A Methodology for Product Architecture Decisions Based on Market Segmentation

by

Jason Scott Dell

Bachelor of Mechanical Engineering
Georgia Institute of Technology, 1992

Submitted to the Systems Design and Management Program in Partial Fulfillment of the Requirements for the Degree of

Master of Science
at the
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Signature of Author: ______________________________
Department of Aeronautics and Astronautics
August 9, 1996

Certified by: ______________________________
Steven D. Eppinger
Associate Professor of Management Science
Thesis Supervisor

Accepted by: ______________________________
Edward F. Crawley
Professor of Aeronautics and Astronautics
Head, Department of Aeronautics and Astronautics

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ABSTRACT

A new methodology is described which focuses on defining product architecture within a product family. Ultimately, one wants a product family to satisfy the needs of several different market segments with minimal cost. This author examines product modularity with its inherent advantages in re-use and economies of scale as a solution.

Numerous factors, such as a company's available resources, the allocation of these resources, the expected market size and growth of each potential product, can affect the outcome of product architecture decisions. The method provides tools to examine these and other issues at a relatively high level and ultimately generates suggestions concerning tactical planning for a product family. The tools also provide a graphical representation to help initiate discussion of various architectures.

Thesis Supervisor: Steven D. Eppinger
Title: Associate Professor of Management Science

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To my wife, Lori, whose tremendous
support in my pursuit of knowledge
has shown me her love.
(or is it her tolerance)

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1. Introduction

A recent initiative instituted by the Advanced Messaging Group of Motorola, Inc. includes evaluating product modularity and the concept of platforming as a possible solution to growing the new market of "two-way paging" quickly and efficiently. This initiative has lead to the research and derivation of the methodology presented in this document.

Two-way paging is a new industry within the telecommunications realm. Significant distinction of the new system is that it allows an end user to respond to a message from their hand-held messaging unit, rather than having to make a telephone call. The system also benefits service providers, those who sell messaging services to the end user, by reducing their infrastructure utilization for both local and national service.

Infiltration into the market is a challenge that faces this and any new technological advancement. One strategy to address this issue is to provide a proliferation of products into the market quickly. If successful, the strategy will generate first-mover advantage, establish brand recognition, and create an industry standard; all of which are very favorable to a company in a growing market.

Lastly, so as not to violate any proprietary or confidentiality policies within Motorola, Inc., figures and data within this document are representative only. Points demonstrated by the methodology and the case study will still be valid and are not affected by the adjustment in data.

2. Prior Literature

The literature search focuses on three main areas: documents supporting the strategy of using modularity for rapid product development, examples of product platforms in industry, and structured methodologies for achieving said strategy. Examining these areas identified where work needed to be performed in the field of product architecture decision-making.

Much of the recent literature supports the notion of using modularity as a method for rapid product (family) development with reduced costs due to re-use. Smith and Reinertsen [1991] state that not enough companies utilize a product's architecture for rapid time to market. They recommend planning an expandable architecture that will allow for anticipated variations. Pine [1992 and 1993] adds to this concept and coins the term "mass customization" to define such a strategy. The goal of mass customization is to achieve both economies of scale and scope by using product modularity. Pine states that companies can achieve economies of scale by standardizing components within the product family, and then using these components in different combinations to create various products and, thereby, achieving economies of scope. Michael J. Wicken, president and CEO of Boston Digital, also agrees with this strategy. He states that it allows Boston Digital to "provide customers with machines as they like it, when they want it" [Vasilash 1994]. Pawar, et al. [1994] build on these thoughts by highlighting a case study of a "family" of stoves and express the benefits of using this strategy to bring a product family to market quicker than any competitors. Wu, et al. [1995] tend to focus more on the cost advantages than the rapid release factor associated with such a strategy. They discuss the concept of using modularity as a method to satisfy product variant constraints while lowering the average unit cost of the product family. They declare that this is especially important to small and medium-sized companies where resources are critical. Meyer and Utterback [1993] emphasize tracking a company's core competencies over different phases of product family development. Although these authors highlight a different area of consideration when discussing modularity, they do mention that a "strong platform...facilitates the far more rapid development of specific product variations."

Several examples of modular designs are used as illustrations within the literature. The more significant examples are from General Motors, Nippondenso, Black & Decker, and Sony. General Motors investigated a modular strategy emphasizing standardization to eliminate 67 of the 131 axles in their truck line [Fonte 1994]. Through modularity, Nippondenso can generate 288 different types of gauges after they standardized 48 modules into 16 and implemented a combinatorial strategy [Whitney 1993]. Black & Decker used the same strategy for cost reducing motorized products [Pine 1992 ; Meyer and Utterback 1993]. Lastly, using only three product platforms, Sony was able to have over 180 different product variations of the "Walkman" on the market in 1990 with nearly half of them being introduced in the preceding twelve months. Each platform changed about every eighteen to twenty-four months [Wheelwright and Clark 1992].

A gap in the literature is found in two areas: methods and timing. Structured methods for determining architecture are difficult to find in the literature [Pimmler and Eppinger 1994]. Ulrich [1995] supports this view by emphasizing the need for the development of decision support models. To answer the request, structured methods are starting to be developed. Two cases can be found in Pimmler and Eppinger [1994] and Fonte [1994]. Unfortunately, this leads to the next deficiency in the literature- timing. The methods described in the cited literature are performed AFTER several products are already on the market. In other words, modular decision making was performed in hindsight.

In contrast, this author intends to reduce the gap in methods and timing by providing a structured methodology that lays a foundation for product family planning BEFORE the product(s) are released into the market. In essence, the methodology takes the form of foresight versus the typical hindsight.

3. Motorola: Case Definition

Product architecture decisions are based on several issues that play a significant role in the strategy and goals of the development team and the company as a whole. Some of the more significant issues include product change, product variety, component standardization, product performance, manufacturability, and product development management [Ulrich and Eppinger 1995]. For the sample case, Motorola has chosen a strategy that utilizes modular design to achieve product proliferation. All of the above issues are of particular concern, but more so is the relationship of product variety and component standardization to product architecture. Inherent in these issues is the concept of product family scope, or which market segments will be targeted by the products.

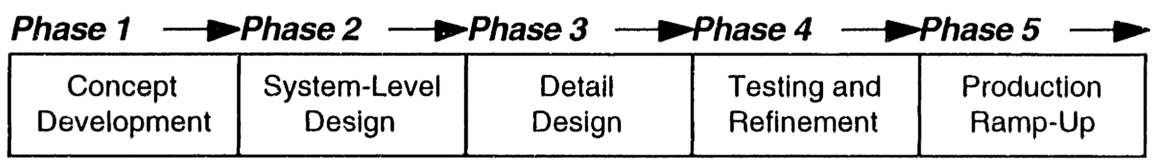
For Motorola, the initial scope consists of three large segments that can utilize the new two-way technology: Personal Messaging Units (PMUs), Personal Computer Messaging Card International Association (PCMCIA), and Original Equipment Manufacturers (OEMs). PMUs are what the general population refers to as "two-way pagers." A PCMCIA unit is a thin card that acts as a wireless modem when inserted into a laptop computer port. Finally, OEMs are manufacturers that purchase a "black box" from Motorola, insert it into their product, and then sell it. The "black box" contains basic paging functionality which could also be viewed as a generic pager "kit." An example of this might be an automotive company. The automobile manufacturer may buy the "black box", place it in the vehicle, and then sell the entire vehicle.

Now that the scope has been bounded, analysis can begin regarding the product family architecture. The following sections will proceed through the methodology in a step-by-step manner using the above case as an example.

4. Methodology

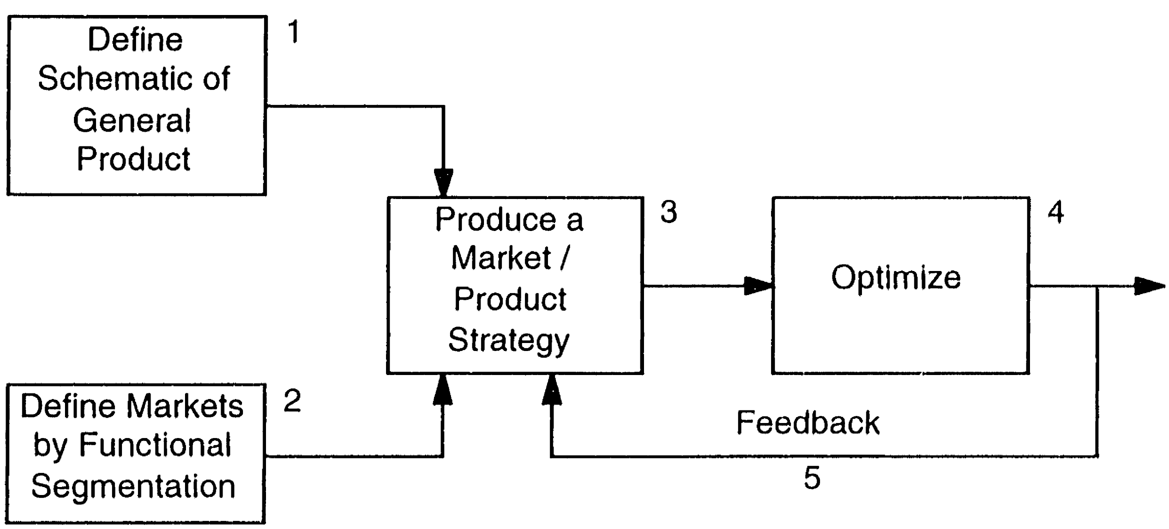
Figure 1 provides an initial frame of reference as to when architecture decisions are made in the product development cycle [Ulrich and Eppinger 1995]. The process which this author has developed should be performed in "Phase 2: System-Level Design." The significance of the placement is due to the need of having both the market segments and the general product concept (but not the detail design) established.

Figure 1. Product Development Cycle



Five steps define the new methodology for developing a product family's architecture. The steps are 1) Define schematic of the general product; 2) Define markets by functional segmentation; 3) Produce a market/product strategy; 4) Optimize; and 5) Feedback. Figure 2 contains a graphical representation of the process.

Figure 2. Methodology Overview



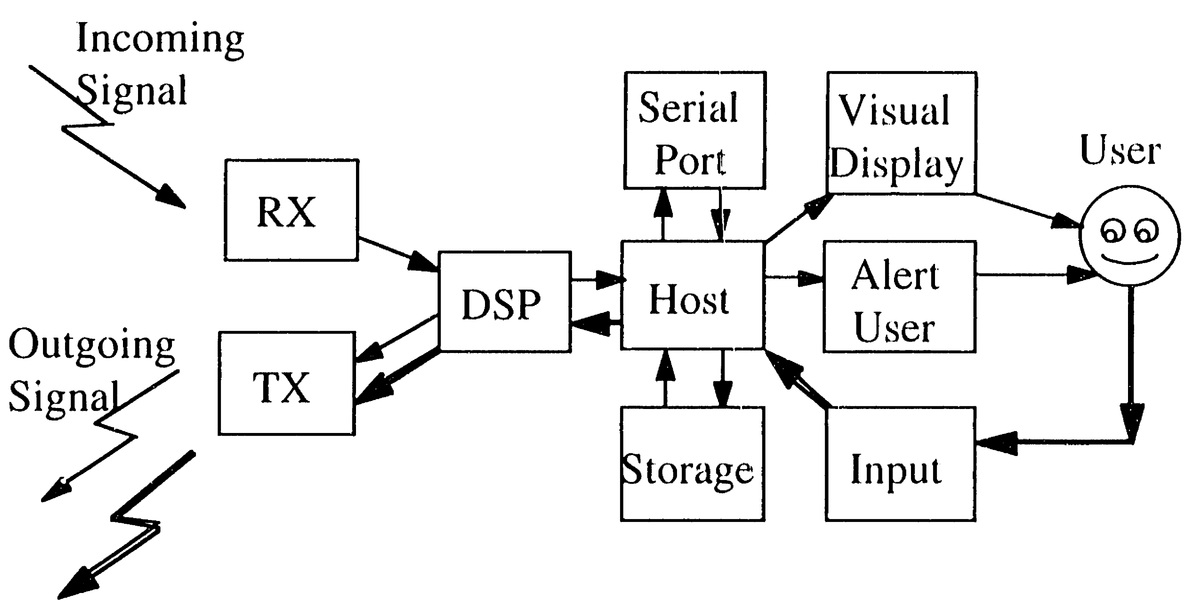
The process closely mimics the fusion model described in Dutson [1995]. The fusion model obtains its name by the fusion of market needs with a solution concept into a new product idea.

4.1. Step 1: Define Schematic of General Product

Most of Step 1 should already be completed by the actions taken in "Phase 1: Concept Development" described in Figure 1. Some of the components will have already been selected, while others will still be labeled as functions with no concepts linked to them. There are several methodologies that can be used to derive the schematic.

For the Motorola example, this author uses a process defined in Ulrich and Eppinger [1995]. The process includes having the schematic reflect the best representation to date and, thus, may contain both functional and physical components. The process also states that the schematic should not include every detail. These details will be addressed later in the development cycle.

Figure 3. General Schematic of a PMU

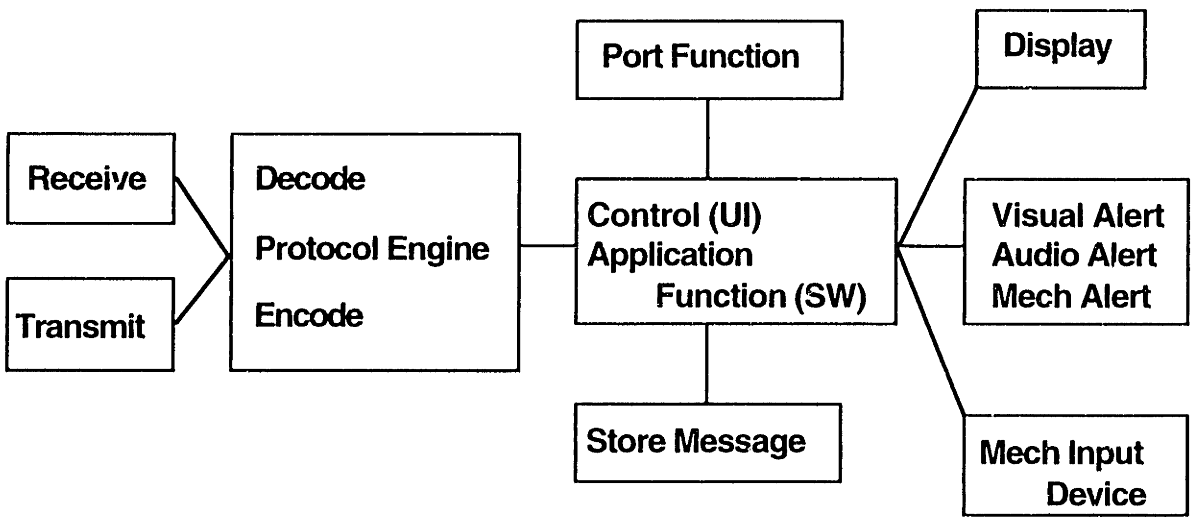


Text	Description	Text	Description
TX	Transmitter	Storage	Information Storage
RX	Receiver	Visual Display	Visual Display
DSP	Digital Signal Processor	Alert User	Alert User
Host	Host Processor	Input	Input Mechanism
Serial Port	Serial Port	User	Happy User

Figure 3 illustrates the general architecture of a PMU. Arrows between the blocks denote information flow. Double arrows indicate the flow of data that was entered from the user. Each block represents either a function or a generalized component.

From the general schematic diagram (Figure 3) a more functional representation can be made. In Figure 4, the blocks from Figure 3 are replaced with their corresponding function(s). The blocks remain in the same relative locations in the diagram to aid in the transition from Figure 3 to Figure 4.

Figure 4. Functional Representation



This breakdown in functional and physical units has established the elemental units for the analysis. In the following steps of the methodology, these units will be coupled and decoupled within the product architecture.

4.2. Step 2: Define Market by Functional Segmentation

There are several different ways to segment a market. Some of the more common ways are by age, professional status, or geography. Ideally, one wants to segment a market by criteria that would result in the most effective analysis. In Motorola's case, this author is examining product architecture, so divisions in the market will be based on the desired/required functions of each segment.

Separating a market into functional segments entails dividing the market into groups requiring the same product function(s). Table 1 illustrates a method to aid in the grouping process.

Table 1. Functional Segmentation of Market Segments

Customer Functions	PMU			PCMCIA	OEM	Functional Segment
	Low	Mid	High			
Receive	X	X	X	X	X	A
Transmit	X	X	X	X	X	A
Decode Message	X	X	X	X	X	A
Encode Message	X	X	X	X	X	A
Protocol Control (SW)	X	X	X	X	X	A
Power Unit	X	X	X	X	X	A
House Unit	X	X	X	X	X	A
External Info Transfer	X	X	X		X	B
UI Control (SW)	X	X	X		X	B
Alert User Visually	X	X	X			C
Alert User Audibly	X	X	X			C
Alert User Mechanically	X	X	X			C
Display Information Visually	X	X	X			C
Input Information (Mechanical)	X	X	X			C
Application Function (SW)	X	X	X			C
Store Message	X	X	X			C

In Table 1 customer functions are listed on the left. Each of the targeted market segments are specified as columns. For Motorola, the PMU market is very large and is divided even further into low, middle, and high tiers. If a market segment requires one of the functions on the left, then an "X" is placed in the column. Once all of the columns under the market segments are accurately noted with either an "X" or a blank, then a "sort" is performed on the table which groups the functions horizontally. Lines denoting horizontal groupings are placed at the end of the columns and are labeled in Table 1 as Functional Segments A, B, and C.

By grouping the segments in this manner, one can examine the market in terms of common functions and begin to notice opportunities for design re-use. The next step in the process will expand this chart and align the groupings with a marketing strategy.

4.3. Step 3: Produce a Market/Product Strategy

Step 3 is where the direction for the next family of products and its associated architecture is established. The process builds on Table 1 discussed in the last section. Within this step, marketing strategies come together with the results of Step 1 and 2 to arrive at an initial product family portfolio.

In the last step, tiering was introduced in the PMU market segment. What tends to happen in such cases is that the products do not change in functionality, but in fact change in the *degree* of functionality between tiers.

Figure 5. Change Mapping for Visual Display

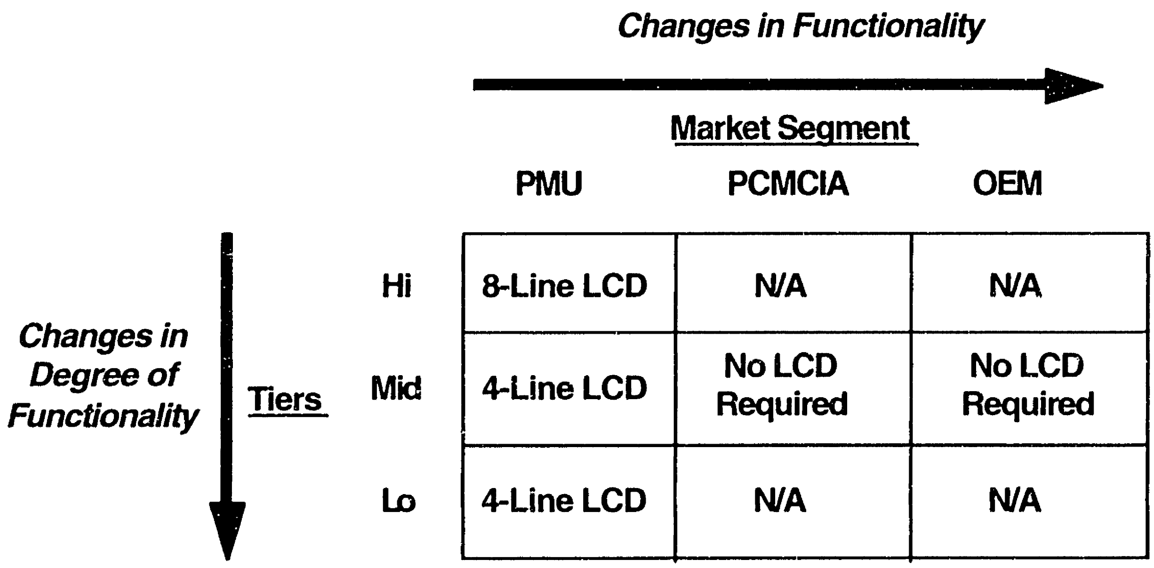


Figure 5 illustrates how tiering a market segment can change the degree of functionality and not the functionality itself. Between the market segments of PMU, PCMCIA, and OEM, the requirement of having an LCD changes. Only the PMU segment requires such a device. On the other hand, as one moves down the PMU column, the function of having a LCD does not change. What does change is the degree of functionality of that LCD. In this case the degree of functionality changes from an 8-line display for the PMU High-Tier to a 4-line display for the PMU Low-Tier.

Table 2 is formatted to accommodate product variety provided by tiering as well as the outputs from previous steps. The first column is labeled as "Functional or Physical Unit," and the number in each block represents a component option for that unit. For instance, the horizontal row next to "Display Information Visually" reads "1, 1, 2, X, X." This indicates that the Low and Mid-Tier PMU both use Option 1, the High-Tier PMU uses Option 2, and the PCMCIA and OEM do not require this function. From the discussion of Figure 5, Option 1 represents a "4-Line LCD," and Option 2 represents an "8-Line

Display." Options change for each "Functional or Physical Unit" and are listed in the "Options Description" column. Note that in rows where all "1's" are listed, each group uses the same component.

Table 2. Option Chart

Functional Or Physical Unit	PMU Low	PMU Mid	PMU High	PCMCIA	OEM	Options Description
Receive	1	1	1	1	1	
Transmit	1	1	1	1	1	
Application Function (SW)	1	2	3	X	X	Functionality: Lo,Mid,Hi
Decode Message	1	1	1	1	1	
Encode Message	1	1	1	1	1	
UI Control (SW)	1	1	1	X	1	
Protocol Control (SW)	1	1	1	1	1	
Store Message	1	2	3	X	X	Capacity: Lo,Mid,Hi
External Info Transfer	1	1	1	X	1	
Alert User Visually	1	1	1	X	X	
Alert User Audibly	1	1	1	X	X	
Alert User Mechanically	1	1	1	X	X	
Input Information	1	1	2	X	X	6 Button, Alpha Pad
Display Information Visually	1	1	2	X	X	4 line, 8 line
House Unit	1	2	3	4	5	"Look": 1,2,3,4,5
Power Unit	1	1	1	2	2	Battery, Source

Once the table is completed as in Table 2, it should be sorted by the option numbers in multiple columns. Table 3 is the result of a sort performed on Table 2.

Table 3. Sorted Option Chart

Functional Or Physical Unit	PMU Low	PMU Mid	PMU High	PCMCIA	OEM	Options Description
Receive	1	1	1	1	1	
Transmit	1	1	1	1	1	
Decode Message	1	1	1	1	1	
Encode Message	1	1	1	1	1	
Protocol Control (SW)	1	1	1	1	1	
External Info Transfer	1	1	1	X	1	
UI Control (SW)	1	1	1	X	1	
Alert User Visually	1	1	1	X	X	
Alert User Audibly	1	1	1	X	X	
Alert User Mechanically	1	1	1	X	X	
Power Unit	1	1	1	2	2	Battery, Source
Display Information Visually	1	1	2	X	X	4 line, 8 line
Input Information (Mechanical)	1	1	2	X	X	6 Button, Alpha Pad
Application Function (SW)	1	2	3	X	X	Functionality: Lo,Mid,Hi
Store Message	1	2	3	X	X	Capacity: Lo,Mid,Hi
House Unit	1	2	3	4	5	"Look": 1,2,3,4,5

Table 3 is a very significant table; one can begin to recognize natural groupings emerge by the way it is structured (sorted by option number). For instance, the horizontal lines denote sectioning according to shared functions. This grouping is typically used when there are only "1's" in the rows.

Special ways of grouping functional units are necessary when different option numbers are involved. Tables 4 through 6 are the bottom section of Table 3 with different grouping methodologies illustrated. Table 4 illustrates a strict modular design where each "option" defines a module. Table 5 demonstrates a strict integral design where each drawn box defines a module, and there is a one-to-one correspondence between each module box and each product. Table 6 denotes a "mixed" architecture where the grouping is a combination of both modular and integral grouping schemes.

Table 4. Modular Grouping

Power Unit	1	1	1	2	2	Battery, Source
Display Information Visually	1	1	2	X	X	4 line, 8 line
Input Information (Mechanical)	1	1	2	X	X	6 Button, Alpha Pad
Application Function (SW)	1	2	3	X	X	Functionality: Lo,Mid,Hi
Store Message	1	2	3	X	X	Capacity: Lo,Mid,Hi
House Unit	1	2	3	4	5	"Look": 1,2,3,4,5

Table 5. Integral Grouping

Power Unit	1	1	1	2	2	Battery, Source
Display Information Visually	1	1	2	X	X	4 line, 8 line
Input Information (Mechanical)	1	1	2	X	X	6 Button, Alpha Pad
Application Function (SW)	1	2	3	X	X	Functionality: Lo,Mid,Hi
Store Message	1	2	3	X	X	Capacity: Lo,Mid,Hi
House Unit	1	2	3	4	5	"Look": 1,2,3,4,5

Table 6. Mixed Grouping

Power Unit	1	1	1	2	2	Battery, Source
Display Information Visually	1	1	2	X	X	4 line, 8 line
Input Information (Mechanical)	1	1	2	X	X	6 Button, Alpha Pad
Application Function (SW)	1	2	3	X	X	Functionality: Lo,Mid,Hi
Store Message	1	2	3	X	X	Capacity: Lo,Mid,Hi
House Unit	1	2	3	4	5	"Look": 1,2,3,4,5

Since the methodology contains an optimization model based on these groupings, the modular grouping method is the most beneficial for the initial analysis. The selected grouping strategy may change once the results of the optimization model is fed back into the system (Step 5).

As suggested, the Motorola case uses modular grouping. Results from this process are in Table 7. The last column has now been transformed from "Options Description" to "Module." The letter in the Module column now denotes the module(s) that will satisfy the corresponding function(s) in the first column. Again, located in the column under each product is a number that indicates which module will be used for each function in the first column. For instance, in the horizontal row for "Power Unit" the "1" corresponds to Module D, and the "2" corresponds to Module E.

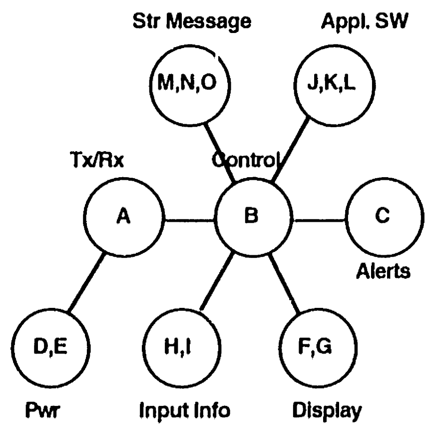
Table 7. Module Chart

Functional Or Physical Unit	PMU Low	PMU Mid	PMU High	PCMCIA	OEM	Module
Receive	1	1	1	1	1	A
Transmit	1	1	1	1	1	
Decode Message	1	1	1	1	1	
Encode Message	1	1	1	1	1	
Protocol Control (SW)	1	1	1	1	1	
External Info Transfer	1	1	1	X	1	B
UI Control (SW)	1	1	1	X	1	
Alert User Visually	1	1	1	X	X	C
Alert User Audibly	1	1	1	X	X	
Alert User Mechanically	1	1	1	X	X	
Power Unit	1	1	1	2	2	D,E
Display Information Visually	1	1	2	X	X	F,G
Input Information (Mechanical)	1	1	2	X	X	H,I
Application Function (SW)	1	2	3	X	X	J,K,L
Store Message	1	2	3	X	X	M,N,O
House Unit	1	2	3	4	5	P,Q,R,S,T

Another significant architecture issue can be addressed using Table 7 - the interfacing schematic. The table generates two heuristics which apply to interfacing. The first states that if the option number changes while moving horizontally across the row, then the interface between the options (modules) and the module to which both attach should be standardized. For instance, Module D or Module E can satisfy the function denoted as "Power Unit." Since all products need either Module D or Module E for that function (from Table 7), one would want to standardize the interface between Module D, Module E, and the main unit. Therefore, when manufacturing the product, one would choose either Module D or Module E to fill the slot designated for the component to satisfy the "Power Unit" function.

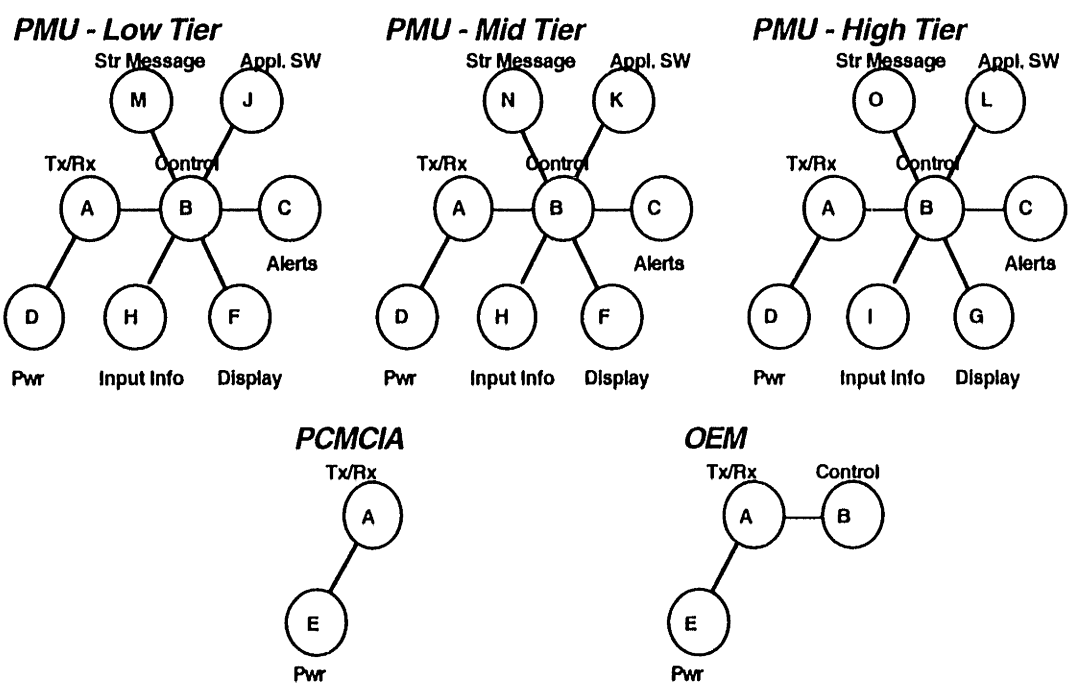
The second heuristic is a little more complicated and requires some data manipulation. First, one needs to define "base modules." These are modules where function(s) are satisfied by only one module. In Motorola's case, the base modules are A, B, and C. Secondly, for each function which has more than one module that satisfies it (e.g. Power Unit with Module D and Module E) is grouped into a "super module." Each base and super module will then have a "hierarchy number" assigned to it. The hierarchy number is determined by counting the number of products in which the module is used. For instance, "Power Unit" can be satisfied with Module D and Module E. These modules are then grouped into Super Module DE. Super Module DE is assigned a hierarchy number of 5, since Super Module DE is found in all of the products. Note that the hierarchy number is actually the number of blocks in the row that are filled with an "option number." Once all of the hierarchy numbers have been assigned, the second heuristic states that a super module with hierarchy number N should only interface with other super modules or base modules with a hierarchy number ≥ N, and the products containing the super module should be a subset of the products containing the module (base or super) to which it is attached. Again, using these heuristics with the example, Super Module DE should only attach to Module A. Figure 6 illustrates one of the possible product family architectures under these heuristics.

Figure 6. Preliminary Product Family Architecture



The heuristics allow all of the required modules to be present in all of the product family permutations without modifying interfaces. Figure 7 illustrates the permutations for Motorola's case.

Figure 7. Product Family Permutations



Although the tables so far have been very useful for generating a preliminary product family in terms of modules, the actual physical products are difficult to visualize. To aid in viewing the product family from a "product portfolio" perspective, Table 8 is included.

Table 8. Product Family Portfolio

Functional Or Physical Unit	PMU			PCMCIA	OEM	Module
	Low	Mid	High			
Receive	Yes	Yes	Yes	Yes	Yes	A
Transmit	Yes	Yes	Yes	Yes	Yes	
Decode Message	Yes	Yes	Yes	Yes	Yes	
Encode Message	Yes	Yes	Yes	Yes	Yes	
Protocol Control (SW)	Yes	Yes	Yes	Yes	Yes	
External Info Transfer	Yes	Yes	Yes	X	Yes	B
UI Control (SW)	Yes	Yes	Yes	X	Yes	
Alert User Visually	Yes	Yes	Yes	X	X	C
Alert User Auditly	Yes	Yes	Yes	X	X	
Alert User Mechanically	Yes	Yes	Yes	X	X	
Power Unit	Battery(D)	Battery(D)	Battery(D)	Direct Source(E)	Direct Source(E)	D,E
Display Information Visually	4 line(F)	4 line(F)	8 line(G)	X	X	F,G
Input Information (Mechanical)	6 Button(H)	6 Button(H)	Alpha Pad(I)	X	X	H,I
Application Function (SW)	Lo(J)	Mid(K)	Hi(L)	X	X	J,K,L
Store Message	Lo(M)	Mid(N)	Hi(O)	X	X	M,N,O
House Unit	Sport(P)	Stylish(Q)	Professional(R)	Flat(S)	Box(T)	P,Q,R,S,T

4.4. Step 4: Optimize

At this point a preliminary architecture has been established. The next step is to evaluate the architecture decision using business criteria. To address these decisions, a model describing the life of a product family is developed and optimized.

Optimization is used to determine the optimal product family in terms of profit over the life of the family. Due to the dependencies between resource availability, development costs, product life cycle, market size and growth per product, all of the initial products may not be selected for the optimal product mix. Output from the optimization will detail which products should be in the product mix, when they should be released into market, and how management should allocate resources toward module development in order to achieve the release schedule.

The scenario in which the model portrays can be described as follows. The preliminary architecture of the product family has been generated. Management must now choose how they will allocate their limited resources to develop the modules. There are several variables which management would find valuable if they could be incorporated into a model. The first is a constraint stating that all the modules of a product must be complete before the product can be released to the market. Second, markets for the five products should have different sizes as well as growth rates. Third, manufacturing costs of modules used in multiple products should take advantage of economies of scale. Finally, since revenues and expenditures are realized at different times, a discount rate must be used in all monetary calculations.

4.4.1. The Model

To accommodate such a scenario, the optimization model is developed as a two-stage integer model [Lindo 1994; Bradley, et al. 1977]. The first stage determines the optimal resource allocation for the development of Modules A through T, while the second stage examines cash flow after Products #1 through #5 (PMU Low-Tier, PMU Mid-Tier, PMU High-Tier, PCMCIA, and OEM, respectively) are released in the market.

4.4.1.1. Stage 1

Stage 1 of the model is set up as a linear model which optimizes the resource allocation needed to develop modules for the products. Input information to the model was divided into four factors. The four factors are man-hours required for each module to be developed, total cost associated with the development of each module, number of man-hours available, and discount rate.

Assumptions for Stage 1:

1. A new product platform (and hence family) will be introduced every 2.5 years; therefore, development resources are utilized for only 2.5 years before they are removed from the current platform.
2. Time is recorded on six-month intervals.
3. All costs are recorded at the end of a time interval.
4. Man-hours are generic and do not differentiate between engineering disciplines (e.g. electrical engineers and mechanical engineers are recorded as the same).
5. The maximum number of man-hours available is recorded for each six-month period.
6. Development costs for individual modules in each time period are proportional to the percent completed in terms of man-hours (i.e. development cost per module per six-month period = total module development cost * [allocated man-hours for a six-month period / total man-hours required for module to be completed]).

The above information is submitted to the model through Table 9 and Table 10 which are extracted from the spreadsheet model in Appendix A. Information regarding development costs (in current dollars) and man-hour requirements are placed in the shaded areas under Module Costing Information (Table 9). Available resources in terms of man-hours per period are located in the Resource Allocation Information (Table 10). All shaded areas indicate cells requiring inputs.

Table 9. Module Costing Information

	Development Costs		Manufacturing Costs	
Module	Total Man-hrs Required	Total Dev Cost	Base Mfg Cost	Slope
A	70,000	3,100,000	*750,000*	*35*
B	10,000	700,000	*390,000*	*4.5*
C	5,000	200,000	N/A	3
D	2,000	100,000	N/A	1
E	2,000	100,000	N/A	1
F	3,000	200,000	N/A	15
G	3,000	200,000	N/A	22
H	4,000	300,000	N/A	2
I	4,000	300,000	N/A	6
J	17,000	1,000,000	N/A	7
K	17,000	1,000,000	N/A	9
L	17,000	1,000,000	N/A	11
M	4,000	400,000	N/A	7
N	4,000	400,000	N/A	9
O	4,000	400,000	N/A	11
P	30,000	2,000,000	N/A	4
Q	30,000	2,000,000	N/A	4
R	30,000	2,000,000	N/A	4
S	30,000	2,000,000	N/A	4
T	25,000	1,500,000	N/A	3

Italics Indicate Modules Using Economies of Scale

Table 10. Available Resource Information

	Time Period (1/2 Years)				
	1	2	3	4	5
Available Man-hours	48,000	48,000	48,000	48,000	48,000

Table 11 is the output for Stage 1. The figures in the table denote the allocated resources for the development process. These figures are decision variables and will, therefore, be optimized when the model is solved.

Table 11. Resource Allocation

Modules	Time Period (1/2 Years)										Sum
	1	2	3	4	5	6	7	8	9	10	
A	21,000	48,000	1,000	0	0	No Development On This Platform During These Time Periods					70,000
B	0	0	10,000	0	0						10,000
C	0	0	0	5,000	0						5,000
D	0	0	0	2,000	0						2,000
E	2,000	0	0	0	0						2,000
F	0	0	3,000	0	0						3,000
G	0	0	0	0	0						0
H	0	0	0	4,000	0						4,000
I	0	0	0	0	0						0
J	0	0	0	3,000	14,000						17,000
K	0	0	17,000	0	0						17,000
L	0	0	0	0	0						0
M	0	0	0	0	4,000						4,000
N	0	0	0	4,000	0						4,000
O	0	0	0	0	0						0
P	0	0	0	0	30,000						30,000
Q	0	0	17,000	13,000	0						30,000
R	0	0	0	0	0						0
S	0	0	0	0	0						0
T	25,000	0	0	0	0						25,000
Total Work	48,000	48,000	48,000	31,000	48,000						
Dev Cost	2,631,200	2,299,173	3,461,903	2,390,182	3,921,916						

The objective function for Stage 1 is to minimize the cost for the development of the product family. Total development cost is a function of present worth [Steiner 1992] and a percentage of work performed on a specific module during various periods (Assumption #6). Since development costs are in current dollars, the typical exponential term for present worth calculations is not expressed in the equation. Equation (1) is the mathematical formula describing the relationship.

$$(1) \qquad Minimize TDC = \sum_{j=1}^{5} \sum_{i=A}^{T} \left[\frac{MHA(i,j)}{TMR(i)} * DC(i) \right]$$

Where:

TDC	= Present Worth of Total Development Cost for Product Family
j	= Period Number
i	= Module Letter
MHA(i,j)	= Man-hours Allocated to Module (i) in Period (j)
TMR(i)	= Total Man-hours Required to Complete Module (i)
DC(i)	= Total Development Cost for Module (i)

Constraints for Stage 1 consist of variable non-negativity and resource limitations in terms of man-hours available per period and man-hours required to complete a module. The non-negativity constraint is represented in Equation (2). Constraints for man-hours available per period and man-hours required to complete a module are represented in Equation (3) and Equation (4), respectively.

$$(2) \qquad MHA(i,j) \geq 0$$

$$(3) \qquad \sum_{i=A}^{T} MHA(i,j) \leq TMH(j)$$

$$(4) \qquad \sum_{j=1}^{5} MHA(i,j) \leq TMR(i)$$

Where:

i	= Module Letter
j	= Period Number
MHA(i,j)	= Man-hours Allocated to Module (i) in Period (j)
TMH(j)	= Total Man-hours Available in Period (j)
TMR(i)	= Total Man-hours Required to Complete Module (i)

4.4.1.2. Stage 2

Stage 2 of the model is set up as an integer model which optimizes the release of various products when all of their respective modules are completed. Key factors that are required to be submitted for this stage are manufacturing cost data and market/product information. Required inputs for manufacturing cost are data describing economies of scale for common modules and average manufacturing cost data for the remaining modules. The market/product information contains the number of modules which compose each product, data describing the market demand over time, and the selling price of each potential product.

Assumptions for Stage 2:

7. The total life of the product platform (and hence family) is 5 years (10 six-month periods). The 2.5 years of development effort is included in the 5 year period.
8. Time is recorded on six-month intervals.
9. All costs are recorded at the end of a time interval.
10. The discount rate is the same as in Stage 1.
11. Economies of scale are only evaluated on common modules (Modules A and B in Motorola's case).
12. For each module in which economies of scale are used, the total manufacturing cost for a specified demand is represented as a single linear equation where the slope and y-intercept are known [Bradley, et al. 1977].
13. The market demand for each product is represented by a single linear equation where the slope and y-intercept are known.
14. Once a product is released to the market, it cannot be taken off the market until the end of the 5 year period (when a new product platform is released).

The above information is submitted to the model through Table 12 and Table 13 which can also be found in full form in Appendix A. Shaded areas represent cells in which information must be placed. In Table 12, modules that utilize economies of scale are denoted by italicized cells. In these cases, "base mfg cost" is the y-intercept and "slope" is the slope of the linear mathematical equation representing total manufacturing cost for the quantity of modules manufactured. For modules not using economies of scale, only the slope is recorded; the y-intercept is zero (i.e. not applicable, N/A) [Bradley, et al. 1977]. Similarly, in Table 13 "market base" is the y-intercept and "market rate" is the slope of the linear mathematical equation representing market demand at period (t) where (t) is the number of periods the product is on the market.

Table 12. Module Costing Information

	Development Costs		Manufacturing Costs	
Module	Total Man-hrs Required	Total Dev Cost	Base Mfg Cost	Slope
A	70,000	3,100,000	*750,000*	*35*
B	10,000	700,000	*390,000*	*4.5*
C	5,000	200,000	N/A	3
D	2,000	100,000	N/A	1
E	2,000	100,000	N/A	1
F	3,000	200,000	N/A	15
G	3,000	200,000	N/A	22
H	4,000	300,000	N/A	2
I	4,000	300,000	N/A	6
J	17,000	1,000,000	N/A	7
K	17,000	1,000,000	N/A	9
L	17,000	1,000,000	N/A	11
M	4,000	400,000	N/A	7
N	4,000	400,000	N/A	9
O	4,000	400,000	N/A	11
P	30,000	2,000,000	N/A	4
Q	30,000	2,000,000	N/A	4
R	30,000	2,000,000	N/A	4
S	30,000	2,000,000	N/A	4
T	25,000	1,500,000	N/A	3

Italics Indicate Modules Using Economies of Scale

Table 13. Market/Product Information

Product	# of Modules	Sell Price	Market Rate	Market Base
1	9	120	40,000	50,000
2	9	135	40,000	50,000
3	9	150	35,000	10,000
4	3	65	25,000	25,000
5	4	70	35,000	20,000

Table 14 is the output for Stage 2 of the model. Both a decision variable set and dependent variable set are represented in the table. The decision variables are constrained as binary integers and will be optimized for periods 1 through 5 for all products. These are the periods in which products can be released by development to the market. The dependent variable set consists of the remaining cells and are equal to the value of the last decision cell in its row. This is necessary in order to maintain Assumption #14. A "0" or "1" denotes whether the product is on the market at each time interval. Zeros indicate that the product is not on the market, and ones indicate that the product is indeed on the market and selling.

Table 14. Product Introduction

	Time Period (1/2 Years)									
Product	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	1	1	1	1	1	1
2	0	0	0	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1

Also, hidden within the spreadsheet model are ten more binary decision variables. Similar to the values stated in Table 14, these variables indicate whether or not a module is being manufactured during each time period. These variables are only required for modules whose manufacturing costs are modeled using economies of scale. For Motorola's example, only Modules A and B have these variables. They can be found in Appendix A under Economies of Scale within the Data Analysis section.

Maximizing the profit for the product family is the objective function for Stage 2. Total profit for the product family is a function of present worth [Steiner 1992], market demand, selling price, and manufacturing cost. Since the objective function (profit) is rather complicated, the relationship model is divided into the six simpler mathematical representations: a simplified objective function, Equation (5); demand functions for both products, Equation (6), and modules, Equation (7); a revenue function, Equation (8); a total manufacturing cost function for modules utilizing economies of scale, Equation (9); and a total manufacturing cost function for modules not affected by economies of scale, Equation (10).

$$(5) \qquad Maximize TRV = \sum_{j=1}^{10}\left[\left(\frac{1}{1+d}\right)^{j} * \left(REV(j) - EMC(j) - TRM(j)\right)\right]$$

$$(6) \qquad DEM(k,j) = \left[\sum_{j=1}^{j} B(k,j)\right] * MR(k) + B(k,j) * MB(k)$$

$$(7) \qquad DEM(i,j) = \sum_{k_i} DEM(k,j)$$

$$(8) \qquad REV(j) = \sum_{k=1}^{5}\left[DEM(k,j) * SP(k)\right]$$

$$(9) \qquad EMC(j) = \sum_{i=A}^{B}\left[SL(i) * DEM(i,j) + B(i,j) * BMC(i)\right]$$

$$(10) \qquad TRM(j) = \sum_{i=C}^{T}[DEM(i,j) * BMC(i)$$

Where:

TRV	= Present Worth of Profit Generated by the Product Family in the Market
j	= Period Number
i	= Module Letter
d	= Discount Rate
k_i	= Products (k) Using Module (i)
REV(j)	= Total Revenue Generated in Period (j)
EMC(j)	= Total Cost of Modules for Period (j) Which Use Economies of Scale
TRM(j)	= Total Cost of Modules for Period (j) Which Do Not Use Economies of Scale
DEM(i,j)	= Demand for Product (k) in Period (j)
B(k,j)	= Binary Adjustable Variable Whose Value (0 or 1) Indicates Whether Product (k) is (1) or is not (0) on the Market in Period (j)
MR(k)	= Market Rate of Product (k)
MB(k)	= Market Base of Product (k)
DEM(i,j)	= Demand for Module (i) in Period (j)
SP(k)	= Sell Price of Product (k)
SL(i)	= Slope of Module (i)
B(i,j)	= Binary Adjustable Variable Whose Value (0 or 1) Indicates Whether Module (i) is (1) or is not (0) Being Manufactured in Period (j)
BMC(i)	= Base Manufacturing Cost of Module (i)

Constraints for Stage 2 are determined by the results from Stage 1; thus, the constraints are equations that link Stage 1 to Stage 2. The equations include: marking the decision variables as binary, Equation (11) and Equation (12); making sure that products are not released to the market prior to having all of their respective modules completed, Equation (13); and constraining the binary decision variable representing the manufacturing state of a module so that it corresponds with the binary decision variable representing the release state of the products that contain that module, Equation (14).

$$(11) \qquad B(k,j) = 0\_or\_1$$

$$(12) \qquad B(i,j) = 0\_or\_1$$

$$(13) \qquad B(k,j) * N(i_k) \le \sum_{k_i} \sum_{j=1}^{j} \frac{MHA(i,j)}{TMR(i)}$$

$$(14) \qquad B(i,j) * N(k_i) \ge \sum_{j=1}^{j} B(k,j)$$

Where:

B(k,j)	= Binary Adjustable Variable Whose Value (0 or 1) Indicates Whether Product (k) is (1) or is not (0) on the Market in Period (j)
B(i,j)	= Binary Adjustable Variable Whose Value (0 or 1) Indicates Whether Module (i) is (1) or is not (0) Being Manufactured in Period (j)
i_k	= Modules (i) in Product (k)
k_i	= Products (k) Using Module (i)
$N(i_k)$	= Total Number of Modules (i) in Product (k)
$N(k_i)$	= Total Number of Products (k) Using Module (i)
MHA(i,j)	= Man-hours Allocated to Module (i) in Period (j)
TMH(j)	= Total Man-hours Available in Period (j)
TMR(i)	= Total Man-hours Required to Complete Module (i)

4.4.1.3. Full Model

The full model is completed by combining the objective functions from both Stage 1 and Stage 2. This relationship is represented mathematically in Equation (15) below. No other governing equations are required.

$$(15) \qquad Maximize\,TFP = TRV - TDC$$

Where:

TFP	= Present Worth of Profit Generated by the Product Over the Life of the Platform.
TDC	= Present Worth of Total Development Cost for Product Family
TRV	= Present Worth of Profit Generated by the Product Family in the Market

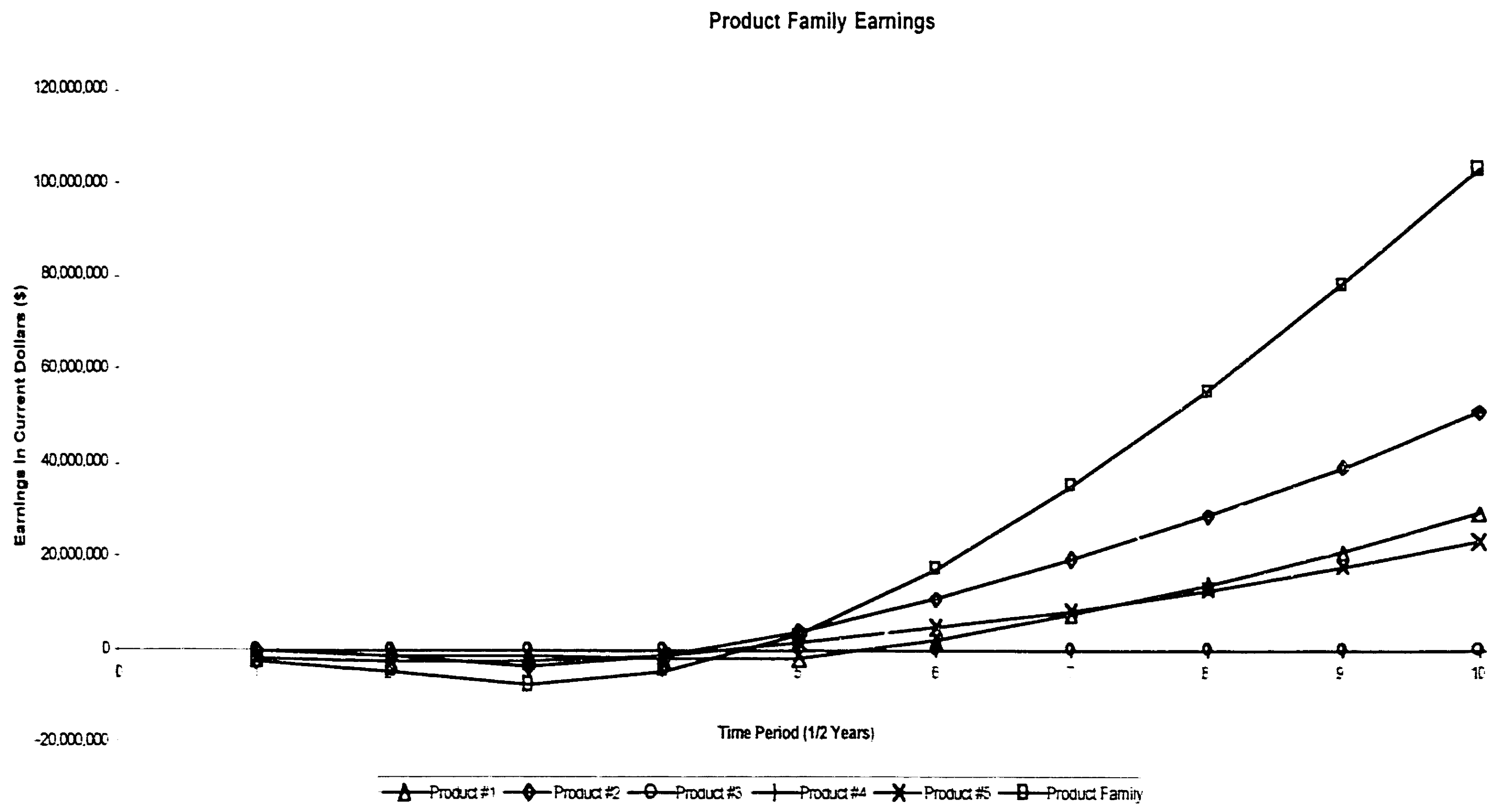
Since the two stages are now represented as a system, additional outputs can be examined. For this model, the system output is in the form of a product report. In the report, a financial summary is generated for each product for the 5 year period. Development costs for common modules are divided among the products that were released and require the modules. Break-even points for each product as well as the product family are illustrated in the table. The resulting Product Report for the previously discussed inputs is found in Table 15. A graphical representation for the product family earnings is in Figure 8.

Table 15. Product Reports

Product	Time Period (1/2 Years) 1	2	3	4	5	6	7	8	9	10	Totals
Product #1											
P1 Demand	0	0	0	0	90,000	130,000	170,000	210,000	250,000	290,000	1,140,000
Revenue	0	0	0	0	10,800,000	15,600,000	20,400,000	25,200,000	30,000,000	34,800,000	136,800,000
Dev Cost	322.400	766.391	391.560	557.403	3,921.916						5,959.670
Mfg Cost	0	0	0	0	7,362.391	10,205.000	13,345.000	16,485.000	19,625.000	22,765.000	89,787.391
Profit	-322.400	-766.391	-391.560	-557.403	-484.308	5,395.000	7,055.000	8,715.000	10,375.000	12,035.000	41,052.938
Present Worth*	-310.000	-708.571	-348.095	-476.471	-398.066	4,263.747	5,361.220	6,367.965	7,289.337	8,130.415	29,171.481
Cumulative PW*	-310.000	-1,018.571	-1,366.667	-1,843.137	-2,241.203	2,022.544	7,383.764	13,751.729	21,041.067	29,17[illegible].481	
Product #2											
P2 Demand	0	0	0	90,000	130,000	170,000	210,000	250,000	290,000	330,000	1,470,000
Revenue	0	0	0	12,150,000	17,550,000	22,950,000	28,350,000	33,750,000	39,150,000	44,550,000	198,450,000
Dev Cost	322.400	766.391	2,791.270	1,832.778	0						5,712.839
Mfg Cost	0	0	0	7,995.000	11,154.565	14,025.000	17,325.000	20,625.000	23,925.000	27,225.000	122,274.565
Profit	-322.400	-766.391	-2,791.270	2,322.222	6,395.435	8,925.000	11,025.000	13,125.000	15,225.000	17,325.000	70,462.596
Present Worth*	-310.000	-708.571	-2,481.429	1,985.045	5,256.581	7,053.557	8,378.094	9,590.309	10,696.883	11,704.149	51,164.618
Cumulative PW*	-310.000	-1,018.571	-3,500.000	-1,514.955	3,741.626	10,795.183	19,173.277	28,763.586	39,460.469	51,164.618	
Product #3											
P3 Demand	0	0	0	0	0	0	0	0	0	0	0
Revenue	0	0	0	0	0	0	0	0	0	0	0
Dev Cost	0	0	0	0	0						0
Mfg Cost	0	0	0	0	0	0	0	0	0	0	0
Profit	0	0	0	0	0	0	0	0	0	0	0
Present Worth*	0	0	0	0	0	0	0	0	0	0	0
Cumulative PW*	0	0	0	0	0	0	0	0	0	0	
Product #4											
P4 Demand	0	0	0	0	0	0	0	0	0	0	0
Revenue	0	0	0	0	0	0	0	0	0	0	0
Dev Cost	0	0	0	0	0						0
Mfg Cost	0	0	0	0	0	0	0	0	0	0	0
Profit	0	0	0	0	0	0	0	0	0	0	0
Present Worth*	0	0	0	0	0	0	0	0	0	0	0
Cumulative PW*	0	0	0	0	0	0	0	0	0	0	
Product #5											
P5 Demand	0	0	55,000	90,000	125,000	160,000	195,000	230,000	265,000	300,000	1,420,000
Revenue	0	0	3,850,000	6,300,000	8,750,000	11,200,000	13,650,000	16,100,000	18,550,000	21,000,000	99,400,000
Dev Cost	1,986.400	766.391	279.073	0	0						3,031.864
Mfg Cost	0	0	3,532.500	4,485.000	5,850.543	6,960.000	8,482.500	10,005.000	11,527.500	13,050.000	63,893.043
Profit	-1,986.400	-766.391	38.427	1,815.000	2,899.457	4,240.000	5,167.500	6,095.000	7,022.500	7,950.000	32,475.092
Present Worth*	-1,910.000	-708.571	34.161	1,551.470	2,383.142	3,350.934	3,926.875	4,453.557	4,933.915	5,370.735	23,386.217
Cumulative PW*	-1,910.000	-2,618.571	-2,584.410	-1,032.941	1,350.201	4,701.135	8,628.010	13,081.567	18,015.482	23,386.217	
Product Family											
Demand	0	0	55,000	180,000	345,000	460,000	575,000	690,000	805,000	920,000	4,030,000
Revenue	0	0	3,850,000	18,450,000	37,100,000	49,750,000	62,400,000	75,050,000	87,700,000	100,350,000	434,650,000
Dev Cost	2,631.200	2,299.173	3,461.903	2,390.182	3,921.916						14,704.373
Mfg Cost	0	0	3,532.500	12,480.000	24,367.500	31,190.000	39,152.500	47,115.000	55,077.500	63,040.000	275,955.000
Profit	-2,631.200	-2,299.173	-3,144.403	3,579.818	8,810.584	18,560.000	23,247.500	27,935.000	32,622.500	37,310.000	143,990.627
Present Worth*	-2,530.000	-2,125.714	-2,795.363	3,060.044	7,241.657	14,668.238	17,666.189	20,411.831	22,920.136	25,205.299	103,722.317
Cumulative PW*	-2,530.000	-4,655.714	-7,451.077	-4,391.033	2,850.624	17,518.862	35,185.051	55,596.882	78,517.018	103,722.317	

* PW=Present Worth Using Entered Discount Rate

Figure 8. Graphical Representation of Product Family Earnings



4.4.2. Product Architecture Analysis

The product architecture analysis proceeds in the following manner. A base case scenario is run through the optimization model to identify the optimal product introduction with respect to profit. Then, alterations to the base case are examined to check sensitivities with respect to fluctuations in certain parameters. Unfortunately, due to the integer nature of the linear model, typical linear sensitivity analysis techniques (i.e. shadow pricing) do not hold true; therefore, sensitivities have to be examined using various point cases [Lindo 1994].

Base case information was presented in the discussion of the model and will, therefore, not be reiterated in detail now. Also, Appendix A contains the spreadsheet model in its entirety. Summarized results from the base case analysis are listed in Table 16. The product introduction scenario, in order of release, is Product #5, Product #2, and then Product #1.

Table 16. Base Case Results

Variable Changed	Product Introduction Scenario (In Order of Release)	Profit (Present Worth)
Base Case	5,2,1	$103,722,317

Variations to the base case will be discussed on an individual basis and include changes in discount rate, selling prices, and available man-hours. A summary of the results with changes in discount rate are listed in Table 17. Results indicate that the product introduction scenario of 5,2,1 does not change when the discount rate is altered between 2% and 6% and is, therefore, not very sensitive to discount rate fluctuations.

Table 17. Sensitivity With Respect to Discount Rate

Variable Changed	Product Introduction Scenario (In Order of Release)	Profit (Present Worth)
Base Case	5,2,1	$103,722,317
Six-Month Discount Rate From 4% to 6%	5,2,1	$87,724,507
Six-Month Discount Rate From 4% to 2%	5,2,1	$122,812,356

Table 18 shows the sensitivity of the product introduction scenario and profit with respect to changes in selling price. Two types of variations are examined. The first variation consists of increasing and decreasing all selling prices by 20% at the same time. The second focuses only on changing the selling price of Product #4 which has not been selected for release in any scenario yet. In both cases, the product introduction scenario is still rather stable. Product #5, Product #2, and Product #1 consistently appear in each scenario except for when Product #4 receives a rather exorbitant price increase of 54%.

Table 18. Sensitivity With Respect to Changes in Selling Price

Variable Changed	Product Introduction Scenario (In Order of Release)	Profit (Present Worth)
Base Case	5,2,1	$103,722,317
20% Increase Of All Selling Prices	5,2,1	$167,856,779
20% Decrease Of All Selling Prices	5,1,2	$37,538,476
Selling Price Of Product #4 Set At $72 (10% Increase)	5,2,1	$103,722,317
Selling Price Of Product #4 Set At $100 (54% Increase)	4,2,1	$124,911,150

Results for the final sensitivity analysis are in Table 19. In this instance, analysis consists of varying the total man-hours available. Changes in man-hours available vary in increments of 10% from -20% to +20%. Results in this case are unlike the others; the product introduction scenario tends to be very sensitive to the amount of resources available. No two product introduction scenarios are the same in any of the variations.

Table 19. Sensitivity With Respect to Changes in Man-hours Available

Variable Changed	**Product Introduction Scenario (In Order of Release)**	**Profit (Present Worth)**
Base Case	5,2,1	$103,722,317
20% Decrease In Available Man-Hours (From 48,000 to 38,400)	2,5	$62,006,515
10% Decrease In Available Man-Hours (From 48,000 to 43,200)	5,2,4	$82,922,478
10% Increase In Available Man-Hours (From 48,000 to 52,800)	2,1,3	$129,59,052
20% Increase In Available Man-Hours (From 48,000 to 57,600)	5,2,3,1	$161,778,331

Table 20. Resource Constraint Evaluation Chart

Change In Available Man-Hours	Man-Hours Available Per Period	Total Man-Hours Available In Six-Month Period	Product Introduction Scenario (PIS)	Total Man-Hours Required For PIS
-20%	38,400	192,000	2,5	172,000
-10%	43,200	216,000	5,2,4	202,000
0% (Base)	48,000	240,000	5,2,1	223,000
10%	52,800	264,000	2,1,3	254,000
20%	57,600	288,000	5,2,3,1	281,000

The high sensitivity is explained by the system wanting to release as many products as possible with priority going to higher profit products. Table 20 illustrates the total number of man-hours available in a six-month period and the man-hours required by each product introduction scenario. The model attempts to utilize all of the man-hours available to develop products (assuming that the products to which the work is being allocated will make a profit). As capacity for development increases, more products are added to the product introduction scenario. The order by which these products are added to the product introduction scenario is dependent on the amount of profit that the product will generate through the entire system. For instance, with a 10% decrease in man-hours the product introduction scenario is 5,2,4 with only 8,000 man-hours unused. Once the capacity is increased to the base case, the new product introduction scenario is 5,2,1. Capacity has increased to a point where either Product #1 or Product #4 could be developed. Since the model maximizes profit, it selects the more profitable Product #1 over Product #4 for the product introduction scenario.

For Motorola's base case, the analysis results indicate that the optimal product introduction scenario consists of Product #5, Product #2, and Product #1. This product introduction scenario will now be forwarded to the next step in the methodology.

4.5. Step 5: Feedback

The final step in the methodology is Feedback. This is not a mandatory step, but should be at least discussed in order to understand the implications of the current architecture decisions.

In this stage the results from the optimization model are fed back into Step 3: Produce a Market/Product Strategy. The process of feeding back the optimal product introduction can change the preliminary product architecture. For instance, in Motorola's case, the optimal product introduction is Product #5, Product #2, and Product #1 (OEM, PMU Mid-Tier, and PMU Low-Tier). Knowing this information, Product #3 and Product #4 (PMU High-Tier and PCMCIA) will not be developed and will no longer influence the architecture grouping decisions. This may lead to integrating modules that were at one time separated due to the functional requirements dictated by the PMU High-Tier and PCMCIA products. For example, without these two products, Module A and Module B could be grouped as one. In the initial grouping this consolidation could not be performed due to the functional constraints of the PCMCIA product and Module B (see Table 7).

This feedback and reiteration process was considered for Motorola's case, but was not performed due to the high sensitivity to fluctuations in resources. In this case, flexibility was more important than making the architecture more integral. If fluctuations were to occur in available man-hours, then the product introduction scenario can be changed without significant redesign costs.

5. Conclusion

Structured methods for product architecture decisions are rather difficult to find, especially those that deal with planning a product family. This author describes an empirical methodology that aids decision making in situations emphasizing modular product architecture. Within the methodology, market needs and product design are brought together in a preliminary product family architecture. The methodology then tests the preliminary architecture to determine if the architecture is realistic with respect to business constraints. This is performed by modeling and optimizing the product family life cycle from start to finish. The process continues by feeding the optimal product introduction scenario back into the system where preliminary architecture decisions are modified to correlate with the new product mix. This process then repeats and eventually culminates into a product family architecture that reflects the needs of various market segments. The process also provides a management plan for the successful completion of the product family based on development operating constraints.

Future use of the methodology should reside in the strategic planning of a product family. The methodology is a tool used to examine modular product development as a system. The optimization model provides strategic managers and engineering managers with information that is beneficial to their respective roles. Strategic managers receive information on markets and resource allocation issues required for tactical planning. Engineering managers receive information on product architecture needed for engineering design and rapid product development. With the availability of this system-level information, the methodology addresses both business and engineering issues, and hence, provides a cross-functional tool for architecture decisions within a product family.

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Appendix A

Optimization Model for Product Architecture Decisions

Input Information

Module Costing Information

Module	Development Costs		Manufacturing Costs	
	Total Man-hrs Required	Total Dev Cost	Base Mfg Cost	Slope
A	70,000	3,100,000	*750,000*	*35*
B	10,000	700,000	*390,000*	*4.5*
C	5,000	200,000	N/A	3
D	2,000	100,000	N/A	1
E	2,000	100,000	N/A	1
F	3,000	200,000	N/A	15
G	3,000	200,000	N/A	22
H	4,000	300,000	N/A	2
I	4,000	300,000	N/A	6
J	17,000	1,000,000	N/A	7
K	17,000	1,000,000	N/A	9
L	17,000	1,000,000	N/A	11
M	4,000	400,000	N/A	7
N	4,000	400,000	N/A	9
O	4,000	400,000	N/A	11
P	30,000	2,000,000	N/A	4
Q	30,000	2,000,000	N/A	4
R	30,000	2,000,000	N/A	4
S	30,000	2,000,000	N/A	4
T	25,000	1,500,000	N/A	3

Italics Indicate Modules Using Economies of Scale

Available Resource Information

	Time Period (1/2 Years)				
	1	2	3	4	5
Available Man-hours	48,000	48,000	48,000	48,000	48,000

Economic Information

Discount Rate (Six-Month) =	0.04

Market/Product Information

Product	# of Modules	Sell Price	Market Rate	Market Base
1	9	120	40,000	50,000
2	9	135	40,000	50,000
3	9	150	35,000	10,000
4	3	65	25,000	25,000
5	4	70	35,000	20,000

Legend

Product #1 = PMU Low-Tier
Product #2 = PMU Mid-Tier
Product #3 = PMU High-Tier
Product #4 = PCMCIA
Product #5 = OEM

Output Information

Product Introduction

	Time Period (1/2 Years)									
Product	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	1	1	1	1	1	1
2	0	0	0	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	1	1	1	1	1	1	1	1

Resource Allocation

	Time Period (1/2 Years)											
Modules	1	2	3	4	5	6	7	8	9	10	Sum	
A	21.000	48.000	1.000	0	0						70.000	<=
B	0	0	10.000	0	0						10.000	<=
C	0	0	0	5.000	0						5.000	<=
D	0	0	0	2.000	0						2.000	<=
E	2.000	0	0	0	0						2.000	<=
F	0	0	3.000	0	0						3.000	<=
G	0	0	0	0	0						0	<=
H	0	0	0	4.000	0						4.000	<=
I	0	0	0	0	0			No Development On This			0	<=
J	0	0	0	3.000	14.000			Platform During These			17.000	<=
K	0	0	17.000	0	0			Time Periods			17.000	<=
L	0	0	0	0	0						0	<=
M	0	0	0	0	4.000						4.000	<=
N	0	0	0	4.000	0						4.000	<=
O	0	0	0	0	0						0	<=
P	0	0	0	0	30.000						30.000	<=
Q	0	0	17.000	13.000	0						30.000	<=
R	0	0	0	0	0						0	<=
S	0	0	0	0	0						0	<=
T	25.000	0	0	0	0						25.000	<=
Total Work	48.000	48.000	48.000	31.000	48.000							
Dev Cost	2.631.200	2.299.173	3.461.903	2.390.182	3.921.916							

Data Analysis

		<=	<=	<=	<=	<=					
Man-Hours Available		48.000	48.000	48.000	48.000	48.000					
Dev COST											
TOTAL2		2.631.200	2.299.173	3.461.903	2.390.182	3.921.916					
P1		<=	<=	<=	<=	<=					
Sum Compl		0	1	3	6	9					
On*#Mod		0	0	0	0	9					
P1 Demand	Omit	0	0	0	0	90,000	130,000	170,000	210,000	250,000	290,000
Rev	Omit	0	0	0	0	10,800,000	15,600,000	20,400,000	25,200,000	30,000,000	34,800,000
Mfg Cost-no A,B	Omit	0	0	0	0	3,510,000	5,070,000	6,630,000	8,190,000	9,750,000	11,310,000
P2		<=	<=	<=	<=	<=					
Sum Compl		0	1	5	9	9					
On*#Mod		0	0	0	9	9					
P2 Demand	Omit	0	0	0	90,000	130,000	170,000	210,000	250,000	290,000	330,000
Rev	Omit	0	0	0	12,150,000	17,550,000	22,950,000	28,350,000	33,750,000	39,150,000	44,550,000
Mfg Cost-no A,B	Omit	0	0	0	3,870,000	5,590,000	7,310,000	9,030,000	10,750,000	12,470,000	14,190,000
P3		<=	<=	<=	<=	<=					
Sum Compl		0	1	2	4	4					
On*#Mod		0	0	0	0	0					
P3 Demand	Omit	0	0	0	0	0	0	0	0	0	0
Rev	Omit	0	0	0	0	0	0	0	0	0	0
Mfg Cost-no A,B	Omit	0	0	0	0	0	0	0	0	0	0
P4		<=	<=	<=	<=	<=					
Sum Compl		1	2	2	2	2					
On*#Mod		0	0	0	0	0					
P4 Demand	Omit	0	0	0	0	0	0	0	0	0	0
Rev	Omit	0	0	0	0	0	0	0	0	0	0
Mfg Cost-no A	Omit	0	0	0	0	0	0	0	0	0	0
P5		<=	<=	<=	<=	<=					
Sum Compl		2	3	4	4	4					
On*#Mod		0	0	4	4	4					
P5 Demand	Omit	0	0	55,000	90,000	125,000	160,000	195,000	230,000	265,000	300,000
Rev	Omit	0	0	3,850,000	6,300,000	8,750,000	11,200,000	13,650,000	16,100,000	18,550,000	21,000,000
Mfg Cost-no A,B	Omit	0	0	220,000	360,000	500,000	640,000	780,000	920,000	1,060,000	1,200,000

Economies of Scale

		>=	>=	>=	>=	>=					
Sum P's		0	0	100	100	100					
Module A		0	0	1	2	3					
On/Off		0	0	1	1	1					
		>=	>=	>=	>=	>=					
Sum P's		0	0	100	100	100					
Module B		0	0	1	2	3					
On/Off		0	0	1	1	1					
Mfg-Cost(A,B)	Omit	0	0	3,312,500	8,250,000	14,767,500	18,170,000	22,712,500	27,255,000	31,797,500	36,340,000
PROFIT	Omit	-2,631,200	-2,299,173	-3,144,403	3,579,818	8,810,584	18,560,000	23,247,500	27,935,000	32,622,500	37,310,000
		-2,631,200	-2,299,173	-3,144,403	3,579,818	8,810,584	18,560,000	23,247,500	27,935,000	32,622,500	37,310,000
OBJECTIVE	103,722,317										

Product Reports

Product	Time Period (1/2 Years) 1	2	3	4	5	6	7	8	9	10	Totals
Product #1											
P1 Demand	0	0	0	0	90,000	130,000	170,000	210,000	250,000	290,000	1,140,000
Revenue	0	0	0	0	10,800,000	15,600,000	20,400,000	25,200,000	30,000,000	34,800,000	136,800,000
Dev Cost	322,400	766,391	391,560	557,403	3,921,916						5,959,670
Mfg Cost	0	0	0	0	7,362,391	10,205,000	13,345,000	16,485,000	19,625,000	22,765,000	89,787,391
Profit	-322,400	-766,391	-391,560	-557,403	-484,308	5,395,000	7,055,000	8,715,000	10,375,000	12,035,000	41,052,938
Present Worth*	-310,000	-708,571	-348,095	-476,471	-398,066	4,263,747	5,361,220	6,367,965	7,289,337	8,130,415	29,171,481
Cumulative PW*	-310,000	-1,018,571	-1,366,667	-1,843,137	-2,241,203	2,022,544	7,383,764	13,751,729	21,041,067	29,171,481	
Product #2											
P2 Demand	0	0	0	90,000	130,000	170,000	210,000	250,000	290,000	330,000	1,470,000
Revenue	0	0	0	12,150,000	17,550,000	22,950,000	28,350,000	33,750,000	39,150,000	44,550,000	198,450,000
Dev Cost	322,400	766,391	2,791,270	1,832,778	0						5,712,839
Mfg Cost	0	0	0	7,995,000	11,154,565	14,025,000	17,325,000	20,625,000	23,925,000	27,225,000	122,274,565
Profit	-322,400	-766,391	-2,791,270	2,322,222	6,395,435	8,925,000	11,025,000	13,125,000	15,225,000	17,325,000	70,462,596
Present Worth*	-310,000	-708,571	-2,481,429	1,985,045	5,256,581	7,053,557	8,378,094	9,590,309	10,696,883	11,704,149	51,164,618
Cumulative PW*	-310,000	-1,018,571	-3,500,000	-1,514,955	3,741,626	10,795,183	19,173,277	28,763,586	39,460,469	51,164,618	
Product #3											
P3 Demand	0	0	0	0	0	0	0	0	0	0	0
Revenue	0	0	0	0	0	0	0	0	0	0	0
Dev Cost	0	0	0	0	0						0
Mfg Cost	0	0	0	0	0	0	0	0	0	0	0
Profit	0	0	0	0	0	0	0	0	0	0	0
Present Worth*	0	0	0	0	0	0	0	0	0	0	0
Cumulative PW*	0	0	0	0	0	0	0	0	0	0	
Product #4											
P4 Demand	0	0	0	0	0	0	0	0	0	0	0
Revenue	0	0	0	0	0	0	0	0	0	0	0
Dev Cost	0	0	0	0	0						0
Mfg Cost	0	0	0	0	0	0	0	0	0	0	0
Profit	0	0	0	0	0	0	0	0	0	0	0
Present Worth*	0	0	0	0	0	0	0	0	0	0	0
Cumulative PW*	0	0	0	0	0	0	0	0	0	0	
Product #5											
P5 Demand	0	0	55,000	90,000	125,000	160,000	195,000	230,000	265,000	300,000	1,420,000
Revenue	0	0	3,850,000	6,300,000	8,750,000	11,200,000	13,650,000	16,100,000	18,550,000	21,000,000	99,400,000
Dev Cost	1,986,400	766,391	279,073	0	0						3,031,864
Mfg Cost	0	0	3,532,500	4,485,000	5,850,543	6,960,000	8,482,500	10,005,000	11,527,500	13,050,000	63,893,043
Profit	-1,986,400	-766,391	38,427	1,815,000	2,899,457	4,240,000	5,167,500	6,095,000	7,022,500	7,950,000	32,475,092
Present Worth*	-1,910,000	-708,571	34,161	1,551,470	2,383,142	3,350,934	3,926,875	4,453,557	4,933,915	5,370,735	23,386,217
Cumulative PW*	-1,910,000	-2,618,571	-2,584,410	-1,032,941	1,350,201	4,701,135	8,628,010	13,081,567	18,015,482	23,386,217	
Product Family											
Demand	0	0	55,000	180,000	345,000	460,000	575,000	690,000	805,000	920,000	4,030,000
Revenue	0	0	3,850,000	18,450,000	37,100,000	49,750,000	62,400,000	75,050,000	87,700,000	100,350,000	434,650,000
Dev Cost	2,631,200	2,299,173	3,461,903	2,390,182	3,921,916						14,704,373
Mfg Cost	0	0	3,532,500	12,480,000	24,367,500	31,190,000	39,152,500	47,115,000	55,077,500	63,040,000	275,955,000
Profit	-2,631,200	-2,299,173	-3,144,403	3,579,818	8,810,584	18,560,000	23,247,500	27,935,000	32,622,500	37,310,000	143,990,627
Present Worth*	-2,530,000	-2,125,714	-2,795,363	3,060,044	7,241,657	14,668,236	17,666,189	20,411,831	22,920,136	25,205,299	103,722,317
Cumulative PW*	-2,530,000	-4,655,714	-7,451,077	-4,391,033	2,850,624	17,518,862	35,185,051	55,596,882	78,517,018	103,722,317	

* *PW=Present Worth Using Entered Discount Rate*

Module Development Costs

Module	Time Period (1/2 Years)				
	1	2	3	4	5
A	930,000	2,125,714	44,286	0	0
B	0	0	700,000	0	0
C	0	0	0	200,000	0
D	0	0	0	100,000	0
E	100,000	0	0	0	0
F	0	0	200,000	0	0
G	0	0	0	0	0
H	0	0	0	300,000	0
I	0	0	0	0	0
J	0	0	0	176,471	823,529
K	0	0	1,000,000	0	0
L	0	0	0	0	0
M	0	0	0	0	400,000
N	0	0	0	400,000	0
O	0	0	0	0	0
P	0	0	0	0	2,000,000
Q	0	0	1,133,333	866,667	0
R	0	0	0	0	0
S	0	0	0	0	0
T	1,500,000	0	0	0	0
Total(Current $)	2,530,000	2,125,714	3,077,619	2,043,137	3,223,529
Total	2,631,200	2,299,173	3,461,903	2,390,182	3,921,916

Graphical Product Output

Time(1/2 Yrs)	0	1	2	3	4	5	6	7	8	9	10
Product #1		-310,000	-1,018,571	-1,366,667	-1,843,137	-2,241,203	2,022,544	7,383,764	13,751,729	21,041,067	29,171,481
Product #2		-310,000	-1,018,571	-3,500,000	-1,514,955	3,741,626	10,795,183	19,173,277	28,763,586	39,460,469	51,164,618
Product #3		0	0	0	0	0	0	0	0	0	0
Product #4		0	0	0	0	0	0	0	0	0	0
Product #5		-1,910,000	-2,618,571	-2,584,410	-1,032,941	1,350,201	4,701,135	8,628,010	13,081,567	18,015,482	23,386,217
Product Family		-2,530,000	-4,655,714	-7,451,077	-4,391,033	2,850,624	17,518,862	35,185,051	55,596,882	78,517,018	103,722,317