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Decomposition in Product Development

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Abstract

Product development organizations seek to create profitable product designs. This paper discusses how the decomposition of the profit maximization problem leads to traditional product development processes. Decomposition provides a framework that integrates the conceptual models of decision-based design and the traditional description of product development processes. This paper identifies the key reasons for decomposition and discusses why the decomposition varies among product development organizations.

Keywords: Engineering design, product development, decomposition, decision-making.

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1 Introduction

The design engineering community has focused much effort on understanding design as a decision-making activity. This work has yielded Decision-Based Design (DBD), a perspective that views design as a decision-making process involving values, uncertainty, and risk (Chen *et al.*, 2003). The research on DBD includes a wide variety of approaches. Some research on DBD includes efforts to reformulate product development using approaches that integrate numerous design decisions and solve large optimization problems whose objective function is to maximize company profit (see, for instance, Hazelrigg, 1998; and Li and Azarm, 2001). Such an integrated formulation is meant to simplify the product development process and lead to better designs because the integrated model includes all of the competing performance measures and maps them to more fundamental objectives (such as profitability and market share) that are important to the manager of the manufacturing firm. This approach sounds reasonable, so why does it appear to be so novel (or even controversial)?

For the most part, profit maximization, though always present, has been concealed and consequently ignored. For anything beyond the simplest settings and products, the complexity of product development has led firms to develop sophisticated product development processes to develop profitable products. As discussed in more detail later in this paper, the complexity led to a division of labor, and most of the people involved do not have to worry about profit. As design researchers and educators studied these processes and taught them to the next generation of design engineers, they saw no discussion of profit and thus didn't include that topic in the curriculum.

Only a few models make explicit the link between product development decisions and profits (see, for example, Smith and Reinertsen, 1991). Many texts neglect the topic, though Ulrich and Eppinger (1995), Magrab (1997), and Schmidt *et al.* (2002) present product profit models and their use in making tradeoffs. Otto and Wood (2001) also describe the ways in which product development teams consider profit and other business objectives.

Product development organizations exist to design profitable products within a reasonable amount of development time and cost. Given this simple objective, it is noteworthy that the structure of product development organizations varies widely from firm to firm, and the product development processes used in these organizations also vary widely. This diversity results from the various ways that firms decompose the problem. Each firm's decomposition reflects their unique situation and their ability to balance the benefits of decomposition and the advantages of integration.

The education of design engineers, both in classrooms and on the job, usually describes a typical product development process as a sequence of tasks, though instructors are careful to emphasize that iterations almost always occur. Most texts fail explain or justify the decomposition, so the fundamental justification for this sequence of tasks remains implicit and mysterious. A rare exception is Dym (1996), who discusses the decomposition of a design problem into a set of subproblems that are easier to solve.

Still, there is a need for a clear description of how profit maximization both motivates and (through decomposition) shapes product development processes. This paper seeks to provide the needed clarity. Product development processes reflect the need to decompose the difficult challenge of profit maximization into a set of activities and decisions that humans can execute rationally. The need for decomposition results from many sources, including cognitive limitations, the indefinite relationships between detailed design decisions and profitability, and the effort of maintaining complex models. However, there exists a tension between the benefits of decomposition (the ability to make rational decisions using a reasonable amount of effort) and the desire to integrate decisions and subproblems into more comprehensive formulations that yield higher-quality designs.

This paper discusses how product development decomposes the problem of finding profitable products into an interrelated set of design activities. The decomposition is a rational strategy given the time, cognitive, and resource constraints that exist. Understanding this reality will help managers and researchers design and implement product development process improvements. Decomposition transforms the idealized concept of product development (“find the design that maximizes profit”) into the practical world of time and resource constraints. This is the decomposition of the design problem (or designing activity), not the decomposition of the product design, though these two things are certainly related.

(Note that this paper will be discussing product development, that is, engineering design practiced in manufacturing firms that design and manufacture products to make a profit. Certainly engineering design is also practiced in many other types of settings. In these cases, the bottom-line objective may be different, but the general principles of decomposition will still apply. Also, the product development process begins after the firm has decided that it needs a new design of a particular type of product. The questions of product positioning and redesign timing are beyond the scope of this paper, though they are crucial to understanding the overall function of a product development organization.)

The remainder of this paper is organized as follows. Section 2 discusses the objectives of manufacturing firms, including profitability. Section 3 describes product development. Section 4 discusses the motivation for decomposition. Section 5 considers the diversity of decomposition. Section 6 concludes the paper.

2 Corporate Objectives

In a capitalist, free enterprise system, manufacturing firms serve the interest of their community by employing workers, purchasing materials, producing goods, generating profits, and not harming the community. Guiding the activities of a firm are the ethical standards of the community, the firm’s civic responsibilities, regulatory constraints, and the values and consciences of the owners and executives.

Making a profit is certainly an important objective to manufacturing firms. One can describe product development conceptually by defining it as the creation of the most profitable product design. Hazelrigg (1998) proposes a framework for product development in which the firm chooses the product’s price and design to maximize the expected utility of the design, where the utility function reflects not only the profits but also the inherent uncertainty and the corporation’s tolerance for risk.

A more practical approach is a high-level analysis of profitability based on unit costs, development costs, marketing costs, sales price, and projected sales. Walton (1997) describes the use of such analysis early in the vehicle development process. Executives approve funding for the product development project based on such analysis. In some firms, this type of model, called a product profit model (Smith and Reinertsen, 1991), is used during product development to understand how changes in costs and sales (changes that result from design decisions) affect profitability.

Simon (1997) argues that most decision-makers do not explicitly consider profit, though that is the overall objective of the manufacturing firm, because decision-making is “loosely coupled.” Profit is an indirect influence on most decision-makers. The mechanisms linking decision-makers to the overall corporate goals are constraints and incentives such as schedules, rewards, and penalties. Other corporate objectives indirectly influence decision-makers throughout the firm in the same way.

3 Overview of Product Development

Product development is a necessary and important part of the activities performed by a manufacturing firm. Due to changes in manufacturing technology, consumer preferences, and government regulations (to name a few influences), existing products will become less profitable over time. The sales volume of a typical product starts slowly, accelerates, becomes flat, and then steadily declines. Although there may be a few products that remain profitable for many years, firms continually develop new products that will generate more profits. Product development determines what the firm will manufacture and sell. That is, it attempts to design products that customers will buy and to design manufacturing processes that meet customer demand profitably. Poor decisions during product development lead to products that no one wants to buy and products that are expensive to manufacture in sufficient quantity.

A *product development process* is the set of activities needed to bring a new product to market. A *product development organization* includes the engineers, managers, and other personnel who make process and product engineering decisions and perform these activities. (Note that, in this paper, the term *new product* covers the redesign of an existing product as well.)

A *product development project* is the set of actual activities that are performed during the development of a specific new product. Typically, the product development project will follow the product development process, but the project will deviate from the process as circumstances warrant, just as the actual operation of an airline deviates from the published schedule as bad weather, equipment failures, and other unexpected events occur.

Product development requires a wide variety of decisions (see, Krishnan and Ulrich, 2001, for instance). Because making good decisions requires expertise and an organization of people can be experts in only a few things, a manufacturing firm specializes in a certain class of products. It focuses its attention on the market for that class of products, the technologies available to produce that class, and the regulations relevant to that class.

Like other parts of the business, a product development organization seeks to maximize the profit of the manufacturing firm subject to the relevant regulatory and ethical constraints and other conditions that the firm's owners impose based on their values. A product development organization does this by regularly introducing new products that the firm can manufacture, market, and sell. Fundamentally, then, a product development organization transforms information about the world (e.g., technology, preferences, and regulations) into information about products and processes that will generate profits for the firm. It performs this transformation through decision-making (Herrmann and Schmidt, 2002). Because the design problem is highly complex, product development teams decompose the problem into a product development process, which provides the mechanisms for linking a series of design decisions that do not explicitly consider profit.

The following nine steps are the primary activities that many product development processes accomplish (Schmidt *et al.*, 2002):

- Step 1. Identify the customer needs.
- Step 2. Establish the product specification.
- Step 3. Define alternative concepts for a design that meets the specification.
- Step 4. Select the most suitable concept.
- Step 5. Design the subsystems and integrate them.
- Step 6. Build and test a prototype; modify the design as required.
- Step 7. Design and build the tooling for production.

Step 8. Produce and distribute the product.

Step 9. Track the product during its life cycle to determine its strengths and weaknesses.

This list (or any other description that uses a different number of steps) is an extremely simple depiction that not only conveys the scope of the process but also highlights the inherent (but unquestioned) decomposition. There are many other ways to represent product development processes and the component tasks, including the use of schedules or a design structure matrix (Smith and Eppinger, 2001).

Manufacturing firms understand that design decisions (though made early in the product life cycle) have an excessive impact on the profitability of a product over its entire life cycle. Consequently, product development organizations have created and used concurrent engineering practices for many years (Smith, 1997, provides a historical view). Many types of tools and methods (such as cross-functional product development teams and design for manufacturing guidelines) have been created, adopted, and implemented to improve decision-making. Cooper (1994) identifies three generations of formal approaches to product development, all of which involve decomposition.

It should be noted, however, that decomposition is not the only way to describe product development. As an alternative to decomposing a system design problem into subproblems, Hazelrigg (1996) proposes creating and refining system design models to express how detailed design variables affect the overall system performance. This approach suggests that a product development process would end with using the model to find the optimal design. Hazelrigg (1998) encourages this type of optimization but does not discuss the process of generating the profit maximization model.

4 Motivation for Decomposition

Holt *et al.* (1960) describe an ideal decision making system:

First, management wants good decisions—the goal is to select those that are less costly and have the more desirable outcomes. Second, since making decisions takes time, talent and money, we do not seek the very best decision without some regard to the cost of research. Rather, management wants decision-making methods that are easy and inexpensive to operate. Third, it would be desirable, if the techniques were available, to handle large and complex problems more nearly as wholes, in order to avoid the difficulties that occur when problems are treated piecemeal. Fourth, it is certainly advantageous to use fully the knowledge and experience available within the firm. Intimate knowledge of the decision problem is indispensable to improvement in decision-making methods.

Product development organizations seek to make good decisions. In practice, they decompose a design problem into a series of subproblems, and design engineers and other members of the team must try to satisfy a variety of constraints and make tradeoffs between multiple competing objectives. The primary question that must be raised is why is decomposition popular?

4.1 Large problems

First, decomposition is a natural strategy for attacking large problems. Cognitive limitations force human decision-makers to decompose problems into subproblems. Many writers have documented these cognitive limitations (see Simon, 1981, for example). Fallin and Thurston (1994) present a structured methodology for decomposing a multivariable, multiobjective design problem. In practice, however, the decomposition is created in an informal, heuristic way.

Decomposition occurs in a wide variety of problem domains. In manufacturing facilities, the manufacturing planning and control systems are decomposed into modules that solve a variety of problems that range from aggregate production planning to master production scheduling and material requirements planning and down to detailed shop floor scheduling (see, for example, Hopp and Spearman, 1996; Vollmann, Berry, and Whybark, 1997.)

Closely related to product development processes are the typical forms of processes used in systems engineering. Blanchard and Fabrycky (1998) discuss various systems engineering processes, including top-down and bottom-up approaches, all of which involve some kind of decomposition. Manheim (1966) describes the decomposition of a highway location problem, which, given the two ends of the highway, must specify the centerline of the highway from one end to the other and the shape of the road (its cross-section and relationship to the ground surface) at regular intervals along this path.

De Neufville (1990) does describe system design as an optimization procedure. However, it is not a monolithic mathematical program that can be solved directly. Instead, the analyst must first search for a small set of nondominated solutions, conduct sensitivity analysis to determine their robustness, evaluate the solutions in more detail, establish a sequence of configurations so that the system can change over time (if feasible and desirable), and then validate and present the results. The initial screening for a small set of solutions is needed to reduce the effort of the system design process.

Related to this issue is the question of constraints. Constraints exclude solutions that are infeasible with respect to one or more of the many different conditions that a successful design must satisfy. It must be understood, however, that their role is to reduce the search effort. If the objective is to maximize profit, one can formulate a design problem with no constraints. In this approach, the evaluation of profit must penalize any unreasonable solution. For instance, if the power tool is too heavy, few customers will buy the tool and sales and profit will be low. While theoretically possible, this approach clearly results in a huge search space and a complex objective function. Thus, the computational effort will be extremely large.

By contrast, including constraints (such as an upper bound on weight) limits the search space and simplifies the objective function, which makes solving the problem much easier. Hazelrigg (1996) gives additional examples of constraints that simplify design problems.

Another aspect of solving a large problem is balancing the need to gather information about the product and its future performance against the time and cost of information gathering. The decision to stop gathering information and to proceed with making the next decision is a key part of decomposing and solving a large problem. This affects the number of alternatives that are generated and considered for each subproblem as well as the accuracy and precision of performance evaluations. The fact that information gathering costs time and money is one way in which a product development process involves resource allocation. Simon (1981) discusses this topic in more detail.

The classic information gathering problem is to decide how much information should be obtained. More information should lead to better decisions and more profitable products, but this (expected) benefit occurs in the future, and the time and cost of information gathering is an expense in the present. Moreover, the experience of most people is that gathering more information leads to diminishing returns. Thus at some point the cost of gathering more information will outweigh the benefits that the information yields. The concept of the "value of information" refers to a well-understood decision analysis problem where one can determine whether additional information is worth the cost (see de Neufville, 1990, for example).

In practice, decision-makers rely on expert judgments of the value of information. Where there is a great deal of uncertainty, they are more likely to spend time and money gathering information. For instance, automobile manufacturers build and destroy expensive prototypes to obtain estimates of crash-worthiness because they know that this important performance measure is impossible to estimate accurately for a new vehicle due to the complex nature of the phenomenon. But in many more cases, decision-makers rely on their own (or an expert's) experience to get dependable information quickly without detailed analysis. In either type of situation, the decision-makers don't formally evaluate the value of information but instead judge information requirements based on their experience.

4.2 Missing models

The lack of useful models is a second motivation for decomposition. It is difficult to understand how detailed design decisions affect profitability. Profitability is determined by a huge number of variables, many of which are beyond the firm's control. Managers and researchers are still trying to understand how high-level design decisions affect expected profitability. Product profit models can estimate the total profit that a new product will yield (Smith and Reinertsen, 1991). Such models include estimates and projections that are based on the firm's experience with similar products. This type of model clearly shows how unit cost, sales price, sales, and development costs affect expected profitability. Although it is certain that the product's design (along with its price) will affect these measures (unit cost, sales price, sales, and development costs), knowledge of these relationships is incomplete. (Note that Smith and Reinertsen suggest that, when using this model, one should start with an educated guess about sales volume and refine this as more information becomes available.)

Since a manufacturing firm pays for the labor, material, and components and has extensive knowledge in this domain, the relationship between product design and unit cost is the one area where the most work has been done, and there exists a large amount of research on technical cost modeling and manufacturability analysis. Manufacturing system performance also affects profitability (see, for instance, Chincholkar and Herrmann, 2001). In other cases, experience is needed to estimate how a design change will change, say, total sales.

Models that relate lower-level decisions to profitability do not yet exist except in simple cases. For instance, Gupta and Samuel (2001) use conjoint measurement of customer survey data to estimate demand of a product based on price and critical design attributes such as dimensions and weight and then proposes an approach to find the most profitable design alternative.

The term "fuzzy front end" (Cagan and Vogel, 2002) is used to describe the early phase of new product development. Cagan and Vogel propose qualitative methods for understanding customer needs, wants, and desires, including scenario development, new product ethnography, ergonomics, and lifestyle reference. These steps clearly decompose a major portion of the design problem. Cagan and Vogel describe their approach as a series of funnels. Each funnel is a subproblem that selects a solution from the many possible ways to implement the solution to the previous subproblem.

It is very difficult (if not impossible) to formulate an optimization problem that includes qualitative methods, since these have extremely complex interactions among a variety of qualities. If the qualitative approaches (compared to quantitative, market-survey type of approaches) are more effective at generating successful products, then it is clear that decomposition is a necessary part of successful product development. Moreover, the fuzzy front end of product development has contributed a great deal to the decomposition that underlies product development processes.

4.3 Model maintenance

Third, even if one could create valid models for determining how the product design (from its concept and architecture to the many details) affects profitability, the product development organization would have to spend time to construct, validate, and maintain these models. To date, organizations have not done this. One can view these models as information sitting on a shelf waiting to be used. It will be difficult to convince managers to invest the time and talent of their staff on tasks that have no immediate need.

Some firms have developed models for understanding the impact that high-level decisions have on profitability. Stonebraker (2002) describes a decision analysis model that Bayer uses to decide whether or not to start development of a drug. This model evaluates the net present value of a drug development project and describes the data collection and influence diagram used in the evaluation. Although this was not linked directly to the design decisions, it does give a good example of evaluating profitability in the presence of uncertainty. And the amount of effort required to create a model to evaluate a small number of decisions shows that larger models that evaluate the impact of many decisions will require much more effort.

Investments in the future are not unknown in manufacturing. Many manufacturing firms invest time and money on technology research and development, and certainly a great deal of that effort is wasted exploring impractical ideas or developing concepts that never see the outside of the lab. However, the fruits that do ripen into advances (and the occasional breakthrough) reward this toil. The firm can patent (or keep as a secret) the advance, and during the period that the firm has this exclusive advantage, the profits due to the advance are great.

At this point it is not known if a firm can benefit from a profitability model as greatly as from a new technology. The alternatives to investing in technology research include licensing the technology from those who invent it, duplicating the technology (through reverse engineering) to create a similar product, and waiting until the patent expires. These are less risky and reasonable, though the firm may fall behind a competitor. The alternative to investing in profitability models is decomposing the problem. Firms are unlikely to lose much doing this, since everyone is doing this.

Profitability models may lead to faster product development, since, it is proposed, one can simply populate the models and then solve the optimization problem to find the most profitable product. But these tasks still require time. The optimization problem will be large and difficult to solve. No one has yet developed a product in this manner much less shown that such a process reduces product development time or increases profitability from some combination of reduced time-to-market or a “better” (more profitable) product.

5 Types of Decomposition

Table 1 briefly reviews the first seven steps of the product development process (as described in Section 3) and how they form a decomposition of profit maximization problem. The discussion is deliberately brief and general to illustrate the idea. Note that this decomposition starts with the assumption that maximizing profit relies upon maximizing sales.

Table 1. Subproblems in the product development process.

Step in the product development process	Subproblem being solved
Identify the customer needs.	Which customer requirements should the product satisfy to maximize sales? Constraints: product line, market segment.
Establish the product specification.	Which product performance targets (including cost) should the product meet to satisfy the customer requirements? Constraints: customer requirements, available technologies.
Define alternative concepts and select the most suitable concept for a design that meets the specification.	Which set of product features best satisfies the product performance targets? Constraints: product performance targets, available technologies.
Design the subsystems and integrate them.	Which shapes and materials can be used to make the product features? Constraints: conceptual design, manufacturing feasibility, safety, and government regulations.
Build and test a prototype; modify the design as required.	Does the selected design meet the product performance targets? Constraint: product performance targets.
Design and build the tooling for production.	Which tools and manufacturing processes can be used to manufacture the product? Constraints: shape and material of components.

The specific decompositions used by different firms vary within this general pattern. The next question to consider is why different firms use different decompositions.

A product development process follows a decomposition scheme that reflects the experience of the organization and the individuals that inhabit the organization. This relationship explains the design of many organizations and business processes, of course, and obviously applies to product development processes as performed in the real-world. (The study of contingency theory has explored the relationship of organization structure to the organization's goals and environment.) The evolution of the product development process is influenced by exceptional events (such as disasters that cause managers to implement controls or regulations designed to ensure that "it never happens again"), by executives and managers who participated in or observed different processes used by other organizations, and by natural processes of continuous improvement. These influences are resisted by the inertia of individuals in the organization ("that's not the way we do it here"), and the implementation of innovations may fail for other

reasons. Klein and Sorra (1996) argue that the implementation effectiveness depends upon implementation climate and implementation policies and practices.

Holt *et al.* (1960) mention a three-stage process for the evolution of a decision-making system. In the first stage, when an organization is small, skilled managers make decisions as situations arise. In the second stage, the complexity of the operations increases, and the firm installs a system of decision-making. For routine decisions, heuristics or simple rules guide decision-making. In the third stage, the firm seeks to improve decision-making by implementing decision support tools. Often these tools help decision-makers treat problems in a more integrated fashion.

In conclusion, rarely are product development processes explicitly designed to optimize profitability. Still, the never-ending quest to improve processes leads managers to change them, first hoping to improve this metric, then hoping to improve another, always seeking changes that improve all metrics simultaneously. Because different firms find themselves in different positions, they seek different things from their processes. More precisely, there exist a large set of objectives, and each organization prioritizes these objectives differently. Thus, each firm finds a different process most desirable for itself, in the same way that different families looking at the houses for sale in the same city choose different houses based on their own priorities on location, price, number of bedrooms, and so forth.

Being unique, each product development organization has a unique product development process that embodies a unique decomposition. If each process has changed over time due to many different reasons, it may seem unreasonable to describe the forces that shape specific product development processes. Indeed, Blanchard and Fabrycky (1998) state that a development process is a generic template that must be “tailored” to a specific project’s need. They describe three common processes: the waterfall model, the spiral model, and the V model. They observe that preferences among these models are subjective and that careful study is needed to select the best model for a specific project.

Still, some authors have described some of the factors that make certain types of processes more or less successful. For instance, Loch and Terwiesch (1998) use an analytical model of concurrent engineering to show how uncertainty (and the speed of uncertainty reduction) affects the optimal amount to overlap activities and the optimal frequency of meetings used to coordinate the concurrent activities. More generally, Pich, Loch, and De Meyer (2002) identify three project management strategies (instructionism, learning, and selectionism) that handle uncertainty in different ways. Accordingly, project managers must determine the adequacy of what is known about the world and the effects of different actions and must determine whether any inadequacy is due to ambiguity or complexity. The paper proposes some simple rules suggesting when to use each strategy.

6 Summary and Conclusions

The discussion of product development has included two observations that appear contradictory:

1. Product development should solve a profit-maximization problem.
2. Product development is a sequence of steps that transform customer requirements into a satisfactory product design.

This paper reconciles this contradiction and synthesizes these ideas by highlighting the role of decomposition in product development. Because the profit-maximization problem is extremely complex, it cannot be solved directly. Instead, product development organizations decompose the problem into a set of subproblems that form the product development process. The tendency towards decomposition

(which reduces search effort) is checked by the desire for integration (which improves the quality of the solution).

This synthesis contributes to a theory of design describes how design happens in practice and explains this behavior. The fundamental axioms include the profit maximization objective, bounded rationality (including limited time and resources available for product development), and the presence of uncertainty.

Extending this theory of design will require better understanding of the advantages and drawbacks of different decompositions. Also useful will be understanding the relationship between the effort spent to solve a design subproblem and the quality of the resulting solution.

It will be interesting to see how improvements in information technology and decision support systems increase the amount of information that one decision-maker can process and how these improvements change the balance between decomposition and integration.

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