TECHNICAL RESEARCH REPORT

Viewing Product Development as a Decision Production System

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Abstract

Product development includes many different types of decision-making by engineers and managers. Design decisions determine the product form and specify the manufacturing processes to be used. Development decisions, however, control the progress of the development process by defining which activities should happen, their sequence, and who should perform them. This paper introduces the concept of a *decision production system* to describe a product development organization as a system of decision-makers who use and create information to develop a product. This perspective does not advocate any particular type of product development process. Instead, it looks at the organization in which the product development process exists and considers the decision-makers as a manufacturing system that can be viewed separately from the organization structure.

A new perspective is needed to reconcile product development practice and design theory. This paper argues that viewing product development as a decision production system provides a perspective to understand the costs and benefits associated with different forms of product development processes. The paper describes some of the benefits that this perspective and decision production system models would bring to product development organizations and to the design research community. Comprehensive models are needed to improve communication about the nature of product development and to understand the impact that changing product development processes will have on the organization's overall performance and profitability.

1. Introduction

It is agreed that product development includes decision-making. The design engineering community has spent much effort on understanding how design is a decision-making activity. Primarily, researchers have focused on making better design decisions (e.g., selecting the best design alternative) and have employed the methods used in operations research, including optimization and decision analysis. Proponents of decision-based views of design are, for the most part, not proposing abandonment of traditional engineering analysis techniques. Rather they encourage expansion of engineering methods to recognize the equivalent need for education and research in decision-making.

In practice, there exist many different interpretations of what designers should be doing. A study of Volvo engineers responsible for the final development of new engines revealed that some engineers believed that their job was to make the engine meet performance specifications, others thought that they needed to resolve trade-offs between performance categories, and a third set wanted to make the engine provide the customer with a good driving experience (Sandberg, 2001). These different goals reflect different interpretations of the product development organization.

There remains a gap between design practice and engineering design education, and what this growing body of research is suggesting be done. This disconnect fosters any nascent resistance to the teaching of decision-making as an essential role of engineers. We believe that this gap can be bridged by first understanding how we came to accept the view of engineering design as problem-solving (not decision-making) and how that notion is reinforced by the very organization structures of our manufacturing enterprises. Only a change in the view of the product development operations within a corporate environment will help clarify the role that both engineering analysis and decision-making must play in effective product development.

This paper proposes that a product development organization is a decision production system that requires different information processing models than traditional business organization charts. We argue that it would be advantageous for a manufacturing enterprise to explicitly articulate and communicate its decision production system so that decision support responsibilities, decision authority, and influence among business units is clear. Finally we believe that the decision production system view of product development is consistent with existing models of design practice in the field. In all, the decision production system view of new product development provides support for the recent shift in design research to improving decision-making in design. The view also provides great insight into why product development (in practice) does not match the ideal decision-making processes prescribed by mathematical, behavioral, economic, and information processing models of decision-making.

The remainder of this paper is organized as follows: Section 2 briefly reviews the traditional view that product design is problem-solving and discusses information flow. Section 3 describes the types of decision-making that occur in product development and introduces the concept of decision production systems. Section 4 describes decision-based design and its role in decision production systems. Section 5 describes our results using this perspective to teach an engineering design course. Section 6 concludes the paper, outlines the benefits of modeling decision production systems, and discusses future work that is needed.

2. Product Design and Problem-Solving

One can view product development as a process that seeks to select for design variables those values that maximize the profitability of the product over its life cycle. In practice, product development organizations have sought to achieve this goal promptly and inexpensively through the decomposition of the process into a sequence of steps performed by a variety of experts. This section discusses this practice, the hierarchical nature of product development organizations, and common responses to the associated limitations.

2.1 Hierarchical Product Development

A product development organization is a set of people working together to develop new products that will, when manufactured and sold, generate revenue for the manufacturing enterprise.

Organization theory and management science fields grew from the observation that business entities exist to process information with the ultimate goal of making decisions that will benefit the organization. The appropriateness of the hierarchical structure is a topic of ongoing research in economics. A recent review paper by Borland and Eichberger (1998) concludes that hierarchies are structured so that agents of an enterprise can reduce the time necessary for completing tasks and reduce the risks associated with making decisions based on imperfect or incomplete information. The authors of that review call for more research on applying theories of bounded rationality to organizational design.

Information processing studies from economics tell us that hierarchical nature of corporations (including those that design and produce goods) evolved naturally out of the need to process information efficiently. For instance, Malone (1997) argues that the economic benefits of centralized decision-making motivated the rise of large organizations. Centralized decision-makers can integrate diverse kinds of remote information efficiently and make better decisions than unconnected local decision-makers. Figure 1 illustrates a hypothetical, but typical organization chart.

Thus, product development organizations developed hierarchical structures in part because the rest of the manufacturing enterprise used this type of structure. Other factors contributed to the hierarchical structure as well.

In practice, product development organizations have sought to develop profitable product lines through the decomposition of a complex problem into a sequence of steps that a variety of experts perform. Some of them solve more manageable subproblems. This decomposition is a natural way to overcome human limitations and find satisfactory solutions directly.

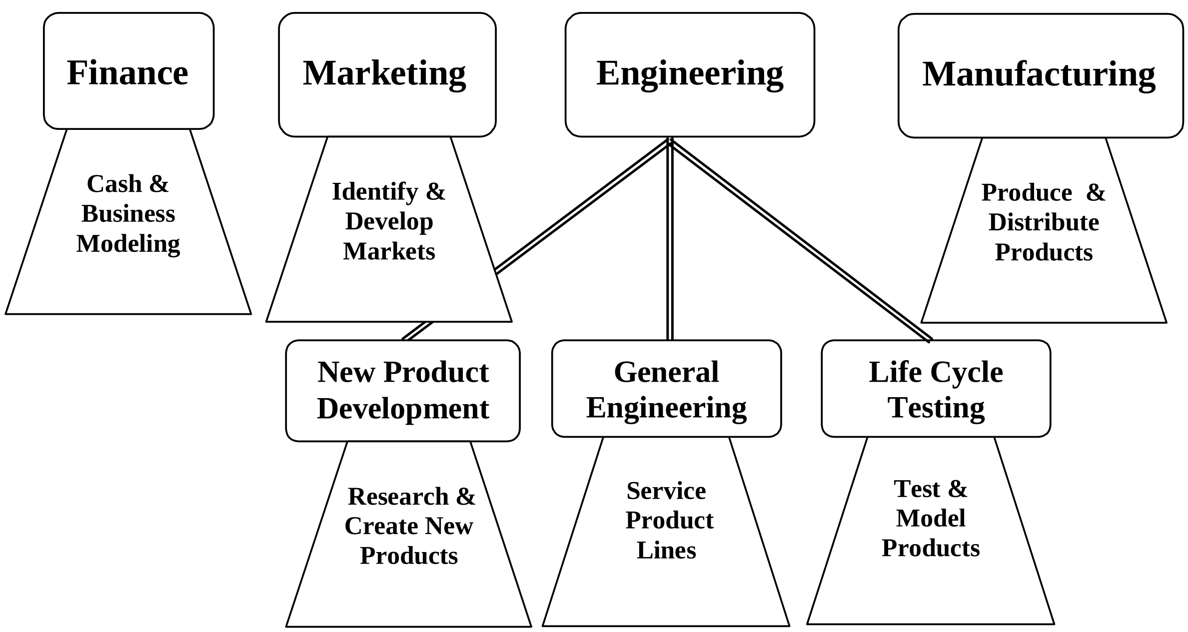

Figure 1. Organization chart of a manufacturing enterprise
(with details about the engineering organization)

It is convenient to view a product as a hierarchy of subsystems, subassemblies, and components. Since designing a product requires designing its subsystems, subassemblies, and components, a product development project involves a hierarchy of decisions. A decision at one level sets targets and constraints or provides information for decisions at another level. A typical example is aircraft design (see, for instance, Kalsi *et al*., 2001). The conceptual design phase selects wing area, fuselage length, wingspan, take-off weight, and installed thrust, and the detailed design steps must respect these constraints. Setting these constraints makes component (or subsystem) design easier, though the constraints prevent system-level optimization (*cf.* Hazelrigg, 1996, page 218).

For many products, an important development step is the specification of the product architecture, which defines the primary modules (or subsystems) and the interfaces between them. This decision not only affects the design of the product but also the process that will be followed during the rest of the product development project. If the architecture uses decoupled modules with well-defined interfaces, many remaining activities can be done in parallel and with little information flow between them. Designing interdependent subsystems will require greater information flow, leading to a process with many iterations. (Reinertsen, 1997, discusses the important role of architecture in more detail.)

This hierarchy insulates design engineers from decision-making. Thus, design engineers view their job as problem-solving. They solve the problems that others give to them. They don't need to worry about enterprise-level objectives (such as profitability or market share). The academic training of engineering students, which emphasizes engineering science, lays the foundation for this attitude.

2.2 Information Flow in Product Development

Although the hierarchical organization chart is a natural way to structure a product development organization, it is not the best way to structure information flow in a product development process. Product development activities generate information such as drawings, solid models, test results, and process plans. The flow of information from one activity to another creates precedence constraints between activities (*cf.* Smith and Eppinger, 2001).

If information flow were restricted to the paths on the organization chart in Figure 1, the product development process would be back to the "throw-it-over-the-wall" mentality. (Each business unit performs their part of the development process alone, making decisions suited to their objectives, and then passes the design-in-progress to the next business unit.) Good product development practice led designers away from that restrictive model years ago, as discussed below.

The business of product development in a manufacturing enterprise is quintessentially different from other businesses because most types of products achieve the required performance from the coupled behaviors and complex interactions of various subsystems. Managing the development of such products is different than overseeing making independent business units (as in a large retailer, for instance).

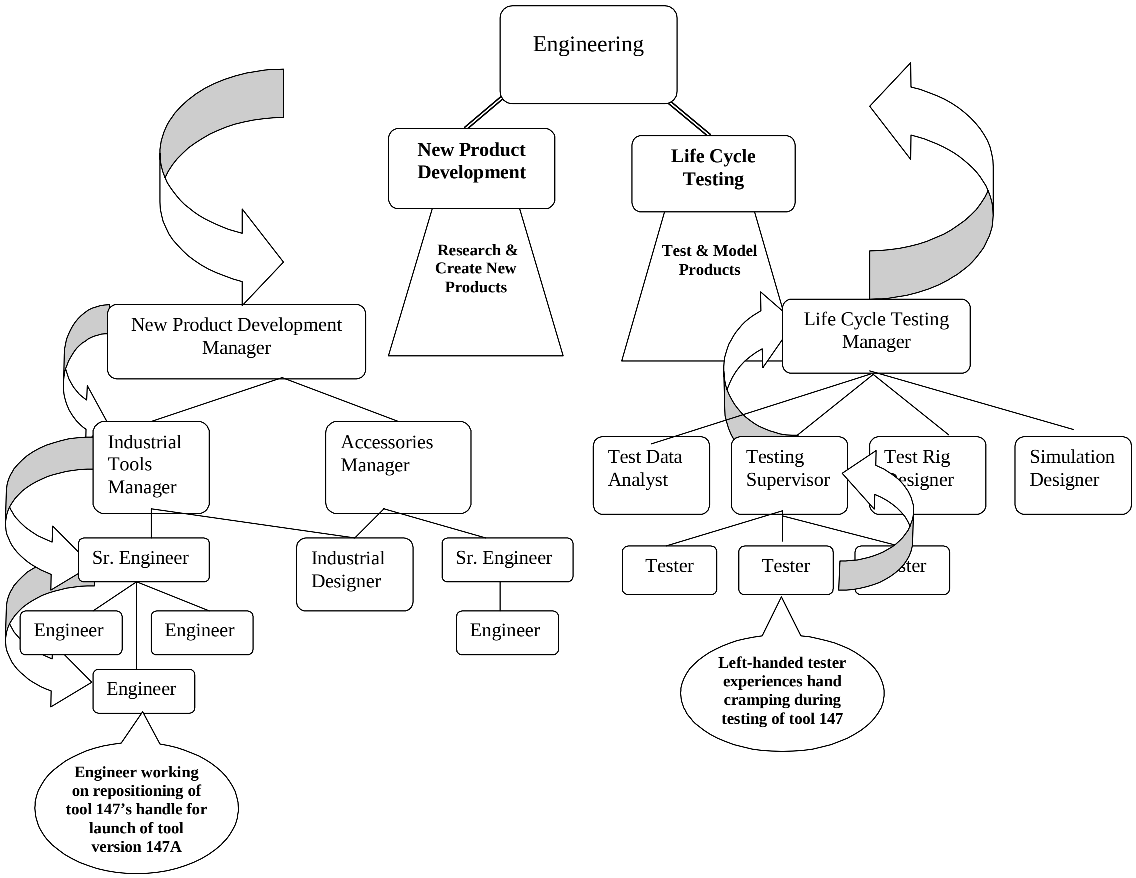

Figure 2. Communication distance in a hierarchical organization structure.

To illustrate the difficulties in communication that may arise in a purely hierarchical organization, consider the example described by Figure 2. Here a left-handed tester experiences hand cramps while performing manual tests on tool 147. This information is important to the design engineer (in New Product Development) who is redesigning a handle to launch a companion version of tool 147. The arrows in the organization chart indicate that the tester's observation must take seven communication steps to reach the appropriate member of the design team. Communicating this information through managers wastes valuable time. In addition, this example assumes that the tester is aware that reporting such things as discomfort in use is an appropriate action. But this is unlikely to occur because the tester's responsibility is to test a number of samples of tool 147 in a prescribed mode until it fails. It does not include reporting any difficulties in using the tool. Personnel at the bottom of the organization chart have the least decision-making authority, are the furthest away in the communication chain from those individuals who make strategic decisions, *and yet they are performing the most fundamental information processing tasks necessary to the objectives of their unit*.

Under the pressure of time and budget constraints, product development organizations have found that information must flow through channels outside the organization chart. One common solution is to form interdisciplinary project teams, which are ad hoc organizations created for specific product development projects. Every product development textbook mentions some of the different forms of product development teams. For instance, Cunniff *et al.* (1998) describes functional, modified-functional, balanced, and independent teams. Smith (1997) reviews these and other techniques that organizations have developed to improve product development.

Figure 3 depicts how an interdisciplinary or cross-functional product development team is formed. The team members come from multiple business units and have different levels of experience and decision-making authority. Such teams meet regularly to share project-related information, and members communicate information between the team and their respective business units. The team will dissolve when the new product has been established in the marketplace, and responsibility for the product will return to the appropriate place in the organization.

Product development teams of this type report periodically to a group of more senior personnel who have decision-making authority over all aspects of the project. Product development review systems come in many forms. Typically, the project review and oversight group formally reviews each project at predetermined points in the development process (e.g., stage-gate or phase review). See also McGrath (1996) and Reinertsen (1997). A manufacturing enterprise has many different project teams operating at any one time. While the project teams report to the oversight group, they may not communicate directly with each other. This yields a new (albeit shortened) hierarchy of independent organizations (as shown in Figure 4).

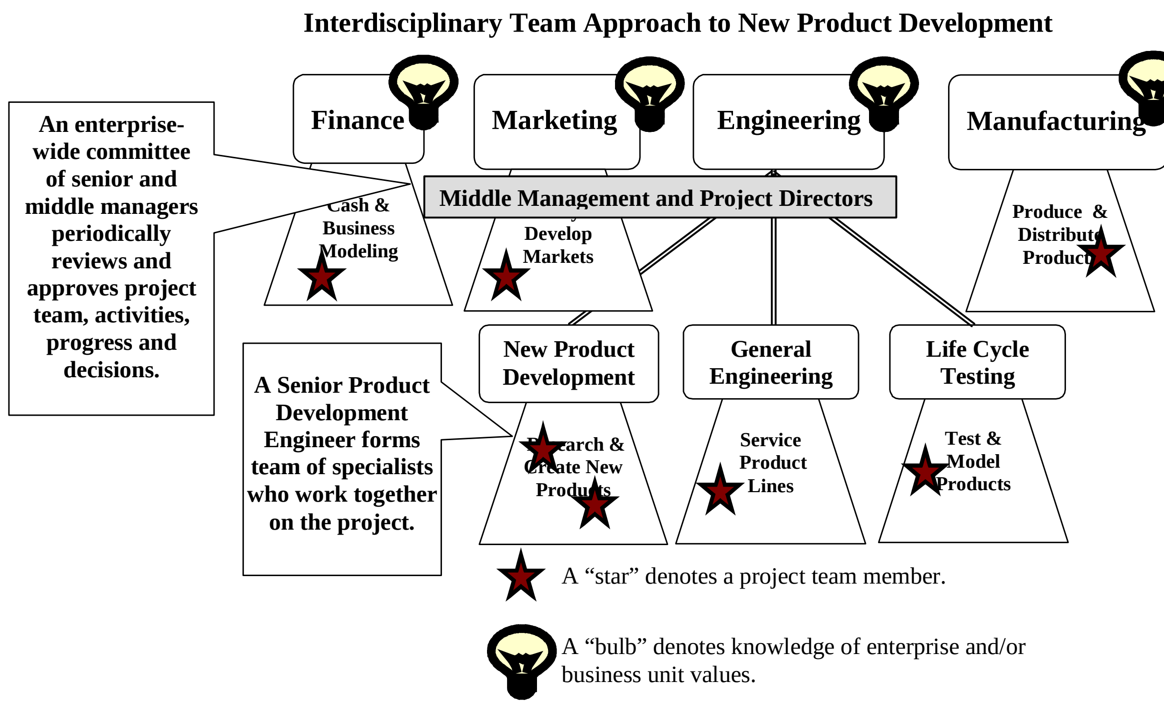

Figure 3. An interdisciplinary team approach to new product development.

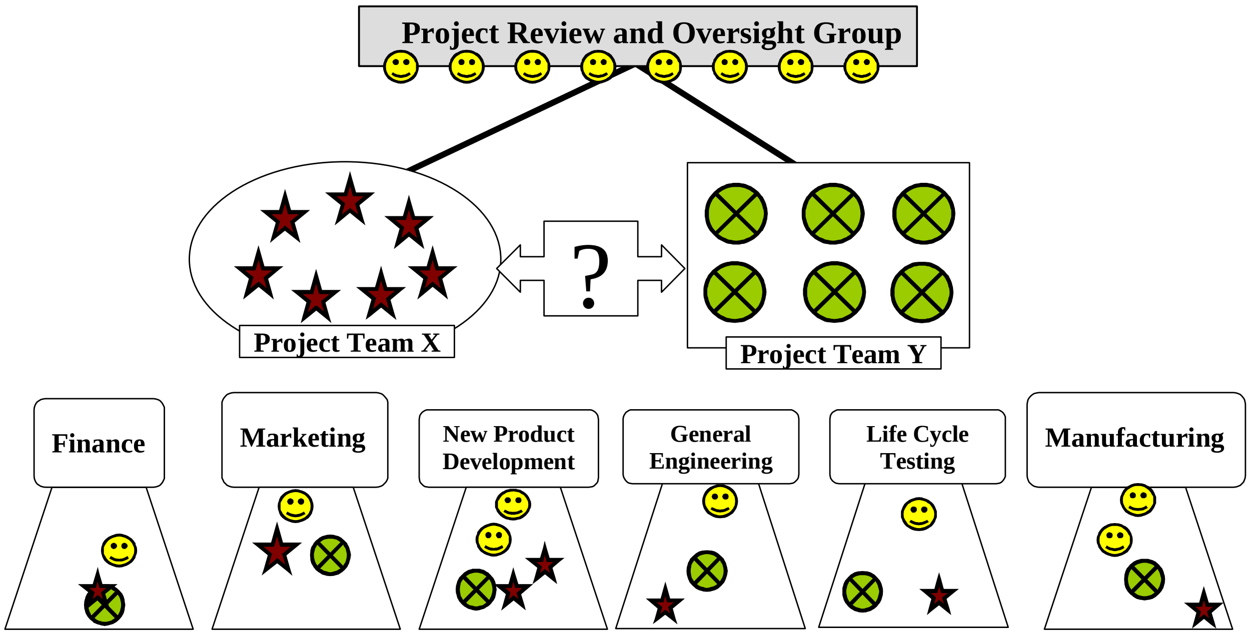

Figure 4. Communication isolation between ad hoc project teams.

One advantage of the project team approach is that team members (who will eventually be on multiple teams) have a greater chance of becoming aware of the key objectives of all relevant business units because they are no longer insulated from these units. Because project teams are temporary, the communication channels mentioned before lack the permanence and stature of an organization chart reporting line. Still, over time, the collection of these channels, along with the relationships formed on interdisciplinary project teams, fashions a network through which information flows. This network overcomes the limitations of the organization's hierarchical structure, and it more accurately represents the organization's behavior.

3. Product Development and Decision-Making

Although they may not realize it, design engineers are making decisions. Identifying the "best" product design commits the organization to this choice (though later steps may require a change of plans), and this decision generates information that other activities then use. The nature of the design engineer's decisions reflects the ambiguity in the design task assigned.

When the design task is extremely well-formulated (a clear set of alternatives, inflexible constraints, and a single objective), the design engineer's decision-making process is the solution of an optimization problem. Here decision-making is problem-solving. In contrast, when the set of alternatives, constraints, performance objectives, and business goals are vague, uncertain, or unknowable, design engineers are less able to apply formulaic numerical techniques to "solve the design problem." In these cases, the design engineer's decision-making process is a collection of heuristics that generate and evaluate solutions until a satisfactory one is found.

In some design tasks, multiple people may work together to perform the required decision-making. One traditional view of decision-making is as a process in which a person, given a question, generates alternatives, evaluates them, and selects one. An alternative view specifies the following four steps: (1) generate alternatives; (2) evaluate (using engineering analysis techniques) the outcome(s) associated with each alternative (note that this is primarily an objective process); (3) formulate judgments about the relative value of each outcome and tradeoffs between outcomes (which is a subjective process); and (4) choose an alternative. Each step (which involves decisions of some type of another) may be a specialized task performed by different people.

3.1 Types of Decisions

Product development includes many different types of decision-making by engineers and managers. Some decisions are *design decisions* and others are *development decisions*. Design decisions determine the product form and specify the manufacturing processes to be used. Design decisions generate information about the product design itself and the requirements that it must satisfy. Development decisions, however, control the progress of the development process. They affect the resources, time, and technologies available to perform development activities. They define which activities should happen, their sequence, and who should perform them. That is, what will be done, when will it be done, and who will do it.

In studying design projects, Krishnan and Ulrich (2001) consider whether the decision occurs within a product development project or before the project starts. Decisions within a project include those in the following areas: concept development, supply chain design, product design, performance testing and validation, and production ramp-up and launch. Decisions made before beginning a project include those in the following areas: product strategy and planning, product development organization, project management. They provide a large list of questions that follows the typical decomposition of product development, as discussed in Section 2.1. Though most of them are development decisions, their list includes the following design decisions: What is the product architecture? What will be the overall physical form and industrial design of the product? What are the values of the key design parameters? What is the configuration of the components and assembly precedence relations? What is the detailed design of the components, including material and process selection?

Kidder (1981) describes the development of a minicomputer by Data General. The development team included the following people: Tom West, Carl Alsing, Ed Rasala, Chuck Holland, Steve Wallach, and dozens of other engineers. The process began in the fall of 1978 and ended during the spring of 1980, a duration of approximately eighteen months. The team created microcode, diagnostic programs, system software, flow charts, schematics, videotape, and two functioning computers.

The book's scope includes not only the history, personalities, and thoughts of the people involved but also more general topics about designing, testing, and debugging computers, including the hardware and the software. As part of the narration, the book describes many of the decisions that the development team made during the computer's development. Tables 1 and 2 highlight some of those decisions. (Many of the design decisions that were made during development are not listed because either the book did not describe them or describing them would require too much room.)

Each item in the tables describes the decision made and who made it. References are to the pages in the book where the decision is described. Both types of decisions occur at different levels in the organization structure. Higher development decisions affect more people and more of the process, while higher design decisions affect more of the computer.

Table 1. Selected development decisions for a new computer (Kidder, 1981).

1. The vice-president of engineering approved the project (page 47).
2. West decided to hire inexperienced engineers who had just graduated (page 59).
3. West decided to have two teams: one for designing the hardware, one for designing the microcode (pages 59, 105).
4. West decided that Wallach should be the architect (page 68).
5. Wallach decided to begin designing the architecture by organizing the memory (page 76).
6. West reviewed the designs (page 119).
7. Rasala created the debugging schedule (pages 130, 145)
8. West approved using microdiagnostic programs (page 134).
9. West approved building a simulator for testing microcode (page 161).
10. Alsing picked Dave Peck and Meal Firth to write simulators (page 163).
11. West decided who would work on which new projects (page 232).
12. Rasala decided to work in the lab to increase morale (page 256).

Table 2. Selected design decisions for a new computer (Kidder, 1981).

1. West decided that the new computer should be a 32-bit computer that can run older programs written for another computer (page 42).
2. Wallach decided to worry about preventing accidental damage, not malicious theft (page 78).
3. Wallach decided that the memory protection scheme should use the segment number as the security level (page 80).
4. Wallach defined the instruction set (page 83).
5. Engineers negotiated the design details (page 116, 159).
6. West decided that the computer would use PAL integrated circuits (pages 118, 121, 268).
7. The engineers wrote the microcode and the schematics (page 121).
8. Holland organized the microcode (page 158).
9. West and Rasala decided to keep the ALU on one board by limiting its functionality (page 213, 255).
10. West decided which cables and connectors should the computer use (page 230).
11. West decided how the machine should be started (page 230).

3.2 Decision Production Systems

A product development organization has a formal organization structure like the one depicted in Figure 1. Usually, this structure groups employees by functional area. This hierarchical structure is necessary for a variety of management and administration purposes. As discussed in Section 2.2, organizations also create cross-functional groups to develop products (as illustrated in Figure 3), and this results in a network of information flow.

During the design and development phases of its life cycle, a product development project requires many related activities and decisions. Typically, a product development organization performs multiple projects concurrently, and thus many of these activities are occurring at the same time. Each activity requires many people to perform the necessary data collection, design, analysis, and decision-making tasks.

Clearly, independent of its formal organization structure, a product development organization is a dynamic network of people using information, making decisions, and generating information. Thus, product development is an information flow governed by decision-makers who make both design decisions and development decisions under time and budget constraints. We call this a *decision production system*.

3.2.1 Models of Product Development Organizations

There is some related work on modeling product development organizations. For instance, Adler *et al.* (1995) use capacity analysis and discrete event simulation to evaluate the performance of a product development organization. The organization is modeled as a queueing system. Jobs representing product development projects are processed by workstations representing groups within the organization. The models are used to evaluate resource utilization and project cycle times.

Reinertsen (1997) discusses methods that use sensitivity analysis to estimate how development expenses, unit costs, product performance, and development delays affect the profitability of a product development project. This analysis can be aggregated to understand how these factors affect the profitability of the entire enterprise. This approach is useful for helping managers make specific decisions that make small changes, but they don't predict performance changes due to more significant changes.

McGrath (1996) and Reinertsen (1997) discuss methods for managing a pipeline of product development projects. However, these methods and models do not address how the behavior of human decision-makers affects the performance of the product development organization. Engineering researchers who want to improve product development need to understand the decision-making processes in which design optimization occurs. Unfortunately, this insight has not yet reached engineering research and development activities and is not part of engineering instruction.

There exist information-based models of product development processes. The design structure matrix represents the activities in a product development project, their duration, and the probabilities of repeating them. See, for example, Smith and Eppinger (2001), Carrascosa, Eppinger, and Whitney (1998), and Yassine *et al.* (2000) for more information.

Using a more abstract model, Natter *et al.* (2001) represent product development organizations using two agents (one called marketing, one called production) that can learn but have limited knowledge and computational ability. The model uses neural networks to model each agent's learning and a life cycle model to predict the organization's profitability over time. Experimental results suggest how the organization structure, search techniques, incentive schemes, and other factors affect profitability.

Ford and Sterman (1997) describe a model that represents the dynamics of a project development project. The system dynamics model includes development processes, project resources, scope, and targets. Khurana *et al.* (2001) use a Markov decision process to determine optimal policies for managing a project development project.

3.2.2 A New Perspective

Figure 5 presents the perspective of the product development organization as a decision production system. This perspective results from the careful study of product development organizations and the observations that other experts have made, but we know of no models that employ this perspective. The decision production system resembles a production system that has units dedicated to specific tasks. The information flow routing for a typical new product development process is also shown in Figure 5. In a decision production system, each unit is equipped to make decisions based on information received from other units and the internal processing of that information by members of the unit. For example, when Marketing receives a request for a sales forecast, they will assign the processing of that task to a member who will perform a study based on the history of similar products and information about competitors.

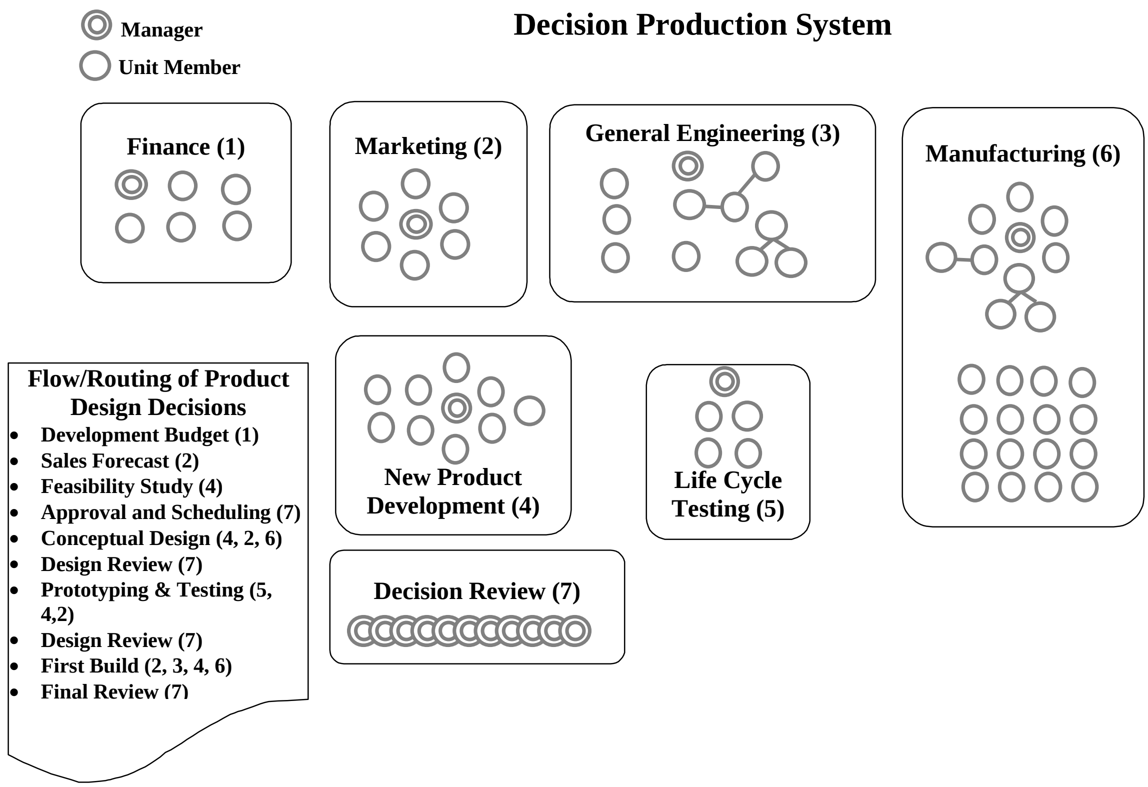

Figure 5. Viewing product development as a decision production system.

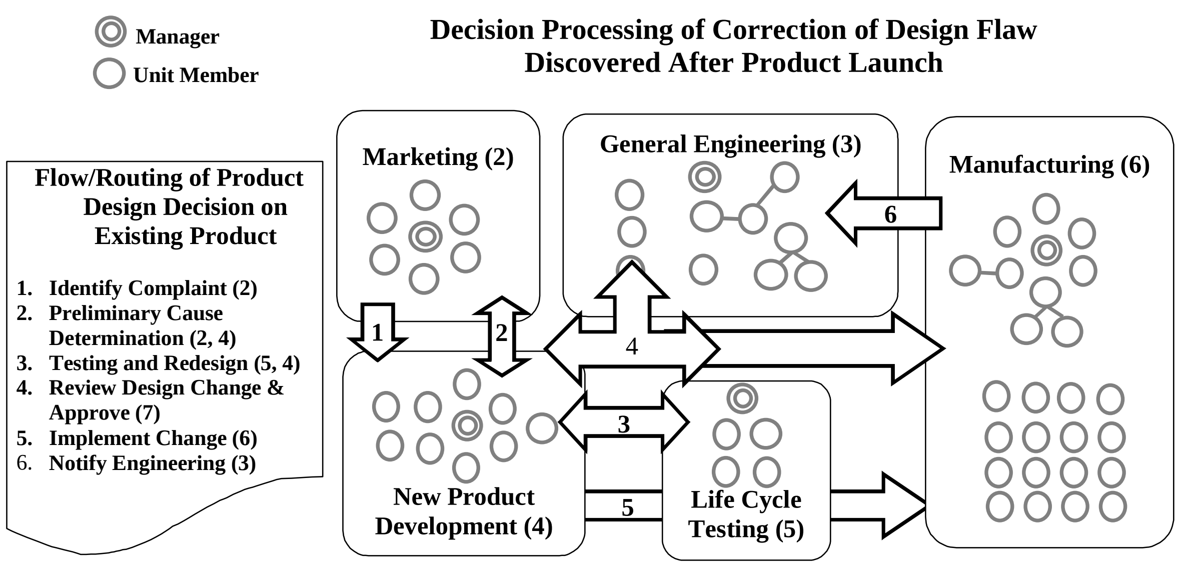

Figure 6. Information flow for producing a design change.

It is likely that information exchange will occur between members of the units shown in parentheses at each step. Figure 6 highlights information flow among units for producing a design change. The decisions may be made concurrently by members from different units. However, it is useful to view the "product" of the decision production system as the culmination of a number of decisions made within and among members of units. The decision production system view puts all decision-makers on the same level, because they are all working on the same virtual shop floor.

The decision production system perspective does not advocate one particular type of product development process. Instead, it looks at the organization in which the product development process exists and considers the decision-makers as a manufacturing system that can be viewed separately from the organization structure.

One advantage of viewing the decision production system in this way (both literally and conceptually) is the focus on information processing flows instead of personnel reporting relationships. Consider the sales forecast request in Figure 5. The member may team with the manager to review the data and include projections based on experience of the senior members of the team. Alternatively, the marketing person may contact directly a member of the New Product Team to follow up on results on a similar product. The decision production system view is a meta model that can be used to help organization members understand the flows of decision-making in the same way as an organization chart describes administrative authority relationships.

Malone (1997) predicts that, as communication costs fall, connecting local decision-makers, who have local knowledge that is hard to communicate, and giving them valuable information about the whole system can yield another, more efficient, decision-making structure. If this happens to product development organizations, it will yield changes to the information flow and the responsibilities of decision-makers. The decision production system perspective provides a way to understand this change and predict its impact.

4. Decision-Based Design

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. (Details on DBD can be found online in the Decision-Based Design Workshop at http://dbd.eng.buffalo.edu/). Although approaches to implementing DBD strategies vary, they generally convert the hierarchical engineering design problem-solving approach into a three-step decision-making process that (1) generates alternatives; (2) determines expected outcomes for each; and (3) selects one alternative by rank ordering the expected outcomes according to decision-maker's values (e.g., their impact on the well-being of the manufacturing enterprise). Note that, in this section, decision-making refers the overall product design decision.

4.1 Background

The research on DBD includes a wide variety of approaches. DBD researchers have primarily focused on making better design decisions (e.g., selecting the best design alternative). Because decision-making often involves multiple objectives, some DBD researchers have developed techniques for helping decision-makers make tradeoffs among competing objectives and methods that quantify and combine the multiple objectives into a single objective. The techniques of decision analysis, especially utility theory, are an important component. Thurston (2001) gives an overview of DBD and discusses the role of utility theory in DBD. Research in this area continues. For example, Bleichrodt *et al*. (2001) discuss the inconsistencies of traditional utility measurements and use the ideas of probability transformation and loss aversion suggested by prospect theory to develop improved utility-elicitation procedures that correct for biases and deviations. For an overview of rational decision-making, including subjective expected utility theory and prospect theory, see, for example, Hastie and Dawes (2001).

Some research on DBD includes efforts to illustrate how engineering design should be done. That is, they claim that there is an alternative to the traditional decomposition of design. Specifically, researchers have developed 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). Because this simplifies the process, product development will take less time. Also, the integrated model includes all of the competing performance measures and maps them to more fundamental objectives that are important to the manager of the manufacturing firm. These include profitability and market share.

Li and Azarm (2001) describe a DBD approach for designing a product line that maximizes the net present value of the revenues and expenses and the average market share. (The product design is a conceptual design; for instance, the design variables of a cordless screwdriver are the motor type, the cell type (for the battery pack), the number of cells, the gear type, and the gear ratio.) The approach has two basic steps: (1) conduct a marketing survey and use conjoint analysis to determine customer utility functions for product attributes; (2) formulate and solve a design optimization problem that yields the optimal product line. Note that step (2) involves a design decision that integrates two (usually distinct) types of decisions: determine the attributes that each product should have and find the product designs that meet these attributes.

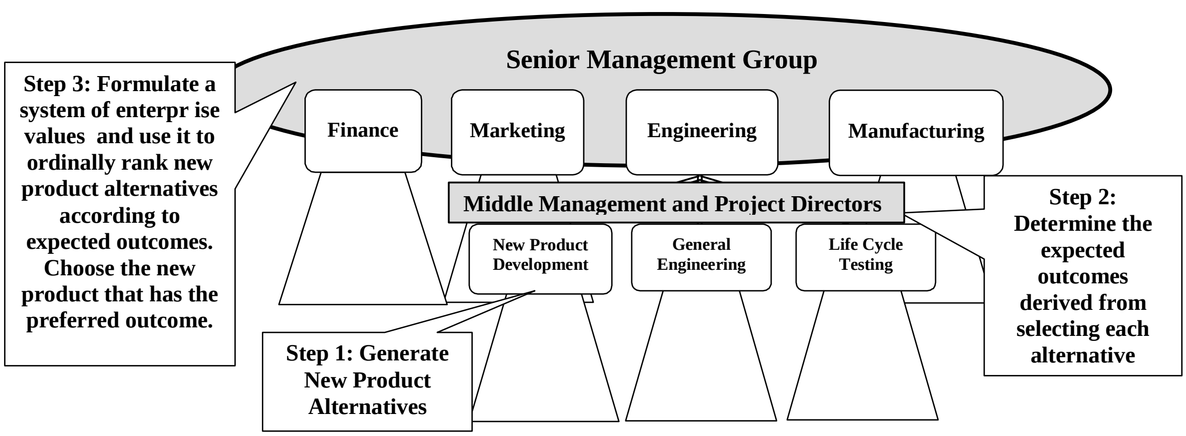

Figure 7: The distribution of decision-making tasks in a manufacturing enterprise

4.2 DBD in Decision Production Systems

In practice, product development organizations perform decision-making. Figure 7 illustrates the usual way that the responsibilities for decision-making are delegated throughout a manufacturing enterprise's traditional organization chart. Since only the senior management group is privy to the discussions of strategic objectives of the enterprise, it is difficult for design engineers who are participating in the generation of new product alternatives to integrate these objectives into their work. As discussed previously, designers doing key design tasks are insulated from the decision-making process. Instead of considering broader objectives in their work, they assume that they are "problem-solving" and the higher-level considerations will be handled further up the organization chart. The authors have heard engineering students express this perceived separation of design work from product development decisions. In response to being asked to make design decisions according to the strategic goals of a business, students say, "That's not going to be my problem; I will be the engineer doing the design analysis." This attitude (also discussed in Section 2.1) is the antithesis of the DBD philosophy.

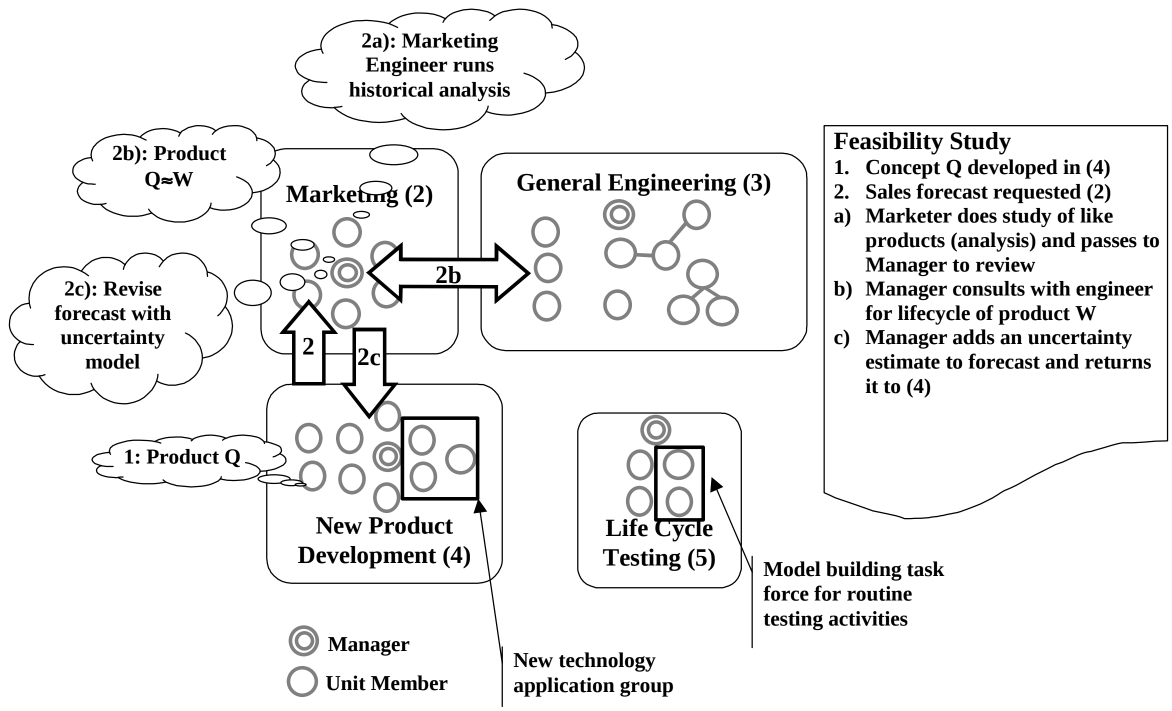

Figure 8. Analysis and decision-making activities using the decision production system perspective

However, the decision production system perspective makes clear that the design engineers are indeed participating in a decision-making process. While the role of engineering analysis and evaluation is not obvious in the standard statement of DBD decision-making (the three steps), they are, as discussed in Section 3, performing the necessary evaluation step that precedes formulating judgments and choosing an alternative. That is, the decision production system perspective argues not only that a decision-making process may require multiple participants but also that some of them do not “make decisions.”

Some participants make decisions and some do not. A decision-maker gets some information, makes a decision, and consequently generates new information. Part of the “makes a decision” step may involve sending and receiving information from others. For example, a designer in New Product Development (Unit 4) may send a solid model of a component to the finite element analysis expert (in Unit 5), who determines how the part will behave and returns a report to the designer. Thus, we can view product development as information flow governed by decision-makers. Figure 8 illustrates this in more detail using the activities of a request for a sales forecast of a potential new product (Q). New Product Development unit initiates the request from Marketing. The request is fulfilled with analysis, information exchange across units, and a decision to deviate from analysis results.

It may be useful for DBD proponents to realize that implementing DBD approaches in a manufacturing enterprise requires wide-ranging changes to the existing decision production system. Moreover, if personnel think that decision processes follow the information channels in the organization chart, communicating the necessary changes becomes more difficult. It requires that design engineers understand the concepts of decision-making and the role it plays in their part of the overall product development process. Transitioning design engineers to a DBD philosophy can be made easier by creating a non-hierarchical decision production system view of the manufacturing enterprise to break the myth of distance from decision-making activities.

As described above, selecting design variables to maximize profitability is the objective of any product development organization. There are many ways to approach this problem. Implementing DBD as a large-scale design optimization problem is an extreme position, representing the complete integration of the product design phase of a product development project. The concurrency (indeed, simultaneity) that this integration achieves is generally viewed as superior to a traditional sequential design process.

However, the DBD integration requires models and information that must be built, maintained, and updated during the project and from one project to the next. These off-line activities and costs affect the decision production system, though they are not included in the DBD framework. Thus, the decision production system perspective links the (on-line) project-specific activities and decisions with the (off-line) research and support activities that generate information and models that will be used in future projects (see Units 4 and 5 in Figure 8). This inventory of knowledge makes feasible integrated DBD approaches, and its importance can be understood from this new perspective.

5. An Experiment in Decision Tracking

We tested our idea of decision production system in a graduate system engineering design class. In the course, students formed four design teams. Each team was responsible for the design of a particular system during the one-semester course. We deliberately chose a wide variety of projects: a wireless local-area network in a multipurpose campus building; a manufacturing system for high-volume production of electronic packages; a miter saw emergency braking system; and a university library electronic research facility.

In addition to other requirements, each team had to track the decisions that they made during the project. Each decision was described by the following information: the nature of the decision, the person(s) who made the decision, when it was made, the alternatives considered (and the selected alternative), the criteria on which the alternatives were compared, and the method used to make the selection. Each team submitted lists of decisions at multiple points during the project. At the end of the project, each team wrote a short report discussing their decision-making.

This information showed that students understood the role of decision-making in engineering design. The teams realized that they made different types of decisions. One group listed decisions about the design itself, the models used to evaluate design alternatives, and administrative decisions about allocating finite resources. Another team classified decisions based on the type of information used to make the decision. The teams often discussed decisions with their customer to get information about preferences. Because they worked in teams, they often used informal discussion and consensus to make a decision. Sometimes, the teams used more quantitative techniques (such as the Analytic Hierarchy Process). The teams viewed tracking the decisions as a useful way to understand how they arrived at their final system design. Note however, that the students had no pre-existing hierarchical organization to overcome.

From these results we believe that emphasizing decision-making and asking engineers to track decisions can improve product development. Over time, engineers and managers will become aware of the heuristics that they use, and this will provide an incentive to learn some of the systematic techniques that exist. Also, decision tracking will provide a way to store valuable knowledge about product development.

It may be useful to divide the category of development decisions into two subclasses. *Administrative decisions* concern resource allocation and project management. *Technical decisions* concern the selection of a tool or model to generate or process information. This category reflects the observation that part of an engineer's task is to choose the right tool, if multiple possibilities exist. The impact of a technical decision may seem limited, since it affects explicitly only the person performing the task, but the capabilities and limitations of the tool can have important implications if not well-understood by everyone using the information.

6. Summary and Conclusions

Traditional product development organizations follow a hierarchical organization structure. This structure is a natural and efficient way to make decisions. However, this hierarchy insulates design engineers from decision-making. Thus, design engineers have viewed their task as one of problem-solving. They solve the problems that others give to them.

Under the pressure of time and budget constraints, however, product development organizations have found that information must flow through channels outside the organization chart. Cross-functional teams and other concurrent engineering techniques are examples.

Although they may not realize it, design engineers are making decisions. Identifying the "best" product design commits the organization to this choice (though later steps may require a change of plans), and this decision generates information that other activities then use. When the design problem is extremely well-formulated, the decision is made by solving an optimization problem. In other cases, the decision-making process is a collection of heuristics to generate solutions, evaluate them, and select the best one.

A product development organization is (independent of its formal structure) a network of people using information, making decisions, and generating information. Thus, product development is an information flow governed by decision-makers who make both design decisions and development decisions under time and budget constraints. It is a decision production system.

This perspective builds on the ideas of decision-based design and moreover shows that decision-based design not only is compatible with traditional product development organizations but also provides tools to improve them. First, DBD provides techniques for improving decision-making by individuals throughout the product development organization. Second, DBD proposes changes to the product development organization, changes that can be evaluated by understanding how they impact the information flow and decision-making in the organization. Thus, the decision production system perspective provides a way to reconcile product development practice and engineering design research.

Starting from this perspective could yield a range of useful models of product development organizations. As discussed in Section 3.2, existing models are limited and focus primarily on individual product development projects. Although one can attempt to draw maps of product development processes (to compare the old and the new, for instance), product development projects rarely follow the script. Combined with learning, a constantly changing environment leads to constantly changing processes.

Creating models of a decision production system would yield many benefits:

1. They would make explicit the behavior of a product development organization and identify the roles that different individuals have. For instance, in proposed DBD approaches, a decision production system model would explain the role of traditional engineering modeling and analysis. Modeling is thinking made visual. Effective models would improve communication about production development.

2. They would help identify problems in an organization (e.g., bottlenecks, wasted activity, and people using the wrong objectives).

3. They would predict the performance impact of changing the processes or the structure of an organization. As information technology and decision support systems continue to become less expensive and more common, managers will have more opportunities to reorganize product development processes and the network of decision-makers who perform them. The decision production system model will be a helpful tool for comparing the costs and benefits of different versions of the organization.

4. They would evaluate the value of engineering support activities. Product development organizations often conduct research to develop technologies in anticipation of future needs. Since these activities are not urgent, the people and funds allocated to them might be used for other tasks, though this degrades the performance of the entire product development organization. Models of decision production systems can show how these resources are a

necessary part of the organization's success and help managers increase productivity by exploiting the off-line activities more intelligently.

5. They would lead to decision-tracking systems and methodologies for monitoring and improving decision-making in a dynamic system (similar to the way that process engineers monitor and improve the operation of manufacturing processes).

6. They would be useful tools for learning about product development, for both engineering and management students.

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