity measure and a modular design method. The "best" measure was created and verified after correcting common performance problems among the seven measures, finally subtracting the averaged relationships external to modules from the averaged relationship within modules. After comparing and finding better design elements among four representative modular design methods, the "best" method was developed that includes product decomposition, multi-component reconfiguration and elimination, and an extended limiting factor identification. The "best" method/measure package quickly yields redesign products with higher modularity. To seek out relationships between product life-cycle modularity and product life-cycle cost, modular product design experiments were implemented for four off-the-shelf products using the new measure/method package applied to increase both functional and retirement modularity. The modularity data recorded for each redesign included retirement modularity, manufacturing modularity and assembly modularity. Each redesign's life-cycle cost was also obtained based on several classical cost models. The cost data recorded for each redesign included retirement cost, manufacturing cost, and assembly cost. The best relationships came from the retirement viewpoint. However, there is not a significant relationship between any life-cycle modularity and any life-cycle cost unless there are significantly large modularity changes. Life-cycle modularity-cost relationships are more likely to exist in data pools generated from that life-cycle redesign viewpoint. The beginning of modular redesign, where greater modularity improvements are seen, is more effective at reducing costs. Cost savings depend the appropriateness of the modularity matrix's product architecture representation from a cost savings viewpoint.

Keywords Product modularity · Life-cycle modularity · Life-cycle cost

Introduction

Research in product modularity is not new. The definition and benefits or more modular products have been discussed for over 20 years. In particular, the cost savings benefits of product modularity have always been professed, especially within the engineering design community. However, only a few attempts have been made to actually prove a broad relationship between modularity and cost and these attempts have not been very definitive.

Modularity and its benefits

Modularity is the separation of a system into independent parts or modules that can be treated as logical

---

F. Guo · J. K. Gershenson (✉)
Department of Mechanical Engineering–Engineering Mechanics,
Michigan Technological University,
Houghton, MI 49931 USA,
e-mail: jkgershe@mtu.edu

units (Siddique et al. 1998). Modular product design entails creating and selecting modules, and designing module interfaces so that more modular product architectures can be achieved with fewer or weaker interactions among modules. Ulrich and Tung (1991) discuss the benefits of modular design, including component economies of scale, ease of product updating, increased product variety, decreased order lead-time, ease of design and testing, and ease of service. As firms strive to rationalize their product lines and to provide an increasing diversity of products at a lower cost, the concept of modularity has gained attention. Despite the work by many researchers in modular product design, the true benefits of product modularity remain unproven and there is still no systematic method to achieve product modularity (Gershenson et al. 2003, 2004).

The relationship between modularity and costs

The functional and development benefits of modular products seem to be considerable. The benefits of modular design include, "streamlined suppliers, reduced inventory, fewer works in progress, faster process time …reduced drawings, etc." (Ishii et al. 1994), as well as component economies of scale, ease of product update, increased product variety from a smaller set of components, decreased order lead-time, and ease of service (Ulrich 1995). Other works (Chang and Ward 1995; Chen et al. 1994; Coulter et al. 1998; He and Kusiak 1996; Ishii 1995; Kirk 1996; Marshall et al. 1998; Pimmler and Eppinger 1994; Shah 1996; Sosa et al. 2000; Stone et al. 1999; Ulrich 1995; and others) have also concentrated on the role of modularity in the design process. (Newcomb et al. 1996) propose the hypothesis that modular architecture will lead to decreased life-cycle costs even if the modules are not made with other life-cycle characteristics specifically in mind. This is probably true in general, but targeted design will increase these benefits and add structure to the process.

One of the more prominent life-cycle benefits and their corresponding design objectives as discussed by (Sosale et al. 1997) is that modular design allows the grouping of components into easily detachable modules and components with different materials into different modules. Grouping allows ease of reuse, recycling, and disposal. Reducing separation cost for recycling and remanufacturing necessitates that subassemblies "should be designed with modularity in mind" to put parts that are repaired often within a module so they can be accessed easily (Graedel and Allenby 1995).

Nearly all works in the area of modular design have either implied or stated that more modular products have lower life-cycle costs. Gurumurthy (1998) states that, including modular design tradeoffs "early in the design process" will decrease life-cycle costs. Hillstrom (1994) said that economies of scale and increased variety within product families cost savings are possible with modular design when product variety is required. Hopwood (1995) considered that labor cost would be reduced due to product modularity in the field of electronics manufacturing. Several have been specific in stating that retirement (or recycling) costs will be reduced in modular products (Coulter et al. 1998; Dimarco et al. 1994; Ishii et al. 1994; Newcomb et al. 1996; Sosale et al. 1997; and others). These statements make sense for the reasons stated in the previous benefits. However, nowhere in the literature is it shown where people have begun to prove these statements. It was the goal of this work to begin that process.

Our previous attempts at quantifying the modularity-cost relationship

Gershenson and Allamneni (2000) studied a flashlight to gain insight on the relation ship between increased modularity and decreased cost. They redesigned a flashlight 14 times to increase its retirement modularity. The retirement cost of this product was evaluated in each stage of the redesign. Using regression analysis, it was shown that modularity and retirement cost share an inverse relationship, indicating that more modular products have lower retirement costs than their less modular counterparts. Gershenson and Allamneni's work on this was just an initial step to explore the relationship between modularity and life-cycle cost. All of the life-cycle costs of the flashlight corresponding to the original design and each redesign should have been investigated, so that the relationship between a single life-cycle modularity and life-cycle costs could be studied completely. The relationship between modularity and life-cycle cost of a single product is far from convincing.

Zhang et al. (2001) again sought the relationship between modularity and cost, this time for twelve products. The total life-cycle cost and individual life-cycle costs were determined for successive redesigns of each product. An analysis of the total life-cycle modularity and the total life-cycle costs indicates that there is no relationship between them. Among the individual life-cycle modularities and costs, only the relationship between assembly modularity and assembly cost was proven to exist marginally. Further statistical analysis indicated that the popular belief that more modular products have lower costs is not necessarily true. The relationships between the normalized life-cycle costs and life-cycle relative modularities of the products were proven not to exist. The assumption that there are relationships between life-cycle costs and life-cycle relative modularities was also rejected. For analyzing the relationship between modularity and cost, a more thorough examination of the modular design procedure was needed.

Motivation

It has often been said that increased modularity leads to decreased life-cycle costs. Newcomb et al. (1996) even propose the hypothesis that modular architecture will lead to decreased life-cycle costs even if the modules are not made with other life-cycle characteristics specifically in mind. However, this desirable relationship - decreased costs associated with the increased modularity - has never been proven. No research has been done that proves there exists a relationship between modularity and cost. However, many projects have been based on this unproven assumption.

The measure and method used in this research

In modular product design, modularity measures play a vital role in guiding the design process and yielding more modular products. Modular product design methods enable the redesign of complex products to improve the overall modularity. Many modularity measures and design methods exist in the literature. They differ considerably in application. In previous research (Guo and Gershenson 2003, 2005a, b), the "best" measure was found among existing measures (Allen and Carlson-Skalak 1998; Coulter et al. 1998; Gershenson et al. 1999; Huang and Kusiak 1998; Rosen et al. 1998; Sosa et al. 2000; Stone et al. 1998) based on consistency analysis and sensitivity analysis and correcting problems that emerged by subtracting the averaged relationships external to modules (Eq. 1).

$$\text{Modularity} = \frac{1}{M}\left(\sum_{k=1}^{M}\frac{\sum\limits_{i=n_k}^{m_k}\sum\limits_{j=n_k}^{m_k}R_{ij}}{(m_k-n_k+1)^2} - \sum_{k=1}^{M}\frac{\sum\limits_{i=n_k}^{m_k}\left(\sum\limits_{j=1}^{n_k-1}R_{ij}+\sum\limits_{j=m_k+1}^{N}R_{ij}\right)}{(m_k-n_k+1)(N-m_k+n_k-1)}\right) \tag{1}$$

Where: n_k: index of the first component in the kth module. m_k : index of the last component in the kth module. M : total number of modules in the product. N : total number of components in the product. R_{ij} : the value of ith row and jth column element in the modularity matrix.

A modular design method (Guo and Gershenson 2004, 2005a, b) with the "best" performance was also created (Table 1) based on the comparison of a set of representative methods (Coulter et al. 1998; Sosale et al. 1997; Stone et al. 2000; Zhang and Gershenson 2003). For the same initial design and the same measure of modularity, the method that generates more modular products, more efficiently is considered the best one among the methods. The modular design method was based on the work of Coulter et al. and Zhang and Gershenson. The complete measure and method package was applied to analyze the relationship between modularity and cost by redesigning four products and generating modularity and cost data pools.

Modularity and cost data generation and analysis

Four products were redesigned to increase retirement, manufacturing, and assembly modularity and generate three redesign data pools for each of the four products (a Kodak single-use camera, a Conair supermax hairdryer, an Adhesive Tech mini glue gun, and a Regent halogen clamp lamp). Modularity and the cost of each redesign from each viewpoint were calculated to generate a modularity data pool and a cost data pool. It was our hypothesis that redesign results using the package of the selected modularity measure and method are good approximation of real redesigns, and that analyzing relationship between the generated modularity data pool and the cost data pool reflects the real relationship between modularity and cost.

Generation of the modularity data pool

Each of the four products was redesigned from retirement, manufacturing, and assembly viewpoints (intents) to generate three sets of redesign data pools for each of the four products. For each redesign data pool, modularity was calculated from each of the three viewpoints. A total of 36 modularity data pools were generated including three retirement modularity, three manufacturing modularity, and three assembly modularity data pools for each of the four products (Tables 2–5).

Generation of the cost data pool

The individual life-cycle costs (manufacturing cost, assembly cost, and retirement cost) were determined by

Table 1 Implementation and application of the new method

Product used: Four products: a Kodak single-use camera, a Conair supermax hair dryer, an Adhesive Tech mini glue gun, and a Regent halogen clamp lamp

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

Purpose: Product modularity improvement from two or more life-cycle viewpoints, can be applied to improve product modularity from only one life-cycle viewpoint if limiting factor identification is performed on the same matrix as is the clustering algorithm.
Search method: Clustering algorithm based on Kusiak and Chow (1987), a search for three types of possible redesigns (module elimination, component elimination, and module reconfiguration), and limiting factor identification
Redesign steps: (described based on application to two life-cycle viewpoints - physical modularity matrix$_1$ and another life-cycle modularity matrix$_2$)

1. Cluster the physical matrix$_1$ and reconfigure the other life-cycle modularity matrix$_2$ to align with the component clusters in the matrix$_1$
2. Check the feasibility of each cluster reconfiguration and construct the new matrix$_1$ and matrix$_2$ based only on feasible reconfigurations
3. Find all possible module eliminations with improved modularity: if the elimination of one module improves total modularity, accept this elimination as one redesign candidate
4. Find all possible component eliminations with improved modularity: if the elimination of one component improves total modularity, accept this elimination as one redesign candidate
5. Find all possible reconfigurations of one or more components with improved modularity: if one or more components from an unchecked module is moved into another module or to a new module with improved modularity, accept this reconfiguration as one redesign candidate
6. Check the feasibility of each redesign candidate in descending order of modularity until one feasible redesign candidate is found
7. Implement the redesign and store the redesigned matrices, go to step 3 and iterate until no further redesigns can be achieved
8. Compare the values in the latest updated matrices (matrix$_1$ and matrix$_2$) to get all off-block elements that have a high interaction value in matrix$_2$ but not in matrix$_1$: $X_{ij}^{(out)}$
9. Change any attribute of component *i* to make it independent or dissimilar to component *j* with respect to the considered life-cycle viewpoint for all off-block limiting factors, and calculate modularity improvement of each change
10. Check the feasibility of each change in descending order of modularity improvement, redesign based on only feasible changes until no further redesigns can be achieved or the total number of redesign iteration is reached
11. Compare the values in the two updated matrices to get all in-block elements that have a low interaction value in matrix$_2$ but not in matrix$_1$: $X_{ij}^{(in)}$
12. Change any attribute of component *i* to make it more dependent on or similar to component *j* with respect to the considered life-cycle viewpoint for all in-block limiting factors, and calculate modularity improvement of each change
13. Check the feasibility of each change, redesign based on only feasible changes until no further redesigns can be achieved or the total number of redesign iteration is reached
14. Store the final product architecture and the corresponding modularity

Table 2 Life-cycle modularities of the camera redesigns

Camera		Retirement modularity	Manufacturing modularity	Assembly modularity
Redesign from retirement	0	−0.5661	−0.3446	−1.6186
	1	−0.5540	0.4391	−0.2882
	2	0.7123	0.5398	−0.2413
	3	0.9908	0.5976	−0.1515
	4	1.4545	0.5076	−0.1599
	5	2.4494	0.1823	−0.2867
Redesign from manufacturing	0	−0.5661	−0.3446	−1.6186
	1	−0.5540	0.4391	−0.2882
	2	−0.0280	0.6279	−0.2377
	3	0.0064	0.7764	−0.0431
	4	−0.0345	0.8680	−0.0482
	5	−0.0224	1.0061	−0.0300
Redesign from assembly	0	−0.5661	−0.3446	−1.6186
	1	−0.5540	0.4391	−0.2882
	2	−0.0352	0.5109	−0.0812
	3	0.0296	0.6080	0.0280
	4	−0.0316	0.4780	0.1442
	5	−0.0016	0.2736	0.2268
	6	0.0019	0.2790	0.2278

Table 3 Life-cycle modularities of the camera redesigns

Mini glue gun		Retirement modularity	Manufacturing modularity	Assembly modularity
Redesign from retirement	0	1.1929	0.8001	0.1743
	1	1.3998	0.8648	0.1232
	2	1.4325	0.7731	0.1346
	3	1.4601	0.6982	0.2017
	4	1.6226	0.6923	0.2632
	5	1.8441	0.5937	0.0776
	6	1.8481	0.7528	0.0810
Redesign from manufacturing	0	1.1929	0.8001	0.1743
	1	1.2336	0.9007	0.1896
	2	1.0775	0.9643	0.0842
	3	0.9247	0.9962	0.0868
	4	0.7459	1.0803	0.0350
	5	0.6985	1.1080	0.0569
	6	0.7560	1.1489	0.1520
	7	0.7216	1.1966	−0.0064
Redesign from assembly	0	1.1929	0.8001	0.1743
	1	1.0259	0.7267	0.3173
	2	1.1524	0.7606	0.4129
	3	1.1741	0.8350	0.4292
	4	0.9946	0.7314	0.4317
	5	0.9667	0.7745	0.4736
	6	0.9292	0.7834	0.4813
	7	0.9040	0.7946	0.4836
	8	0.8970	0.8086	0.4873

Table 4 Life-cycle modularities of the hair dryer redesigns

Hair dryer		Retirement modularity	Manufacturing modularity	Assembly modularity
Redesign from retirement	0	−0.2725	−0.0821	−1.1900
	1	0.4049	0.1990	−0.6470
	2	0.8733	0.3379	−0.3797
	3	1.1836	0.4016	−0.0196
	4	1.3365	0.4683	−0.0153
	5	1.4940	0.4328	−0.0124
	6	1.6870	0.4583	0.0567
	7	1.9315	0.2534	0.1786
	8	2.0061	0.2489	0.1562
	9	2.0236	0.3001	0.1688
	10	2.0302	0.2975	0.1570
Redesign from manufacturing	0	−0.2725	−0.0821	−1.1900
	1	0.4049	0.1990	−0.6470
	2	0.3007	0.4262	−0.5994
	3	0.5911	0.5771	−0.2812
	4	0.4625	0.7226	−0.4757
	5	0.4583	0.8751	−0.4789
	6	0.1765	1.0057	−0.6339
	7	0.2027	1.1875	0.4688
Redesign from assembly	0	−0.2725	−0.0821	−1.1900
	1	0.4049	0.1990	−0.6470
	2	−0.2306	0.4168	0.2136
	3	0.6344	0.3660	0.1140
	4	0.6410	0.2488	0.1754
	5	0.4098	0.2882	0.2002
	6	0.5006	0.3127	0.3129
	7	0.6358	0.3213	0.3322
	8	0.6635	0.2957	0.3425
	9	0.5249	0.2122	0.3911

Table 5 Life-cycle modularities of the lamp redesigns

Lamp		Retirement cost	Manufacturing cost	Assembly cost
Redesign from retirement	0	0.3830	0.9690	7.3420
	1	0.3200	0.9430	7.3420
	2	0.3240	0.9430	7.3420
	3	0.3240	0.9430	7.3420
	4	0.2750	0.9430	7.3420
	5	0.2750	0.9430	7.3420
	6	0.2600	0.9250	6.9590
	7	0.2610	0.9060	6.9320
Redesign from manufacturing	0	0.3830	0.9690	7.3420
	1	0.3200	0.9430	7.3420
	2	0.3200	0.9430	7.3420
	3	0.3200	0.8810	7.2920
	4	0.3200	0.8810	7.2920
	5	0.3200	0.8810	7.2920
Redesign from assembly	0	0.3830	0.9690	7.3420
	1	0.3200	0.9430	7.3420
	2	0.3200	0.9290	7.3430
	3	0.3200	0.9290	7.3430
	4	0.3200	0.9290	7.3430
	5	0.3200	0.9250	7.3430
	6	0.3200	0.9250	7.3430
	7	0.3200	0.9150	7.3430
	8	0.3200	0.9140	7.3430
	9	0.3110	0.8990	7.2320
	10	0.3100	0.8820	7.2030
	11	0.3100	0.8510	7.1780
	12	0.3090	0.8410	7.1230
	13	0.2600	0.7630	7.0480

the product's material, volume, manufacturing process, geometry, etc. The design of a product and its components determines those parameters and therefore determines a product's individual life-cycle costs. Zhang et al. (2001) applied cost equations to calculate a camera's life-cycle costs. These equations were from Boothroyd et al. (1994) (manufacturing cost and assembly cost), Chen et al. (1993) (recycling and remanufacturing costs), and Klausner et al. (1998) (reuse and disposal cost). In this research, we used the same cost models to calculate the cost of each redesign from each of three viewpoints – retirement, manufacturing, and assembly (Tables 6–9).

Construction of relationship graphs

For each of the four products, the relationship between modularity and cost was defined using regression analysis for three types of relationships (three subplots in each of Figs. 1–4 for each product) – the relationship between retirement modularity and retirement cost, the relationship between manufacturing modularity and manufacturing cost, and the relationship between assembly modularity and assembly cost. For each type of relationship, there are three types of redesign data pools from three design viewpoints that yield three types of modularity and cost data pools (included in each subplot) to analyze. Graphs for each of the four products are shown with the relationship ratio *b* and its significance *p* in Tables 10–13. (Note: *p* values less than 0.05 are bolded, indicating a modularity-cost relationship exists with a significance greater than 95%. The corresponding *b* values are also bolded to show specific relationship ratios).

Data analysis

Using regression analysis to evaluate whether the relationship between a particular life-cycle modularity (X modularity) and its cost (X cost) exists, the *p* value was calculated for each relationship based on the data pool from each design viewpoint. If the *p* value is less than 0.05, the relationship between X modularity and X cost exists with a 95% significance. Based upon the relationship graphs and the *b* and *p* values, the relationships with a greater than 95% significance are shown with their corresponding sign indicting whether the relationship is negative or positive in Table 14.

Table 14 shows that the relationship between retirement modularity and cost exists for six out of 12 data

Table 6 Life-cycle costs of camera redesigns

Camera		Retirement cost	Manufacturing cost	Assembly cost
Redesign from retirement	0	−3.2248	0.1237	6.9367
	1	−3.1383	0.1237	6.7957
	2	−3.4087	0.1319	6.9335
	3	−3.4089	0.1319	6.9367
	4	−3.4089	0.1319	6.9367
	5	−3.4089	0.1319	6.9367
Redesign from manufacturing	0	−3.2248	0.1237	6.9367
	1	−3.1384	0.1237	6.7982
	2	−3.1384	0.1237	6.7982
	3	−3.1384	0.1237	6.7982
	4	−3.1384	0.1237	6.7982
	5	−3.0456	0.1056	6.7305
Redesign from assembly	0	−3.2248	0.1237	6.9367
	1	−3.3237	0.1237	6.9335
	2	−3.3238	0.1223	6.9337
	3	−3.3238	0.1223	6.9337
	4	−3.2602	0.1165	6.5933
	5	−3.2602	0.1165	6.5933
	6	−2.7015	0.1128	6.5934

Table 7 Life -cycle costs of mini glue gun redesigns

Mini glue gun		Retirement cost	Manufacturing cost	Assembly cost
Redesign from retirement	0	0.1070	3.3800	0.7020
	1	0.1070	3.3800	0.6800
	2	0.1070	3.2330	0.6620
	3	0.0910	3.2310	0.6620
	4	0.0910	3.2310	0.6620
	5	0.0910	3.2310	0.6620
	6	0.0910	3.2240	0.6580
Redesign from manufacturing	0	0.1070	3.3800	0.7020
	1	0.1020	3.2170	0.6380
	2	0.0080	3.0010	0.6260
	3	0.0880	3.0010	0.6260
	4	0.0880	3.0010	0.6260
	5	0.0880	3.0020	0.5830
	6	0.0880	3.0020	0.5890
	7	0.0880	3.0020	0.5830
Redesign from assembly	0	0.1070	3.3800	0.7020
	1	0.0880	3.3770	0.6780
	2	0.0880	3.3770	0.6780
	3	0.0880	3.2150	0.6600
	4	0.0880	3.2150	0.6520
	5	0.0880	3.2080	0.6480
	6	0.0880	3.1480	0.6280
	7	0.0880	3.0880	0.6090
	8	0.0880	3.0870	0.5760

pools; four from the retirement design data pool, one from the lamp manufacturing design data pool, and the other one from hairdryer assembly design data pool. The relationship between manufacturing modularity and cost exists for only three out of 12 data pools. All pools come from the manufacturing design viewpoint except the hairdryer for which no manufacturing modularity-cost relationship exists. The relationship between assembly modularity and cost exists for four out of 12 data pools, including three from the assembly design data pool (all except the camera) and one from hairdryer retirement.

It is also noticeable from the graphs that relationship data pools based upon their own redesign viewpoints are more spread out than the data pools from the other viewpoints. For the relationship data pools from their own redesign viewpoints, the relationship curves generally are negative in the very beginning and then plateau,

Table 8 Life -cycle costs of hairdryer redesigns

Hair dryer		Retirement cost	Manufacturing cost	Assembly cost
Redesign from retirement	0	0.2380	6.9640	0.6270
	1	0.2310	6.9650	0.5740
	2	0.2260	6.9650	0.5620
	3	0.2260	6.9650	0.5590
	4	0.2260	6.9350	0.5590
	5	0.2260	6.9650	0.5590
	6	0.1990	6.9650	0.5220
	7	0.1990	6.9650	0.5220
	8	0.1910	6.7230	0.5050
	9	0.1910	6.7130	0.4970
	10	0.1910	6.6790	0.4910
Redesign from manufacturing	0	0.2380	6.9640	0.6270
	1	0.2310	6.9650	0.5740
	2	0.2140	6.9640	0.5150
	3	0.2140	6.9640	0.5290
	4	0.2590	6.9640	0.5290
	5	0.2590	6.9640	0.5290
	6	0.2360	6.9640	0.5040
	7	0.2360	6.9650	0.5040
Redesign from assembly	0	0.2380	6.9640	0.6270
	1	0.2310	6.9650	0.5740
	2	0.2440	6.9650	0.5740
	3	0.2190	7.0390	0.5830
	4	0.2190	7.0390	0.5830
	5	0.2190	7.0390	0.5670
	6	0.2190	7.0390	0.5670
	7	0.2190	7.1950	0.5540
	8	0.2060	7.1020	0.5460
	9	0.2060	7.1020	0.5460

Table 9 Life -cycles cost of lamp redesigns

Lamp		Retirement modularity	Manufacturing modularity	Assembly modularity
Redesign from retirement	0	−0.0094	0.2063	−0.5816
	1	0.3984	0.3575	0.1119
	2	0.7561	0.3751	0.1723
	3	0.9196	0.4124	0.1450
	4	0.9798	0.5001	0.1441
	5	1.0433	0.4351	0.1639
	6	1.0457	0.4642	0.1556
	7	1.0511	0.5095	0.1775
Redesign from manufacturing	0	−0.0094	0.2063	−0.5816
	1	0.3901	0.3577	0.1191
	2	0.3668	0.5480	0.1568
	3	0.3492	0.7681	0.1434
	4	0.4263	0.8970	0.2070
	5	0.4846	1.0038	0.2060
Redesign from assembly	0	−0.0094	0.2063	−0.5816
	1	0.3901	0.3577	0.1191
	2	0.4889	0.4337	0.2819
	3	0.3019	0.5153	0.3779
	4	0.3964	0.6649	0.4080
	5	0.2985	0.5576	0.5042
	6	0.3802	0.6010	0.5595
	7	0.2356	0.6206	0.6363
	8	0.2106	0.6014	0.6529
	9	0.2305	0.6278	0.6640
	10	0.1989	0.0179	0.6737
	11	0.2739	0.6219	0.6835
	12	0.2633	0.6439	0.6907
	13	0.3016	0.6402	0.7092

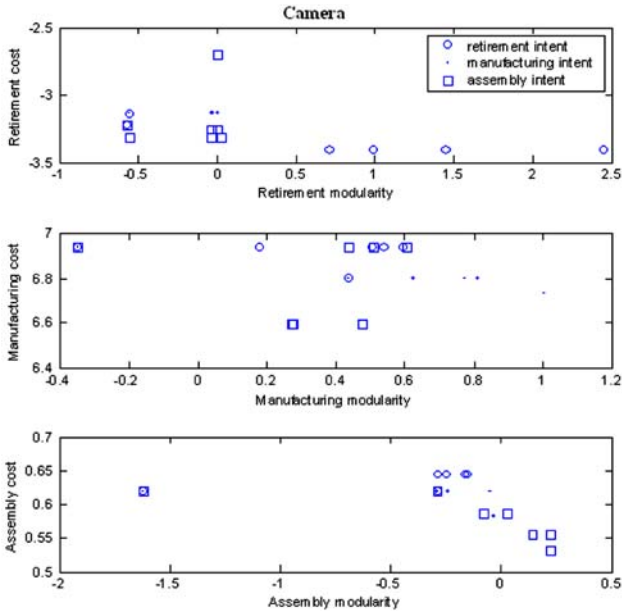

Fig. 1 Modularity and cost relationship graphs from three viewpoints for the camera

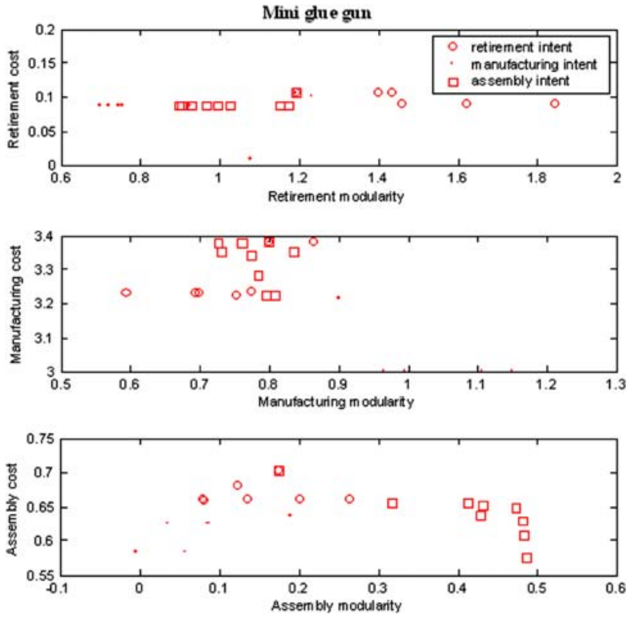

Fig. 3 Modularity and cost relationship graphs from three viewpoints for the mini glue gun

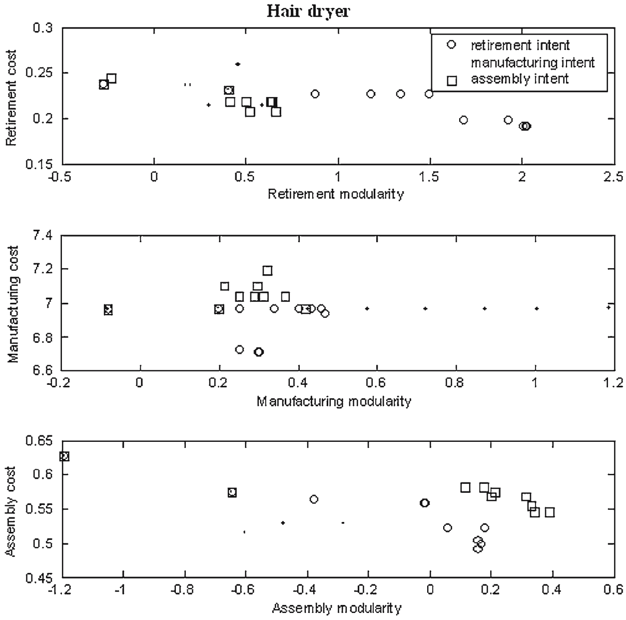

Fig. 2 Modularity and cost relationship graphs from three viewpoints for the hair dryer

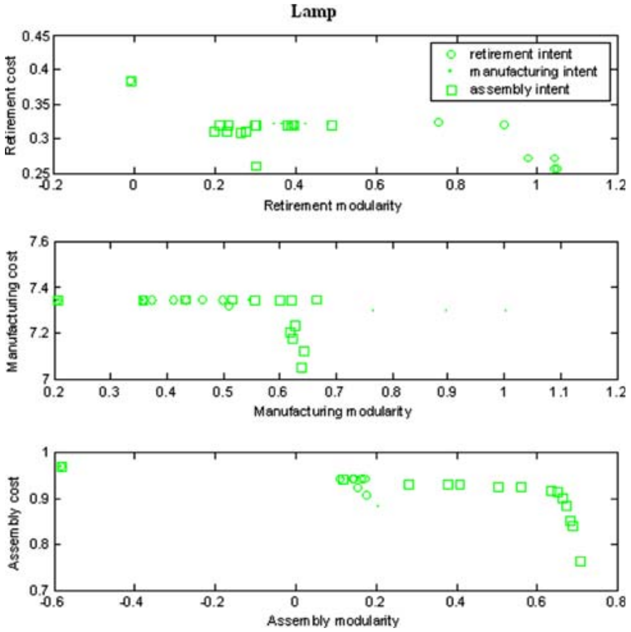

Fig. 4 Modularity and cost relationship graphs from three viewpoints for the lamp

after which modularity improves further with few cost reductions.

These results indicates that the X–X relationship is different for each of retirement, manufacturing, and assembly modularity-cost relationships, and that the data pools generated from X design viewpoints have a greater probability of yielding a negative relationship between X cost and X modularity with a 95% significance. In addition, while the data and analysis is not shown here due to space limitations there were no significant relationships between functional modularity and any of the life-cycle costs.

Table 10 *b* and *p* values for relationships based on the camera redesigns

	Viewpoint			
	R	M	A	Total
b value				
Retirement–Retirement	−0.0866	0.1231	0.1893	−0.0964
Manufacturing–Manufacturing	−0.0259	−0.1350	−0.0422	−0.0887
Assembly–Assembly	0.0148	−0.0067	−0.0376	−0.0212
p value				
Retirement–Retirement	**0.0363**	0.2012	0.6221	0.0516
Manufacturing–Manufacturing	0.7573	**0.0029**	0.8755	0.2745
Assembly–Assembly	0.1442	0.5970	0.0623	0.1023

Table 11 *b* and *p* values for relationships based on the hair dryer’s redesigns

	Viewpoint			
	R	M	A	Total
b value				
Retirement–Retirement	−0.0215	−0.0014	−0.0295	−0.0186
Manufacturing–Manufacturing	0.0400	0.0007	0.1655	0.0003
Assembly–Assembly	−0.0822	−0.0627	−0.0372	−0.0389
p value				
Retirement–Retirement	**0.0006**	0.9582	**0.0018**	**0.0000**
Manufacturing–Manufacturing	0.8739	0.1932	0.3873	0.9967
Assembly–Assembly	**0.0003**	0.0537	**0.0033**	**0.0040**

Table 12 *b* and *p* values for relationships based on the mini glue gun’s redesigns

	Viewpoint			
	R	M	A	Total
b value				
Retirement–Retirement	−0.0275	−0.0100	0.0285	0.0101
Manufacturing–Manufacturing	0.6051	−0.8898	−0.7091	−0.7180
Assembly–Assembly	0.0284	0.3254	−0.2749	−0.0137
p value				
Retirement–Retirement	**0.0391**	0.8657	0.1309	0.4156
Manufacturing–Manufacturing	0.0665	**0.0118**	0.2931	**0.0000**
Assembly–Assembly	0.7997	0.1351	**0.0078**	0.7744

Table 13 *b* and *p* values for relationships based on the lamp’s redesigns

	Viewpoint			
	R	M	A	Total
b value				
Retirement–Retirement	−0.1042	−0.1437	−0.1013	−0.0759
Manufacturing–Manufacturing	−0.0388	−0.0794	−0.3373	−0.1572
Assembly–Assembly	−0.0484	−0.0917	−0.0949	−0.0802
p value				
Retirement–Retirement	**0.0022**	**0.0022**	0.0808	**0.0000**
Manufacturing–Manufacturing	0.3199	**0.0124**	0.1146	**0.0408**
Assembly–Assembly	0.0577	0.1206	**0.0160**	**0.0001**

Table 14 Summary of relationships with a greater than 95% significance

Products	Relationship	Design Viewpoint		
		R	M	A
Camera	R-R	-		
	M–M		-	
	A–A			
Hair dryer	R-R	-		-
	M–M			
	A–A	-		-
Mini glue gun	R-R	-		
	M–M		-	
	A–A			-
Lamp	R-R	-	-	
	M–M		-	
	A–A			-

Why a X–X relationship is more likely to exist in data pools from the X redesign viewpoint

For the 36 data pools, with 12 for each design viewpoint, ten significant relationships came from their own redesign viewpoint and only three significant relationships came from other viewpoints. Obviously, the data pool within a design viewpoint is different from that of other viewpoints.

Redesign from the X viewpoint results in much more X modularity improvement in each redesign and therefore spreads out the modularity space. The corresponding cost changes more too. However, redesigns from one X viewpoint (e.g., the retirement modularity improvements based on redesigns intent on increasing assembly modularity) yield more condensed data points with lesser modularity improvements in the Y and Z viewpoints. Larger modularity improvements usually lead to more dramatic cost changes and these cost changes include more cost changes that can be calculated from changes in the modularity matrix (e.g., simplification of the interface to reduce assembly cost, reconfiguration of components into the same retirement process to avoid unnecessary disassembly cost, elimination of components to reduce manufacturing cost, etc.) in addition to cost changes that can not be reflected in the modularity matrix (e.g., component size and shape change). For small modularity improvements, these non-reflected cost changes become dominant and the relationships become unclear.

Why the retirement relationship exists in more data pools than the manufacturing or assembly relationships

Out of the 13 existing relationships with a greater than 95% significance from the 36 data pools, six of 12 cases came from retirement relationships, compared to only three from manufacturing and four from assembly relationships. There must be something significant about the retirement relationships.

Modularity matrices, the representation from which the design method proceeds, that are based on the retirement process are more appropriate representations of product architecture from a cost savings viewpoint than those from manufacturing or assembly. No matrices are ideal representations of a product architecture from a cost saving point of view. Modularity matrices are obtained by evaluating the relationships between the component and each life-cycle process (function, manufacturing, assembly, retirement, etc.) and then calculating the relationships between components for any specific process under consideration Gershenson et al. (1999). The life-cycle processes used to achieve these matrices define the character of the product architecture as it is captured and analyzed. The specificity of the processes is another factor that impacts the accuracy of product architecture representation using any modularity matrix.

The manufacturing matrix captures the similarity and dependence between components with respect to their manufacturing processes. Specifically, the similarities are the similarity of the manufacturing processes by which the components are manufactured and the dependencies are the dependence of two components' designs on a common manufacturing process. However, cost savings in the manufacturing process are heavily dependent upon the impact of redesign on tooling costs, tooling changes, material cost, etc. Therefore, we miss most elements of cost savings by using the current manufacturing modularity matrix representation. Note that the matrix used is based on the best in class of the other representations in the literature, and there currently is no known representation that can tackle the needs of costing and the needs of modularity. The information used to modularize the product architecture with respect to the manufacturing processes and which components have similar processes is very difficult to fine tune enough to impact manufacturing costs. Even refining the process list to include more processes will not help clarify the relationships unless the variables of modularity are redefined to represent architecture from manufacturing cost saving viewpoint.

The assembly matrix, based on the Boothroyd et al. (1994) manual assembly codes, is also too rough to accurately describe assembly cost savings. If two components' assembly codes are within the same assembly category, they will have highest relationship even if their assembly codes are far off. Refining the assembly modularity quantification is not difficult, but this will still not improve its relationship with assembly cost. The assembly matrix is not constructed to reflect all relevant assembly costs. The similarity or dependency relationship between two components' assembly codes does not differentiate the ease of assembly nor the most cost effective assembly order. The goal of modular design from the assembly viewpoint is not only to simplify the structure of the assembly fishbone (to change the order of assembly), but also to redesign the assembly steps by simplifying the assembly interfaces. This is quite different from functional modular design, where saving design cost due to function itself is not an issue for modular product design. Therefore, when interface relationships between functions are extracted using similarity and dependency as in modular design, it is not the same as when interface relationships between assembly steps are extracted. Assembly code information should be included directly in the modularity matrix. That is, if one component is assembled onto another component with relatively low assembly costs, then the relationship is low, otherwise there is a high relationship. Then modularization will group components with difficult assembly steps together as modules and leave simple assembly interfaces between modules.

The retirement matrix represents architecture more appropriately from a cost saving viewpoint. The modularity matrix is constructed so that each element represents the similarity or dependency of retirement process between components. Components with different or independent retirement processes are grouped into different modules. Components with highly similar or dependent retirement process are grouped together in one module to be recycled, reused, or disposed without further disassembly, which therefore reduces retirement costs.

Why negative relationships are more obvious in the very beginning of modular design

The initial product architecture has more opportunity for modularity improvements and cost savings that can be driven by architecture change. The modular design method enables these relatively larger improvements at the beginning of the redesign process. Smaller, more detailed cost savings are made at the component level, which is not well reflected in modular product design. After several iterations of the redesign method, the architecture reconfigurations and component reconfigurations/eliminations with sizeable modularity improvements have been implemented. The remaining redesigns with big modularity improvements are at the module interfaces. These interface redesigns do not affect the product architecture. While these module interface changes yield noticeable modularity improvements, their implementation is not reflected in any of the cost equations because their impact on cost is minimal. The redesign graphs show horizontal lines for these cases.

Why different products' redesigns yield different relationship significances

Four out of nine design data pools from the lamp and four out of nine design data pools from the hair dryer have relationship significances above 95%. The camera and mini glue gun have two and three data pools respectively with above a 95% significance. Different products' redesigns yield different relationship significances due to differences in product architecture.

The lamp has many interface-based components that act only as connectors. Most redesign changes are implemented on these components. These low function connectors also make design changes easier to implement since on must only satisfy the interface requirements. In other products, function satisfaction plays a major role in the feasibility of redesign changes, making it harder to achieve major modular changes. In addition, the more interface-dependent components there are, the more easily retirement and assembly costs are reduced. The availability of elimination possibilities in the lamp redesigns played a significant role in building an X–X relationship in the manufacturing viewpoint.

Since the hairdryer has primarily electrical interfaces, it is more difficult to redesign its components and to improve the interfaces. There are therefore more horizontal data points in the hairdryer redesign graphs and a complete lack of any manufacturing cost change in the hairdryer redesigns from the manufacturing viewpoint.

On the other hand, the hairdryer has some components whose functions can be integrated into larger components, resulting in cost savings from reduced assembly and disassembly steps.

The camera and mini glue gun do not have many mechanical interfaces, and most components are involved in one, long dynamic function. If one component needs to be changed, then the whole mechanism needs to be redesigned. However, alternatives for all of these functions can not be found easily. Therefore, most redesign changes and modularity improvements result from the reconfiguration of components in which less real interface redesign or component change is needed, but there are not significant cost changes.

Cost models' affect on defining the relationship between modularity and cost

The cost models include both reflected costs and the non-reflected costs from the modularity matrices. Some reflected costs are not included in most cost models, such as design costs, updating or risk costs (for any process), etc. Modular design has an important impact on these costs by simplifying module and component interfaces. The corresponding cost savings come from fewer design team interactions, fewer equipment changeovers for manufacturing or assembly, reduced training for new assembly or design work, improved component performance, consistency in durability testing, etc. It is necessary to construct cost models that include these cost elements. This will better expose the significance of the modularity-cost relationships.

Conclusions

Our modularity-cost relationship analyses show that 13 out of 36 redesign data pools have a significant negative relationship between a life-cycle modularity and a life-cycle cost. After analyzing the relationships within retirement, manufacturing, and assembly, the best relationship significance came from the retirement relationship analysis (six out of 12), which is still not enough to show a statistically significant relationship. The manufacturing and assembly relationship analyses yielded no statistically significant relationships. Therefore, our conclusion is that there really is not a significant relationship between modularity and cost unless there are significantly large modularity changes or unless there are some changes in how modularity and cost are represented in modularity matrices. Note that our work validates the existing measure and method and their ability to increase and quantify modularity, the issue is with the matrix representation to which they are applied.

Our analysis indicates that some relationships should be expected, but that the data generated in this research is still not good enough to show it clearly. There are three major road blocks to defining these relationships; all are relationship or cost modeling issues.

(1) X–X relationships are more likely to exist in data pools generated from an X redesign viewpoint than that from a Y or Z redesign viewpoint, since redesign within an X viewpoint yields greater X modularity improvements. In addition, the beginning of modular redesign, where greater modularity improvements are seen, is more effective at reducing costs than the latter stages of modular redesign where less modularity improvement is seen. This upfront reduction indicates that there is a relationship between cost reduction and modularity when bigger modularity improvements occur.

(2) Although costs remain unchanged at a plateau when modularity continues to improve, this cost plateau can show cost reductions if design cost, product updating and risk cost, etc. are considered, and if the design space is broadened to allow more architecture-level solutions.

(3) Modularity matrices from the retirement process are more appropriate representations of product architecture from a cost savings perspective, and demonstrate a more significant relationship between modularity and cost during redesign. Therefore, a good modularity matrix representation from each viewpoint is a key to achieving cost reductions by modularity improvement.

It is our conclusion that when modularity improvement is just beginning, there is a higher probability of achieving cost reductions than that when modularity improvement has progressed. This is not to say that greater modularity changes lead to greater cost changes, but that, with lesser modularity changes, not relationship exists and costs can move up or down. How likely the cost savings are to occur depends on how appropriate a representation of the product architecture the modularity matrix is from a cost savings viewpoint, how much design flexibility there is in technology, knowledge, and requirements to realize modular improvements without limitations, and how comprehensive the cost modeling is at calculating all real cost changes. Current cost models and modularity matrices need to be improved to reflect real cost savings and clearly show the relationship between modularity and cost. Key questions in making these changes include: do the current process list and modularity variables include enough information so that the constructed modularity matrix is still cost driven; and which modularity variables appropriately represent product architecture from a cost savings perspective. The next step is a better understanding of product architecture itself and a comprehensive exploration of what specific costs are reflectable and driven by modular product design.

References

Boothroyd, G., Dewhurst, P., & Knight, W. (1994). *Product design for assembly and manufacture*. New York: Marcel Dekker.

Chang, T. S., & Ward, A. C. (1995). Design-in-modularity with conceptual robustness. *Proceedings of the 1995 ASME design technical conferences – 21st design automation conference, September, Boston, Massachusetts*.

Chen, W., Navin-Chandra, D., & Prinz, F. B. (1993). Product design for recyclability: A cost benefit analysis model and its application. *Proceedings of the 1993 IEEE conference*, pp. 178–183.

Chen, W., Rosen, D., Allen, J. K., & Mistree, F. (1994). Modularity and the independence of functional requirements in designing complex systems. *Proceedings of the 1994 ASME design technical conferences – conference on concurrent product design, Minneapolis, Minnesota*.

Coulter, S. L., Bras, B., McIntosh, M. W., & Rosen, D. W. (1998). Identification of limiting factors for improving design modularity. *Proceedings of the 1998 ASME design engineering technical conferences – 10th international conference on design theory and methodology, September, Atlanta, Georgia*.

Gershenson, J. K., Prasad, G. J., & Allamneni S. (1999). Modular product design: A life-cycle view. *Journal of Integrated Design and Process Science, 3*(4), 13–26.

Gershenson, J. K., Prasad, G. J., & Zhang, Y. (2003). Product modularity: Definitions and benefits. *Journal of Engineering Design, 14*(3), 295–313.

Graedel, T. E., & Allenby, B. R. (1995). *Industrial ecology*. Englewood Cliffs, New Jersey: Prentice Hall.

Guo, F., & Gershenson, J. K. (2005). A measure of product modularity: Comparison, selection, improvement, and verification. under review for the *Journal of Mechanical Design*.

Guo, F., & Gershenson, J. K. (2005). A modular design method: Comparison, selection, improvement, and verification, under review for the *Journal of Mechanical Design.*

Gurumurthy, J. P. (1998). *Life-cycle modularity in product design*. M.S. Thesis, University of Alabama.

He, D. W., & Kusiak, A. (1996). Performance analysis of modular products. *International Journal of Product Research, 34*(1), 253–272.

Hillstrom, F. (1994). Applying axiomatic design to interface analysis in modular product development. *Advances in Design Automation*, DE-Vol. 69–2, 363–371.

Hopwood, K. (1995). Modularity transforms manufacturing. *Electronic Engineering Times*, August, pp. 72.

Huang, C.-C., & Kusiak, A. (1998). Modularity in design of products and systems. *6th Industrial engineering research conference proceedings*.

Ishii, K. (1995). Life-cycle engineering design. *Journal of Mechanical Engineering - Transactions of the ASME, 117*, 42–47.

Ishii, K., & Lee, B. (1996). Reverse fishbone diagram: A tool in aid of design for product retirement. *Proceedings of the 1996 ASME design engineering technological conferences -1st design for manufacturing conference*, August, Irvine, CA.

Ishii, K., Eubanks, C. F., & Dimarco, P. (1994). Design for product retirement and material life-cycle. *Materials and Design Journal, 15*(2), 225–233.

Ishii, K., Juengel, C., & Eubanks, C. F. (1995). Design for product variety: Key to product line structuring. *Proceedings of the 1995 ASME design technical conferences - 9th international conference on design theory and methodology, September, Boston, Massachusetts*.

Klausner, M., Grimm, W. M., & Hendrickson, C. (1998). Reuse of electric motors in consumer products: Design and analysis of an electronic data log. *Journal of Industrial Ecology, 2*(2), 89–102.

Kusiak, A., & Chow, W. S. (1987). Efficient solving of group technology problem. *Journal of Manufacturing Systems, 6*(2), 117–124.

Marshall, R., Leaney, P. G., & Botterell, P. (1998). Enhanced product realization through modular design: An example of product/process integration. *Proceedings of the SDPS/ASME/IEEE third world conference on integrated design and process technology, Berlin, Germany, 3*(4), 143–150, ISSN 1090-9389.

Newcomb, P. J., Bras, B., & Rosen, D. W. (1996). Implications of modularity on product design for the life cycle. *ASME Journal of Mechanical Design, 120*(3), 483–490.

Pimmler, T. U., & Eppinger, S. D. (1994). Integration analysis of product decompositions. *Proceedings of the 1994 ASME design engineering technical conferences - 6th international conference on design theory and methodology, September, Minneapolis, Minnesota*.

Siddique, Z., Rosen, D. W., & Wang, N. (1998). On the applicability of product variety design concepts to automotive platform commonality. *Proceedings of 1998 ASME design engineering technical conferences - 10th international conference on design theory and methodology, Atlanta, Georgia*.

Sosa, M. E., Eppinger, S. D., & Roales, C. M. (2000). Designing modular and integrative systems. *Proceedings of the 2000 ASME design technical conferences – 14th international conference on design theory and methodology, Baltimore, Maryland*.

Sosale, S., Hashemian, M., & Gu, P. (1997). Product modularization for reuse and recycling. *Concurrent product design and environmentally conscious manufacturing ASME 1997*, DE-Vol. 94/MED-Vol. 5.

Stone, R. B., Wood, K. L., & Crawford, R. H. (1998). A Heuristic method to identify modules from a functional description of a product. *Proceedings of 1998 ASME design engineering technical conferences - 10th international conference on design theory and methodology, September, Atlanta, Georgia*.

Stone, R. B., Wood, K. L., & Crawford, R. H. (2000). A Heuristic method for identifying modules for product architectures. *Design Studies, 21*(1), 5–31.

Stone, R. B., Wood, K. L., & Crawford, R. H. (1999). Product architecture development with quantitative functional models. *Proceedings of 1999 ASME, design engineering technical conferences - 11th international conference on design theory and methodology, September, Las Vegas, Nevada*.

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy* (Vol. 24). the Netherlands: Elsevier Science B.V.

Ulrich, K., & Tung, K. (1991). Fundamentals of product modularity. *Proceedings of the 1991 ASME design technical conferences - conference on design / manufacture integration, September, Miami, Florida*, pp. 73–79.

Zhang, Y., Gershenson, J. K., & Allamneni, S. (2001). Determining relationships between modularity and cost in product retirement. *Proceedings of 2001 design engineering technical conferences 13th international conference on design theory and methodology*, September, Pittsburgh, Pennsylvania.

Zhang, Y., & Gershenson, J. K. (2003). An initial study of direct relationships between life-cycle modularity and life-cycle cost. *Journal of Concurrent Engineering Research and Applications, 11*(3), 121–128.