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ASSESSING PRODUCT ARCHITECTURE COSTING: PRODUCT LIFE CYCLES, ALLOCATION RULES, AND COST MODELS

Sebastian K. Fixson
Assistant Professor
Industrial and Operations Engineering
University of Michigan
Ann Arbor, MI 48109
fixson@umich.edu

ABSTRACT

Product families and product platforms have been suggested as design strategies to serve heterogeneous markets via mass customization. Numerous, individual cost advantages of these strategies have been identified for various life cycle processes such as product design, manufacturing, or inventory. However, these advantages do not always occur simultaneously, and sometimes even counteract each other. To develop a better understanding of these phenomena, this paper investigates the cost implications of the underlying design decision: the product architecture choice. The investigation includes factors such as product life cycle phases, allocation rules, and cost models, all of which impact the cost analysis results. Based on this investigation, directions for future research on product architecture costing are provided.

Keywords: Cost Estimation, Life Cycle Costs, Design, Product Architecture, Modularity

1 INTRODUCTION

In recent years, many markets have exhibited increasing demand heterogeneity, fragmenting into more and smaller market niches. This development threatens the large-scale assumption of many mass production processes. As a result, firms face the dilemma of how to provide a wide variety of goods for prices that can compete with mass produced products. To respond to these challenges, many firms have begun searching for ways to combine the efficiency of mass production with the variety of customer-oriented product offerings. A major focus of these efforts has been the fundamental structure of the product: the product architecture. Examples for this development are Sony's personal music players (Walkman) that use common drives across different models [1], different power tools that use similar motors [2], PDAs (personal digital assistant) that with different attachments

can be turned into an MP3 player, a camera, or a telephone [3], or automobiles with common components across models [4].

In academia, researchers of disciplines ranging from engineering to management have focused their attention on these phenomena, and have developed tools to guide the difficult process of providing variety to the customer while maintaining near-mass production efficiency, i.e., to 'mass customize' [5]. The approaches vary in their perspective and level of analysis. Some focus more on ways to increase (external) product variety while maintaining low costs, while others target their efforts on internal variety reduction without losing the variety appeal for the customer. The underlying idea of most of these approaches is to increase commonality across multiple products. The level in the product hierarchy at which commonality is pursued varies, it can be focused on common components [6, 7], on modules [8-10], on product platforms and product families [11-13] or on production processes [14, 15], although the lines between these levels are often blurred.

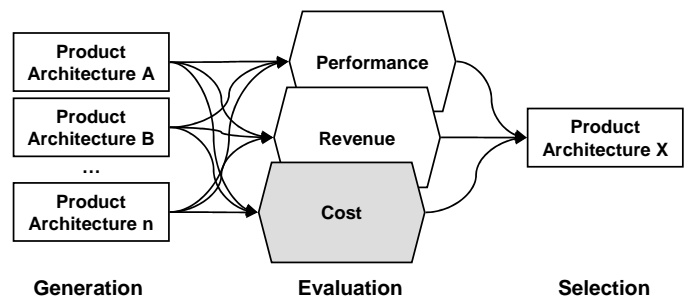


Figure 1: Process of product architecture determination

From a strategic perspective, a firm needs to balance all benefits it can achieve by increasing commonality across products with all the costs this approach creates. For example, it needs to weigh the revenue decreasing effects through cannibalization that product commonality can cause against the

cost savings that commonality can achieve [16]. In many cases this multi-objective problem requires the balancing of cost, revenue, and performance effects when selecting a product architecture from a set of candidates (Figure 1).¹

There are, however, many other cases in which a focus on costs alone is a reasonable assumption. First, many products contain two types of components, those with a strong influence on product quality and those with weak influence on product quality [6]. For components of the latter type cost becomes the only decision variable, provided that their performance level is sufficient [18]. Second, in some cases it is difficult to separate revenue effects due to the product architecture choice from those that are caused by factors that determine market dynamics, such as competition, marketing efforts, or regulatory conditions. For these reasons, this paper focuses on the cost impact of product architecture differences.²

While effects of commonality decisions on individual costs have been demonstrated [21], a more comprehensive understanding of the effects product architecture decisions have on various cost elements is currently lacking. In other words, the complex relationship between product architecture and costs is still insufficiently understood [17]. For example, using regression analysis Zhang and Gershenson find no general relationship between modularity, an aspect of the product architecture, and cost [22].

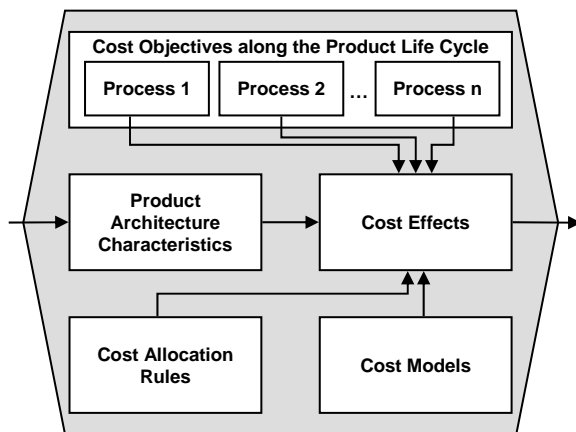


Figure 2: Factors relevant for product architecture costing

Ideally, a design engineer would like to be equipped with cost models that enable the continuous assessment of cost consequences of parameter choices on all decision variables. Knowing both the objective function and all constraints would allow to make optimal design decision [23]. This paper strives to contribute to the understanding of how to determine the economics consequences that serve as constraints for design optimization tasks. As a step towards developing a more general understanding of the complex product architecture-cost

¹ To limit its scope, this paper focuses on the evaluation part of product architecture determination. How to generate different product architectures is an additional field of research [17].

² Some researchers have addressed the higher level trade-off between revenue and cost to maximize profits, for example for lift tables [19] and analog quartz wristwatches [20]. The models employed, however, while conceptually powerful, reduce the architectural question to one of a combinatorial configuration to keep the problem's complexity manageable. In other words, they do not allow the commonality decision to change the product architecture. Consequently, they do not investigate how product architecture *differences* affect costs.

relationship, it dissects four areas in detail that contribute to the observed cost effects (Figure 2). First, it decomposes the concept product architecture into multiple, individual characteristics. Second, it discusses in detail the effects these individual product architecture characteristics have on various cost elements along the product life cycle, and points to some of the tradeoffs to be made. Third, it describes how the choice of cost allocation rules can influence the observed cost effects. Fourth, it categorizes existing cost models and assesses their requirements for data accuracy and sample size, as well as their ability to predict costs for different product architectures. The paper concludes with proposing further research steps to build a product architecture costing roadmap.

2 THE PRODUCT ARCHITECTURE AS A DESIGN DECISION VARIABLE FOR COST ESTIMATIONS

Product designers make numerous decisions throughout the design process. Each of these decisions has consequences for some costs along the product life cycle. Two characteristics label the links between these decisions and their consequences. The first characteristic describes how difficult it is to construct the link, the second how valuable it is to know it.

The level of difficulty to establish a link between design decisions and their cost effects depends on the hierarchy level at which the decisions are made. On the very detailed level, it is fairly straightforward to construct a link between the design decision and its cost implication. This is for two reasons. First, on the detailed level it is often clear on what costs to focus on, and second, for well known links historical data often exist. For example, there is ample data on how a more stringent surface smoothness requirement affects the manufacturing cost to create the surface. Design textbooks typically provide cost tables or functions to guide these design decisions [24, 25]. On the next higher level of abstraction design decisions affect material, production process, or part feature choices. Material has been used as a cost determining decision variable for a long time since in many mass production environments materials cost represent a significant fraction of total production cost [26]. For this reason, rules-of-thumb have been developed to allow quick rough cost estimates. To assess the cost impact of selecting manufacturing processes, a simple model has been developed that requires the input of only a few parameters [27]. The primary aim of that method, however, is the relative ranking of multiple processes with respect to cost, not to predict exact costs. Product features have also been used as decision variable for which cost models have been developed. Often the models combine cost estimations on the feature level with cost estimations on component and assembly levels [28] and the product family level [21]. Yet another level up in abstraction is populated by design guidelines such as Design for Manufacturing (DFM) or Design for Assembly (DFA). They represent codified knowledge of links between design decisions and costs. However, they are not cost prediction tools but present the knowledge in a condensed form such that they direct the designer's attention to cost creating design issues, and lead him towards (relatively) lower cost solutions [29]. Finally, on the level of product architecture there are numerous examples for relationships between *individual* aspects of the product architecture and *individual* costs, but no approach exists that provides a generic yet comprehensive description of this multidimensional relationship.

The second characteristic that describes the link between design decisions and cost elements along the product life cycle, is the leverage to influence the costs if the link is actually known. It is generally assumed that earlier design decisions have greater ability to influence costs than later ones.³ This creates a dilemma for the designer: it is the early design decisions where the potential to influence total life cycle cost is greatest, and yet early in the design process is where the fewest data for detailed cost estimations exist.

As a first step towards addressing that problem, this paper employs a descriptive methodology to distinguish different product architectures along *multiple* dimensions. The product architecture is the fundamental structure and layout of a product and is defined during concept development [39]. When the product architecture is selected, typically detailed information on components and subsystems are not yet available. However, in order to assess the cost impact of product architecture decisions an operationalization is required. Building on Ulrich's description of product architectures [40], a multi-dimensional product architecture description method has been developed [41].

A key attribute of the method is that it describes product architectures in two dimensions simultaneously but independently. The first dimension is concerned with the extent to which a product's functions are isolated on physical components⁴. It measures for each function (on the relevant architecture level) the level of *function-component allocation*. In other words, each function is assigned two indices that place it between the extremes of 1-to-1 and many-to-many relationships between functions and components. It is important to take this measure for each function individually, because the reuse of a component across a product family depends to a large extent on the role a component can play in different products. The second dimension is itself multidimensional and is concerned with three characteristics of the interfaces that connect the components. *Interface intensity* describes in detail the role the interface plays for the product function. Interfaces can be spatial, or they can transmit material, energy, or signals or any combination of the above [42]. *Interface reversibility* describes the effort it requires to disconnect the interface. This effort depends on two factors: the difficulty to physically disconnect the interface, and the interface's position in the overall product architecture. Finally, *interface standardization* depends both on product features as well as the population of alternatives. While some researchers have used different types of interfaces to categorize types of modularity like swapping, sharing, bus, and sectional [5, 43], the method presented here views the extent to which an interface allows different kinds of interchangeability as a matter of perspective. In other words, the level of standardization can

³ Various authors present the idea that somewhere between 60% and 90% of the total life cycle cost are committed during product design. Interestingly, although these numbers are used by a variety of authors from diverse fields ranging from accounting to engineering to management (e.g., [30] p.100, [31] p.231, [32] p.561, [33] p.25, [34] p.21, [35] p. 118, [36] p.7, [28] p.1, [37] p.28), none of them backs his or her claim with real data. One exception exists that models costs in more detail, however, it also does not specify a particular fraction of the total life cycle cost that is committed during design, but rather assesses the cost influence potential of the design phase versus the one of the production phase [38].

⁴ The term *component* serves as a pure placeholder. It represents all components above simple connectors, i.e. parts, components, modules, chunks, and subsystems.

be different for either component that is involved in the interface. Standardization is a function of the number of alternatives that exist on either side of the interface.

The next three sections will refer to these dimensions of product architecture when discussing life cycle costs, allocation rules, and cost models.

3 PRODUCT LIFE CYCLE COST OBJECTIVES

Every product and every system, regardless of size, value and lifetime, runs through different phases over its lifetime: design and development, production, use, and retirement. In each of these life cycle phases different processes and activities are performed with the product (Figure 3). Each of these processes and activities creates a cost. These costs can occur at different points in time, at different locations, and can be borne by different constituents.

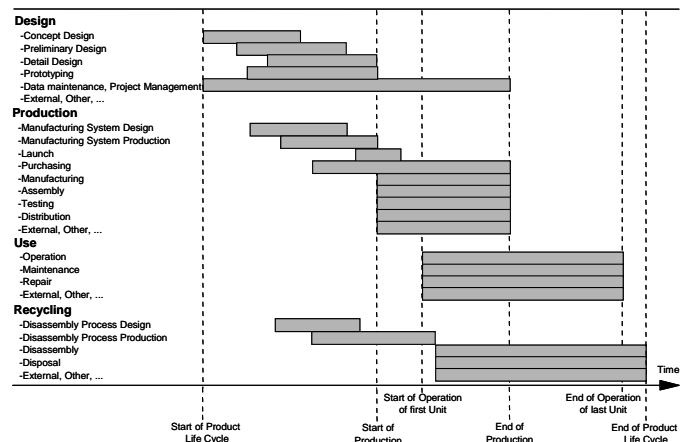


Figure 3: Activities throughout the Product Life Cycle⁵

Given that various costs occur in different phases of a product's life, one of the first decisions of a cost evaluation is to determine those costs that are relevant for the design decision at hand. The relevance of individual costs depends on the life cycle cost profile and the ownership of the costs. A product's life cycle cost profile is determined by both absolute values and relative distributions of the costs across the life cycle, the durations of the individual phases, and the production volume. To separate products according to their absolute values of total lifetime and total life cycle costs, it has been suggested to cluster the universe of different products into three major categories: large-scale, medium-scale and small-scale systems [44]. Large-scale systems can have total lifetimes of several decades and total life cycle costs of billions of dollars. Lifetimes of medium-sized products are typically measured in years, with total life cycle costs ranging from thousands to millions of dollars. Small-scale products can have lifetimes as short as a few months and life cycle costs as low as tens of thousands of dollars.

In addition to the absolute values, the relative distribution of time and cost over the different life cycle phases plays an important role. For example, a small product, say a radio clock,

⁵ Note that the diagram describes the product life cycle of all units produced during a model's life. In case of only one unit produced (e.g., expensive or special equipment), the diagram collapses into the individual product's life cycle. For the discussion in the paper the term *product life cycle* is used to describe the life of a single product.

will require very small maintenance and support costs during its use, whereas for long living and large scale products as, for instance, a navy ship, these costs represent almost 2/3 of total lifetime ownership costs [35]. Similarly, a small production volume results in relatively higher development cost per unit compared to the situation in which these costs can be spread over a large production volume. The consequence of the differences in total value, total life time, life cycle cost distributions, and production volumes are different life cycle cost incurrence curves (Figure 4).

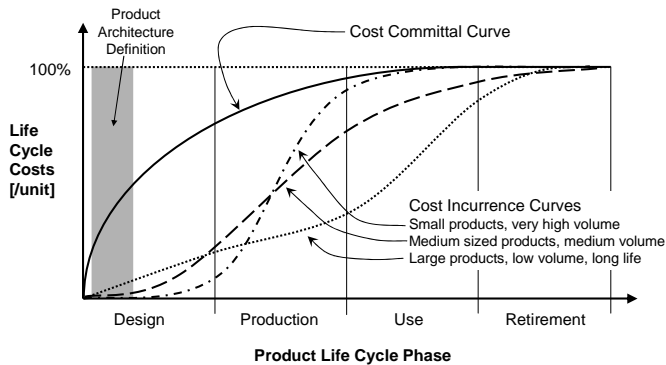


Figure 4: Cost Committal and Incurrence Curves

Finally, the life cycle phase in which certain costs occur does not necessarily determine who bears these costs. For example, warranty policies can transfer costs between producer and user [45], and most of so-called external costs are often borne by the society at large while the product user pays only a fraction of it directly. More generally, depending on a variety of additional factors such as market dynamics, level of competition, or institutional environment, a number of different cost allocation schemes are conceivable, enforced by different contractual agreements. Since most of these factors are not decision variables for the designer, the following discussion of each life cycle phase individually looks at costs independently from the ultimate ownership. Finally, while the primary focus of this paper is on cost effects triggered by architectural design decisions, other performance measures - such as time, and to some extent revenue - that are impacted by those decision, are discussed where relevant.

3.1 Product Design and Development Phase

The first phase of a product's life encompasses activities such as conceptual and preliminary design, detail design and prototyping, testing, as well as supporting functions such as data maintenance and project management. For engineered products, the costs for these processes represent primarily engineering resources, i.e., personnel. To address the question of how differences in product architecture affect the resource consumption during the design phase, some researchers have linked the task structure of the design process to the product architecture [46-48]. Over time, a firm's organizational structure often mirrors the product structure of the products it produces [49]. Thus, the design decision on the number and size of 'chunks' (subsystems, modules, parts, etc.), i.e., the function-component allocation scheme, translates into the number and size of teams working to develop the product. The number and size of the teams determines their internal complexity as well as their external communication efforts.

Both factors in turn determine the teams' efficiency. Either extreme, i.e., one very large team or many, very small teams, appears to be a relatively inefficient organizational form, the former requiring many internal iterations, the latter producing a long sequence of information transfers. Therefore, creating product architectures that balance the design complexity that incurs between the chunks (integration effort) on one hand, with the sum of the design complexity within the chunks on the other, by designing chunks of medium complexity, seems to be a resource efficient approach.

For the second product development performance measure next to cost, total development time, a similar effect has been found. For the development of a turbopump of a rocket engine, it has been shown that there is a number of blocks of the product architecture (modules, chunks, etc.) that translates into a medium number of teams that minimizes the duration of the project development project [50]. Apparently, both costs and time functions exhibit a minimum if the product is decomposed into a medium number of subunits, and increases when fewer but larger subunits are chosen, and increases when more, but smaller subunits are selected.

The relative value of *time* compared to *cost* depends on a number of market parameters as well as the ratio between revenue and costs. For example, companies operating in fast pace market environments will especially value a product architecture's potential to reduce the time-to-market. Product architectures that allow conducting much of the design process in clusters in parallel in order to arrive at the shortest possible total design time are of particular value to them. In a specific case about a Polaroid camera housing, for example, it has been found that the foregone sales in case of a longer development time far outweigh any achievable cost savings in manufacturing [51]. In a case like this, to reduce development time is far more valuable than any cost savings in the production phase due to architectural changes.

Also, strictly speaking, the design phase is only one component of the time-to-market. If market is understood as sale (or start of operation) of the first unit, then production preparations become part of the time-to-market, in particular tool design and manufacturing. Hu and Poli have compared assemblies made from stampings with injection molded parts regarding their effects on time-to-market [52]. They find that parts consolidation, i.e., the reduction of the number of chunks the product consists of can be disadvantageous with regards to time-to-market when the time to produce the tool for larger, more complex parts extends the total time-to-market.

In addition to the particular product function-component allocation scheme, the characteristics of the interfaces between the chunks are likely to affect the efficiency of the design process, and thus its costs.. The weaker the interface connections are, i.e., the lower their *intensity*, the more the different design teams can be working independently on different subsets of the product. This can reduce the number of iterations between the teams, and thus increase overall design process efficiency. In a case study of the development of an automotive climate control system, strong coupling has been identified as one reason for development cost increases [53]. Weaker interface dependencies may also shorten the total development time (time-to-market) because it allows the design tasks to proceed in parallel. Similarly, analyzing the product development of integrated circuits, it has been found that higher

levels of interface independence increase the design flexibility and reduce the risk of having to repeat experiments [54].

Finally, both characteristics of a product's architecture, i.e., its function-component allocation and its interfaces, affect development costs in a particular way as a consequence of the nature of design work. Design costs are one-time costs in the product program's life, i.e., their contribution to the unit costs is highly sensitive to changes in the production volume. If only one product is ever produced, say a racing boat, this single unit has to bear all development costs. In contrast, for mass-produced products like vacuum cleaners, the design costs are shared by potentially millions of identical products. For the assessment of cost implications of architectural decisions this issue is also relevant when product architectures allow sharing of portions (parts, modules, components) of a product across product families, and, therefore, allow the sharing of their development costs. The savings through the re-use of designs affect both development cost and time [55-58].

3.2 Production Phase

With respect to the impact of product architecture decisions on costs that occur during the production phase, two sub-sets of processes require separate discussion: (1) manufacturing and assembly, and (2) logistics.

To understand how the first dimension of product architecture, i.e., the size and number of components (the function-component allocation scheme) affects manufacturing and assembly costs it is helpful to review the basic idea behind design for manufacturing (DFM) and design for assembly (DFA) guidelines. Both guide the designer to focus on product characteristics that consume avoidable resources during manufacturing and assembly, but each with a different rationale. DFM aims at simplifying manufacturing processes, which results – in addition to lower investment - in reduction of process variability and ultimately in faster process rates and higher yields, and thus lower cost. In contrast, DFA generally emphasizes part count reduction, the use of only one assembly direction and the preference of symmetrical parts [29]. Empirical evidence exists that supports both claims individually. In case of automobile rear lamp production, for instance, it has been found that complex products requiring complex manufacturing processes result in higher costs compared to simpler parts with simpler processes [59]. On the other hand, in an analysis of the costs of electromechanical assemblies it has been found that the assembly cost savings through part count reductions can be significant [60]. Part count reduction is generally seen as a cost reduction tool [61, 62]. These findings result in cost curves that increase in opposite directions and the minimum of the sum of the two depends on the specific shape of these two curves (Figure 5).

The argument for products requiring simpler manufacturing processes rests essentially on the idea that these processes perform faster and more reliably than their more complex counterparts. Assuming that simpler products require simpler manufacturing processes, this means the product feature complexity affects the efficiency of the process which in turn directly affects the costs via process speeds and yields. In other words, a design that allows processes to be robust is more likely to consume fewer resources. With respect to product architecture, this observation means that the designer

should strive to keep the size of modules or chunks below a complexity level that makes them difficult to manufacture.

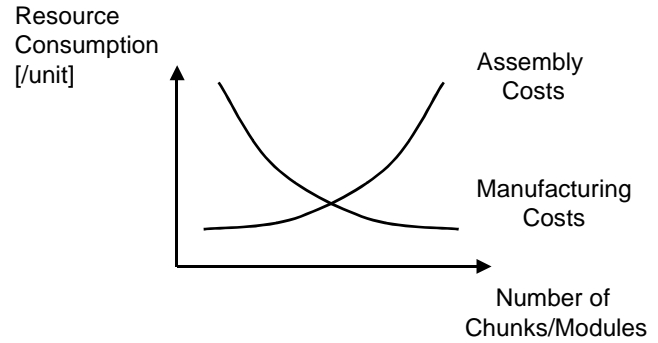


Figure 5: Manufacturing and Assembly Costs

On the other hand, the argument for products requiring fewer parts (and, likely, less manufacturing processes and assembly steps) to achieve lower costs is immediately obvious, as long as the reduction of processes is not paid for with lower yields. A shift from one manufacturing process to another to reduce part count can have a dramatic impact on assembly time and cost. For example, the instrument panel for the cockpit of the commercial aircraft Boeing 767-4ER used to be manufactured from 296 sheet metal parts and assembled with 600 rivets. A move to precision casting has reduced the part count to 11 and the assembly time from previously 180 hours to 20 hours [63]. In sum, the product's function-component allocation, i.e., its number and size of components, affects both manufacturing and assembly costs, typically in opposing directions, and designers need to develop an understanding of the relative importance of these cost elements in their particular environment.

From a unit cost perspective there is one other effect of product architecture on production costs: this is the use of common components *across* product families. If the fixed cost portion of manufacturing and assembly can be distributed across a larger number of units, the unit production costs decrease. However, the magnitude of these savings needs to be compared with the potential cost penalties for over-designing a sub-unit or module. For example, products whose costs are dominated by materials costs, i.e., variable costs, such as automotive wire harnesses, may not gain much through the use of commonality [18].

In addition to the product architecture characteristic number and complexity of chunks, the characteristics of the interfaces between the chunks impact production costs. Interfaces preferred from the low cost production perspective are such that they minimize complexity and uncertainty within the production process. This means, the better the process is known and the more likely it can be performed successfully, and the lower the total number of different processes in the production system is, the lower the expected production costs. The nature and intensity of the interfaces can also be relevant to the production. For example, electronic interfaces consisting of only a plug and a socket may be easier to assemble error-free than a complex mechanical rod connection.

The second subset of production costs is concerned with the aspects of logistics. For the purpose of this work logistics costs encompass costs for storage, transportation, inventory,

and work-in-process (WIP). Storage and transportation need to be considered both inside and outside the plant, between suppliers and plant, and between plant and customers. Product architectural decisions are most likely to affect these costs to the extent to which they determine packing space and protection requirements.

Architectural differences also impact the costs for inventory and WIP. The more a product architecture allows late customization or postponement strategies, the more it can contribute to savings in storage and WIP costs through pooling effects. Parts commonality has been identified as a way to reduce the safety stock level for a given service level [64]. Others have shown, however, that while the stock for a common part can be lower compared to the unique parts it replaces, the safety stock of the remaining unique components increases if a certain service level is to be maintained [65]. These findings have been confirmed for an arbitrary number of products and joint distribution as long as the costs for the product-specific components (that are replaced by a common one) are the same [66]. For the two-product case, cost ratios have been derived that bound the advantage of the use of common components [7]. In sum, the use of common parts can reduce inventory, but it needs to be investigated with the specific demand pattern, the relative costs of the components, and other potential cost penalties in mind.

The architecture's effect on time can have additional impacts on costs via the detour of increasing demand volatility. Because demand volatility increases upstream ('bullwhip-effect'), architectures can reduce this effect if they allow for parallelization of production to achieve short lead times. Long lead times, together with high levels of demand uncertainty, can amplify the bullwhip-effect and create significant additional costs in the supply chain [67].

Overall, a complete assessment of the impact of architectural characteristics on production costs should incorporate manufacturing, assembly, and logistics costs, and evaluate how to balance these different effects.

3.3 Use Phase

In general, three types of costs occur during product use. These are the costs for operation, for maintenance, and all external costs incurred by the operation of the product.

Most products require some input to operate them. The costs for these inputs can be for fuel or utilities like energy, water, or pressurized air, or costs incurred by the product's characteristic, for instance labor requirements for a machine operation. While it is very difficult to make a general statement about the relationship between product architecture characteristics and operation costs, some issues can be pointed out. For example, product architectures utilizing common components across members of a product family (which requires proper function-component alignment) may allow a reduction in personnel training costs. Aircraft producers are trying to install similar, if not identical, cockpits into airplanes of different sizes to reduce for the operators the need to retrain the crews. Or, if a product is frequently used in multiple modes, e.g., a machine tool, architectural characteristics that allow to reconfigure the product quickly, i.e., function-component alignment and interface reversibility, improve the productivity of the product by reducing its operating costs as measured by units produced.

With respect to maintenance costs, there are two major questions with which to be concerned. First, what is the likelihood that maintenance (and its costs) will occur during the product's use phase and, second, what will be the anticipated costs for this maintenance? Grouping parts with similar expected lifetimes together (function-component allocation) is likely to reduce the repair and replacement costs [68]. In addition, a product architecture that allows easy and fast access (interface reversibility) for maintenance and repair may result in lower maintenance costs. Also, in case that a product has multiple identical parts (function component allocation), fewer parts need to be stocked in inventory (compared to unique parts) for providing the same level of availability [69]. Like the risk pooling across products, this strategy translates into lower spare part inventory costs as part of the maintenance costs. Note that the different elements of maintenance costs may react differently to the same product architecture design decision.

Finally, the operation of any product may also cause so-called external costs, e.g., damages to public health or the environment through emissions. A link between product architecture design decisions and external costs is very difficult - if at all - to establish, and goes beyond the scope of this work.

3.4 Product Retirement Phase

In the last phase of a product's life cycle, costs are created by activities like disassembly or disposal. In addition to these direct costs, external costs, like degradation of the environment or air quality, can occur.

To estimate disassembly costs as a function of the product architecture is very difficult, particularly since it is often unclear which of several possible disassembly sequences is the most economic one. The reverse of the assembly process may, or may not, be the most cost effective way to disassemble the product. Researchers have suggested a number of scoring processes to compare disassembly efforts for different designs. Some suggest comparing disassembly costs for different designs on a relatively high level of aggregation. Emblemsvag and Bras [70], for instance, propose to list all activities the disassembly of various products would require, compute the costs for each activity per time unit, determine the time each design requires each activity, and compare the results. This type of analysis, however, does not reveal specifically what architectural features make one design more costly to disassemble than another. To answer this type of question, more detailed analyses are required. Das et al. [71], for example, propose to compute a disassembly effort index based on seven factors, like time, tools, fixtures, access, instruct, hazard, and force requirements. The fact that both the score for each of these factors as well as the weights among them are based on qualitative assessments, demonstrates the difficult nature of the task to determine disassembly costs unambiguously. Others have extended this work to include bulk recycling in addition to disassembly activities [72]. However, while the product architecture affects disassembly costs (via dimensions function-component allocation scheme and interface reversibility), its impact on bulk recycling is only relevant together with the specific values of the materials involved. Finally, while determining the costs to landfill a product or parts of it are relatively straightforward, the results, however, are unlikely to depend on architectural characteristics of the product (leaving material consideration aside).

4 COST ALLOCATION RULES

While the previous section discussed the various cost types that can occur over a product's life and the relationships between product architecture design decisions and these costs, a second issue relevant to determine these relationships is concerned with the cost allocation procedures. Particularly relevant for the results of any cost analysis are the – often implicit – assumptions on the analysis boundaries, on the overhead allocation, and on the dynamics of the process.

4.1 Unit of Analysis

Most often, product unit costs are chosen for cost comparisons of assembled products. There are, however, other units of analysis that could be selected alternatively, for example, product families, programs, departments, factories, companies, or entire economies. The order of this list of potential levels of analysis indicates an increasing distance from the physical object itself. While a cost analysis focusing on a product makes it easy to assess costs that are directly related to the product (e.g., material consumption), it makes the allocation of more 'distant' costs (e.g., factory guards) very difficult. On the other hand, for cost analyses on a company level, almost all costs are somewhat 'direct' (Figure 6).

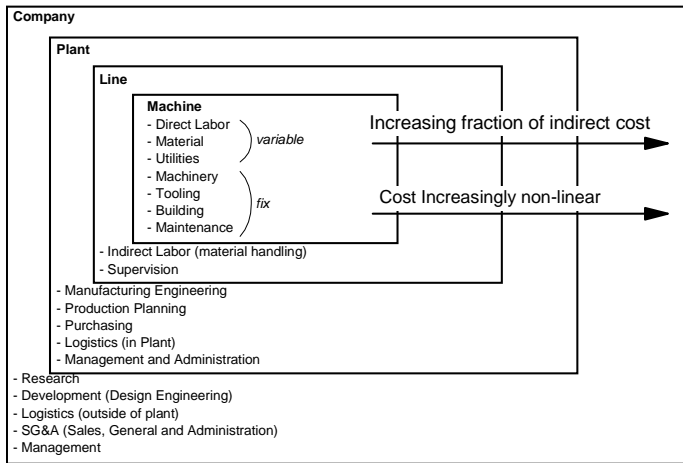


Figure 6: Different levels of cost analysis

The direct-indirect classification depends on the choice of the cost object. "A useful rule of thumb is that the broader the definition of the cost object, the higher the proportion of its total costs are its direct costs – and the more confidence management has in the accuracy of the resulting cost amounts. The narrower the definition of the cost object, the lower the proportion of its total costs are its direct costs – and the less confidence management has in the accuracy of resulting cost amounts." ([73], p. 28) Since this paper is concerned with the cost effects product architecture choices trigger, it is logical to focus the cost analysis on a level where product architectures can be distinguished, i.e., on the product or product family level. This in turn creates the above mentioned allocation problem of how to allocate the significant indirect cost portion, often called 'overhead.' Overhead usually encompasses costs with various levels of 'indirectness.' For the interpretation of cost consequences of product architecture design decisions, it is very important to understand the mechanisms by which these overhead costs are allocated.

4.2 Allocation of Overhead Costs

The accounting literature employs two distinctions for costs: direct versus indirect costs and fixed versus variable costs. While the first uses the cost traceability to separate direct from indirect costs, the second uses the dependency with regards to changes in production volume as a measure to classify fixed and variable costs.

In the production arena, costs that are typically considered variable are costs for direct labor, materials, or utilities. In contrast, machinery, tooling, and building costs are usually considered fixed costs. These distinctions, however, are not clear-cut, but depend on the chosen time horizon, the chosen manufacturing technology, and the chosen accounting principle. A change in the chosen time horizon can turn the same costs from fixed into variable costs. Labor costs are typically viewed in short time frames as fixed costs, whereas in the long run they are typically treated as variable in nature. The choice of a manufacturing technology may determine whether a specific or a generic tool is deployed. A shear as a cutting tool that can be used to produce other products as well exhibits variable cost behavior, whereas a specific cutting die that does the same job, but can only be used for this specific product, becomes fixed costs. Finally, certain accounting principles can shift costs from the fixed cost category into the variable cost category, and vice versa. The assumption, for example, that free machinery capacity can be employed for other jobs turns the allocated machine cost effectively into variable cost, whereas the assumption that the machinery is dedicated to a specific product results in fixed cost behavior.

In sum, what is typically called overhead is a broad category with often fuzzy boundaries. It is, however, a category that becomes increasingly important due to increasing product and process complexity, shrinking direct labor content, shorter product life cycles, and increasingly heterogeneous markets [62, 74-76]. Table 1 gives an overview of the magnitude of some overhead costs found in recent studies.

Table 1: Overhead costs found in recent studies

Author(s)	Total Costs (=100%)			Activities considered	Industry
	Direct Materials	Direct Labor	Manufacturing Overhead (MO)		
Banker, Potter and Schroeder (1995)	65.4%	8.9%	25.7%	Plant level study	Electronics, Machinery, Automobile components (mean values of 32 facilities)
Foster and Gupta (1990)	54.3%	6.6%	39.1%	Procurement, Production, Support	Electronics (mean values of 37 facilities)
Galsworth (1994) [p.85]	40%-65%		35%-60%	Total Costs: Function cost: 40% Variety cost: 25% Control cost: 35%	Manufacturing
Hundal (1997)	45%-65%	8%-20%	22%-40%	Not specified	Aerospace, Computers, Electronics, General Equip., Automobiles
Miller and Vollmann (1985)	20%-40%		60%-80%	Overhead Costs: G & A 20% Indirect Labor 12% Engineering 15% Equipment 20% Materials OH 33%	Electronics

One characteristic feature of overhead costs is their lack of direct dependency on production volume. Activities that support in various ways the actual production processes do not necessarily vary in direct proportionality with the production volume. It has been argued that the costs for these activities vary with the intensity or frequency of these activities. For example, the time and manpower to write a purchasing order does not vary with the number of equal parts ordered, but each order incurs an average cost for the transaction 'write purchasing order.' This insight triggered the development of activity-based costing (ABC) [77, 78]. ABC promotes a cost allocation process in proportion to the activities consumed by the products produced. The basic idea of ABC is to calculate the costs of activities (cost drivers) and 'charge' products with the time with which they consume an activity times the use rate per time unit. The cost drivers can be on various levels in the firm: "While some activity cost drivers are unit-related (such as machine and labor hours), as conventionally assumed, many activity cost drivers are batch-related, product-sustaining, and customer-sustaining" ([79], p. 4).⁶

ABC argues that many overhead costs are related to activity frequency rather than production volume. Standard ABC typically assumes a linear relationship between activity and cost. The impact of this assumption, however, is particularly difficult to understand in case of product variety.

Product variety often causes additional work in activities such as planning, control, monitoring, and coordination [84]. Not only does this propagation effect make it more difficult to trace individual costs, but it often creates an additional allocation problem. If product variety creates costs above the sum of the individual costs, which fraction gets allocated to which product?

In addition, product variety can take on different forms which have different effects on costs. For example, Ittner and MacDuffie [85] defined three levels of product variety in their study of overhead costs in automotive assembly plants: core or fundamental (model mix complexity), intermediate (parts complexity), and peripheral (option complexity). They find empirical support only for the latter two affecting overhead costs, "... reflecting the considerable logistical, coordination, and supervisory challenges that accompany an increase number of parts and more complex manufacturing tasks." ([85], p. 29) Another approach to specify product variety has been followed by Anderson [86]. She measures the impact of product mix heterogeneity on manufacturing overhead costs by identifying seven independent product attributes from engineering specifications. By measuring on the attribute-level, Anderson finds that increased overhead cost "is associated with increases in the number and severity of setups and increased heterogeneity in process specifications (expected downtime)

⁶ Some have criticized ABC as guiding to poor short-run decisions, and suggested the Theory-of-Constraints (TOC) as a better tool for short-run cost allocations. TOC assumes all costs other than direct material as fixed [80]. Then, to maximize profitability, TOC recommends to maximize the throughput. TOC promotes finding the bottleneck in an existing system and adjusting all other production to it to eliminate inventory. In the debate about whether ABC or TOC is the superior way of interpreting costs, various authors argue to understand both methods as opposing ends of a continuum with respect to planning time horizon: ABC for long-range planning, TOC for short-term decisions [81-83]. Since the choice of the product architecture is a rather long-term decision, ABC is the more relevant method for the purpose of this paper.

and quality standards (defect tolerance heterogeneity) of a plant's product mix" ([86], p. 383).

Finally, how product variety is distributed over time can affect the effort to balance and sequence a production line. Taking a production perspective, a study of product variety finds that "[o]ption variability has significantly greater negative impact on productivity than option content in automobile assembly" ([87], p. 785). In this case, variety's impact on indirect and overhead labor is much greater than it is on direct labor. The authors explain this with the built-in slack in automotive assembly lines that allows handling option variation in the first place. They point out that because these costs are born through the variability complexity it is difficult to allocate these excess costs to any specific product.

With respect to the question of how characteristics of the product architecture affect the cost allocation process, some general observations can be made. An architecture that allows operations conducted closer on a per-unit basis allows more precise cost allocation. For example, a process that produces only one part at a time allows easy allocation of all non-direct costs (setup, purchasing, etc.). In contrast, architectures that cause complex logistical, balancing, sequencing, or quality processes may make the cost allocation more difficult. Within limits, these arguments call for products with architectures consisting of fewer components (dimension function-component allocation) and with high levels of interface standardization. Taking a product perspective, it has been suggested to estimate (a) the likelihood of component change from one product generation to the next, and (b) the design impact on other components of this change qualitatively, and to interpret the impact of these changes in economic terms [88].

4.3 Process Dynamics

The third assumption concerns the extent to which the processes under consideration are considered static or dynamic. There are two cases of non-static situations: (1) a one-time change followed by a stable period, and (2) a change over longer periods of time. In the first case, the ratio of 'ramp-up period' to 'normal production period' is the relevant factor. If, for example, the whole production run will extend over several years and the ramp-up takes only a few days, the focus can be put on the system costs assuming it in its static stage. In contrast, if the production run is relatively short and the ramp-up takes up a significant portion of it, the systems costs are not well represented by the production run alone. In some production environments the ramp-up time can represent a significant fraction of total production time. For example, it can take up to six months to bring an automotive assembly plant up to full production load [89].

Cost changes over longer periods of time can occur in two ways: the change itself can either be constant or not. The case where the change is (to some extent) constant is often caused by what has come to be known as the learning curve effect. The argument is that with accumulating production volume workers and engineers are getting better in what they are doing. They optimize the processes and their work environment in a manner that continuously improves their productivity. Often times the learning effect is measured as a constant cost reduction with every cumulative doubling of the production volume, e.g., 20%. Empirical evidence has been presented that

this effect indeed exists [86]. Activity-based costing systems can help to detect these learning effects [90].

In the second case of changing unit costs, the change itself is dynamic, i.e., unit costs do not change by a constant rate but follow dynamic patterns. An example of this phenomenon is non-constant unit costs as a result of different ways of sequencing different products through jointly used production processes. Flexible manufacturing systems (FMS), for example, can manufacture different products on the same machine. The set-up time, however, may depend on what product has been produced prior to the one under consideration. Will the same tool be used? If not, is the tool change time dependent on what tool was used for the prior product? This problem has been addressed through the use of activity-based costing systems in conjunction with production planning models [91].

With respect to the effects of product architecture choice on unit cost, the phenomenon described in this section cannot be determined with product architecture data alone, but requires data (or assumptions) on the production environment including scheduling and the production program information.

5 COST MODELS

A number of cost models have been developed to help designers to assess the economic consequences of their design decisions. Typically, the existing methods are grouped into three categories: parametric, analogous, and analytical. Parametric models aim at establishing scaling factors of cost drivers found through analysis of historical data. Regression analysis is a typical method to extract such scaling factors. Due to the simplicity in use, parametric techniques are used in many industries [92, 93]. In addition, non-parametric methods such as neural networks have also been applied to find parameter-cost relationships [94].

The underlying idea for analogous models is to search for similarities between the design at hand and a large number of historical cases stored in databases. To be able to compare products on multiple levels (product, subassembly, part, etc.) hierarchically structured approaches have been developed [95-97]. Other approaches focus more on abstract elements like features [98, 99].

Finally, analytical cost models come in two very different flavors. One category is represented by abstract mathematical models, often used to generate insights in general questions. Their emphasis is mostly on structural trade-off modeling, while the functions of relationships between design decisions and costs are typically assumed to be known in their shape [18, 100, 101]. The other flavor of analytical models is represented by detailed models of (mostly) manufacturing processes to estimate the associated costs [102-105]. In the interest of brevity, the existing cost modeling techniques are not discussed here in detail. For details the interested reader is referred to recent reviews [44, 106].

Four criteria are helpful to select the appropriate technique to assess cost implication of product architecture design decisions. First, does the technique or model require a substantial data set of similar cases? Regression analyses or neural networks, for example, usually require sufficient cases to be able produce relevant cost predictions. Second, how large is the number of acceptable cost drivers? Most cost modeling techniques allow only a limited number of cost drivers. To

some extent is this question related to the previous one in that the number of available cases restricts the number of acceptable cost drivers. Third, how large are the acceptable differences between product architecture under investigation? This criterion is particularly relevant if substantially different product architectures are to be analyzed. Modeling techniques that build on a set of known cases are usually limited here. Finally, what certainty level is required for the input data? As indicated earlier, cost analyses in early design stages typically lack detailed and accurate product data. The assessment of the cost models along this fourth criterion reveals the underlying modeling philosophy. Some models use search procedures to find relevant data among existing cases (e.g., expert systems) whereas others build the cost analysis for every case anew (e.g., process-based cost models). Depending on the goal of the product architecture analysis and the available data, different methods are advantageous. Table 2 summarizes the cost model assessment.

Table 2: Application criteria for various costing techniques

Costing Technique	Application Criteria		Data Set Requirement (minimum case base)	Acceptable Number of Cost Drivers	Acceptable Difference in Architecture Decomposition	Required Certainty of Data Input
	Source					
Parametric	Regression Analysis		Large	Low	Small	Medium
	Complexity-theory based		Medium	Low	Small	High
Analogous	Neural Networks		Large	Low	Small	Medium
	Feature-based		Medium	Low	Small	High
	Expert systems		Large	Medium	Medium	High
Analytical	Abstract modeling		Small	Small	Small	None
	Process-based cost models		Small	Medium	Large	Medium

6 CONCLUDING REMARKS

This paper has laid out the land of cost consequences of a major early design decision: the choice of the product architecture. It provides a comprehensive discussion of how individual product architecture characteristics affect specific cost elements over a product's life cycle. This discussion can serve as a guideline to formulate various tradeoffs. For example, a manufacturer of long-living products, e.g., a ship builder, might want to trade-off costs for building the ship with costs for operating it. In contrast, a manufacturer of mass-produced consumer goods might be more interested in the cost trade-off between parts fabrication and assembly costs. For any given firm, the determination of the relevant trade-offs is impacted by such factors as the firm's business model, its warranty policies, or its competitive and legal environment. The paper also provides an overview of how cost allocation rules can affect cost analyses results, and thus the implied cost advantage of one product architecture over another. Finally, the paper presents a categorization of existing cost models, and illustrates which one to select depending on the size of the available data set, the given data set's level of accuracy, and the number of acceptable cost drivers.

Two areas can be identified as opportunities for future research on product architecture costing. The first is the question of how to build dynamic cost models. While knowing the cost effects, allocation rules, and cost models discussed in

this paper allows to evaluate cost consequences of *differences* along individual product architecture characteristics, this knowledge does not automatically feed back into the product architecture design process. If it were possible to turn product architecture characteristics into continuous variables, they could be used to find optimal architectures – optimal with respect to the cost determined as relevant. As a step in this direction a firm might build a repository of their own cost data and associate the data with the corresponding product architecture characteristics. This way the firm might populate the product architecture-cost space with more data points. Over time, this would offer the chance to introduce internal learning into the product architecture design process [31]. With respect to the product architecture development process, this would replace the process as depicted in Figure 1 of generation and selection with one that guides designers towards more cost effective - for the selected purposes - product architectures.

The second area of promising research on product architecture costing is the treatment of uncertainty. While uncertainty is inherent in any estimation of future data, the way in which it is modeled might provide additional insights for the product architecture selection decision. While deterministic cost models can be augmented with sensitivity analyses, more sophisticated measures of risk and uncertainty could advance the cost modeling tools, and by extension, the product architecture creation.

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