Proceedings of DETC'03
ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Chicago, Illinois USA, September 2-6, 2003

DETC2003/DFM-48132

MODULARITY: INTERNATIONAL INDUSTRY BENCHMARKING AND RESEARCH ROADMAP

Kosuke Ishii
Department of Mechanical Engineering
Stanford University
Stanford, CA
ishii@stanford.edu
(Corresponding Author)

Tae G. Yang
Department of Mechanical Engineering
Stanford University
Stanford, CA
tman@stanford.edu

ABSTRACT

Increased time to market pressure and globally distributed engineering design environments demand a modular product structure that provides affordable life-cycle cost, high quality, and efficient development work tasks among the engineering enterprise, its partners and its suppliers. This project intends to develop a systematic methodology to achieve effective product modularity and work tasks that will enhance product development process. As an initial effort, we conducted a two-phased survey to explore the level of understanding and to benchmark modularity practice in various industries. The results indicate that the form and the extent of modularity practice depend on industry specific drivers, which are largely affected by strategic preferences, external uncertainties and tactical alternatives. This paper presents an introductory overview of modularity as defined in academia, presents the results of the survey, and then proposes potential directions for future research.

1. INTRODUCTION

1.1 Motivation

The pressure on product development process is ever increasing due to more global working environments, complex partner/supplier networks, shorter time-to-market windows, fierce competition, etc. Thus, companies seek an effective product modularity that enables faster development and production, affordable life-cycle cost, high quality, and is ultimately in concert with the company's long-term strategic goal. The term "modularity" is familiar to industry and academia, but often is not clearly understood because of its broad interpretation. Thus, extensive benchmarking of industry's understanding, practice, and benefits (if implemented by any) would be of value for developing research program.

Some product development related studies, such as design for Variety (dfV) and product architecture/platform design, incorporate the modularity concept extensively, but often are limited to a specific focus, in particular, generational/spatial product varieties and associated life-cycle related issues. This research proposes to develop a generic methodology for product modularity and associated product development work tasks. The goals of the intended methodology include 1) identification of modularity drivers, 2) corresponding modularization technique, and 3) value assessment of modularity.

1.2 Related Work

The concept of modularity is applied in many fields of studies, including both the product and process oriented areas. In product oriented areas, Martin and Ishii [13] developed a dfV methodology for developing a robust product platform architecture that provides reduced design effort and time-to-market for future generations of the product. Otto et al. [5, 22] investigated platform architecture (PA) for designers to develop a portfolio of products based on common technology. Both approaches are heavily dependent upon functional characteristics of the product and their mapping on its physical structure.

In the process-oriented areas, Eppinger et al. [4, 18] took Design Structure Matrix (DSM) and Dulmage-Mendelsohn Decomposition (DM Decomposition) as a general framework for analyzing and improving the engineering process. Their proposal was to use DSM to analyze the precedence relationships among various design tasks and seek to optimize the overall plan. Ishii and Mori [14] took a functional modularity based approach in design task modeling, using DM decomposition technique in matrix-based process model and a graph-based process model. These methodologies concern design and development stages.

The importance of modularity in life-cycle perspective has been studied extensively as well. Dahmus and Otto [5] discussed the impact of the partitioning of a product on the design and manufacturing of a product. Rosen [20] also emphasized the importance of product's modular architecture in enhancing a company's ability to customize, assemble, service and recycle the product. Ishii [11] investigated modularity's impact on every stage of the product life-cycle, capturing also the supply chain factors such as outsourcing technology and postponed differentiation.

In each area of different studies, modularity has been adapted as a strategic or tactical guidance to achieve either a product or process oriented values within a single lifecycle of a product. Baldwin and Clark [1] approache modularity in a broader sense such that they derive the true value of modularity from a multi-generational impact. They use the real options valuation concept, by treating the modules as design options within a system, which carry a certain amount of uncertainty and risk to the product's lifecycle in multiple generations. However, the proposal remains high level and conceptual. Erixon [6] offers several categories of module drivers that the designers can prioritize and utilize in the development process. The modularization methodology proposed is called Modular Function Deployment (MFD), and is an iterative product development process with module driver as the key criteria, assuming that the product had clearly defined splitting points into components or proto-modules.

1.3. Project Approach

Review of the past studies indicates that modularity is a broad concept that could be interpreted and applied specifically to the different levels and areas of business activities surrounding a product. Depending upon how modularity is applied, its value could be measured in different forms. This research will attempt to maintain the generic characteristics of modularity, which could be easily customized for specific business or design and development processes.

This report in particular attempts to capture the practical issues affecting modularity by conducting and analyzing an extensive survey on industries from diverse product areas and global presence. We hope the survey results will provide a concrete needs-basis for the intended subsequent activities of this research. The report outlines the major findings from the survey, interprets the findings, and then suggests future directions.

2. MODULARITY SURVEY

2.1 Survey Method

Stanford's MML conducted a 2-phsaed international industry survey. The Phase-I conducted a generic questionnaire based survey for all of the MML's past and present collaborators. Then, Phase-II interviews were followed in coordination with the selected companies. Phase-I was intended to capture the general benchmark of a wide variety of industries on the significance and the practice patterns of modularity. Phase-II interviews were aimed at gaining deeper insights to different shapes and form of modularity practice.

2.2 Phase-I

The questionnaires in Phase-I survey were designed to benchmark the current industry practices, so that the follow-up interviews can focus more on the information rich sources. The 3 goals of this survey were;

1. Understand the definition of modularity in various industries.
2. Capture industry perceptions on the benefits & pitfalls of modularity
3. Identify information-rich companies with the potential for Phase-II follow-up

The survey intentionally did not provide any preparatory information in order to capture the industry specific definitions and interpretations of modularity. Questions were left open-ended in order to prevent biased responses.

2.3 Phase-II

Based on the Phase-I results, MML selected the companies with the most representative practice potential as well as the uniqueness. The interviews were designed to investigate the following;

1. Level of modularity practice: System (whole product as delivered to customers) level vs. sub-system level.
2. Modularity drivers

This approach would help with understanding how companies use modularity in their business strategies and engineering practices. Based on interview results, the enablers or the constraints of modularization would also be identified. In-person visits and teleconferences were conducted.

2.4 Participants

The subjects of the survey represented diverse product-oriented industries, including automotive, consumer electronics, aircraft engines, commercial equipment, and IT companies, distributed across the United States, Japan and Europe.

	Phase-I	Phase-II
USA	- Agilent - GE Aircraft Engines - GM - HP - Sun Microsystems	- GE Aircraft Engines - GM - HP
Europe	- ABB - Philips - BMW - SAP - Ericsson	- BMW - Ericsson
Japan	- Canon - SONY - Hitachi - Toshiba - Nissan - Toyota	- Hitachi - Toshiba - Toyota

Figure 2.1. Participants in Stanford MML Modularity Survey

Respondents' positions at their respective companies included product development and/or equivalent project managers, senior technology/project engineers, directors of various engineering related divisions, and researchers. In Phase-I, a few companies had more than one individual participating. However each response was considered as a single qualitative input since industry type-dependent quantitative analysis was not the objective of the survey. For Phase-II, interviews were conducted with one or two individuals from the selected companies.

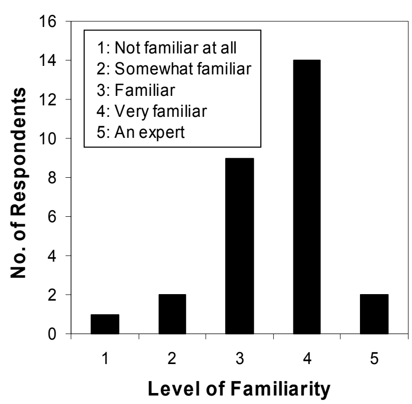

Figure 2.2. Respondents' Level of Familiarity with the Term, Modularity.

Phase-I included a general survey on the respondents' familiarity with modularity. The survey asked the respondent of his/her level of understanding the term, modularity, in 5-point scale: 1 being "Not at All" to 5 being "An Expert." As the distribution in Figure 2.4.2 shows, most respondents were in the "Expert" half of the scale.

3. SURVEY RESULTS

3.1 Definition of Modularity: Phase-I Result

The responses on the definition of modularity were in the form of sentences, and primarily consisted of a short description from the respondents' own perspective, reflecting his/her experiences with modularity. For purposes of analysis, a number of keywords that best represent each description were carefully selected and affinitized. Overall, most descriptions referred to product-oriented practices rather than non-product type practices (i.e. process, manufacturability, supply chain, etc.).

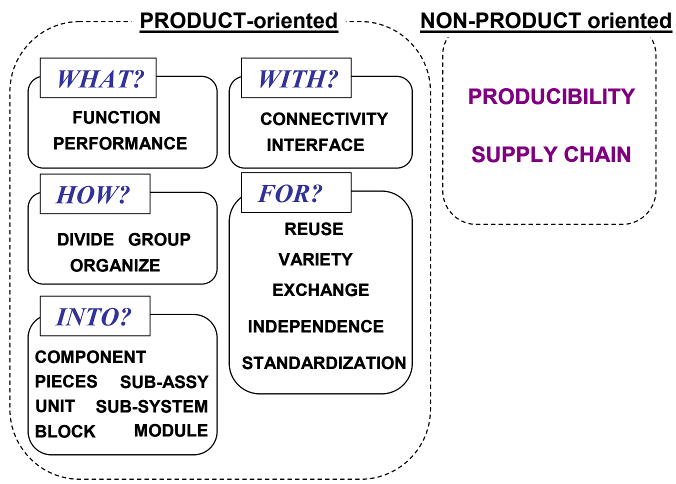

Figure 3.1. Affinity Diagram on Respondents' Key Descriptions of the Definition of Modularity

Non-product oriented descriptions consist of only two words: *producibility* and *supply chain*. These are from the automotive industries, in reference to the *main assembly line* for vehicle production.

Product-oriented descriptions were rather overwhelming in that they represented different aspects of product development. Namely, "What," "How," "Into," "With," and "For" groups were formed. "What" refers to the object of modularity, in that "what" is to be *worked on*. "How" refers to the activities that achieve modularity; the modularization process. "Into" describes the outcome of the activities, i.e. what the object is to be transformed into. "With" group is the list of *rules to be considered* in the overall activity, and the "For" group describes the *goal* of modularity, all in terms of product development.

One interesting response, actually, was the refusal to respond from one of the IT-product companies. The reason for refusal illustrates an interesting perspective, and is quoted below:

"I think one could easily argue that modularity is simply a name for a set of design rules or best practices. Depending on the company, a set of best practices can have different nomenclature - such practices can be named differently across internal groups."

3.2 Anticipated Benefits: Phase-I Result

A majority of the respondents commented that the benefits from modularity are their own views of the *anticipated*, not *measured,* results. This is because modularity has not been the highest priority or a part of similar concepts such as design for assembly or variety. Thus, the comments from the respondents only represent common understanding of the modularity benefits based on each respondent's professional experience.

Category	Description
Better Quality	- Per module development & Testing - Less # of Parts in Assembly
Shorter Development Time	- Concurrent Development - Use of Previous Design Solutions - Shorter Assembly Line - Possibility of Automation
Flexibility & Variety	- Easier Product Variety - Faster Time-To-Market for a New Variety - Faster Response to Customer Requirements
Risk Reduction	- Integration of Proven Technology (module)
Cost Reduction	- Development, Supply Chain, MFG, Assembly, Service

Figure 3.2. Common Understanding of Benefits from Modularity

Quality, time, flexibility & variety, and risk were the 4 main categories of the anticipated benefits, which would ultimately lead to cost reduction effects.

Quality: Comments indicated two major sources of quality enhancement effects of modularity: per-module testing and less complexity in assembly. Developers can develop and test the modules of a product independently before they reach the assembly line. Thus, each module carries validated quality, which is independent of the assembly related errors. Then, only the system integration related errors would contribute to the system level quality. If the assembly stations were to operate with modules instead of numerous parts, the complexity of assembly operations would be drastically reduced. The inverse relationship between the product quality and assembly operation complexity would suggest the positive impact of modularity on product quality.

Time: Two time saving opportunities were identified in development and assembly fields.

- For development, there are two sub-aspects: concurrent development and design solution re-use. If a product consists of modules with well-defined interfaces, each module may be developed in parallel as opposed to serially. This would obviously save a significant amount of development time. When a company develops generational variety, only those modules of concern must be worked on. This expectation is exactly one of the merits of the design for variety concept.

- For assembly, modular products would have shorter throughput time, since the final assembly line would be simplified. Each workstation in an assembly line would be simply "connecting" the interfaces of modules, rather than "building" a part or sub-assembly of a given product. The respondents also noted the possibility of assembly process automation with well-modularized products as a significant time saving potential area.

Flexibility & Variety: This category is closely related to the time related merits, since the contents relate to the efficiency of product development process. Flexibility refers to the product variety context. With a well-defined modular product architecture, many respondents, especially those from the IT industry, anticipated increased flexibility in product development in terms of "late point differentiation for product variety." For example, an IT product industry would need to develop a product that can accommodate rapidly changing technology, thus the customer requirements. If the product modularity architecture were established such that only a few modules are related to such changes, those affected modules may be developed at the latest possible stage of the development process. The company thus acquires the flexibility in the design process that allows faster time to market for a new variety and faster response to the latest change in customer requirements. The key to this approach would be a well-designed modular architecture that can allow this "late point differentiation."

Risk: With a modular design, many noted that the risk would be minimized, especially in terms of product quality. Separate and completely independent processes of development and test prior to main assembly contributes to the quality, but also designers/engineers may decide to use the modules from market-approved products, in which case, the risk associated with both the product quality and market acceptance are reduced.

The 4 categories of anticipated merits of modularity all comes down to financial impact. A product with better quality, accurate response to the voice of customers, faster response to the change in customer's demands, and a relatively less risk would constitute criteria for a competitive product. Such a product would decrease the cost and bring new opportunities for additional revenue, for example, service and recycling, in all stages of product life cycle.

3.3 Anticipated Pitfalls: Phase-I Result

Comments on the negative aspects of the modularity were not as extensive as the anticipated benefits. Figure 3.3.1 lists the representative items of the responses, and they are also categorized into 4 groups.

Category	Description
Lower Quality (↔ Better Quality?)	- Integrated “look & feel” - Good+Good+Good=Good?
Integration Issues (↔Shorter Lead Time?)	- Module interface difficult to define - Not proven until integration
Lack of Creativity (↔Flexibility & Variety?)	- Use of “mature” of “off-the-shelf” modules - Limits integration of “state-of-the-art” technology - Limits customization
Organization Issues (↔Risk Reduction?)	- Requires robust systems engineering - Requires monitoring system → hierarchy? - Involves supply chain
Cost Increase?	- Development, Supply Chain, MFG, Assembly, Service

Figure 3.3. Common Understanding of Pitfalls from Modularity

Quality: This would be the effect of extensive modularization. Most comments are from consumer electronics and IT product industries. Products that are well-modularized may lack the integrated “look and feel.” New product development activities involving the use of existing modules may consider only functional aspects to arrive at a design solution. The modules selected for the new product may have customer-approved quality in each one of them from previous products that used these modules, however, the resulting new product may lack the aesthetic quality that the customers desired. Thus, An overall product-level quality may be perceived as downgraded.

Integration Difficulties: This is an issue concerning the development stage. When a modularity concept is to be implemented in a product, “modularizing” the product structure is quite a difficult process, during which the interfaces among modules must be defined. These interfaces are often a major challenge in terms of definition and performance. A quality of a module’s internal performance is one thing, but the system level performance quality is another. While module-level quality could be assured through independent development and testing, system-level performance will depend on how well the interfaces function. Thus, the overall product level quality may not be measured until the last integration stage. In cases where the final integration imposes major performance/quality problems, a system level iteration may be needed, leading to longer development time than expected.

Lack of Creativity: This issue deals with post-modularization development activity. When designers are tasked to develop a generational variety of a modularized product, especially under a tight time constraint, they may tend to prefer incorporating customer-approved modules. These modules mostly do not contain the state-of-the-art technology, but a “mature” technology. Thus, any room for new ideas and new technology is minimized in the process. Pre-defined customization may be supported by modular design as long as such customer demands are incorporated in the first generation of the product. However, a product with a previously modularized structure may be limited in accommodating new customer demands. Therefore, a fully modularized product architecture can carry the potential of losing such flexibility.

Organizational Issues: Modularization may be the answer to inefficient product development practice to some industries, and the anticipated benefits have been noted in the previous section. The development of an integrated product usually involves only one team of designers and engineers who carry responsibility for the entire product, often with support from other departments such as marketing. As a product becomes modular, the team can be broken into a number of smaller teams, with modular tasks that correspond to independent development of a module. Such parallel tasking provides a time-saving advantage to the company, however, there could be a number of organizational issues.

Managing multiple teams as opposed to one team for a single product can create an additional monitoring task required by the company, resulting in an introduction of additional levels of hierarchy in the company organizational structure. Communication concerning functional interdependencies and interfaces must occur promptly and accurately, which, in practice, is often difficult to do. Thus, the concept of modularity needs to expand to the corresponding process and organization domain, to establish an efficient work task modularity, organization, and robust communication precedence and interfaces among tasks and organizations. Certain modules could be so well defined such that it could be outsourced to a qualified supplier, as long as outsourcing is justified strategically and economically. With the introduction of outside organizations, there can be more management problems, and at worst, the supplier may end up being the sole entity with the technological know-how of the module. If the module evolves to be the core competency of the product, the negative impact is even higher. These issues may impose additional risks that never were of a concern in the development of an integrated product, which directly translates into more cost to the company.

3.4 Examples of Modularity in Practice: Phase-II Result

Phase-II interviews concentrated on benchmarking the process specific activities in companies with in-depth modularity practice. Interviews confirmed the belief that the timing of modularity related decisions must be made very early in design stage. The following sections describe three examples of relatively mature modularity practices at different levels and drivers.

3.4.1 GE-Aircraft Engines – System Level Modularity

A generic New Product Introduction (NPI) process was discussed in reference to modularity. For each NPI, a "Systems Engineering Group (SEG)" takes the overall performance and technical responsibilities for a new product. The SEG performs technical supervising and management roles, and establishes "module datum" and interface requirements at the onset of the project launch. For each module, a corresponding team performs detailed design based on the module datum and the interface requirements. GE, with its diverse international partners and suppliers, can sometimes outsource complete design-to-manufacturing tasks for specific modules.

Because such practices have been inherent at GE for the past 4 decades, the intended and observed benefits were identified as;

1) design solution re-usability which reduces the NPI time-to-market
2) better serviceability
3) easy accommodation of planned/unplanned technical/regulatory requirements.

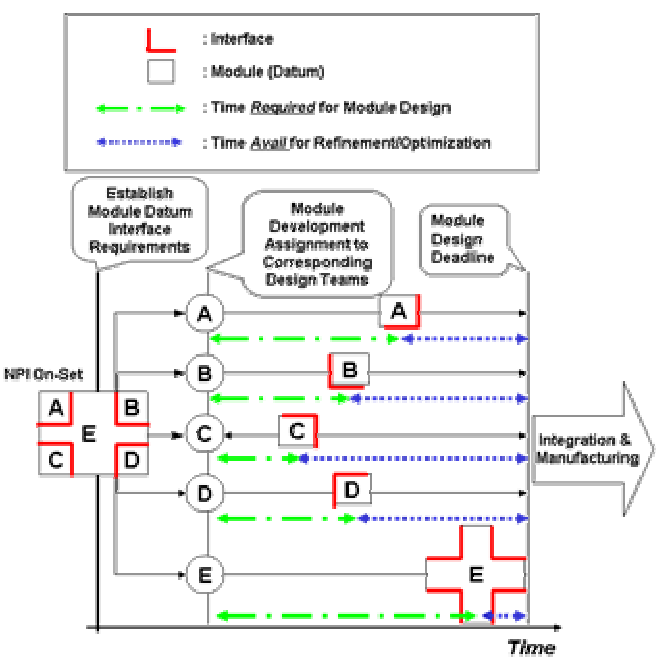

Figure 3.4. Modularized Product and Module Development & Optimization Time

GE clearly identified modularity decisions as a business matter. Also, GE considered the strategic partnership and supply chain networks as critical players since their product had the modularity to allow a complete outsourcing of the selected modules.

However, such a modularized product structure and corresponding NPI process introduces several challenges. These challenges include differences in the level of module optimization, differences in levels of module, and the implicit requirement of strict physical interfaces.

Different levels of module maturity can cause variance in module quality. One module might be able to utilize up to 70~80% of the previous generation's design solution, where as another module might have to be developed almost from scratch. With the development time of a system fixed for integration and manufacturing, different modules are left with varying amounts of time for refinement and optimization. Thus, a product could yield a low system quality corresponding to the module with the lowest optimization time allowance.

GE Aircraft Engine considered the physical interface as a critical requirement. This is not to underestimate the importance of functional interface, however, the volumetric and geometric constraints on aircraft engines are obviously dominant requirements.

3.4.2 HP Laser Printers – Partnership based system level modularity

HP had a unique modularity practice inherent in its laser printer products and development activities. Two levels of modularity decisions are made at HP – the strategic partnership influences project level decisions and the customer driven requirements affect tactical design level decisions. Based on current partnership agreement, the partner company holds the technology related decision making rights, develops and manufactures the particular component. With the partner company's component, HP designs printers to suit local customer requirements and its own business objectives. Because such an arrangement has to be made very early in the development cycle, the product concept is pre-determined for HP designers, leaving most modularity related decisions at HP at a tactical level. Thus, modularity decisions at HP are mostly made in an '*ad-hoc*' manner among the design engineers.

Serviceability was the tactical module driver for HP engineers; HP printers are modularized with the criteria derived from a customer executed or service labor involved services. Thus, assembly and disassembly metrics would be the indicators of effective tactical printer modularity. However, the engineers at HP did not clearly identify their design activities as a modularity practice. This is because the product architecture at a system level has been predetermined based on the strategic partnership agreements from multiple generations ago, and the remaining tactical level design activities at HP are mostly product-history driven. Because the architecture is well modularized, HP benefits from rapid and vast product variety introduction to the market.

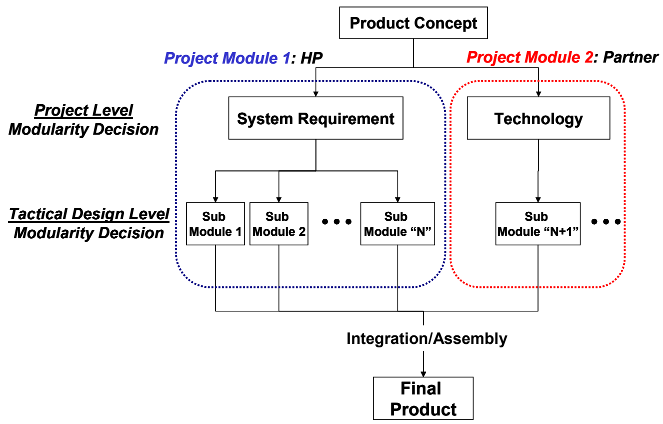

Figure 3.5. Two-Stage Modularity Decisions at HP

3.4.3 BMW – Component based modularity

As a high-end luxury automotive company, BMW's system level modularity practice is faced with many challenges. Currently, BMW maintains 3 levels of product development groups. One level is the Product Family Organization (PL), and the typical example would be a Small Car Group for the 3-series BMWs. Another level is Specific Project Group, and the groups belonging to this level are responsible for specific automobile type, for example, a 3-series 4 door sedan base model. The other level is at the Center of Competency (COC), and the COC teams develop, for example, power train, electronics, body structure, etc.

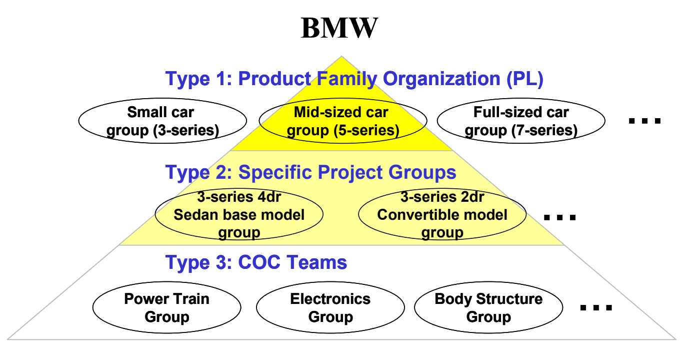

Figure 3.6. Product Development Organizations at BMW

Currently, BMW's modularity practice is at COC team level. The engineers in these teams make modularity decisions when developing a specific area of competency for a specific model. For example, the power train team analyzes the power train system requirements in the very beginning of the project launch, then, decides to modularize certain components. The criteria for good modularity is derived mainly from the current technological, time and cost constraints, but a very little emphasis is placed upon design solution reusability for the follow-up generation. Such a practice is acceptable at BMW because a typical life-cycle for a single model generation spans up to 8 years (2~3 years of development plus 4-5 years of market sales for a typical model). By the time the follow-up generation is due for development, too many changes may have occurred in technology, supply chain, and partnership relationships, introducing new opportunities as well as unexpected constraints. Because BMW places more value on providing customers with state-of-the-art technology in an 'integrated car,' a system level modularity had not been a major interest. However, BMW recognizes the benefits of system level modularity, and is currently investigating the methods of modularization at the Product Family Organization level.

In summary, the challenges BMW faces with the system level modularity are as follows:

1) higher customer perception value emphasized on 'integrated car' concept,
2) relatively long life-cycle of a typical car product,
3) difficulty in modularizing the physical and functional complexity of an automobile,
4) continuous integration of new technology,
5) large investment required in making any changes to the main assembly line,
6) contractual complexities in supply chain and partnership.

3.5 Discussions

3.5.1 Additional Observation from the Survey: Industry Trends & Opportunities

Phase-I survey extracted valuable information on various industry interpretations of modularity, and their current understanding of the benefits and pitfalls. Additional observations include;

- Not all companies have clear directions on modularity practice; most consider modularity as a natural way of design practice and were not clear on how long they implemented the concept.

- Automotive industries have semi-systematic practice in place largely influenced by the production and supply chain concerns.

- Industry anticipation on the benefits and pitfalls are in the same categories, implying that the industry have not been tracking the implications of modularity.

- Majority of the industry did not recognize the value of modularity in product development work tasks.

Above observations provide insights to the following opportunities in modularity research;

- a structured modularization methodology development,
- expansion of modularity coverage out to the supply chain domain,
- modularity valuation methodology development, and
- the value of modularity in terms of design work tasks.

3.5.2 Modularity as a Business and Product Development Strategy

In Phase-II, discussions with various industry experts have provided interesting perspectives on the definition and the value of modularity.

a) Modularity, in general, is a broad concept, and
   i) Its main driver is complexity
   ii) Its value and the form varies depending on the business/product specific modularity drivers
   iii) Is scalable from business strategy to product development strategies.
   iv) Most widely accepted and practiced metric is the return on investment (ROI).

b) At the business level, modularity strategy
   i) Is a long-term investment, which could bear high cost with more than one product life-cycle long amortization period.
   ii) Must consider available resources including supply chain, partnership, and production infrastructure.
   iii) Its value is closely related to the uncertainties associated with the product, market, and organizational constraints/opportunities.

c) At product development level, modularity strategy
   i) Is a set of design rules derived from industry specific modularity drivers
   ii) Impacts the life-cycle issues

3.5.3 Modularity Drivers based on Decision Analysis Approach

Both the Phase-I and Phase-II survey results represented a wide variety of interpretations and implications of modularity for different industries. Thus, the modularity decisions are unique to a specific product, company and industry. Howard [10] states that "decision analysis specifies the alternatives, information and preferences of the decision maker, and then finds the logically implied decision." By applying this concept, making modularity decisions should involve;

1) strategic *preference*,
2) tactical *alternatives*, and
3) uncertainty based on available *information*.

These 3 categories of modularity drivers should be customized for a specific company with specific products and/or services.

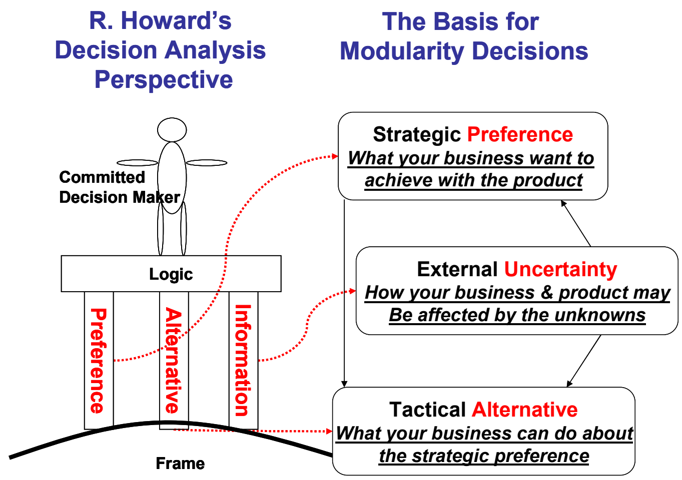

Figure 3.7. Basis for a Good Decision

Strategic *preference* is what the company pursues with the given product or service in its business domain. The survey results listed several outstanding strategic preferences of different companies why modularity is desired in their businesses and products. For example, GE's strategic preference can be stated as "increased profit via development time reduction, utilization of global partnerships, and leverage of service and maintenance opportunities."

Tactical *alternatives* are what a company can and cannot do within the scope of the strategic preference. For example, Phase-II interviews included discussions with well-established automotive companies foreseeing difficulties in 'tailoring' the labor resources for their product's modularity requirements due to previously committed labor union agreements. Often, modularity is defined based on labor requirements and the availability of production capital. On the other hand, GE has leveraged its strong international partnership base as one of their modularity drivers. Tactical alternatives, while it is a level lower than and more detailed than the strategic preference, forms another critical base to modularity decisions.

External uncertainty refers to *information* in Howard's decision analysis approach, and is something that the decision maker has no control over. The uncertainties inherent to the business and the product are the subjects of diversification in modularization. The more diversified the risk, the less likely the business and the product would fail both in terms of business finances and product functionality. For example, BMW is currently not practicing system level modularity because BMW has not yet clearly identified and investigated the effects of uncertainties such as technological advancement and change in customer preferences in automobiles. If an appropriate modularization technique had been in place, 'technological advancement' would be a system level modularity driver in an external uncertainty category for BMW. In contrast, the PC industry has modularized its product architecture such that it can quickly adapt to fast changes in technology.

4. RESEARCH ROADMAP

4.1 Three Stages of Modularity Research

The value of modularity involves metrics that need to be tracked over multiple product life-cycles. To facilitate the measurement of such metrics, modularity implementation can be viewed in 3 stages;

1) pre-modularization
2) modularization
3) post-modularization

In pre-modularization stage, company must make modularity decisions based on its strategic preference, tactical alternative, and external/internal uncertainty. Modularization stage would be the actual implementation stage, and the post-modularization would involve measuring and evaluating the success of those metrics over subsequent product life cycles. Authors propose the following steps for modularization research.

***Step 1:** Problem Framing and Modularity Driver Identification*

The use of the three modularity driver categories would facilitate the framing of the modularity decision. Because modularity concept is scalable, the company and/or the engineers must clearly define the scope of the extend to which the anticipated modularity would apply. The authors are currently investigating methods to incorporate decision analysis approach to enable appropriate framing of modularity decisions, including a decision hierarchy, strategy diagram and decision diagram [10].

The same decision analysis tools can be applied in generating a prioritized list of modularity drivers. Erixon [6] provides a generic list of module drivers, which is used in Module-Indication-Matrix, a QFD-like mechanism, that maps the drivers in the list to the sub-functions of a system. While the list entails most common module drivers from the development & design stage to the after-sales stage, it leaves the company-specific category blank, so that each company may customize the process to their modularity needs. As shown in the survey result, the form of modularity relies heavily upon specific and unique characteristics of the business and the product. Authors propose to develop a decision analysis based methodology that identifies and hierarchically organizes such critical module drivers. This methodology, when developed, should allow companies and/or engineers to create a scope of the modularity problem, and produce the required decision framework for modularization.

***Step 2:** Modularization Methodology Development*

Once the scope of the problem is defined and a prioritized list of modularity drivers is identified, the company and/or engineers need a methodology to modularize their product or service and its development process. Baldwin and Clark [1] presents 6 module operators, that can be "applied at various points and in different combinations," to generate "all possible evolutionary paths for the structure."

- SPLITTING a design (and its tasks) into modules
- SUBSTITUTING one module design for another
- AUGMENTING → adding a new module to the system
- EXCLUDING a module from the system
- INVERTING to create new design rules
- PORTING a module to another system

For this modularization methodology to be as generic as possible, authors intend to assume that the company and/or engineers are tasked with a new conceptual designs. Therefore, the main module operator in this process, for a new system, is "splitting" a design (and its tasks) into modules, and "inverting" to create new design rules. The other 4 module operators would apply to the subsequent generations of a system.

Baldwin and Clark points out that *splitting* involves "previously interdependent set of design parameters and corresponding tasks," however, "the predecessor design structure needs to be 'block-interconnected' – there have to be components or protomodules that suggest where to split." Authors are currently investigating the 'pre-splitting' methodology, which can sufficiently incorporate the most important module drivers in the early stages of modularization process.

Baldwin and Clark also demonstrate the *inversion* of a system level design rule via DSM based approach. However, this approach is only appropriate when each module corresponds to a single functionality interfaced through information exchanges. When a module in a system involves multiple functionalities, or when the interfaces require the exchange of something other than information, the size of a certain module may grow much larger than the rest of modules and consequently fail to invert system level design rules. Or, it may disturb the whole interface across the system, ultimately loosing modularity.

The difficulty in developing this methodology would be balancing the trade-offs between the product modularity and development process or work tasks modularity. Traditionally, modularization of a product has been extensively studied and is relatively straightforward to achieve via function-based or structure-based approaches. The company and/or the engineers have the control over the decisions involved. Yet, work tasks modularity involves external constraints and opportunities such as strategic partnership and organizational issues, which are often dictated by existing infrastructures; the company and/or the engineers no longer have a complete autonomy over modularity decisions.

The product and work-task modularity are closely related to the development process of a product, thus impacting the lifecycle. Once the development related modularity is established, companies and/or engineers would need a methodology to map it to the manufacturing and assembly. Issues such as supply chain, quality control, lead-time, and labor will be considered in this process. Ideally, authors intend the development side of modularization to incorporate these issues early in the modularity driver identification phase, however, the methodology would need to consider the real world constraints faced by the industry as well.

Step 3: *Valuation*

This is a step that needs to be closely tied with the modularity driver identification phase. A company and/or engineers need to evaluate whether or not certain modularity decisions have any value to them. Baldwin and Clark suggests *real options* approach by treating each module within a system as a design option. This approach is appropriate when the modularity decisions are based upon modularity drivers with a great deal of uncertainty over multiple product life cycles. Authors view two types of modularity value in terms of life cycles;

1) Static Value
2) Dynamic Value

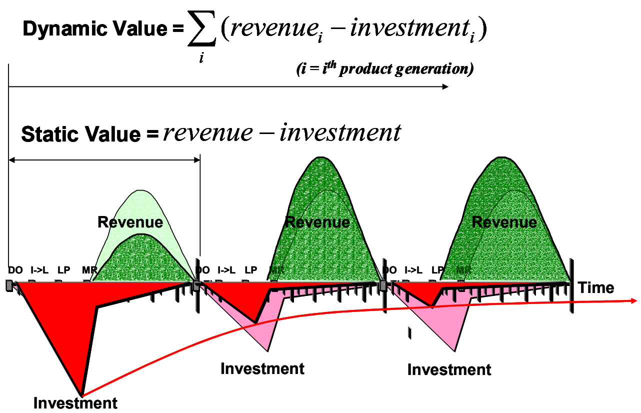

Figure 4.1. Value of modularity in two perspectives

Static value refers to the value generated within a single life-cycle, while dynamic value considers multiple life-cycles. The true value of modularity at company business level is expected to be drawn from the ability of the modularity to adapt to uncertain future, however, design level modularity decisions may affect only single product life-cycle. The metrics in static value analysis would involve time, cost, feature, and quality. The traditional scorecarding methodology may be useful. In dynamic value analysis, the metrics would be derived mainly from the modularity drivers with uncertainties that span over multiple product life cycles. Authors are investigating finance approaches as well as decision analysis approaches. Real options and portfolio theories show promising characteristics in minimizing the risk and maximizing the profit. The utility function and certain equivalent estimation techniques would be useful in making modularization decisions in terms of value.

5. CONCLUSIONS & FUTURE WORK

This report provided a summary of studies on modularity and categorized them into product and process oriented views. The international survey provided interesting viewpoints on the benefits and pitfalls of modularity from many industries. The survey also confirmed that modularity has not been the priority in industries due to its broad context and the lack of appropriate metrics.

While a few in academia and industry started recognizing the value of the broader context of modularity, it still is at a conceptual stage. Other factors that add to the complexity of the problem include strategic partnership/supply chain and organizational issues. To approach modularity from the strategic business angle, the authors formed a 3 stage approach; pre-modularization, modularization and post-modularization. The next step of this research will focus on tying the modularity driver identification phase with the value evaluation step through a dedicated case study, with an emphasis on the modularization of development work tasks. A decision analytic approach serves as a framework for the modularity decision and modularity driver identification. The value analysis portion will first investigate appropriate metrics that are related to the modularity drivers, then explore various methodologies in estimating the value of modularity. The authors hope the case study will provide valuable insights and learning toward future endeavor in modularity research.

REFERENCES

[1] Baldwin, C.Y. and K.B. Clark, *Design Rules, The Power of Modularity, Vol I*, The MIT Press, Cambridge, MA, London, England, 2000.

[2] Bichlmaier, C. and S. Grunwald, "PMM – Process Module Methodology for Integrated Design and Assembly Planning," Proceedings of the 4th Design for Manufacturing Conference, Semptember 1999, Las Vegas, Nevada

[3] Canez, L., D. Probert and K. Platts, "Testing a Make-or-Buy Process," Proceedings of the Twelfth Annual Conference of the Production and Operations Management Society, POM-2001, March 30 – April 2, 2001, Orlando

[4] Cho S. and S.D. Eppinger, "Product Development Process Modeling Using Advanced Simulation," ASME Design Engineering Technical Conferences and

Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, 2001.

[5] Dahmus, J.B. and K.N. Otto, "Incorporating Lifecycle Costs into Product Architecture Decisions," ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pittsburgh, PA, 2001.

[6] Erixon, G., *Modular Function Deployment – A Method for Product Modularization,* The Royal Institute of Technology, Dept. of Manufacturing Systems, Assembly System Division, Stockholm, 1998

[7] Fujita, K. and H. Yoshida, "Product Variety Optimization: Simultaneous Optimization of Module Combination and Module Attributes," ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, 2001.

[8] Fujita, K., H. Sakaguchi, and S. Akagi, "Product Variety Deployment and its Optimization under Modular Architecture and Module Commonalization," ASME Design Engineering Technical Conferences, Las Vegas, Nevada, 1999

[9] Fujita, K. and K. Ishii, "Task Structuring toward Computational Approaches to Product Variety Design," ASME Design Engineering Technical Conferences, Sacramento, CA, 1997.

[10] Howard, R., "The Evolution of Decision Analysis," 1983

[11] Ishii, K., "Modularity: A Key Concept in Product Life-cycle Engineering," Handbook of Life-cycle Engineering,

[12] Lipson H., J.B. Pollack and N.P. Suh, "Promoting Modularity in Evolutionary Design," ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, 2001.

[13] Martin, M.V. and K. Ishii, "Design for Variety: A Methodology for Developing Product Platform Architectures," ASME Design Engineering Technical Conferences, Baltimore, MD, 2000.

[14] Mori, T., K. Kondo, K. Ishii, and K. Ohtomi, "Task Planning for Product Development by Strategic Scheduling of Design Reviews," ASME Design Engineering Technical Conferences, Las Vegas, NV, 1999.

[15] Newcomb, P.J., B. Bras, and D.W. Rosen, "Implications of Modularity on Product Design for the Life Cycle," ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, California, 1996.

[16] Stone, R.B., K.L. Wood and R.H. Crawford, "A Heuristic Method to Identify Modules from a Functional Description of a Product," ASME Design Engineering Technical Conferences, Atlanta, Georgia, 1998

[17] Sand, J., P. Gu and G. Watson, " HOME: House of Modular Enhancement For Product Redesign for Modularization," ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, 2001.

[18] Sosa, M.E., S.D. Eppinger and C.M. Rowles, "Designing Modular and Integrated Systems," ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Baltimore, Maryland, 2000.

[19] Stake, R.B., *On Conceptual Development of Modular Products, Development of Supporting Tools for the Modularization Process*, Royal Institute of Technology, Division of Assembly Systems, Dept. of Production Engineering, Stockholm 2000.

[20] Rosen, D.W., "Design of Modular Product Architecture in Discrete Design Spaces Subject to Life Cycle Issues," ASME Design Engineering Technical Conferences and Computers in Engineering Conference, Irvine, CA, 1996.

[21] Wang, Y. and B.O. Nnaji, "Functionality-Based Modular Design for Mechanical Product Customization over the Internet," Journal of Design and Manufacturing Automation 1 (1&2), 2001, pp 107-121.

[22] http://web.mit.edu/cipd/research/plat_architectures.htm#