Modularity: A Key Concept in Product Life-cycle Engineering

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Key Words

Commonality, Flexibility, Frequency, Lead time, Life-cycle design, Manufacturability, Mass customization, Modular architecture, Recyclability, Repair, Scrap rate, Serviceability, Sort complexity, Supply chain.

Abstract

Modularity in product design impacts every stage of the product life-cycle. Supply chain factors influencing modularity include outsourcing strategy and postponed differentiation. Manufacturing considerations address assembly efficiency and component complexity. Modularity also affects serviceability and recyclability in terms of disassembly, separation, repair, and reprocessing. Manufacturers could benefit from a methodology that analyzes modular product architecture for overall life-cycle efficiency. This chapter introduces a set of metrics and design charts that aid in enhancing life-cycle modularity of product families and generations. The charts should help designers in grouping subassemblies by identifying 1) core platforms, 2) flexible modules, and 3) mating interfaces. Designers should keep in small chunks the features that

require flexibility and standardize other core functions. They should gauge the modular architecture against three evaluation charts that relate design attributes with life-cycle complexities. The modularity evaluation for manufacturing plots part commonality against lead time. Service modularity gauges service complexity vs. frequency. Recyclability chart plots sort complexity against material recovery. This chapter will illustrate the effective use of the charts with a hypothetical family of inkjet printers.

19.1 INTRODUCTION

The goal of product life-cycle engineering is to maximize the values of the manufacturer's line of products, while containing its costs to the manufacturer, the user, and society (Figure 19.1). Engineers must consider performance, costs, and environmental impact. In the past decade, researchers around the world have proposed various systematic methodologies that apply to the early stages of product development in integrating life-cycle quality (Ishii, 1995).

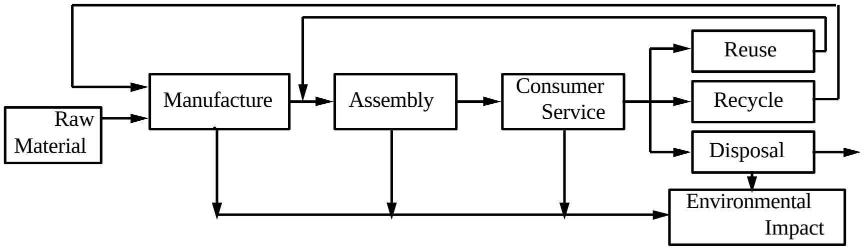

Figure 19. 1 Material flow in a life-cycle of a product

Many prior studies exist in addressing specific life-cycle issues. Perhaps the most successful methodology is design for assembly (DFA; Boothroyd and Dewhurst, 1983). The methodology quantifies the handling, orientation, and insertion difficulty of parts during assembly. Other prominent DFA methods include those of Westinghouse (Sturges and Kilani, 1992) and Hitachi-GE (Miyakawa, et al., 1990). There is also a wealth of research on component design for producibility. Poli (1988) developed a methodology to evaluate a plastic part design. The key question is the part complexity: the number of geometry features such as ribs, bosses, snaps, and cutouts leading to an early estimate for tooling cost and molding cost. Product ownership quality has also attracted attention, since it not only affects warranty costs, but also has a major impact on product image and repurchase intent. Reliability design (Birolini, 1992) and failure modes and effects analysis (FMEA; Ormsby, et al, 1991) are traditional methodologies that identify potential weaknesses in the design. Engineers must also address ease of service and simultaneously specify support logistics. Hence, design for serviceability (DFS) has attracted significant interest as a method to enhance product ownership quality (Gershenson and Ishii, 1992).

More recently, advocates of life-cycle engineering have realized that designers must address not just one product, but entire product families and changes over product generations. In most industries, the current market requires a variety of products with frequent updates. A competitive company must consider product families and generations and seek commonality between parts and subsystems (McDermott and Stock, 1994). In his book *Mass Customization*, Pine (1993) points out that product modularity is the key in developing effective product architecture. Modularity in product design plays an important role in many activities: product cost, DFM/DFA, manufacturing cycle (flow) time, product flexibility, supplier capabilities, supply chain management issues, serviceability, and multi-generation product platform planning. Modularity is particularly important for electromechanical products such as computers, telecommunication devices, and peripherals. The short technology life-cycle of many of the functions in these products, combined with the customer demand for wide variety of features, necessitates designers to optimize the modularity of components and subassemblies for manufacturability and serviceability (Ishii and Lee, 1995). The recent drive for environmentally conscious design and manufacturing adds another dimension to the requirements for modularity (Gradel and Allenby, 1996). Product take-back laws in Europe (Beitz, 1993) and the recyclability laws in Japan (Hattori and Inoue, 1992) demand a more focused goal of design for recyclability in the modularity decision.

The term "modular architecture" describes a low number of functions per component, while "integral architecture" describes high functions per component. Ulrich (1995) points out that as functions per component increase, volume-related costs decrease, while complexity related costs increase. Complexity-related costs include post-manufacturing costs related to life-cycle service (Eubanks and Ishii, 1993) and product retirement and material recycling (Ishii, Eubanks, and DiMarco, 1994). Part commonality will also play a role here (Gerchak and Henig, 1989). Modularity also contributes to effective supply chain management by enabling postponed product differentiation (Lee and Tang, 1996). Product and process designers must find the optimal balance among all the costs (Ishii, Juengel, and Eubanks, 1995). Newcomb et al (1996) proposed two measures of modularity: one that measures module correspondence between several life-cycle viewpoints and another that measures coupling between modules.

This chapter focuses on the concept of product modularity, a key concept in achieving life-cycle quality. At the preliminary design stage it is very difficult to keep all these issues in mind, and designers often rely on simple rules or traditional patterns of aggregation/disaggregation in selecting levels of modular vs. integral design. We feel there is a need for a set of metrics and design charts that aid in enhancing life-cycle modularity of product architecture. Specifically, the charts should help designers in grouping subassemblies by identifying 1) core platforms, 2) flexible modules, and 3) mating interfaces. The next section of the chapter introduces the proposed methodology and identifies and discusses the metrics associated with modularizing product families and generations from life-cycle point of view. Further, we describe a set of design charts that could assist design engineers in optimizing the modularity of a product. We will illustrate these metrics, charts, and their potential benefit by a hypothetical inkjet printer example.

19.2 LIFE-CYCLE MODULARITY METRICS

19.2.1 The Product Requirement and Complexity for Modularity (FD and FC)

Our basic approach is to define metrics that characterize design attributes and complexity related to product requirements and life-cycle costs. For functional requirements, one can characterize modularity in the following two dimensions. FD (functional design attribute) and FC (functional complexity).

FD: Level of modularity, i.e., integral or modular (# of functions in a part or module)

FC: Flexibility required in the function.

Our definition of FD adopts Ulrich's interpretation of modularity (Ulrich, 1995), i.e., number of functions in a part, subassembly, or a "module." FC, the flexibility required in a function may result from various external factors.

- Customers demand a wide variety of functions and features
- Localization requirement (language, regulatory, etc.)
- Technology life-cycle of the functions (e.g., electronics vs. mechanical)

Generally, you can integrate features that do not need to be flexible, i.e., can be standardized. Designers should keep in small chunks the features and functionality that require flexibility. For example, one should not integrate a functionality of a device that can be standardized (e.g., a magnetron in a microwave oven) with a differentiating feature that requires flexibility due to customer demand for variety, localization requirement, or rapid technological change (e.g., user input panel of a microwave oven).

Martin and Ishii (1996) have illustrated the effectiveness of standardizing a core functionality early in the manufacturing cycle (early point standardization) and differentiating late in the manufacturing and supply chain the features with high flexibility demand. In their work on design for variety (DFV), they call the flexibility requirement the "variety voice of the customer" (VVOC) and seek to balance VVOC with effective product architecture and manufacturing and supply chain strategy. The fundamental strategy is to commonize the functionality with low VVOC into an integral structure to be implemented early in the supply chain, while keeping the features with high VVOC in a small module to be differentiated late close to the customer. Whereas their work and other advances in supply chain management (Lee and Tang, 1997) provide an effective tool to address manufacturing modularity, designers must also incorporate serviceability and recyclability concerns.

Life-cycle engineering requires that designers should gauge the proposed modular architecture against complexity and cost beyond manufacturing and supply chain, and include service and product recycling in configuring their design. Here, we define design attributes and complexities that characterize the three major phases of product life-cycle.

MD: Design attributes that impact manufacturing (e.g., parts commonality)
MC: External complexity measure during manufacturing (e.g., lead time)
SD: Design attributes that impact serviceability (e.g., labor steps of repairs)
SC: External complexity measure during service (e.g., service frequency)
RD: Design attribute that impact recyclability (disassembly steps)
RC: External complexity measure during recycling (demand for material reuse/recycle)

The following sections provides a detailed discussion of how one can characterize the above factors in different industries and products.

19.2.2 Manufacturing Perspective on Modularity (MD and MC)

The first perspective in product life-cycle is manufacturing including the supply chain. The supply chain includes the material and information flow from raw material acquisition, component fabrication, product assembly to testing, distribution, and retail. The key in this perspective is to provide the customers their desired customized products at an affordable price and in a timely manner, i.e., mass customization (Pine, 1993).

The key design attribute that characterize manufacturing complexity is ***commonality of components and processes***. While the exact definition of MD may vary from products to products, categories of costs affected by parts and process commonality include:

- Engineering (component and process design)
- Logistics (documentation, supplier management, information technology, etc.)
- Materials (material handling, volume discounts)
- Tooling (capital investment, maintenance, set-up)
- Quality (yield loss due to mistakes, rework)
- Inventory (raw material, work in process, finished goods, field service)

Obviously, a high level of commonality is desirable to minimize the cost of complexity and development and manufacturing cycle time. However, in order to increase sales, you must provide the variety needs of the customers to achieve competitive market coverage. The question is how to provide the variety while maintaining high commonality where it counts. The key is to address the external decision factors that affect the overall complexity. In manufacturing activity including supply chain and distribution, the key metric we propose is the ***lead time of components and subassemblies*** from the time of order initiation to product delivery. Again, the exact definition of MC may vary, but component lead time captures many aspects of manufacturing efficiency. Factors affecting lead time include:

- Supply chain strategy (sourcing of the materials and parts, transportation time, etc.)
- Manufacturing and assembly process sequence
- Variety differentiation point
- Distribution channels

In general, one wants to commonize long lead time and high value subassemblies and differentiate with features that have short lead time and low value. This strategy also indicates that one wants to differentiate late in the manufacturing and supply chain, i.e., keeping the system as common as possible and postponing the commitment to variety requirements. Such a strategy, commonly known as ***late point differentiation*** or ***postponement***, has proven effective for appliances (Ishii et al, 1995) and computer peripherals (Lee and Tang, 1997) as well as many other industries. Section 3 will illustrate a modularity evaluation chart based on the proposed complexity metrics, MD (commonality) and MC (lead time).

19.2.3 Service Perspectives on Modularity (SD and SC)

The second perspective for modularity addresses serviceability and reliability (design for ownership quality, DFOQ). For products such as airplanes, locomotive, power generating plants, and major manufacturing equipment, life-cycle operational cost exceeds that of initial acquisition cost. Some computer peripherals, such as inkjet printers, also exhibit high service cost in terms of routine replacement of consumable parts such as paper and ink cartridge. Users must be able to service easily the components requiring routine maintenance or features that are too expensive to provide high reliability. One needs to prioritize the serviceability in terms of functional importance. A thorough functional analysis, combined with function-based FMEA, guides engineers to an appropriate modularization (DiMarco et al, 1995). There are some competing requirements in serviceability, such as availability vs. service costs, and reliability vs. maintenance. Again, pertinent issues and trade-off strategy will depend on the nature of the products and how the users operate them.

The key design attribute that characterizes service complexity is ***degree of service difficulty for each service mode.*** Here, service modes refer to 1) routine service (oil change, ink cartridge replacement, etc.), 2) monitored or scheduled maintenance (bearing replacement, engine overhaul), and 3) unscheduled repair (malfunction, accidents). In all these categories, pertinent factors leading to difficulty of service include:

- Ease of diagnosing the root cause
- Time or steps required for service (accessibility)
- Cost and availability of replacement parts
- Tool and training requirements
- Inherent reliability of components

Mature products such as automobiles and appliances have a set standard for service and repair for warranty purposes. For new products, one can represent the service difficulty by the number of individual operations (removing, adjusting, or replacing parts) as a rough measure.

Obviously, you must provide ease of repair in the basic design for service modes with high frequency. Hence, we define the external complexity SC to be the frequency of service needs. Pertinent factors here includes:

- Required availability (up-time)
- Operational condition, usage pattern
- Customer impact of failure (criticality of failure)

The key is to provide a design that allows quick and easy high frequency service operations while allowing reasonable serviceability to low frequency items. Modularization of components and functionality with similar frequency range will also be a key strategy to life-cycle efficiency.

19.2.4 Recyclability Perspectives on Modularity (RD and RC)

The third perspective is product recyclability. We contend that recyclability focuses on one dimension of environmental compatibility, i.e., solid waste at end-of-life, and manufacturers must address various other factors that impact the environment such as resource depletion, life-cycle energy use, and air and water pollution (Gradel and Allenby, 1996). However, recyclability is an issue that product engineers can most easily impact. Further, rapidly depleting solid waste landfills are driving many governments to institute regulations mandating manufacturers extended responsibility or "take back" at the product's end of life. To enhance component reuse and material recycle, engineers must embed strategic modularity into the product and reduce the cost to the recycling organizations. Such efforts will lead to overall improvement of industrial ecology through reduction of raw material use, energy use throughout the product life-cycle, and solid waste. The key issue is the up front consideration of recycle modularity at the early stages of product design that addresses product families and its generations.

We believe the key design attribute that affects recyclability is the ***complexity of sorting*** disassembled "clumps" into reusable parts or material according to the designers product retirement strategy. Here, we assume that designers are charged to simultaneously develop an initial demanufacturing specification as they design the product, while the product's end-of-life may be decades later and thus actual demanufacturing to be significantly different. We further assume that designers wish to optimize the total cost of disassembly into clumps and their reconditioning or reprocessing. Factors that determine the sort complexity include:

- The post-life intent (determines non-destructive or destructive separation requirement)
- Isolation of the clump from the product (disassembly, detachment)
- Separation difficulty (how the components are nested)
- Attachment / fastening method among components to be sorted
- Tools / training required

Whereas the designers can control the above factors, there are other external influences and conditions that controls the overall recyclability. The key characterization for external complexity is the ***material recovery rate*** (or conversely, the scrap rate), i.e., how much value out of the recovered clump can you utilize in a useful manner (as opposed to disposal). The scrap rate depends on various factors depending on the post-life intent of each clump.

- Service parts demand for clump to be reused
- Reconditioning cost for reuse
- Material compatibility of clump to be recycled
- Material separation cost (assuming the existence of a separation technology)
- Demand for, and price of, recycled materials
- Reprocessing cost for recycle

Hence, a good modularization for recycling obviously depends on the assessing the post-life demanufacturing or "clumping" strategy. Conversely, product modularization should consider the ease of demanufacturing and optimal overall material recovery. One should modularize components or subassemblies into a module if they have high service demands. A "clump" for recycle module should contain either compatible materials, or a set of materials for which there is an economically feasible separation technology.

Another important insight into recycling is the technology life-cycle of each module. Designers should modularize the clumps according to their technology life-cycle such that functionality with long technology life-cycle can be readily reused, while short technology life-cycle components should be easy to recycle.

19.3 THE PROPOSED LIFE-CYCLE MODULARITY EVALUATION CHARTS

19.3.1 Illustrative Example: Hypothetical Inkjet Printer

Based on the metrics described in section 2, we have developed charts to help designers modularize the product or systems in the early stages of its development. We suggest the use of four charts:

- Modularity Design Chart (Flexibility Requirement vs. Modularity)
- Manufacturing Evaluation Chart (Lead Time vs. Commonality)
- Serviceability Evaluation Chart (Frequency vs. Service Complexity)
- Recyclability Evaluation Chart (Scrap Rate vs. Sort Complexity)

The following sections use a hypothetical inkjet printer to illustrate the charts and their potential use in the overall life-cycle modular design. Figure 19.2 shows a typical inkjet printer on the current market. For our hypothetical example printer, similar in construct to the printer shown above, we have identified the major functional modules as follows:

- Base Chassis (Base)
- Upper Housing (Housing)
- Power Supply (P/S)
- Mechanisms (Mech)
- Electronics (Elec)
- Print Head (Head)
- Paper Tray (Tray)
- Ink Reservoir (Ink)

The key goal is to incorporate these functions into a modular structure that satisfies and customer demand for variety, responds quickly to technology changes, is efficient in manufacturing and distribution, has a low life-cycle service cost and down time, and is recyclable.

19.3.2 Modularity Design Chart (FC vs. FD)

The **modularity design chart** (Figure 19.3) plots the proposed product modules in terms of required flexibility (variety demand, technology life-cycle, uncertainty), vs. modularity as defined by integration of functionality in subassemblies. Our hypothetical inkjet printer has the printhead integrated into the print mechanism, thus, the "head" and "mech" is stuck together. We generated the flexibility numbers (FC) based on survey of graduate students at Stanford (QFD applied to variety and technology life-cycle needs), and the modularity metrics (FD) based on the normalized number of subfunctions per module. Here,

$$FD = (Nf - 1) / (Nmaxf - 1) \tag{1}$$

where:

Nf = number of subfunctions in the module
Nmaxf = number of subfunctions in the module with highest integration

Figure 19. 2 Typical Inkjet Printer

The left side of the chart indicates that customers do not require variety or there is a flexibility requirement due to rapid technology changes and other reasons. The base chassis and the power supply fall in this category. Designers can combine multiple functions into an integral structure due to low flexibility requirement. The right hand side indicates the need for mass customization and/or rapid changes in technology. The upper housing and paper tray fall in this category due to customer requirement for variety, the electronics due to rapid technology changes, and the ink due to combination of both flexibility requirements. Hence, designers should isolate these functions into a modular structure to respond to the flexibility requirement. Generally, the desired region for each module is along the 45 degree line.

One use of this chart is to consider combining functions that are in the same region. Designers certainly should check the technical feasibility, but using the power supply chassis as the base for the whole printer may be an implementable idea. Embedding the electronics into the upper housing is also a possibility.

The combined "head" +"mech" module is a counter example. The module falls outside the desired region primarily due to the integration of functions with different flexibility requirement. The printhead controls the print resolution for which customers have varying requirements. Further, the advances in microfabrication technology leads to the need for rapid changes in this device. Meanwhile, the variety requirement for the mechanism is relatively low while the technology life-cycle is much longer than that of the print head. The arrows indicate the possible improvement in life-cycle modularity by splitting the head and the mechanism.

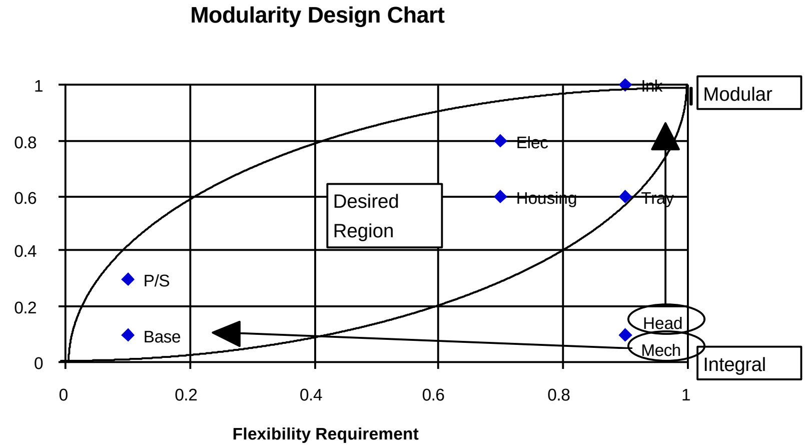

Figure 19. 3 Modularity Design Chart

In either case, combination of functionality or splitting of the module, one should study the implication of such decision on complexity during manufacturing, service, and recycling. Our modularity evaluation charts provide the tools to graphically characterize the complexities.

19.3.3 The Manufacturability Evaluation Chart

Figure 19.4 shows the manufacturability evaluation chart for the functional module identified in the previous section. The chart plots for each module the lead time (MC) and variety complexity (MD).

This example adopts the following definition for these factors:

- MC: Normalized lead time measured from the customer receives the product back to when components are ordered/manufacturing initiated
- MD: Variety of components (as opposed to commonality of components).

$$MD = (Np-1) / (Nm-1) \qquad (2)$$

where:

Nm = number of models

Np = number of unique parts

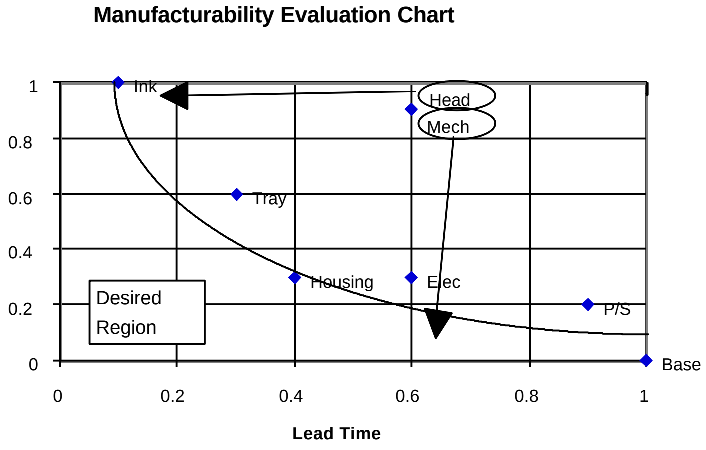

Figure 19. 4 Manufacturing Evaluation Chart

The chart shows that customers require high variety in ink (colors, media), therefore, designers need to provide the function with flexible (short lead time) components. On the other hand, the power supply or the housing base have an integrated structure and therefore long lead time. As discussed in section 2.2, designers need to standardize these long lead items to reduce inventory and manufacturing complexity cost. The paper tray, housing and electronics fall in the middle. The desired region reflects the late point differentiation concept in a broad way: differentiate late in the manufacturing process with short lead time items, and standardize long lead time items and processes early in the supply chain.

In our example, the printhead and mechanism integration leads to this function being provided by high variety, low commonality, and yet long lead time module. This plot clearly indicates inefficiency in manufacturing and supply chain. Designers should investigate splitting the printhead and mechanisms so that: 1) the printhead would be a short lead time item to be integrated late in the supply chain or even by customers, 2) mechanisms have high commonality across different models and generations.

19.3.4 The Serviceability Evaluation Chart

Figure 19.5 shows the serviceability evaluation chart for the functional modules. The chart plots for each module the frequency of service needs (SC) and service operation complexity (SD). This example adopts the number of service operations (e.g., remove parts, reorient the product, etc.) as service complexity. Therefore,

- SC: Frequency of service normalized between the most common routine service and zero, i.e., most frequent being 1.0.
- SD: Normalized number of service operations.

$$SD = (Nsop - 1) / (Nsopmax - 1) \tag{3}$$

where:

Nsop = number of operations in the service mode
Nsopmax = number of operations in the most complex service mode

Figure 19.5 shows that ink replacement has the highest service frequency. The current design allows easy and quick replacement of ink. Servicing the base chassis requires many service operation steps, however, the steps are acceptable in view of the low frequency of service needs. Housing, power supply, electronics, and the tray fall in between. As the common sense confirms, one needs to design the product so that services on the modules with high service frequency can be accomplished easily and quickly, while low frequency modes could afford more complex operations.

The integrated printhead and mechanism module again poses a problem. While the microfabricated printhead are prone to chemical degradation due to ink, the integrated nature of the mechanism requires complex service operations to replace the printhead. By separating these functions, designers can provide quick replacement of the printhead while maintaining high integration of the mechanism and keeping its service frequency low.

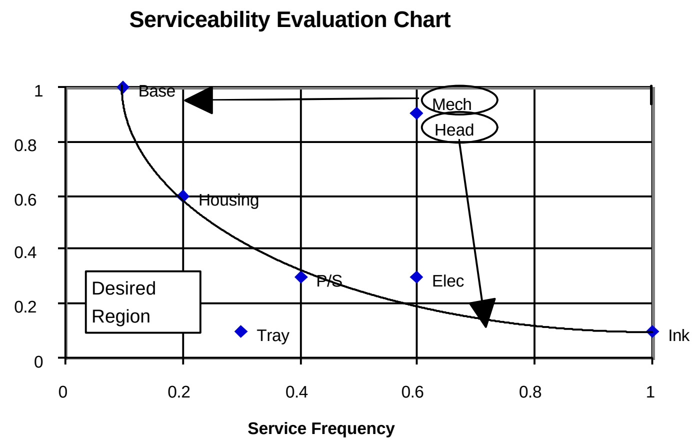

Figure 19. 5 Serviceability Evaluation chart

19.3.5 The Recyclability Evaluation Chart

Figure 19.6 shows the recyclability evaluation chart for the functional modules. The chart plots for each module the frequency of scrap rate (RC) and sort complexity (RD). This example adopts the number of sort bins in the recycling process as sort complexity. Therefore:

- SC: Proportion of materials that are scrapped, i.e., incinerated or landfilled

SC = Weight scrapped / Total weight of module (4)

- SD: Number of sort bins into which the module is separated

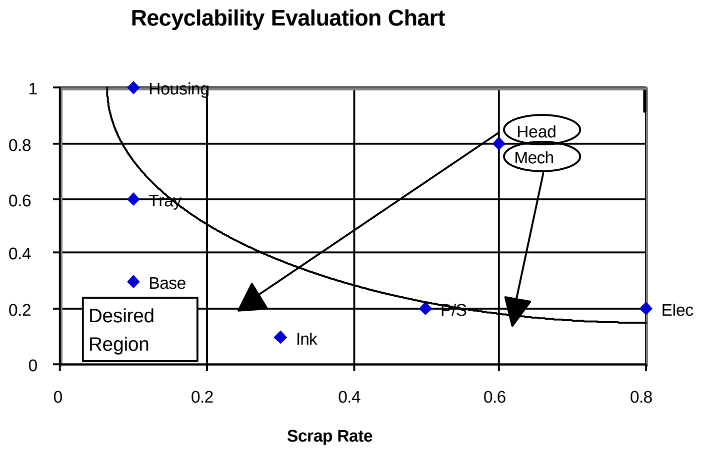

Figure 19. 6 Recyclability Evaluation Chart

The chart shows that the housing, the paper tray, and the basis chassis, all made of plastics, have a high recovery rate, although the housing needs to be separated into several bins. The ink having about 30% scrap rate is due to one color of a multi-color ink cartridge running out before the other colors, thus some ink being disposed. The power supply and the electronics are recovered for service reuse, but have a relatively high scrap rate. These modules are too complex to warrant economical separation into reprocessed materials. For the most part, the proposed retirement strategy seems sound and the modules fall within the desired region that encourages designs that targets sorting of high material recovery modules.

However, again, the combined printhead and mechanism pose a significant problem. For the head and the mechanism to be recovered for reconditioning, the module must go through extensive disassembly and sorting. Further, the service demand for the mechanism is much lower than the recycling opportunity for the head. The chart clearly shows the benefit of separating the printhead and the mechanism, as indicated by the arrows .

This particular chart defines the RC metric defined as scrap rate and RD metric as the number of sort bins. In order to plot the proposed module on this chart, one needs: 1) proposed disassembly and sorting strategy at end-of-life and 2) scrap rate information. While the data may be readily available for relatively short life items such as inkjet printers or for which there exists an established recycling process, accurate information may not be available for long life-cycle products such as appliances and automobiles. The next section discusses the development of recyclability metrics under uncertain end-of-life information.

19.4 DISCUSSIONS

19.4.1 Summary of the Printer Example

Let us review the sample modularity design chart and three life-cycle evaluation charts for a hypothetical inkjet printer shown in the previous section. Flexibility of each module comes from envisioned variety needs and technology life-cycle, i.e., how quickly the technology changes. Assume the printhead (Head) and the electronics (Elec) jointly control the dots-per-inch (dpi) density. Suppose a designer had decided to integrate the Head and the drive mechanism (Mech) into an integral subassembly. Plotting that integral subassembly on each of the charts illustrates that this design lies outside the desired region and results in:

- an integral design used where flexibility need is high
- low commonality subassembly with long lead time and early differentiation
- complex servicing operation on high frequency service modes
- complex sorting yet high scrap rate

One can improve the product architecture by redesigning the subassembly into two modules: a standard drive mechanism and a modular printhead that provides resolution variety and can respond to rapid advances in ink and head microfabrication technology. The three life-cycle evaluation charts (Manufacturability, Serviceability, and Recyclability) would reflect this improvement by the arrows showing how each of the separated components (Mechanism and Head) would move toward the desirable regions.

After the separation, all the charts place the printhead and ink cartridge in roughly the same region. That is, they share the same complexity characteristics in manufacturing, service, and recycling. Hence, the charts indicate the potential of combining these functional features into a single module. In fact, several manufacturers of inkjet printers have taken this approach, although the printhead life may not be fully utilized when ink runs out. The concept is similar to that of personal copiers' toner cartridge that combines functionality that share the same complexity profile in manufacturing variety, service frequency, and recycling concerns. Another manufacturer has kept the ink module separate as a reservoir that "snaps" into the printhead module. The decision is dependent on the user frequency.

Designers can consider other scenarios for integration or separation of functions. The design requirement (Figure 19.3), manufacturability (Figure 19.4), and serviceability (Figure 19.5) perspectives suggest the possibility is to combine the base with the mechanism, that is, provide the strength of the chassis in the mechanism. However, the recyclability evaluation chart (Figure 19.6) shows the base to be in a high material recovery region, while the mechanism does not warrant complete disassembly under the existing recycling technology.

19.4.2 Defining Metrics for Different Products and Systems

Our example adopted simple definitions of life-cycle complexity metrics. The design attributes are those determined by engineers developing the product;

MD: Commonality of components
SD: Steps required to address each service mode
RD: Number of sort bins

Obviously, one can adopt a more sophisticated definition of these metrics, such as commonality in terms of material value, actual estimate of service time, or cost of disassembly. However, the modularity design charts are most effective in the early stages of design during which more detailed information on the design attributes may not be available. The author contends the definitions used in the example are quite appropriate for use in most products and industries.

On the other hand, the definitions on the external complexities are subject to availability of information outside the design engineers control. Our example used the following definitions:

MC: Rough classification of lead time of components (hours, days, months)
SC: Service frequency data of existing printers
RC: Material recovery and reuse components data from the current recycling process

The lead time information should be available to the design engineers, if the organization has an established concurrent engineering practice and simultaneously plans the supply chain and manufacturing system during product development. However, decisions on sourcing partners and geographical location of component manufacturing may come late in the development cycle, in which case designers will have to make the best guess.

The service frequency and scrap rate information may be more difficult to obtain. Our example addressed a relatively short life product going through an evolutionary redesign, thus we relied on the data from the previous (or prevailing) models. This type of information may not be available for completely new products particularly if they incorporate innovative technologies or advanced materials. Designers may want to use **target reliability** of the modules in the absence of past data. Products with long life such as appliances also pose a challenge in recycling information. Details of available recycling technologies and demand for recycled materials twenty years in the future are either scarce or inaccurate. Again, designers will have to resort to the best available estimation for scrap rate, such as **number of types of materials**, existence of hazardous materials, and inherent value of the recovered materials (e.g., gold is worth recovering even at high cost).

In short, designers should use all the available resources in estimating life-cycle complexities, but if data is lacking, will have to use the best judgment in estimating the data. Using **target numbers** for lead time, reliability, and material recovery may involve uncertainties, but will certainly contribute to advanced planning of life-cycle factors at the early stages of design and help achieve concurrent life-cycle engineering design.

19.5 CONCLUSION AND FUTURE DIRECTIONS

This chapter described the importance of modularity in product life-cycle engineering. First, we illustrated the need for modular designs due to customer demand for variety and need to respond to technology changes and other flexibility requirements. Characterization of complexities due to design attributes and external factors illustrated the impact of modularity on manufacturability, serviceability and recyclability. The proposed design and life-cycle evaluation charts plot the planned modules with respect to the following metrics:

- Modularity Design Chart: Flexibility requirement vs. modularity (functions/structure).
- Manufacturability Chart: Lead time vs. variety (commonality)
- Serviceability Chart: Service frequency vs. service complexity (repair steps)
- Recyclability Chart: Scrap rate vs. sort complexity (# of sort bins)

A hypothetical inkjet printer served as an illustrative example. Combining the print mechanism and the printhead, as was the case with the traditional dot matrix printers, leads to high manufacturing costs due to inflexibility in responding to customer demand for variety and rapid technology changes. Further, the integrated module hinders efficient service and recycling. The charts indicate the advantages of splitting the functionality into different modules. On the other hand, combining the printhead with the ink reservoir poses a competitive advantage in focused customization and life-cycle efficiency. In fact, the combined ink and printhead module is a current strategy adopted by several printer manufacturers.

Whereas the example addressed a relatively short-life and currently established product, the author feels the proposed metrics and associated charts can significantly contribute to life-cycle engineering using modular product architecture. The modularity design chart urges designers to address strategically the flexibility requirements arising from variety needs and technology advances. Further, the use of the evaluation charts effectively promotes advanced life-cycle planning. Our current efforts seek to validate and further enhance the methodology through examples from a wide variety of industries, including aerospace, test and measurement, semi-conductor manufacturing, automotive, computer, and telecommunications.

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19.7 ACKNOWLEDGMENTS

The sponsors of this research include the National Science Foundation, General Electric, Matsushita Electric, Lucent Technologies, Hewlett Packard, Boeing, and other members of the Stanford Integrated Manufacturing Association. I deeply appreciate the help of my collaborators, in particular, Warren Hausman and Michael Parker. The idea of design charts for modularity was originally suggested by Mark Steiner of GE. Kazuo Tatsukami of Matsushita developed the original manufacturability commonality charts while being a visiting scholar at Stanford in 1996. Many thanks to the author's students Mark Martin, Steven Kmenta, Kurt Beiter, and Burton Lee. Last but not least, I appreciate the invitation from Arturo Molina to contribute to this important handbook on life-cycle engineering.

19.8 BIOGRAPHY

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