CONCURRENT ENGINEERING: Research and Applications

An Initial Study of Direct Relationships between Life-cycle Modularity and Life-cycle Cost

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Abstract: This work shows the relationship between product life-cycle modularity and product life-cycle costs. Previous statements tying increased modularity to improved costs, specifically product retirement costs, motivated this work.

The benefits of modularity with respect to product functionality, product development, production, the supply chain, and other life-cycle elements have been expounded by many works in several fields. Increased modularity has been widely considered to lead to decreased costs. Many have stated that, including modular design tradeoffs early in the design process will decrease life-cycle costs. Some 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 driven by the increased modularity – has never been shown. No research has been done to prove if there exists a relationship between modularity and cost. Many products and research projects have been based on this unproven assumption.

This work begins the exploration into whether a relationship exists between life-cycle product modularity and life-cycle cost for a wide range of consumer products and a wide range of life-cycle issues. The purpose of this paper is to expand initial results in this vain to the whole life-cycle for a more comprehensive look. The results of our work differ significantly from conventional thought and are therefore interesting to both the research and application communities. It is our hope that this paper will motivate others to take a second look at the science behind product modularity and its application.

Key Words: modularity, life-cycle engineering, DfX, design, design theory.

Background

Product Modularity – Definition

The many definitions of product modularity are summarized in Gershenson et al. [8]. In this work, we use an expansion to independent modules [24], asserting that modules contain a high number of components that have minimal dependencies upon *and* similarities to other components not in the module. These dependencies and similarities include those that arise from component–component interactions and those that arise from the various life-cycle processes the components undergo (component–process interactions). In an ideal module, each component is independent of all components not contained in that module throughout the entire product life-cycle (independence) and each component in the module is processed in the same manner during each life-cycle stage (similarity) [7]. We are not the only researchers to suggest the importance of similarity. This definition of modularity expands the form–function relationship to encompass all life-cycle processes in a form–process relationship. Attribute independence, process independence, and process similarity are the three aspects of modularity. Attribute and process independence results in components whose attributes and processes do not bind them to other components not in their module.

Product Modularity – Measurement

A modularity measure implements product modularity mathematically and allows for the application of the definition, usually through a modular design method for implementation on a product. Gershenson et al. [9] discuss the various existing modularity measures in some detail, grouping them into eight types of measures each with an exemplary measure [1,4,14,20–23,25]. Despite significant differences, these eight measures go through a similar set of five steps: (1) decompose the product architecture; (2) specify the application and define the input variables and method of data evaluation; (3) define the modules; (4) extract the input data based on the decomposed product architecture; and

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(5) construct the mathematic model for the modularity measurement.

Product Modularity – Design Methods

Gershenson et al. [9] group modular design methods into two categories, function-based and matrix-based. Function-based methods [18,23] require some intrinsic knowledge as to how to direct and when to stop function decomposition. Matrix-based methods can be grouped further into five widely applicable types of modular design methods, each with an exemplary method [1,4,19,22,26]. Each of these methods groups or reconfigures components guided by the degree of modularity as calculated by a modularity measure that is based on a modularity matrix or by a matrix clustering algorithm. Most of these matrix-based methods rely on function-based methods at their core. Modular design methods are a form of optimization in that they define how to achieve the maximum relative modularity by redesigning or reconfiguring the product architecture.

Product Modularity – Relationship to Cost

Increased modularity has been widely considered to lead to decreased costs. Gurumurthy [11] states that, including modular design tradeoffs "early in the design process" will decrease life-cycle costs. Newcomb et al. [17] hypothesize that a modular architecture will lead to decreased life-cycle costs even if the modules are not designed with other life-cycle characteristics specifically in mind. This is probably true in general, but targeted life-cycle design will increase these benefits and add structure to the process. Newcomb et al. [17] suggest two principal hypotheses: (1) for a majority of products, the product's architecture plays a predominant role in determining its life-cycle characteristics and (2) high life-cycle modularity can be beneficial across all viewpoints of interest.

One of the more prominent life-cycle benefits is that modular design allows the grouping of components into easily detachable modules and also the grouping of components with different materials into different modules [22]. This increases 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 [10]. Several researchers have been specific in stating that retirement (or recycling) costs will be reduced in modular products [4,5,17,22].

Erixson et al. [6] said that cost savings due to economies of scale and increased variety within product families are possible with modular design when product variety is required [12]. Hopwood [13] considered that, in electronics manufacturing, labor costs would be reduced due to product modularity.

Gershenson et al. [8] studied 14 redesigns of a flashlight showing that product modularity and retirement cost share a possible inverse relationship. This provides an interesting view on the existence of a modularity–cost relationship based on a single product in a single life-cycle stage. However, the data is not convincing because only a small number of data points were collected and because retirement was the only life-cycle stage taken into consideration. Therefore, additional depth is necessary. This paper expands the data set and analysis methods across the product life-cycle and several products to yield a more complete view.

Objectives

This work explores whether a relationship exists between life-cycle product modularity and life-cycle cost for a range of consumer products and a wide range of life-cycle issues. We examined various elements of the product life-cycle in terms of life-cycle costs and modularities, and we used products with varying levels of modularity. We explored relationships between individual/total life-cycle costs and individual/total life-cycle modularities, between and between individual/total life-cycle modularities and number of design modifications.

Methods

To measure or redesign a product involves the following steps [25,26]: making life-cycle graphs to describe a product and the life-cycle processes it undergoes; using these graphs to build a matrix to represent the similarities and dependencies in a product; calculating all necessary modularities using the matrix; estimating individual life-cycle costs of a product and then summing these costs to get the total life-cycle cost; and using the modularity measures to redesign the product to improve its overall modularity. After a redesign is done, a new matrix must be generated based on the changes made to the product. The life-cycle modularities and costs can then be evaluated for the redesigned product.

Modularity Measure

The measure of relative modularity used (based on [7]) is the ratio of intra-module similarities, S_{in}, to all intra- and inter-module similarities, $(S_{\text{in}} + S_{\text{out}})$, added to the ratio of intra-module dependencies, D_{in}, to all intra- and inter-module dependencies, $(D_{\text{in}} + D_{\text{out}})$ (Equations (1)–(6)). Zhang et al. [26] give a detailed explanation of the components of these equations and an example of their application. The measure accounts for component–process similarities and both component–component and component–process dependencies. S_{in}, S_{out}, D_{in}, and D_{out} are calculated using subjective ratings of the above parameters for relationships between each component in the product and all other components as well as each component and each life-cycle process the product goes through. Similar to the calculation of total modularity (TRM), any individual life-cycle modularity makes use of component interactions and the interaction of the life-cycle stage under consideration only.

Modular Design Method – A Brief Overview

The goal of the modular design method [7] is to redesign a product by eliminating components or modules, rearranging components or modules, or changing component attributes. Reconfiguration is the shifting of components to other modules to increase the total relative modularity. Redesign is the changing of component attributes to reduce external similarities and dependencies or increase internal similarities and dependencies. Each step of the method is controlled by the previously discussed relative modularity measure as it is applied to levels, modules, and components. The structure of the method is shown below. A more specific accounting of the method and its development can be found in [7].

The modularity measure developed for computing the modularity rating is as follows:

$$\text{TRM} = \Sigma S_{\text{in}}/(\Sigma S_{\text{in}} + \Sigma S_{\text{out}}) + \Sigma D_{\text{in}}/(\Sigma D_{\text{in}} + \Sigma D_{\text{out}}) \tag{1}$$

$$S_{\text{in}} = \sum_{v=1}^{L} S_{\text{in}}, \quad S_{\text{out}} = \sum_{v=1}^{L} S_{\text{out}}, \quad D_{\text{in}} = \sum_{v=1}^{L} D_{\text{in}\,v}, \quad D_{\text{out}} = \sum_{v=1}^{L} D_{\text{out}\,v} \tag{2}$$

where: L is the total number of levels of the product containing assemblies

$S_{\text{in}v}$: component–component interaction within a module with respect to process v

$$S_{\text{in}_v} = \sum_{m=1}^{M} \sum_{i=1}^{s-1} \sum_{j=i+1}^{s} \sum_{k=1}^{T} \sqrt{(S_{\text{ik}} \times S_{\text{jk}})} \tag{3}$$

where: i, j are components in the same module, k is a task; $\sqrt{(S_{\text{ik}} \times S_{\text{jk}})}$ is component–component similarities with respect to process k; $M =$ number of modules at level v; $s =$ last component in the module m or n; $T =$ number of processes under consideration

$S_{\text{out}v}$: component–component interaction external to a module with respect to process

$$S_{\text{out}_v} = \sum_{m=1}^{M-1} \sum_{i=1}^{s} \sum_{n=m+1}^{M} \sum_{j=1}^{s} \sum_{k=1}^{T} \sqrt{(S_{\text{ik}} \times S_{\text{jk}})} \tag{4}$$

$D_{\text{in}v}$: dependence between each component within a particular module.

$$D_{\text{in}_v} = \sum_{m=1}^{M} \sum_{i=1}^{s-1} \sum_{j=i+1}^{s} \sum_{k=1}^{T} (\sqrt{(D_{\text{ik}} \times D_{\text{jk}})} + D_{\text{ij}}) \tag{5}$$

where: $\sqrt{(D_{\text{ik}} \times D_{\text{jk}})}$ is component–component dependencies with respect to process k; D_{ij} is for computing component-component dependencies

$D_{\text{out}v}$: dependence between components belonging to a module and components external to that module

$$D_{\text{out}\,v} \sum_{m=1}^{M-1} \sum_{i=1}^{s} \sum_{n=m+1}^{M} \sum_{j=1}^{s} \sum_{k=1}^{T} (\sqrt{(D_{\text{ik}} \times D_{\text{jk}})} + D_{\text{ij}}) \tag{6}$$

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MODULE ELIMINATION
At each level, start from the module with the worst TRM
    If eliminating the module will increase the TRM of that level and is feasible then eliminate it
COMPONENT ELIMINATION
At each level, start from the component with the worst TRM
    If eliminating the module will increase the TRM of that level and is feasible then eliminate it
MODULE RECONFIGURATION
At each level, start from the module with the worst TRM
    Within each module, start with the component with the highest TRM
        Move that component into another module, starting from Level 2 and continuing to the next to last level until a
            change is made and starting with the module at that level with the highest TRM, if the move is feasible and if
            the move increases the TRM of both levels.
        If you cannot move it to another module at that level, try creating a new module at that level before moving to
            the next level.
COMPONENT REDESIGN
At each level, start from the component with the worst TRM
    Change the attributes of the component to reduce external similarities and dependencies and/or increase
        internal similarities and dependencies if the change is feasible and if doing so increases the TRM of that
        level.
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Life-cycle Costs

Only manufacturing, assembly, and retirement costs were accounted for; these give a wide variety and allow for a manageable data set. Manufacturing is very machine and process dependent, assembly is very dependent upon product structure and similar to maintenance and service, and retirement has been well studied and offers easy opportunities for modular benefits. The general methods used to evaluate each of those costs in each process are as follows (specifics can be found in the citations or [25]). Note that only a relative cost was used.

MANUFACTURING COST

Boothroyd et al. [2] stated that the total manufacturing cost can be divided into material costs, production costs (including tooling cost and processing cost), and purchase costs. Using these, we can get the overall manufacture costs for the product.

$$C_{\text{manufacturing}} = C_{\text{material}} + C_{\text{production}} + C_{\text{purchase}} \qquad (7)$$

where: $C_{\text{manufacturing}}$ is the cost of manufacturing, (\$); C_{material} is the cost of material, (\$); $C_{\text{production}}$ is the cost of production, (\$); C_{purchase} is the cost of off the shelf parts, (\$). Based on [2].

ASSEMBLY COST

Boothroyd et al. [2] developed a classification system to estimate the manual handling time and manual insertion time for manual assembly. If the cost of operation (\$/h) is known, the assembly cost is given by:

$$C_{\text{assembly}} = C_l(t_h + t_i) \qquad (8)$$

where: C_{assembly} is the cost of assembly, (\$); C_{l} is the cost of labor, (\$/h); t_{h} is the manual handling time (*s*); t_i is the manual insertion time (s). Based on [2].

RETIREMENT COSTS

The costs associated with retirement include recycling, reuse, remanufacturing, and disposal can be measured as follows.

$$\text{Recycling costs}: \ C_{\text{o}} = C_{\text{d}} + C_{\text{s}} + C_{\text{r}} + D_{\text{c}} \qquad (9)$$

where: C_{o} is the cost of recycling, (\$); C_{d} is the cost of disassembly, (\$); C_{s} is the cost of shredding, (\$); C_{r} is the cost of material recovery, (\$); D_{c} is the cost of dumping, (\$). Based on [3].

$$\text{Reuse cost}: \ C_{\text{reuse}} = (1+i)^T[rC_{\text{L}}(t_{\text{R}} + yt_{\text{D}})]x \qquad (10)$$

where: C_{reuse} is the Cost of reuse, (\$); i is the discount rate; T is the time between manufacture and reuse, (h); r is the fraction of components returned; C_{L} is the hourly labor cost, (\$/h); t_{R} is the time required for testing, (h); y is the recovery rate, %; t_{D} is the disassembly time, (h); x is the initial number of components manufactured;

Note: it is assumed that there is no change in demand for the component. Based on [16].

$$\text{Disposal cost}: \ D_c = d_c(W_d) \tag{11}$$

where: d_c is the cost of dumping one ton of solid waste, ($); W_d is the weight of dumped waste, (tons). Based on [3].

Applications

We applied the above methods to the same products used in [26]: the redesigns of a Kodak single-use camera, a Conair hair dryer, an Adhesive Tech mini glue gun, and an Eveready flashlight, and 10 off-the-shelf products with no redesign (a Fisher-Price chatter radio, a Proctor Silex automatic drip coffeemaker, a Johnson reel with pre-spooled line, a Sunbeam home hair trimmer, a Farberware ice-cream scoop, a Regent halogen clamp light, a Black & Decker cordless 2.4v screw driver, a Bell classic portable pump, a Pur faucet mount water filter, and an ANCO premium wiper blade).

Results

Again, the purpose of this work is to develop an initial position on whether increased modularity leads to reduced life-cycle costs. This work looked at that hypothesis for a small set of products and for a small but varied set of life-cycle concerns using one modularity measure. Linear regression, analysis of variance, and correlation are among the statistical analysis used.

The data for total relative modularity and total cost as well as each individual life-cycle modularity (XRM) and its corresponding life-cycle cost (XC) were analyzed for the four redesigned products (Table 1). The high values of R^2 and zero P values of the camera and the mini glue gun indicate that a relationship exists between TC and TRM (all life-cycle aspects together) for the two products. However, the camera actually has a positive relationship ($\beta 1$ or slope value) between TC and TRM. Only 0.7 and 3.9% of the TC for the other two products can be explained by their TRM, and their P values are extremely high. That indicates there are no clear relationships between TRM and TC for the hair dryer and the flashlight. With such results, we therefore conclude that there is no relationship between TRM and TC.

For MRM and MC (manufacturing), the R^2 and P values of the camera and the hair dryer show that there is a relationship between the two variables. Because the P values of the mini glue gun and the flashlight are much higher than 0.05, there are no relationships between MRM and MC for these products. The negative values of β show that the manufacturing cost of the camera, mini glue gun, and the flashlight decreased slightly with the increase of MRM. Only the manufacturing cost of the hair dryer increased when the MRM increased.

For ARM and AC (assembly), the R^2 of the camera shows that more than half of the assembly costs can be explained by the assembly relative modularity. Its P value is zero, which means that there is a definite relationship between the two variables. The R^2 of the other three products range from 26.9 to 36.7% and their P values are less than 0.05. That indicates that there is a definite relationship between ARM and AC. The slopes show that the assembly cost of the camera, hair dryer, and mini glue gun decreased slightly with the increase of ARM. Additionally, the assembly cost of the flashlight increased when the ARM increased.

For RRM and RC (retirement), the R^2 of the hair dryer shows that a high percentage of the RC can be explained by RRM. The RRM of the camera also explained over half of the RC while only 35.7% of RC of the flashlight can be explained. The P values of those three products show that there is a relationship between RRM and RC. The P value of the mini glue gun is greater than 0.05 and proved that there is no relationship between the two values. Thus, there is no relationship between RRM and RC. Note how varied the β_1 slope values are.

These results indicate that there are no obvious relationships between total relative modularity and total cost, manufacturing relative modularity and

Table 1. Results of linear regression on the relationship between TRM and TC and all XRM and XC of the four redesigned products.

Product Name	R^2(%)	P Value	$\beta 1$
TRM vs. *TC*			
Camera	64.80	0	0.668
Hair Dryer	0.70	0.76	−0.027
Mini Glue Gun	64.00	0	−0.181
Flashlight	3.90	0.481	−0.433
MRM vs. TC			
Camera	53.70	0.001	−1.33
Hair Dryer	29.00	0.032	0.158
Mini Glue Gun	1.20	0.691	−0.005
Flashlight	2.90	0.545	−0.274
ARM vs. AC			
Camera	59.60	0	−0.039
Hair Dryer	34.90	0.016	−0.062
Mini Glue Gun	26.90	0.039	−0.07
Flashlight	36.70	0.017	0.086
RRM vs. RC			
Camera	65.10	0	2.27
Hair Dryer	90.40	0	−1.2
Mini Glue Gun	13.10	0.168	−0.019
Flashlight	35.70	0.019	−0.106

manufacturing cost, or retirement relative modularity and retirement cost. Only the relationship between assembly relative modularity and assembly cost was shown to exist. However, for certain individual products, some of these relationships did exist.

Next, we used linear regression to determine if higher life-cycle modularities correspond to lower life-cycle costs for the ten off-the-shelf products. Total life-cycle costs were unavailable for the products; selling prices were used to represent total costs. Understanding that margins may vary significantly and that the prices of different products vary significantly, the prices of the ten off-the-shelf products needed to be normalized for comparison. To get the normalized total costs (NTC) of the products, the selling prices and the average selling prices of similar products were collected. The total costs of the products were normalized as $\text{NTC} = ((\text{Calculated Total Cost})/(\text{Average Selling Price}))$. The individual life-cycle costs can be normalized by multiplying the normalized total cost by the fraction of the calculated individual life-cycle cost to the calculated total cost using $\text{NXC} = \text{NTC} \cdot ((\text{Calculated Individual Life} - \text{Cycle Cost})/(\text{Calculated Total Cost}))$. Table 2 shows extremely low values of R^2 and high P values and therefore no relationships between the normalized life-cycle costs and life-cycle modularities.

We then used scatter plots to explore how strongly the normalized life-cycle costs (NXC) and normalized life-cycle relative modularities (NXRM) are related. A correlation coefficient was used to assess the strength of relationship between the variables. The NAC versus NARM (assembly) and NMC versus NMRM (manufacturing) correlations are positive (0.2207 and 0.1463 respectively) while the other two are negative (−0.3164 for NRC versus NRRM and −0.1501 for NTC versus NTRM). The relationships between normalized retirement cost and normalized retirement relative modularity and normalized total cost and normalized total retirement modularity are inverse. The relationship between the normalized cost and normalized relative modularity for assembly and manufacturing are positive. The correlations show that 14 to 31% of all of the costs can be explained by the modularities. There is no tendency for the costs either to increase or to decrease as the modularities increase.

Table 2. Results of linear regression on the relationship between NXC and XRM of the ten off-the-shelf products.

	R^2(%)	P Value	$\beta 1$
NTC vs. TRM	0.30	0.89	0.106
NMC vs. MRM	4.80	0.545	−0.257
NAC vs. ARM	5.20	0.527	0.092
NRC vs. RRM	2.00	0.697	−0.02

To take a more general look at the data, we explored how changes in life-cycle modularities (CXM) affect changes in life-cycle costs (CXC). The goal was to see if the design method reduces life-cycle cost while increasing product life-cycle modularity. The change in relative modularities and costs were calculated by subtracting the current modularity or cost from the previous modularity or cost for the 14 or 15 redesigns of the four redesigned parts. Four scatter graphs (CTC vs. CTRM, CMC vs. CMRM, CAC vs. CARM, and CRC vs. CRRM) were plotted. Each quadrant in the scatter plot represents a positive or negative change in life-cycle modularity corresponding to a positive or negative change in life-cycle cost. The data points in the second and fourth quadrants indicate increased life-cycle modularities leading to decreased life-cycle costs or decreased life-cycle modularities leading to increased life-cycle costs. The data points at the origin represent no changes in modularities and costs. The data points on the positive or negative x-axis indicate increased or decreased modularities not leading to changes in costs. The data points on the y-axis indicate changes in costs with no changes in modularities.

Table 3 shows the percentages of the data points that are on (0,0), x-axis, y-axis, in the second and fourth quadrants, and in the first and third quadrants for the four groups of parameters. For all life-cycle processes, the percentage of data points in the first and third quadrants is about 32%. This indicates that, even if increased modularities do not definitely lead to decreased costs, at least most of the time (about 70% on average) they are beneficial or inconsequential to cost.

This led us to a related question – does the modular design method lead to more modular products. The

Table 3. Percentage of data points that are on the origin, x-axis, and y-axis, in the second and fourth quadrants versus the first and third quadrants between change in total cost (CTC) and change in total relative modularity (CTRM) of the four products.

	% on (0,0)	% on X-axis		% on X-axis		% in 2nd and 4th Quadrants	Quadrants % in 1st and 3rd Quadrants
		$X+$	$X-$	$Y+$	$Y-$		
CTC vs. CTRM	0	20	0	0	0	49	31
CMC vs. CMRM	2	20	10	0	3	25	32
CAC vs. CARM	2	32	10	0	3	24	29
CRC vs. CRRM	3	20	15	2	2	24	34

averaged, normalized TRM and XRM versus the modification number (redesign number) were explored for the four redesign products. The P values for all groups of variables are zero with R^2 values all above 90%. These indicate a definite relationship between the TRM/XRM and modification number. The result suggests that life-cycle modularities of a product are affected by its number of redesigns. This is significant since the goal in redesigning the four products was TRM, not any individual XRM. The slopes between TRM/XRM and modification number are all positive and almost equal (averaging 0.0651). That indicates that all of the individual life-cycle modularities and the TRM increase nearly equally with the increase of modification number. This shows that the modularization method applied in this research help to increase the total life-cycle modularity as well as each individual life-cycle modularity.

Conclusions

It was our goal to characterize the relationship between product modularity and product cost. While we do not claim that this study should be the first and last, it is by far the most complete study undertaken and it does set a tone for future research. We began with the common hypothesis that increased modularity leads to decreased costs. Based on the statistical analysis of the fourteen products, it is clear that there are no general relationships between relative modularity and cost, or between change in modularity and change in cost.

Only the relationship between ARM and AC was proven to exist. Individual life-cycle relationships were found for individual products. Three of the four redesigned products have a negative relationship between ARM and AC, while the other one has a positive relationship between the two variables. Two products showed relationships between MRM and MC, one positive and one negative. Three products showed relationships between RRM and RC, one positive and two negative. Two products showed relationships between TRM and TC, one positive and one negative. The assumption that there are relationships between the normalized life-cycle costs and life-cycle relative modularities of the ten off-the-shelf products was rejected as well. Therefore, we can conclude that the popular belief that modular products have lower costs is not without some doubt. However, it was found that there are definite positive relationship between normalized XRM and modification number. If more redesigns are made on a product, even if they are made with only TRM in mind, the TRM along with all its individual life-cycle relative modularity will be improved. This indicates that the method to modularize products applied in this research can help improve each aspect of product life-cycle modularity as well as the overall modularity. By applying this design method, increases in modularity were proven to result in mostly steady or decreased costs.

We conclude that, while more work is needed to flesh out the relationship between product modularity and cost, researchers should not be cavalier in their proclamation that such a relationship exists and practitioners should be cautious about relying on this assumption. Our research group is continuing with a significantly broader and deeper examination of this issue.

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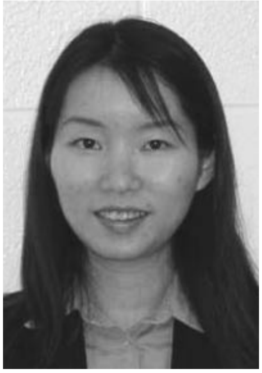

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