Product Development Decisions: A Review of the Literature

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This paper is a review of research in product development, which we define as the transformation of a market opportunity into a product available for sale. Our review is broad, encompassing work in the academic fields of marketing, operations management, and engineering design. The value of this breadth is in conveying the shape of the entire research landscape. We focus on product development projects within a single firm. We also devote our attention to the development of physical goods, although much of the work we describe applies to products of all kinds. We look inside the "black box" of product development at the fundamental *decisions* that are made by intention or default. In doing so, we adopt the perspective of product development as a deliberate business process involving hundreds of decisions, many of which can be usefully supported by knowledge and tools. We contrast this approach to prior reviews of the literature, which tend to examine the importance of environmental and contextual variables, such as market growth rate, the competitive environment, or the level of top-management support.
(*Product Development Decisions; Survey; Literature Review*)

1. Introduction and Scope

This paper is a review of research design and development. We define product development as the transformation of a market opportunity and a set of assumptions about product technology into a product available for sale. Our review is deliberately broad, encompassing work in the academic fields of marketing, operations management, and engineering design. The value of this breadth is in conveying the shape of the entire research landscape. The review is intended primarily for two audiences. First, we hope to benefit new researchers entering the field of product development (e.g., doctoral students). We also hope this review will be valuable to experienced researchers who are interested in learning about the range of research in product development, perhaps to identify new research opportunities or to locate issues that intersect their current interests.

Despite the broad scope, we limit the review in several ways. We focus on product development projects within a single firm. This focus is in contrast to much of the literature on technological innovation, which addresses innovation at the level of an entire industry or an entire firm (e.g., Abernathy and Utterback 1978, Utterback 1994). We also devote our attention to the development of physical goods, although much of the work we describe applies to products of all kinds. We focus on the academic literature, reviewing the practitioner literature only to the extent it has been influential in the research community. Finally, we focus on *decision making* in product development, as discussed in more detail in the next section. The decision-making focus excludes a substantial body of research focused on the importance of environmental and contextual variables, such as market growth rate, the competitive environment, or the level of

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top-management support. (For a review of this literature, see Montoya-Weiss and Calantone 1994.)

There have already been several excellent review articles in the general area of product development (Shocker and Srinivasan 1979; Finger and Dixon 1989a, 1989b; Whitney 1990; Cusumano and Nobeoka 1992; Brown and Eisenhardt 1995; Griffin and Hauser 1996; and Balachandra and Friar 1997). These complement our efforts. In areas where there is an excellent review article, we do not provide a comprehensive survey of the literature, but rather cite the review. We found it challenging to keep the length of the paper manageable when attempting a review of disparate work from several different academic communities. Consequently, we cite only archetypal papers when a substantial amount of prior research exists in a particular area. Our survey is by no means exhaustive, and is intended to serve as a pointer to this vast body of literature on product design and development.

Our contribution in this paper is threefold. First, we provide a structured review of cross-functional product development research with citations to over two hundred papers. We hope that this catalog helps researchers locate papers in new areas. Second, we present a parsimonious approach to organizing the product development literature using what we call the decision perspective, which we develop in the next section. Third, we identify the current research frontier in product development research, offer a cluster of issues on this frontier, and discuss possibilities for future work that would extend the frontier in productive directions. The rest of the paper is organized as follows. Section 2 outlines our theoretical approach, including a conceptual framework contrasting the different functional perspectives of product development, and develops what we call the *decision perspective*. Sections 3 and 4 contain the bulk of the review itself, with § 3 covering development decisions made within a project, and § 4 dealing with decisions involved in setting up a project. In § 5, we discuss how product development decision making relates to the organization of academic research. Section 6 contains our concluding remarks.

2. Theoretical Approach

Our approach to developing theory for this paper is inductive (Babbie 1995). We base our theory, or systematic generalizations of product development practice, on both our observations of industrial product development and our review of the literature.

The existing literature on product development is vast. To sharpen our understanding of the literature, it is useful to organize this literature into a few competing paradigms. Such a clustering is an attempt on our part to elucidate differences, and may lead in some cases to an exaggeration of these perspectives. Indeed, we argue in this paper for a synthesis of these paradigms into the *decision perspective* of product development.

As shown in Table 1, there are at least four common perspectives in the design and development research community: marketing, organizations, engineering design, and operations management. In addition to the dimensions highlighted in this table, these perspectives often differ in the level of abstraction at which they study product development. For instance, the organizational perspective is focused at a relatively aggregate level on the determinants of project success. (An excellent review of the large body of papers from the organizational perspective is Brown and Eisenhardt 1995.) On the other hand, much of the engineering and marketing literature is at a more detailed level of abstraction, with the focus being the individual product engineer or market researcher and the issues confronting them. Finger and Dixon (1989a, 1989b) provide an excellent review of the engineering design literature, while a number of survey papers have been published reviewing the marketing perspective (Green and Srinivasan 1990, Shocker and Srinivasan 1979, Mahajan and Wind 1992). Several articles have been published in recent years reflecting the operations perspective, and some of them even serve to bridge two or more perspectives. There has been no comprehensive survey of these papers, and we intend to fill this void.

The Decision Framework

There are significant differences among papers within each of the perspectives we have identified, not only in the methodology used and assumptions made,

Table 1 Comparison of Perspectives of the Academic Communities in Marketing, Organizations, Engineering Design, and Operations Management

	Marketing	Organizations	Engineering Design	Operations Management
Perspective on Product	A product is a bundle of attributes	A product is an artifact resulting from an organizational process	A product is a complex assembly of interacting components	A product is a sequence of development and/or production process steps
Typical Performance Metrics	"Fit with market" Market Share Consumer utility (Sometimes profits)	"Project success"	"Form and function" Technical performance Innovativeness (Sometimes direct cost)	"Efficiency" Total cost Service level Lead time Capacity utilization
Dominant Representational Paradigm	Customer utility as a function of product attributes.	No dominant paradigm. Organizational network sometimes used.	Geometric models. Parametric models of technical performance.	Process flow diagram Parametric models of process performance.
Example Decision Variables	Product attribute levels, price	Product development team structure, incentives	Product size, shape, configuration, function, dimensions	Development process sequence and schedule Point of differentiation in production process
Critical Success Factors	Product positioning and pricing Collecting and meeting customer needs	Organizational alignment Team characteristics	Creative concept and configuration Performance optimization	Supplier and material selection Design of production sequence Project Management

but also in the conceptualization of how product development is executed. These differences reflect, in part, the enormous diversity of firms developing products, and it is difficult to develop a single theory amidst such differences.

We observe, however, that while *how* products are developed differs not only across firms but within the same firm over time, *what* is being decided seems to remain fairly consistent at a certain level of abstraction. To illustrate how decision at an aggregate level offer an opportunity to generalize, consider the example of developing a product such as an ink-jet printer. Some product development decisions include: *Which (printing) technology will be adopted in the product? Where will the (printer) product be assembled? Who will be on the product development team and who will lead the team? Which variants of the (printer) product will be developed as part of the product family?* Clearly, different organizations will make different choices and may use different methods, but all of them make decisions about a collection of issues such as the product concept, architecture, configuration, procurement and distribution arrangements, project schedule, etc. Adopting the perspective that product development is a deliberate business process involving scores of such generic decisions is what we call the *decision perspective.*

The decision perspective helps us get a glimpse inside the "black box" of product development without being concerned about how these decisions are made, and thereby offers an opportunity to generalize and develop a grounded theory. In fact, at many companies these decisions may be made not by intention but by default. Collecting decisions across the multiple academic perspectives mentioned in Table 1 helps us not only integrate these perspectives but also identify interdependencies among these decisions. The decision perspective also seems to provide a description of product development that is both comprehensive and parsimonious, perhaps because it cuts across the functional perspectives without getting involved in the functional details of how the decisions are made (Whetten 1993).

Note that this approach is consistent with and draws on prior work in that it clearly assumes an organization that manages uncertainty through information processing (Thompson 1967, Galbraith 1977). However, we do not mean to imply, by taking the decision perspective, that firms make all product development decisions in a deliberate fashion, merely that most of these decisions are eventually made, even if through inaction. We believe in the bounded rationality of individuals and teams (Simon 1969), and we acknowledge the role of organizational culture and individual behavior in the effectiveness of product development processes.

Research Method

We adopted a loosely structured method for the mechanics of surveying the literature. As a first step we created a superset of papers related to product development. We did this by searching the tables of contents of major journals over the period from 1988 to 1998, including *Management Science, Marketing Science, Journal of Marketing Research, Research Policy, Strategic Management Journal, IEEE Engineering Management, Journal of Product Innovation Management, Research in Engineering Design*, and *ASME Journal of Mechanical Design*. Using the ISI Citation Index, we selected a subset of these papers that had been highly cited, and collected the reference lists from these highly cited papers. We also conducted an electronic mail survey of approximately 50 researchers in the field of product design and development, asking them to list influential papers. This set of activities left us with a master list of approximately 400 papers.[1] We then filtered this set to create a working list of papers. We eliminated those papers that did not address product development at the project level, that addressed very narrow domains of application (e.g., VLSI design), that were not in archival publications (and would therefore be difficult to locate for our target audience), that were targeted primarily at practitioners, or that, if published before 1994, had not been cited in the subsequent literature. The resulting working list consisted of approximately 200 papers. We collected copies of these papers and used them as the basis of the review.

We then identified about 30 major decisions that are made within product development organizations. We took both a top-down and bottom-up approach to identifying these decisions. Using the top-down approach, we considered a typical multiphase development process (as described, for example, in Ulrich and Eppinger (2000)). From our own observations of industrial practice, we listed the decisions made in each phase. Using the bottom-up approach, we considered the decisions addressed by each research paper. In some cases, a paper addresses a product development decision explicitly, particularly when the paper presents a decision support tool or analytical method. In other cases, the decision within a paper is implicit, particularly when the paper is primarily an attempt to provide insight into "how things work" in industrial practice. By combining, refining, organizing, and synthesizing this set of decisions, we ended up with about 30 decisions. This set is the result of judgments about the appropriate level of detail of the decisions (e.g., we aggregate most engineering design decisions under the overarching question of what are the values of the key design parameters) and about the scope of product development (e.g., we exclude decisions about advanced technology development). We suspect that other researchers would devise a similar list of decisions, but it would certainly not be identical to ours.

3. Decisions within a Development Project

We organize product development decisions into two broad categories (Hultink et al. 1997). In this section, we consider the decisions made within the context of a single project in actually developing the product. In § 4, we consider the decisions a firm makes in establishing an organizational context and in planning development projects. As an organizational convenience, we further divide decisions within a project into four categories: *concept development*, *supply-chain design*, *product design*, and *production ramp-up and launch*. Tables 2 and 3 list references to the literature associated with the product development decisions. We discuss only a small subset of the references, but we hope that Tables 2 and 3 stand alone as a guide to the articles that are likely to be most useful to the reader.

[1] For simplicity, we refer to all publications as *papers*.

Table 2 Product Development Decisions within a Project

	Decision	Selected References		
	Concept development generally:	(Burchill and Fine 1997)	(Cohen and Whang 1997)	
Concept Development	What are the target values of the product attributes, including price?	(Green and Krieger 1989) (Green and Srinivasan 1990) (Griffin and Hauser 1993)	(Hauser and Clausing 1988) (Kaul and Rao 1995) (Ramaswamy and Ulrich 1993)	(Shocker and Srinivasan 1979) (Srinivasan et al. 1997)
	What is the core product concept?	(Bacon et al. 1994) (Bhattacharya et al. 1998b) (Crawford 1987) (Dahan and Srinivasan 2000)	(Kleinschmidt and Cooper 1991) (Otto 1995) (Pugh 1991) (Rangaswamy and Lilien 1997) (Ullman 1997)	(Ulrich and Eppinger 2000) (Urban and Hauser 1993) (von Hippel 1986) (von Hippel 1988)
	What is the product architecture?	(Alexander 1964) (Baldwin and Clark 1999) (Clark 1985) (Henderson and Clark 1990) (Huang and Kusiak 1998)	(Pamas 1972) (Pamas et al. 1985) (Sanchez and Mahoney 1996) (Simon 1969)	(Ulrich and Tung 1991) (Ulrich 1995) (von Hippel 1990) (Whitney 1993)
	What variants of the product will be offered?	(De Groote 1994) (Ho and Tang 1998)	(Ishii et al. 1995) (Kekre and Srinivasan 1990)	(Lancaster 1990) (Martin and Ishii 1996)
	Which components will be shared across which variants of the product?	(Fisher et al. 1998) (Gupta and Krishnan 1999)	(Ramdas and Sawhney 2001)	(Rutenberg 1969)
	What will be the overall physical form and industrial design of the product?	(Agarwal and Cagan 1998) (Lorenz 1990)	(Wallace and Jakiela 1993)	(Yamamoto and Lambert 1994)
Supply Chain Design	Which components will be designed and which will be selected? Who will design the components?	(Clark 1989)	(Ulrich and Ellison 1998)	(Ulrich and Ellison 1999)
	Who will produce the components and assemble the product?	(Dyer 1996) (Dyer 1997)	(Liker et al. 1996a) (Liker et al. 1996b)	(Mahoney 1992) (Monteverde and Teece 1982)
	What is the configuration of the physical supply chain, including the location of the decouple point?	(Fisher 1997) (Gupta and Krishnan 1998)	(Lee 1996) (Lee and Tang 1997)	(Swaminathan and Tayur 1998)
	What type of process will be used to assemble the product?	(Bhoovaraghavan et al. 1996)	(Fine and Whitney 1996)	(Nevins and Whitney 1989)
	Who will develop and supply process technology and equipment?			
Product Design	*Product design generally:*	(Finger and Dixon 1989a) (Finger and Dixon 1989b)	(Hubka and Eder 1988) (Pahl and Beitz 1988)	(Ulrich and Pearson 1998)
	What are the values of the key design parameters?	(Agogino and Almgren 1987) (Antonsson and Otto 1995) (Papalambros and Wilde 1988)	(Papalambros 1995) (Parkinson 1995) (Srinivasan et al. 1996)	(Suh 1990) (Suh 1995) (Taguchi 1986)

Table 2 *Continued*

	Decision	Selected References		
	What is the configuration of the components and assembly precedence relations?	(Bourjault 1984) (Cutkosky et al. 1992)	(De Fazio and Whitney 1987) (De Fazio et al. 1993) (Gupta and Krishnan 1998)	(Rinderle and Krishnan 1990) (Ward 1989)
	What is the detailed design of the components, including material and process selection?	(Boothroyd et al. 1994) (Chen et al. 1994)	(Ettlie 1995) (Navinchandra 1994) (Poli et al. 1993)	(Smith 1997) (Ulrich et al. 1993) (Thierry el al. 1995)
Performance Testing and Validation	What is the prototyping plan? What technologies should be used for prototyping?	(Dahan and Mendelson 1998)	(Thomke 1998)	(Thomke and Bell 1999)
Production Ramp-Up and Launch	What is the plan for market testing and launch?	(Hendricks and Singhal 1997) (Kalish and Lilien 1986) (Hultink et al. 1997)	(Mahajan and Wind 1988) (Kalish, Mahajan and Muller 1995)	(Mahajan et al. 1990) (Urban and Hauser 1993)
	What is the plan for production ramp-up?	(Terwiesch and Bohn 2001)	(Billington et al. 1998)	

Concept Development

Concept development decisions define not only the product specifications and the product's basic physical configuration, but also the extended product offerings such as life-cycle services and after-sale supplies. There are five basic decisions to be made. What are the target values of the product attributes? What will the product concept be? What variants of the product will be offered? What is the product architecture? And, what will be the overall physical form and industrial design of the product?

A useful representation of a product is a vector of *attributes* (e.g., speed, price, reliability, capacity). We intend attributes to refer to both *customer needs* (also referred to as *customer attributes or customer requirements*) and *product specifications* (also referred to as *engineering characteristics* or *technical performance metrics*). Griffin and Hauser (1993) offer a comprehensive discussion of the issues associated with assessing and using customer needs. Given a representation of a product as a set of attributes, conjoint analysis is a structured approach to optimally determine the target values of these attributes. We point the reader to three excellent survey articles by Shocker and Srinivasan (1979), Green and Krieger (1989), and Green and Srinivasan (1990).

Attribute-based methods are limited in their ability to represent the overall appeal of products, especially those for which aesthetics and other holistic product attributes are important. Srinivasan et al. (1997) offer a hybrid methodology in which attribute-based methods are supplemented by the use of realistic physical prototypes to elicit consumer preference information. Much of the research on setting attribute values is also aimed at maximizing customer satisfaction or market share, and does not explicitly consider design and production costs or overall profitability. In addition, the research on setting attribute values (done in the context of packaged goods) often assumes that arbitrary combinations of specifications are possible. While it may be feasible to provide any combination of "crunchiness" and "richness" in a chocolate bar, it is not possible to offer an arbitrary combination of "compactness" and "image quality" in a camera (Ramaswamy and Ulrich 1993).

Attributes are an abstraction of a product. Concept development also involves the embodiment of these attributes into some kind of technological approach, which we call the *core product concept*. The decision of which technological approach to pursue is often supported by two more focused activities: concept generation and concept selection. Most textbooks on design and development discuss concept generation

Table 3 Decisions in Setting up a Development Project

	Decision	Selected References		
	What is the market and product strategy to maximize probability of economic success?	(Mansfield and Wagner 1975)	(McGrath 1995)	(Roussel et al. 1991)
Product Strategy and Planning	What portfolio of product opportunities will be pursued?	(Ali et al. 1993) (Cooper et al. 1998) (Clark and Wheelwright 1993) (Day 1977)	(Dobson and Kalish 1988) (Dobson and Kalish 1993) (Green and Krieger 1985) (Henderson and Clark 1990)	(Kohli and Sukumar 1990) (Krishnan et al. 1999) (McBride and Zufryden 1988)
	What is the timing of product development projects?	(Bhattacharya et al. (1998a)	(Moorthy and Png 1992)	(Padmanabhan et al. 1997)
	What, if any, assets (e.g., platforms) will be shared across which products?	(Adler et al. 1995) (Clausing 1994) (Gupta and Krishnan 1999) (Krishnan and Gupta 2001)	(Meyer and Lehnerd 1997) (Meyer and Utterback 1993) (Meyer et al. 1997)	(Nobeoka 1995) (Nobeoka and Cusumano 1997) (Robertson and Ulrich 1998) (Sanderson and Uzumeri 1995)
	Which technologies will be employed in the product(s)?	(Clark and Wheelwright 1993)	(Iansiti 1995b)	
	Organization generally:	(Brown and Eisenhardt 1995)		
Product Development Organization	Will a functional, project, or matrix organization be used?	(Allen 1977) (Brown and Eisenhardt 1995)	(Davis and Lawrence 1977)	(Dougherty 1989)
	How will the team be staffed?	(Ancona and Caldwell 1992) (Brooks 1975) (Clark and Fujimoto 1991)	(Clark and Wheelwright 1993) (Katz and Allen 1982) (Leonard-Barton 1992)	(Moorman and Miner 1997) (Pelled and Adler 1994)
	How will project performance be measured?	(Clark and Fujimoto 1991) (Foster et al. 1985a, 1985b)	(Griffin and Page 1993) (Terweisch et al. 1998)	(Griffin 1993) (Griffin and Page 1996)
	What will be the physical arrangement and location of the team?	(Allen 1977)	(Morelli et al. 1995)	
	What investments in infrastructure, tools, and training will be made?	(Mahajan and Wind 1992)	(Milgrom and Roberts 1990)	(Robertson and Allen 1993)
	What type of development process will be employed (e.g., stage-gate)?	(Bhattacharya et al. 1997)	(Cooper 1993) (Cusumano and Smith 1997)	(Ward et al. 1995)
Project Management	What is the relative priority of development objectives?	(Bayus et al. 1997) (Blackbum 1991) (Cohen et al. 1996)	(Griffin 1997) (Iansiti and Clark 1994) (Ittner and Larcker 1997)	(Meyer and Utterback 1995) (Reinertsen and Smith 1991)
	What is the planned timing and sequence of development activities? What are the major project milestones and planned prototypes?	(Aitsahlia et al. 1995) (Kalyanaram and Krishnan 1997) (Clark and Fujimoto 1991) (Eppinger et al. 1994) (Iansiti 1995c)	(Krishnan et al. 1997) (Kusiak and Larson 1995) (Loch and Terwiesch 1998) (Milson et al. 1992)	(Smith and Eppinger 1997a) (Smith and Eppinger 1997b) (Steward 1981) (Terwiesch and Loch 1998)

Table 3 *Continued*

Decision	Selected References		
What will be the communication mechanisms among team members?	(Katz and Allen 1982) (Moenaert el al. 1994)	(Morelli et al. 1995)	(Hise et al. 1990)
How will the project be monitored and controlled?	(Ha and Porteus 1995)		

and selection. See, for example, books by Crawford (1987), Ullman (1997), Ulrich and Eppinger (2000), and Urban and Hauser (1993). A common theme is that a wide variety of concepts from a wide variety of sources be considered.

The traditional approach to concept selection stipulates that the concept be frozen before detailed product design commences. However, Bacon et al. (1994) find from their study of high-technology industries that unchanging product specifications in dynamic environments is at best an elusive goal. The work of Srinivasan et al. (1997) cited earlier argues that with the new economics of product development (e.g., declining costs of prototyping, more powerful computer-based tools), it may be optimal to pursue multiple concepts and select the best design later in the process. Their argument is reinforced by the findings of Dahan and Srinivasan (2000) that concept selection and testing using virtual prototypes on the World Wide Web offers nearly the same results as the use of physical prototypes. Bhattacharya et al. (1998b) also find that finalizing specifications later may be desirable in dynamic environments.

The choice of product variants must balance heterogeneity in preferences among consumers and economies of standardization in design and production. Lancaster (1990) provides a comprehensive discussion of the basic economics of product variety. Ho and Tang (1998) is a collection of research articles addressing issues in the management of product variety.

Closely related to the decision of which variants to offer is the decision about which components to share across products in a firm's portfolio. Rutenberg's work is among the earliest in this area. He shows that the problem of determining the cost-minimizing set of components maps into a dynamic program (Rutenberg 1969). More recent papers on this topic are cited in Table 2.

The ability to share components across products is determined in part by the product architecture, which is the scheme by which a product's functionality is partitioned among components. Perhaps the earliest discussions of the architecture of engineered systems are by Alexander (1964) and Simon (1969). Recent research has focused on the implications of product architecture for operations and marketing issues (Ulrich 1995), for organizational design (Sanchez and Mahoney 1996), and for the evolution of entire industries (Baldwin and Clark 1999).

A product concept is generally brought to life through decisions about the physical form and appearance of the product. These decisions are part of an activity generally called *industrial design.* Lorenz (1990) provides an overview of the field of industrial design from a practitioner perspective. Although critical to the commercial success of many mass-market products, with the exception of Yamamoto and Lambert (1994), industrial deign has received almost no research attention.

Supply-Chain Design

We use the term *supply chain* to encompass both the inbound and outbound flows of materials, as well as the supply of intellectual property and services to the firm. Supply-chain design decisions therefore include supplier selection as well as production and distribution system design issues, and address the following questions. Which components will be designed specifically for the product? Who will design and produce the product? What is the configuration of the physical supply chain? What type of process will be used to assemble the product? Who will develop and supply the process equipment?

Most engineered assembled goods are comprised of a mixture of components designed specifically for a product and standard off-the-shelf components. Ulrich and Ellison (1999) find that components are likely to be designed (rather than selected) if the requirements they serve are "holistic" or arise in a complex way from all or most of the elements of the product. If a product contains designed components, decisions must be made about *who* will design these components and who will produce and test them. Ulrich and Ellison (1998) argue that these decisions benefit from being made simultaneously. These decisions are also closely related to the classic *make-buy decision* (Mahoney 1992, Fine and Whitney 1996).

Operations management researchers have directed a great deal of research attention to the design of the physical supply chain. Fisher (1997) argues that the optimal supply chain for innovative products is different from that of noninnovative products, because of differences in the relative magnitude of direct production costs and the costs of a mismatch between supply and demand. Product design has also been found to contribute to leaner supply chains by postponing the point of differentiation in the order-fulfillment process (Lee 1996, Lee and Tang 1997). We highlight those supply-chain papers that link directly to issues of product development in Table 2.

Product Design

We use the term *product design* in its narrow sense to refer to the detailed design phase, which constitutes the specification of design parameters, the determination of precedence relations in the assembly, and the detail design of the components (including material and process selection). These decisions generally result in geometric models of assemblies and components, a bill of materials, and control documentation for production. There is a vast literature in the engineering design community relating to design decisions. Two influential books are authored by Pahl and Beitz (1988) and Hubka and Eder (1988). Finger and Dixon's two-part article (Finger and Dixon 1989a, 1989b) is comprehensive in its review of the literature through 1989. Our review focuses on work since 1989, and we cite archetypal articles in areas where there is too much activity to review comprehensively.

The goal of the parametric design phase is to decide values of design parameters while satisfying and/or optimizing some desired performance characteristics. Parametric design is generally performed after a basic product concept has been established, when creation of a mathematical model of product performance is possible. There is a large body of literature on using mathematical programming approaches to solve the parametric design problem. We refer the reader to the overview article by Papalambros (1995), who also notes that there is a significant gap between theory and practice, and that most "optimal" design in industry is in fact the result of using engineering models in trial-and-error mode. Parametric design problems often have objective functions that are monotone increasing or decreasing in the decision variables, and the optimal solution can be determined by simply solving for the active design constraints. Papalambros and Wilde (1988) have formalized this approach into a technique called *monotonicity analysis*. Attempts have also been made by researchers to integrate artificial intelligence techniques such as qualitative reasoning with optimization to obtain insights about the parametric design problem (for example, see Agogino and Almgren 1987). Other related work on design reasoning and optimization is cited in Table 2.

Nevins and Whitney (1989) address the interactions between product design and production processes, with particular emphasis on assembly processes. In an influential article, De Fazio and Whitney (1987) extended the work of Bourjault (1984) to model the space of possible assembly sequences for a product. Boothroyd et al. (1994) provide a methodology for designing components that are easy to assemble. This work is built on the idea of iteratively refining a design using a metric of assembly performance (e.g., assembly time) to provide feedback on design quality. Ulrich et al. (1993) caution against myopic application of design guidelines, finding that application of common design-for-manufacturing rules can in certain cases reduce profitability. Nevins and Whitney (1989) provide a comprehensive treatment of production process design issues, including the design of tools, facilities, and equipment. Thierry et al. (1995) discuss the importance of including product disposal and recovery considerations in the product design process under the heading of Product Recovery Management (PRM). PRM's objective of recovering as much of the product's economic and ecological value upon disposal is likely to become increasingly important as both customers and governments insist on reducing waste generation. This may indeed require further research on a larger life-cycle perspective in product development with the intention of making the product fit its natural environment as much as it fits the business environment (market).

Performance Testing and Validation

While detailed design decisions are being made and refined, the design is also prototyped to validate for, fit, function, and fabrication. Ulrich and Eppinger (2000) provide a comprehensive description of the prototyping process. Typically, the firm has a choice of developing prototypes sequentially or in parallel with different cost, benefit, and time implications. Dahan and Mendelson (1998) derive optimal hybrid sequential-parallel prototyping policies by modeling prototyping as a probabilistic search process. Thomke and Bell (1999) show that the optimal prototyping and testing strategy should balance, among other things, the cost of prototyping and cost of redesign. Thomke (1998) studies the costs and benefits of different prototyping technologies, and offers insight on which prototyping process to use under what circumstance.

Product Launch and Production Ramp-up

A number of decisions must be made in association with product launch and production ramp-up. For instance, the firm must decide the degree to which test marketing should be done, and the sequence in which products are introduced in different markets. These questions have been researched to a considerable degree in the marketing literature (Urban and Hauser 1993; Mahajan and Wind 1988; Mahajan et al. 1990). Launch timing is a decision that trades off multiple factors, including threat of competitor entry and the completeness of development, as discussed by Kalish and Lilien (1986). The firm must be careful in communicating its launch timing to the market, as not meeting preannounced launch dates can have a significant impact on the market value of the firm (Hendricks and Singhal 1997).

In practice, poor product-design decisions can also slow the rate of production ramp-up. There has been some work on production ramp-up (Terwiesch and Bohn 2001) and on coordinating the rollover of new products (Billington et al. 1999), but essentially none on the relationship between rate of production ramp-up and product-design decision making.

4. Decisions in Setting Up a Development Project

A particular product development project tends to be part of a constellation of other projects within an organization. Here we consider the decisions relating to *product strategy and planning, product development organization,* and *project management* that set the stage for an individual development project. The decisions associated with setting up product development projects are shown in Table 3 with selected references.

Product Strategy and Planning

Product strategy and planning involve decisions about the firm's target market, product mix, project prioritization, resource allocation, and technology selection. Mansfield and Wagner (1975) show that these factors have a significant influence on the probability of economic success. In structured development environments, product planning often results in *mission statements* for projects and in a *product plan* or *roadmap,* usually a diagram illustrating the timing of planned projects. Specific decisions include the following. What is the firm's target market? What portfolio of product opportunities will be pursued? What is the timing of the product development projects? What assets will be shared across products? Which technologies will be employed in the planned products? Efforts are generally made to coordinate these decisions with the firm's corporate, marketing, and operations strategies. Approval of the product plan is often based on how well it meets strategic goals, justification of the product opportunity, and how well the target market fits the company's image and vision (of who it wants to serve). In essence, product planning is the set of decisions that ensures that the firm pursues the right markets and products from a strategic viewpoint.

Because there exists a large body of research on the issue of target market definition, we refer the reader to the excellent discussion by Urban and Hauser (1993). Product/project portfolio selection has also been a topic that has been studied for the last three decades but has received renewed attention in the last decade. See, for example, the work of Ali et al. (1993), who present a taxonomy of the project selection problem and offer detailed references. In deciding which product opportunities to pursue, a potential pitfall is to focus on existing markets. Christensen and Bower (1996) show, using data from the disk drive industry, that successful firms often fail to recognize technological and/or market shifts because product planning is biased towards existing markets.

An operational version of the portfolio decision is the *product line design problem,* in which the number and identity of individual products must be decided. Green and Krieger (1985) pioneered the development of decision support models for product line design by formulating it as a choice problem from a set of candidate products while maximizing an objective function such as social welfare or firm profit. Several heuristic procedures have been developed to solve this combinatorial problem (McBride and Zufryden 1988, Kohli and Sukumar 1990). Others have expanded the scope of the problem to include richer cost structures (Dobson and Kalish 1988, Dobson and Kalish 1993, Krishnan et al. 1999).

In launching a product, the firm decides the timing and sequence of product introduction. An interesting trade-off confronting the timing decision is one of cannibalization versus faster accrual of profit. When products are introduced *simultaneously,* low-end products might cannibalize the sales of the high-end products. Moorthy and Png (1992) were the first to address this trade-off, and argued that in the interest of cannibalization it is inappropriate to introduce low-end products before high-end products. More recent work by Padmanabhan et al. (1997) and Bhattacharya et al. (1998a) suggests that it may be appropriate in some circumstances to introduce low-end products before high-end products (such as in the presence of network externalities or exogenous technological improvements).

Decisions are made about executing product development projects in parallel and sharing resources across different projects. Adler et al. (1995) highlight the congestion effects that arise from pursuing multiple product development projects in parallel. Their production-process metaphor also helps understand the pitfalls of high capacity utilization and processing time variability in development projects. Resource sharing may, however, lead to better utilization of resources, reduction in required development hours, as well as better learning across projects (Nobeoka 1995, Nobeoka and Cusumano 1997). Substantial sharing of assets across products results in the development of product platforms (Meyer and Lehnerd 1997, Meyer et al. 1997). Much of the work on platforms, however, focuses only on platform benefits. Robertson and Ulrich (1998) highlight the loss of customer-perceived differentiation due to platforms, and Krishnan and Gupta (2001) discuss the *overdesign* of low-end products due to product platforms.

A key component of product planning is the decision about which technologies to incorporate in a forthcoming product (Iansiti 1995a). While prospective technologies are attractive along several dimensions, they are also not fully proven, and can increase the degree of risk of the new product development process. Wheelwright and Clark (1992) discuss the "pizza-bin approach," in which products are assembled from proven technologies. While this approach can make the development process more manageable, competitive conditions may require a firm to develop technologies and products simultaneously (Iansiti 1995b, Krishnan and Bhattacharya 1998).

Product Development Organization

By *product development organization,* we mean the social system and environment in which a firm's design and development work is carried out. Related decisions include team staffing, incentives and reward systems, metrics for monitoring performance, and investments in productivity-enhancing tools and "processes" for product development. The literature on organization design is extensive, so Table 3 presents only archetypes of work particularly relevant to product development. We refer the reader to the excellent review article by Brown and Eisenhardt (1995) for a comprehensive treatment of this topic.

Project Management

In managing a development project, decisions are made about the relative priority of development objectives, the planned timing and sequence of development activities, the major project milestones and prototypes, mechanisms for coordination among team members, and means of monitoring and controlling the project.

Product development performance is generally measured by the lead time to develop the product, the cost of the development effort, the manufacturing cost of the product, and the product's quality or attractiveness in the market (Clark and Fujimoto 1991, Griffin 1997, Iansiti and Clark 1994). Foster et al. (1985a, 1985b) provide an excellent discussion on how metrics can be used to clarify the link between research and development and corporate profits. Cohen et al. (1996) have shown that these performance measures are often traded off against each other. Other research studies (Table 3) indicate that these measures may have different effects on firm's profit in different markets, so it may not always be appropriate to force-fit one approach (such as lead-time minimization) to all development situations.

Formal project-scheduling techniques such as PERT and CPM enjoy widespread use in the construction industry for planning the timing and sequence of activities, however product development processes are not as easily modeled with these techniques (Eppinger et al. 1994). The exchange of information among product development professionals can be modeled using a tool called the Design Structure Matrix (DSM), introduced by Steward (1981) and further developed for large projects by Eppinger and his colleagues.

One popular strategy for minimizing lead time is *overlapping* nominally sequential development activities (Clark and Fujimoto 1991). Overlapping coupled development activities, often called *concurrent design*, involves the use of preliminary design information and is challenging to manage because of its ability to lead to development rework (Krishnan, Eppinger and Whitney 1997). Careful management of overlapping requires the detailed representation of the information exchanged between individual tasks and a deeper understanding of the properties of the information (Krishnan et al. 1997, Loch and Terwiesch 1998). Iansiti (1995c) and Kalyanaram and Krishnan (1997) also argue that in turbulent environments overlapping is required in order to provide flexibility in making major changes in the design of the product. Closely coupled to the decision of how to schedule development activities is the decision of what types of communication to facilitate and to what extent. Cross-functional communication (e.g., between marketing and engineering) is widely viewed as positive, although insights about the nature of coupling among development tasks offer the promise of fostering communication where it is most valuable (Moenaert and Souder 1996, Griffin 1992).

The issue of the timing and frequency of project monitoring and intervention has been addressed only to a limited extent in the academic literature (Ha and Porteus 1995), although practitioners seem to struggle to strike the right balance between excessive intervention and inadequate oversight.

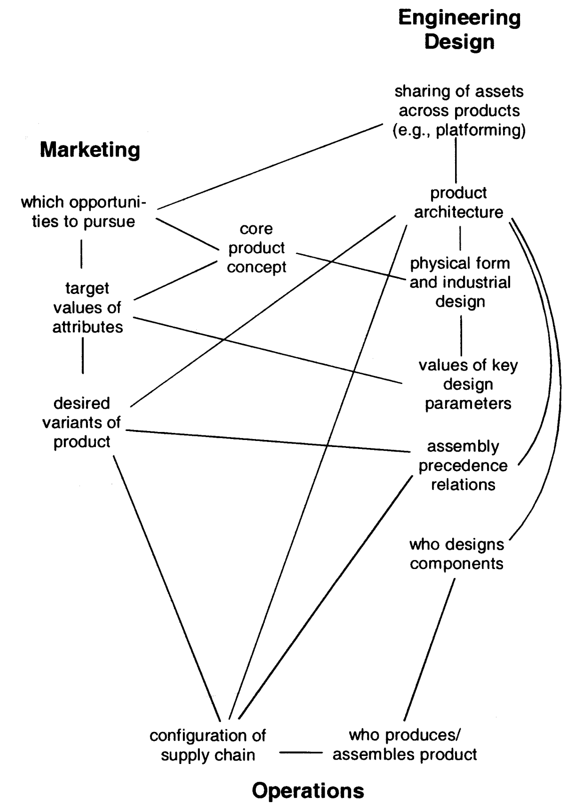
5. The Organization of Academic Research

In our review of the literature, we deliberately did not map product development decisions to organizational functions such as marketing, engineering, and operations. In this section, we consider the different functional perspectives of product development, and then argue that coordinated decision making requires an approach to research that is driven by the intrinsic interdependencies among decisions, rather than being driven by attempts to bridge the extant functional structure of the research community.

The organization of a manufacturing firm into functions is particularly beneficial for managing an ongoing business with stable products, in which marketing is responsible for generating demand and operations is responsible for fulfilling that demand. The task of developing new products, however, presents an organizational challenge in that *it introduces a discontinuity in ongoing operations*. A common approach is to assemble a team of individuals from various functions for the duration of the development process and to allocate among them the task of making subsets of decisions. Typically, the marketing function is responsible for many of the product planning decisions and the operations function for the supply-chain design decisions. Engineering design is entrusted with the task of making the bulk of concept and detailed design decisions. Figure 1 shows a clustering of product development decisions according to this functional logic. This approach benefits to a certain extent from the specialized knowledge that may reside within a function. For instance, product positioning and market segmentation decisions are assigned to individuals with detailed knowledge of market needs. However, the risk is that interdependencies among the development decisions may be ignored. For instance, the number and identity of product variants offered is often decided based only on market preferences and ignores design and operational considerations.

There has been a recent shift in the organization of product development in practice, and many firms have adopted a team structure in which the traditional functional divisions are less pronounced (Ettlie 1997). Despite this shift in practice, academic groups within most schools of business and engineering mirror the typical functional organizations of the 1950s, with groups focused on operations, marketing, and engineering, for example. Like most functional organizations, academic communities are adept at addressing certain decisions in isolation and have honed the associated analytical and pedagogical tools. However, to the extent that they mirror the historical functions of the enterprise, these academic structures impede an understanding of how to coordinate interdependent product development decisions. In Table 1, we highlighted these differences in the way the academic groups view product design and development. Note that these distinctions are somewhat stereotypical, and that there are notable exceptions. In particular, there is an established research community in technology and innovation management, in which a subset of researchers, often distributed across traditional university academic units, are concerned with product development.

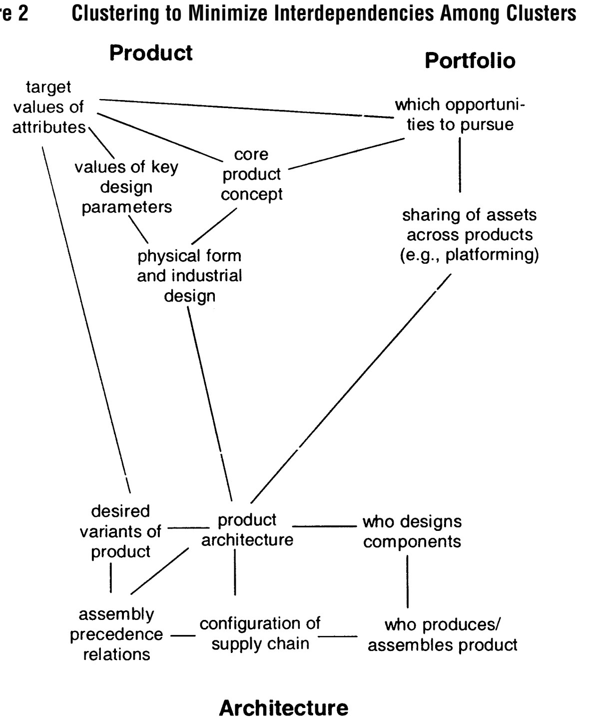
Figure 1 **Clustering of Product Development Decisions by Traditional Functional Categories**



A recent approach to bridge the differences among the different academic groups has been to formulate "cross-functional research problems" such as how to coordinate the marketing-operations interface. An insightful example is Karmarkar (1996). In our opinion, focusing on coordinating marketing and operations addresses an emerging problem with a dated organizational logic. A focus on coordinating these traditional functions may, in fact, confuse and complicate the underlying coordination problem in product development. To express the problem of coordinating product development decisions as one of coordinating, for example, marketing and operations, assumes a particular functional organizational scheme and masks the microstructure of the interdependencies in development decisions. An alternative approach is to let the product development decisions and the underlying interdependencies drive the organization of research problems. For instance, attempts in the operations literature to formulate the "cross-functional product-line design problem" add terms and constraints in a piecemeal fashion to the traditional marketing-based product-line design models. However, these models do not get to the heart of the decision problem, which involves the tension between product differentiation and design and operations complexity, and which we believe is addressed much more effectively by considering an intermediating decision, the choice of product architecture.

One approach to framing integrated research in product development is to consider clusters of decisions that are highly interdependent. Consider a possible reorganization of the decisions shown in Figure 1 into three clusters that minimize the interdependencies between clusters. Note that this clustering, shown in Figure 2, does not correspond to a traditional functional organizational scheme, yet may be a better way to frame the organization of research. This is because

Figure 2 Clustering to Minimize Interdependencies Among Clusters



Note. This diagram is illustrative only. In some contexts the dependencies among these decisions may be substantially different.

an organization encompassing highly interdependent problems is likely to result in better, more systemic solutions. There are other possible criteria for clustering decisions, such as similarities in relevant methodologies (e.g., statistical analysis, optimization), yet we feel the interdependency criterion is promising as a scheme for organizing research.

6. Concluding Remarks

Several areas for future research seem promising. Research in the marketing community has flourished on methods for modeling consumer preferences and for optimally establishing the values of product attributes. Yet, a weakness identified in § 3 is that models of the product as a bundle of attributes tend to ignore the constraints of the underlying product and production technologies. Parametric optimization of complex engineering models is a well-developed area within the engineering design community. We see an opportunity for these communities to work together to apply the product-design methods developed in marketing to product domains governed by complex technological constraints.

We noted that there is essentially no academic research on industrial design, the activity largely concerned with the form and style of products. Yet aesthetic design may be one of the most important factors in explaining consumer preference in some product markets, including automobiles, small appliances, and furniture. The lack of academic research on industrial design may reflect an inherent difficulty in modeling the relevant factors, yet we perceive an opportunity to contribute substantially to development performance by understanding this activity better.

Product planning decisions and development metrics seem particularly ad hoc in industrial practice. For example, there are few research results that inform the question of how to integrate the efficiency issues associated with the use of product platforms with the market benefits of high product variety. We see an opportunity to bring together market, product, and process considerations on the decision of what products to develop, when, and with what level of sharing of resources. Also, firms increasingly are experiencing situations in which the bulk of the profit from the product accrues from postlaunch services and supplies associated with the product. Additional research is needed along the lines of the work of Cohen and Whang (1997), who studied the design of the joint product/service bundle for the product life cycle.

Research on physical supply chains has focused productively on inventory and lead-time considerations. Relatively little attention has been paid to the topic of product engineering and development supply chains. There has been some work on implications of product architecture for supply-chain effectiveness (Ulrich and Ellison 1999, Gupta and Krishnan 1999). We see an excellent opportunity for research in the area of product development supply chains that enable development teams to decide on outsourcing product development, levels of product variety, product architecture, inventory policy, and process flexibility that provide the best combination of customer satisfication and firm profitability.

The development of new information technologies appears to be revolutionizing commerce generally and product development to a considerable degree. The benefit of new tools to manage product knowledge and support development decision making within the extended enterprise needs to be explored in greater detail (Liberatore and Stylianou 1995, Ruecker and Seering 1996). The research challenge is to understand the situations in which advancements in information technology are likely to change the established wisdom about how to effectively manage product development.

Product definition, development, launch and project management methodologies are highly contingent on the market uncertainty and other environmental characteristics (Brown and Eisenhardt 1995, Shenhar and Dvir 1996, Lynn et al. 1996, Chandy and Tellis 1998). Insights on customizing product development practices to diverse environments such as small entrepreneurial firms and varied industries should also help increase the relevance and applicability of the development literature (Meyer and Roberts 1986, Dougherty and Heller 1994, Eisenhardt and Tabrizi 1995, Gatignon and Xuereb 1997).

We observe that research seems to flourish in problem areas with powerful representational schemes. For instance, the development of attribute-based representations by the marketing community led to the large body of work on conjoint analysis. The parametric representation of the engineering design problem led to hundreds of papers on design optimization. More recently, the Design Structure Matrix spawned dozens of research efforts on organizing product development tasks. We might therefore infer that the development of representation schemes should be a high priority in the product development research community.

Finally, we believe that research in product development must be tightly motivated by the needs of industrial practice. This is because product development is essentially a commercial function, and therefore most knowledge about product development does not have much meaning outside of the commercial realm. The models employed in product development research are at best coarse approximations of the phenomena under study, unlike in the physical sciences where the language of mathematics seems to map in a remarkable way to the physical world. We believe that this loose connection between models and practice implies that the product development research community could benefit from stronger adherence to the scientific method, and proceed only a short distance ahead of empirical validation, lest energy be wasted on understanding models with little relevance to the motivating questions.

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