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A PRODUCT FAMILY BASED LIFE CYCLE COST MODEL FOR PART VARIETY AND CHANGE ANALYSIS[1]

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ABSTRACT
This research work aims to develop the dynamic relationships between the level of part variety in a product family and the life cycle cost (LCC). The purpose is to establish a decision-support model that enable better decision-making in product family configuration and part changes based on LCC rather than part procurement costs for a given operation environment. This should provide the means for further reduction of total product costs. It would also give the impact on overall costs when a part change request is raised. Presented in this paper is the framework and initial findings on the factors affecting the LCC and behaviors between part variety level and LCC. The application is focused on the cost impact analysis when a design or customer order change takes place.

Keywords: Life Cycle Cost, Product Family, Part Variety, Impact Analysis

1 INTRODUCTION
Product family design is widely practiced in the industry as a cost-effective approach to satisfy the increasing market trend towards smaller batch and more variety orders [1,2]. In product family design, each product model is a variant of a product platform, and a part can be used in a number of product models. Many efforts have been made to develop applicable concepts and methods that use information technology to assist the development of product family configurations [3-5]. Further works in recent years has resulted in the application of artificial intelligent techniques in the development product configuration in the dynamic mass-customization environment [6-8]. While product mass-customization requires a total solution that encompassing the entire product lifecycle [9], the decision on the use of a part among parts of equivalent function in product models is primarily based on its purchasing price. This leads to the selection of parts that best fit each product model, resulting in a large number of part varieties. Additionally, the use of purchasing price as the decision criteria also contributes to the frequent change of parts whenever a cheaper alternative becomes available. The impacts in costs by increased part variety and frequency of part change are ignored due to the lack of scientific and effective evaluation methods.
Particularly over the past two decades, product manufacturers have raced to invest heavily to strengthen their competitiveness in cost, quality, and deliver lead-time. As the race continues, further improvements rely increasingly on achieving overall performance in these competitive factors over the product life cycle. The needs are intensified by the shortening product life cycle that leads to the requirements for shorter lead-time.
The marketplace has also become much more dynamic. The order-to-delivery time has become much shorter and manufacturers face more uncertainty in order confirmation due to changing market conditions.
Shorter product and component life cycle, coupled with market dynamics, tends to increase the operational costs in product development and manufacturing, resulting in further pressure on cost reduction. Moreover, the pressure together with the available of new and cheaper parts encourages the

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manufacturers to change the design more often for accommodating lower priced parts with the aim to reduce product unit cost. This in turn further aggravates the operational costs.

This paper discusses our work in the establishment of dynamic relationships between the level of part variety in a product family, the part changes, and the Life Cycle Cost (LCC). Understanding of such relationships would allow better decision-making in product family configuration and part changes based on LCC rather than part procurement costs for a given operation environment. This should provide the means for further reduction of total product costs. It would also give the impact on overall costs when a part change request is raised.

2 A REVIEW ON LIFE CYCLE COST MODELING

Much effort has been made in the modeling, analysis and application of LCC. *Fabrycky* and *Blanchard* presented a sophisticated life cycle cost model to address detailed cost analysis of all the costs associated with the product entire life cycle [18]. It decomposes LCC into four categories: research and development costs, production and construction costs, operation and maintenance costs, and retirement and disposal costs.

Works in the 'design for "X"' realm deal with the costs in the phase of production and construction. Among them the most successful methodologies are Design for Manufacturing (DFM), Design for Assembly (DFA) developed by *Boothroyd*, and *Dewhurst* [24, 25, 26, 27], and Hitachi assembly evaluation method (AEM) developed by *Miyakawa* and *Ohashi* [28]. These methods focus on production characteristics that consume avoidable resources during manufacture and assembly [13]. They evaluate a manufacture/assembly based on a number of criteria and compute a numerical score to suggest improvement of the design to reduce the cost of the manufacture/assembly.

Production cost can be estimated by the costs associated with a set of manufacturing activities. The Activity Based Costing (ABC) model focuses on calculating the costs incurred on performing the activities to manufacture a product [14]. It is proved useful in highlighting high-cost elements because the inclusion of uncertainty and the use of Monte Carlo simulation in conjunction with the process steps [19]. Four cost related activities are considered: unit-level, batch-level, product-sustaining, and facility-sustaining activities [17]. The ABC model can be applied when the activities are described in detail. It is proved as a good alternative to traditional estimation techniques since it provided more accurate product manufacturing cost estimates [29]. It can also be utilized to analyze other aspects of cost, such as overhead cost [13].

Woodward's Life Cycle Cost Analysis (LCCA) model aims specially to optimize the value of money in physical assets ownership, by identifying and quantifying the trade-offs between different costs relating to the assets during their operational life. This model has the best potential for effective cost assessment in life cycle design [20].

Design for cost (DTC) model presents a methodology to integrate cost modeling into Quality Function Deployment (QFD) for making trade-off decisions between quality and cost at the early stages of product design [21].

Some studies have been made in developing procedures for evaluation of maintenance of various systems. *Gershenson* and *Ishii* addressed serviceability in design. They divided the drivers of service cost into part cost, labor cost, and failure rate [30]. *Vujosevic, Raskar, Yeturkuri, Jothishankar,* and *Juang* have evaluated the maintainability of systems on the basis of cost of assembly/disassembly [31]. *Kwang-Kyu Seo*, and *Beum Jun Ahn* proposed a method, based on an artificial neural network (ANN), to facilitate an integrated system of design process, allowing approximate and rapid estimation of product maintenance cost based on high-level information typically known in the conceptual phase [15].

The consumer's demand for green products and the rising waste disposal costs lead to a surge in research activities in environmental impact assessment. Life cycle assessment (LCA) is a framework for assessing the potential environmental aspects related to a product [11]. LCA is an environmental and energy audit (accounting procedure) that focus on the entire life cycle of a product from raw material acquisition to final product disposal of environmental emission (*Benda et al.*, and *Weule*) [22, 23].

With the development of product family, many researches have been made to quantify the product costs during platform-based product development. *Fujita, et al.* proposed modeling the total cost for product variety, including design and development cost, facility cost, and material and processing cost. In this model, fixed costs are assumed to be proportional to the attributes of each module, and variable costs are characterized by cost savings from similar and same design instances [16]. *Martin, et al.* described the interaction of product variety and developed three indices – commonality index, differentiation point index, and setup cost index. Environment cost is also considered [16].

The work of this paper focuses on the establishment of relationships between the LCC and the level of part varieties in some major operation processes. The immediate application purpose is for cost impact analysis when a design or a customer order change takes place.

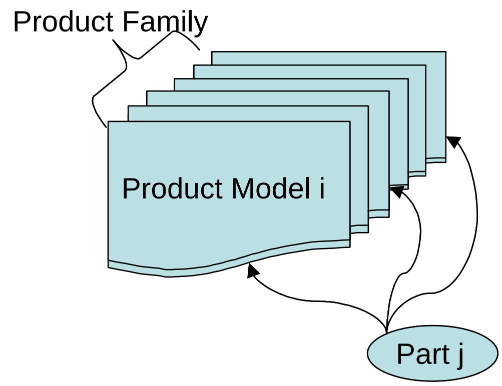

Figure 1. Product Family, Models, and Parts

3 LIFE CYCLE COST MODEL

As illustrated in Figure 1, a product family (PF) is consisted of a number of product models (PM_i, i=1,2,...N), and each product model is consisted of a number of product parts (PP_{ij}, j=1,2,...,K). Within a product family, the models are typically variants of a common base product, and hence are with strong commonalities in functions. The differences may be in capacity, additional functions, some unique features, and just some simple aesthetic attributes such as colors. This offers the possibility for a part to be used in a number of product models. The major constraint is the cost. Without considering modularity of parts in a product family, the product model configuration with parts that best fits itself would result in the lowest unit cost ($C_{PMi}^{\min}$). The highest cost ($C_{PMi}^{\max}$) for each model would be obtained when all functionally substitutable parts in the product family are used cross all the models. However, when certain parts or sub-assemblies can be modularized for use in many or all product models at a lower unit cost, the $C_{PMi}^{\min}$ and $C_{PMi}^{\max}$ conditions would be reversed. In any case, the product family cost can be expressed as:

$$C_{PF}^{Static} = \sum_{i=1}^{N} C_{PM}^{i} \; ; \quad \sum C_{PMi}^{\min} \le C_{PF}^{Static} \le \sum C_{PMi}^{\max} \qquad (1)$$

where C_{PM}^{i} is the sum of costs of parts used in product model i.

When costs arising from operational activities over the product life cycle are considered, the characteristics and value of C_{PF} becomes complex and different. Figure 2 illustrates the major activities at key stages of product life cycle and the possible areas of impacts on C_{PF}. At the product design stage, a design change may result in possible changes in tooling, the needs for new prototypes and tests. If the product were already launched, the part changes from the design change would also impact the product life cycle processes. At the product production stage, it may result in the depletion of affected inventory parts, change in production process, and trigger new efforts in part manufacturing or procurements. At the product services stage, it may require extra part manufacturing and procurements, and depleting affected service parts in the service inventory. At the product end-of-life (EoL) stage, the design change may lead to changes in the EoL process and requirements. All these contribute directly and indirectly the LCC of the product family.

Likewise, when a customer order is changed or the actual sales of particular models of the product family are significantly behind plan, it would cause shortages or over-inventory of production and service parts, and hence the extra costs or wastage respectively.

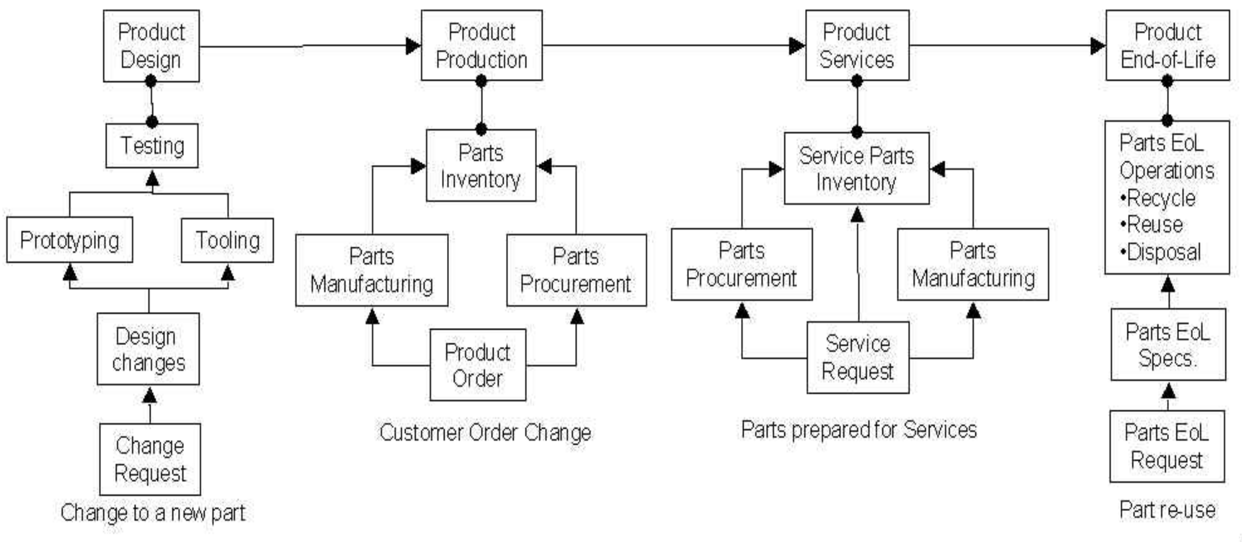

Figure 2. Possible Areas of Impacts at Major Stages of Product Life Cycle

From a product family's perspective, the impacts on LCC by either design or order changes should be a function of the number of parts used in its models. To understand the relationships, a qualitative impact analysis of the changes on the LCC was carried out. The results for a narrowed scope of stage and activities with significant contributions are summarized in Table 1. For all the factors in consideration, only the costs associated with man-efforts for design change tends to become lower. This is mainly because more models need to be attended if a part to be changed is used by more models in the product family. The cost arising from all other factors tends to go up along with more part varieties as more efforts are required for part making and procurements, and more likely some inventory parts are to be depleted. These scenarios indicate the existence of relationships between the level of part variety and life cycle costs in a product family. Hence, we can express the LCC of a product family, LCC_{PF}, as the function of total number of parts, κ, and through the adjustment of part selection in product models to minimize LCC_{PF}, i.e.,

$$LCC_{PF}(\kappa) = \min_{\kappa}(C_{PF}^{Static} + C_{PF}^{Dynamic}) \tag{2}$$

where the static costs of the product family, C_{PF}^{Static}, is defined by equation (1), and the LCC associated with operational dynamics can be defined as

$$C_{PF}^{Dynamic} = \sum_{j=1}^{M} C_j(\kappa_j, \omega_j) : \kappa \geq \sum_{j}^{M} \kappa_j \tag{3}$$

where C_j is the jth cost factor, κ_j is the number of parts affected by a design or order change at cost factor C_j, and ω_j is a function of γ_j^r, i.e.,

$$\omega_j = f(\gamma_j^1, \gamma_j^2, ..., \gamma_j^r, ..., \gamma_j^R) \tag{4}$$

where γ_j^r (r = 1, 2, ..., R) are the cost coefficients of C_j.

Specific to the work of this paper, C_j (j = 1, 2, ..., M) are limited to the following four aspects. The formulation focuses on the cost coefficients that influence the LCC on a given level of part variety when design or order changes take place.

Table 1. Qualitative Impact of Changes on LCC

Change	Stage	Factor	Level of Part Variant	Cost Impact
Part Change	Product design	Manpower on design change	UP	DOWN
		Tooling	UP	UP
		Prototyping	UP	UP
		Testing	UP	UP
	Production	Production part making	UP	UP
		Production part procurement	UP	UP
		Production part inventory	UP	UP
		Production/Assembly	UP	UP
	Service	Service part procurement	UP	UP
		Service part manufacturing	UP	UP
		Service part inventory	UP	UP
Order change	Production	Production part making	UP	UP
		Production part procurement	UP	UP
		Production part inventory	UP	UP
		Production/Assembly	UP	UP
	Service	Service part procurement	UP	UP
		Service part making	UP	UP
		Service part inventory	UP	UP

(1) Cost by the design team, C1 (j=1)

$$C_1 = (\kappa_1, \omega_1) = \sum_{l=1}^{\kappa_1} [T^{manday}(PP_l) * C^{manday-rate}(PP_l) + C^{Tooling}(PP_l) + C^{opportunity}(PP_l)] \quad (5)$$

Here, γ_j^r (j = 1,2,3) are the number of man-days required to change each part PP_l, $T^{manday}(PP_l)$; the man-day rate in dollar terms, $C^{manday-rate}(PP_l)$; the tooling costs due to changing part PP_l, $C^{Tooling}(PP_l)$; and the opportunity cost for the time $T^{manday}(PP_l)$. The value is considered as the sum of required man-days to make a design change for each affected part plus the opportunity cost that the design team might otherwise create value.

(2) Cost by purchasers, C2 (j=2)

$$C_2 = (\kappa_2, \omega_2) = \sum_{l=1}^{\kappa_2} [T^{manday}(PP_l) * C^{manday-rate}(PP_l) + C^{opportunity}(PP_l)] \quad (6)$$

Here, the value is considered as the sum of required man-days to procure each affected part, PP_l, plus the opportunity cost that the purchasers might otherwise create value.

(3) Cost/wastage of production inventory, C3 (j=3)

$$C_3(\kappa_3, \omega_3) = \sigma \sum_{l}^{\kappa_3} \rho_l * \theta_l * \alpha_l * C^{part}(PP_l) \quad (7)$$

where ρ_l is the part's life cycle time; $\alpha_l \in [0,1]$ is a probability coefficient for likely depletion of PP_l after the change; $C^{part}(PP_l)$ is the cost of affected part *l*; and

$$\theta_l = f\{T^{procurement}(PP_l), T^{production}(PP_l), T^{delivery}(PP_l), C^{part}(PP_l)\} \quad (8)$$

is the minimum inventory required to meet the order-to-delivery lead-time, $T^{delivery}(PP_l)$. The factors that also play a major role in the determination of θ_l include the procurement lead-time, $T^{procurement}(PP_l)$, the production/assembly lead-time, $T^{production}(PP_l)$, and $C^{part}(PP_l)$. For cost due to customer order cancellation/change, σ is the cancellation/change rate based on historical data; for the cost due to design change or for evaluating an order change cost scenario, σ =1.

(4) Cost/wastage of service part inventory C4 (j=4)

$$C_4(\kappa_4, \omega_4) = \sum_{l}^{\kappa_4} \rho_l * \mu_l * \alpha_l * C_{part}^l \quad (9)$$

where the minimum number of service part, PP_l, to be prepared in inventory is determined by

$$\mu_l = f\{R^{failure}(PP_l), S^{sale}(PP_l), C^{mass}(PP_l), C^{small}(PP_l)\} \quad (10)$$

where $R^{failure}(PP_l)$ is the part-failure rate; $S^{sale}(PP_l)$ is the projected-units of sales, $C^{mass}(PP_l)$ is the mass-procurement cost; and $C^{small}(PP_l)$ is the small-batch procurement cost.

4 A CASE STUDY AND ANALYSIS OF LCC BEHAVIOR

The LCC models are studied against the operational environment of a manufacturer who design, make, and market a series of instantaneous water heaters internationally. Figure 3 shows two models from a product family of the company's water heaters. There are a total of 9 models in the product family. Each model is governed by a set of product specifications, e.g., power, voltage, water pressure, water volume, color, country, etc., which are aimed to satisfy a certain market or market segment. For each product specification, there can be one or many product configurations that can satisfy the basic product (technical) specifications through the combination of parts (Figure 4). Each part has its type, and each type can have a number of makes and choices. Continuous innovation in heating and supporting parts by part manufacturers provides new and cheaper part alternatives for possible changes to as-is product configurations.

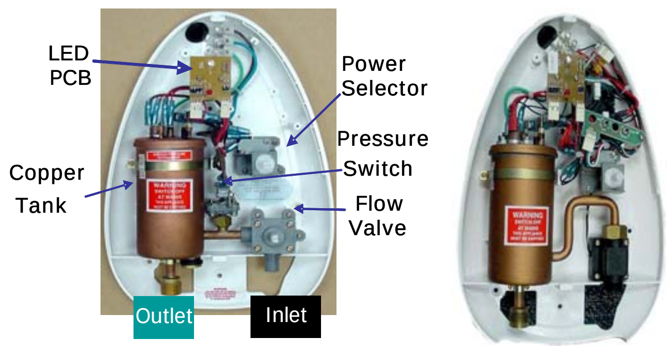

Figure 3. Two models of a family of Instantaneous Water Heaters

The company operates in order-to-assembly mode. The product models are pre-designed and marketed. However, the production will only start when an order is confirmed. The shortest order-to-delivery time can be just 2 days. In order to meet such a lead-time, the company keeps a minimum inventory for both production and services. When a cheaper part becomes available, the company tends to use it to replace the part in current design for the purpose to reduce product unit cost. As this happens often, the company finds it faster and cheaper to avoid the use of part cross product models. This maximizes the part varieties in the product family. The LCC models developed are studied against the company's product life cycle processes and operational environment at the design, procurement, production, and customer services stages.

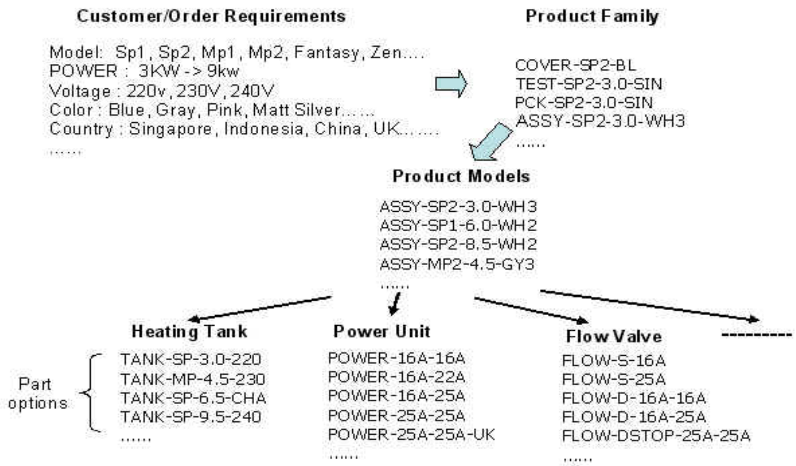

Figure 4. Product model and available configuration elements

The product family can have many possible combinations of parts. However, certain parts in the product family are fixed due to functional and special requirements. In the work of this paper, these types of parts include:

- Product platform structure for all the product models in the product family, e.g., front and back covers, packaging boxes;
- Parts specially required by a certain model for its uniqueness, e.g., heating tank for a specific product model;
- Small and low cost items, e.g., screws and electrical wire.

Disregarding the influences on LCC by the above types of parts, the patterns of LCC by part variety levels for each model can be analyzed based on the static and dynamic behavior described by the cost model (1) and (2) for design and order change, respectively. Figure 5 shows the normalized relative impact level in percentage of cost by each of the 9 models at two extreme situations: highest part variety (lowest modularity) and lowest part variety (highest modularity). The product model is ranged based on its unit cost ranging from the lowest (model 1) to the highest (model 9). The higher cost models are with higher capacity (hence higher cost parts) and more functions. The values for change costs are obtained based on the scenario to change a part priced at \$0.8 - \$6.5 from model 1-9. The results indicate that lower part variety in the product family offers much lower LCC. The lower part variety also has lower impact on LCC when a design change takes place.

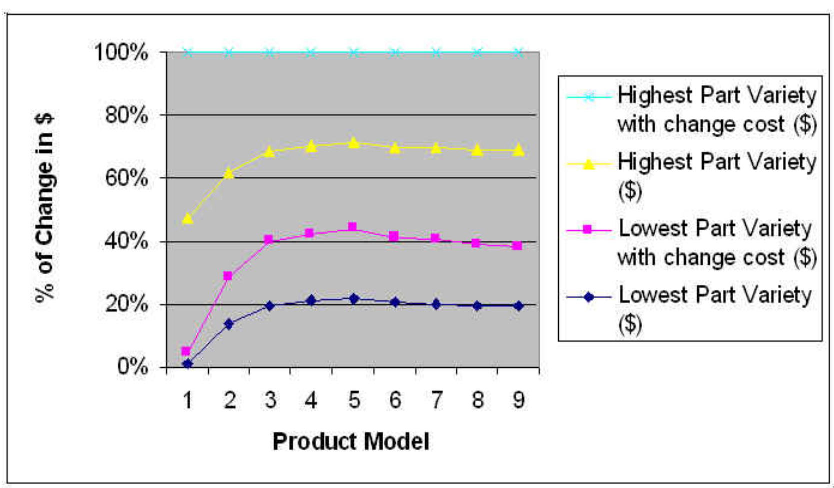

Figure 5. Cost Impact by Part Variety Level on the product models

The LCC model is also found useful for part replacement decision-making when a cheaper part becomes available. A calculation on a case to change a part of $2.54 dollars for a model under the company's operation situation at the time has shown that the change would cost $0.37 per product for the highly modularized product in production. This means that there is no cost benefit to replace the part with a new one unless the new part is more than $0.37 cheaper.

5 CONCLUSION REMARKS

This research work has resulted in the development and preliminary application of a LCC model that considers the dynamic cost due to design and customer change. Major cost elements at the design, procurement, production inventory, and product service inventory stage of a product lifecycle are considered. The results have shown that the cost of changes is significant. The higher the part variety is, the higher the cost of change becomes. A good modularity of major components for use in many or all the models in a product family can greatly reduce both the static and dynamic LCC of the product family. This would give the manufacture a competitive edge in cost as well as in lower the impact from order changes due to market fluctuations. Moreover, the significant cost to make a change indicates that a static cost reduction achievable by replacing an existing part with a lower cost one may not be right decision. The dynamic cost incurred can exceed the static cost benefit, and hence the use of a LCC model in the change decision is recommendable.

Further development of the model would consider additional factors, such as the variations of sale target by each product model. The methods to use real-time and historical data to quantify relevant cost coefficients of the LCC model are deemed essential in order to develop the LCC mode into a decision-support toolkit usable by the industry.

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