OPTIMAL SCHEDULING OF OVERLAPPING PHASES IN THE CONCURRENT/SIMULTANEOUS ENGINEERING APPROACH TO NEW PRODUCT DEVELOPMENT

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ABSTRACT

In this paper we suggest a linear programming model for determining the optimal scheduling of overlapping phases in the New Product Development Process when a concurrent/simultaneous engineering approach is being utilized. The model is developed in a logical fashion, and its use is illustrated via the solution of an example problem.

Keywords: New Product Development, Concurrent Engineering, Precedence Diagramming, Linear Programming Model

INTRODUCTION

Many firms routinely engage in the process of developing a mission statement and a set of strategies intended to ensure that they accomplish their stated mission. One of the first steps in the strategic planning process is making an assessment of external threats (TO the organization), opportunities (FOR the organization), and the internal weaknesses and strengths (OF the organization), i.e., a TOWS analysis [1]. A constant threat to an organization is competition. Competition is an ever-changing arena where firms vie for market share. Today, there are five primary arenas (or factors) that determine a firm's competitiveness. These factors are price, quality, product differentiation, flexibility, and time [2]. Time refers not only to how rapidly a company can deliver an ordered product to a customer, but also how fast it can introduce a new product into the marketplace.

In fact, competition vis-a-vis time to market is so intense that many firms, particularly those in volatile industries, believe (or at least operate under the assumption) that it is preferable to be first to the market with a "less than perfect" product than to be a late entry with a "near perfect" product. Once a product's market life cycle has begun, a competitor with a later entry, particularly in high technology and "fad" markets, assumes the very real risk that there simply may not be sufficient time or demand remaining until obsolescence to recover the costs invested in research and development. Furthermore, firms have been known to tout "vaporware" products simply to forestall competitor's efforts and/or to delay customer purchases. Such competitive pressures contribute to the ever increasing attention given to "time to market" considerations in the new product development arena [3].

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The length of the product introduction cycle (from concept to release) is affected by (1) the complexity of the product being developed, and (2) the "nature" of the new product development (NPD) process. The nature of the NPD process consists of (2a) the structure, operation, and management of the NPD process and (2b) the level of technology employed in the process. The specific nature of the NPD process will not only affect the length of the product introduction cycle, but can also have significant impact on the competitive factors of price and quality, and occasionally on product differentiation.

THE NEW PRODUCT DEVELOPMENT PROCESS

The New Product Development Process is typically described as a set of stages or phases each consisting of a number of major steps depending upon the nature of development taking place and the organization undertaking the development. The nature of new product development has been characterized by Rosenau and Moran as having four main categories depending upon the newness of the product to the firm (low, high) and the newness of the product to the marketplace (low, high) [4]. The four categories of new product development are depicted in Figure 1.

Newness to Marketplace → Newness to Organization ↓	Low	High
Low	Product Modification (Evolutionary Progression)	Product Line Extension (Internal Origin)
High	Product Clone (External Origin)	Original New Product (Revolutionary Design)

Figure 1: Four Categories of New Product Development[4]

The number of stages or phases in the NPD process and the labels attached to them vary widely from firm to firm. Burt & Soukup [5] discuss three phases (investigative, laboratory, and manufacturing/procurement), while General Electric lists 10 stages in its NPD process. Motorola's process has 4 stages, Calcomp has 5 stages, Kodak has 6 stages, and Xerox and Exxon Chemical both have 7 stages in their NPD process [6]. In order to capture the essence of the process and avoid a bias toward any of the organization specific procedures referenced above, we will utilize the following generic phases in our discussion and modeling of the NPD process:

- Phase 1. Concept (product definition)
- Phase 2. Preliminary Product Design (functional specifications)
- Phase 3. Detailed Product Design (engineering design and prototyping)
- Phase 4. Process Planning (volume, capacity, process selection)
- Phase 5. Process Design (equipment selection, layout)
- Phase 6. Process Implementation & Testing
- Phase 7. Commercialization (Product Release)

The methodology that follows can, however, be adapted to fit any number of specific phases.

Traditionally, the NPD process had been a linear sequence of functionally oriented phases, in which each phase in the project was completed in its entirety by the functional group responsible for it. The compilation of all work completed to that point was then passed "over-the-wall" to the next group/phase in the process sequence so that they could perform their specific segment of the overall task. The traditional "stovepipe" approach to NPD leads to many decisions being made in "isolation", e.g., setting tolerances without knowing what material and/or process would be utilized in manufacturing or not capturing customer inputs until the product was in sales. Unfortunately, decisions made in isolation frequently lead to "looping", i.e., the need to revisit upstream decisions once downstream decisions have been made. It has been suggested that the cost of implementing such design changes increases costs by a factor of 10 per phase where the change occurs, i.e., design change cost factor = $10^{(P-1)}$, where P is the number of the phase which the development process is in when a design changes is made. If a change would cost $X to implement during the first phase of the NPD process, then making that same change in the second phase of the process would increase costs by a factor of 10, i.e., $10X, while the same change in the fourth phase would likely raise costs by a factor of 1000, i.e., $1000X [7, p. 18]. Such an operational setting is often associated with a multi-layered hierarchical organizational structure with many communications paths and a requirement for a burdensome array of checks and approvals [8, p. 47]. This traditional NPD process is depicted in Figure 2.

Product Concept	Preliminary Product Specs	Detailed Product Specs	Process Planning	Process Design	Process Implementation	Product Release
Marketing	Product Design	Product Engineering	Process Engrg	Process Engrg	Manufacturing	

Figure 2: Traditional "Over-the-Wall" Approach to NPD

In the past decades, firms competing in the global marketplace have increasingly "scrapped" the traditional approach to NPD, and have adopted a concurrent engineering (CE) approach, along with rapid-prototyping techniques such as stereolithography and selective laser sintering in order to be more competitive with respect to the "time to market" factor. The concurrent engineering approach involves the use of cross-functional teams throughout all phases of the NPD process. When an idea for a new product is being considered, a NPD team consisting of representatives from marketing, product design, product engineering, process engineering, and manufacturing (and occasionally even suppliers and customers) is formed. This cross-functional team begins working in the conceptual phase and continues working together until the product is released (or the project is terminated). In addition, another distinguishing feature of the CE approach is the overlapping of phases, where each phase may start before its predecessor(s) is (are) finished. As shown in Figure 3, the basic concept involved in the concurrent/simultaneous engineering approach is that even if a subsequent phase takes longer to compete – by starting it prior to the completion of the preceding phase the overall duration of the project is reduced. In addition, costly engineering changes are reduced because of early interaction and coordination.

NPD Approach	P	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Traditional	P1	1	2	3	4												
	P2					1	2	3	4	5	6						
	P3											1	2	3	4	5	6
Concurrent	P1	1	2	3	4												
	P2			1	2	3	4	5	6	7							
	P3							1	2	3	4	5	6	7	8		

Figure 3: Concurrent Engineering Approach to NPD

Obviously, the determination of when enough (the critical portion) of a preceding phase has been completed so that the succeeding phase can be started is a key issue in the CE approach to NPD. Our objective in this paper is to suggest a model that accurately represents the factors and relationships that occur in the CE approach to NPD. Further, we wish to provide a procedure for planning the scope and determining the start schedules for the various phases in the NPD process in order to maximize the estimated profits that would result from completing the project by a given target date.

MODEL DEVELOPMENT

General Problem Statement & Assumptions

What should be the timing of product development phases in order to achieve a product release date that maximizes the gross profit derived from the introduction of a (new) product? Since Profits = Revenues - Costs, we present some assumptions regarding each of these elements.

A.) Assumptions regarding REVENUES:
- 1.) Total Market Revenues will be a function of the size and length of the market.
- 2.) Firm Revenues (FR) are a function of Firm Market Share (FMS) over the duration of the market.
- 3.) Firm Market Share (FMS) will be:
  - a.) a decreasing function of later entry date and position in the market, where position refers to first, second, etc.
  - b.) a decreasing function of the number of competitors in the market
  - c.) an increasing function of product quality, which is assumed to increase with the duration of the product development cycle.
  - d.) an increasing function of advertising and promotional expenditures - both in the absolute and relative to the total A&P expenditures in the market.

B.) Assumptions regarding COSTS:
- 4.) A certain "normal" level of costs will be incurred in conducting each of the generic product development phases, where normal is dictated by the firm's practices.
- 5.) Additional costs will be incurred if the scope/duration of individual phases are expanded/contracted during the product development cycle.
- 6.) The cost of making design changes increases "exponentially" during the product development / introduction cycle.

C.) Assumptions regarding CHANGES in normal activity times:
Three (3) things can impact the duration of activity (j):
- 7.) A decision to change the scope of activity (j), i.e., to do more or less than would "normally" be required
- 8.) A change in the scope of activity (i), where activity (i) is a predecessor of activity (j) – in these cases a direct relationship is assumed, i.e., changing the scope of an upstream activity will cause a "same direction" change in the scope of downstream activities
- 9.) The amount of work that remains to complete activity (i) as activity (j) is started will have an inverse impact on the "normal" duration of activity (j)

Specific Problem Statement, Assumptions, and General Solution Methodology

It is assumed that estimates of market size, market share and revenues for the new product have been established. Further, the development team has been provided with a target date for the completion of the project and estimates of the cost (or lost revenue) of missing the target date. Based on those assumptions we are ready to proceed with the development of a model. We are faced with a problem involving the following characteristics:

a.) precedence relationships among the phases of the project are not strictly finish-to-start, but rather are general in nature. In particular, the model must provide for start-to-start precedence, where a successor phase may start after a specific amount of time has elapsed since the start of its predecessor phase,

b.) the model must provide for tradeoffs among the duration and scope of a phase and the associated cost of conducting that phase,

c.) the constraints in the problem are linear, and the nature of the problem lends itself to a linear programming formulation [9].

Network Orientation

We will utilize the Activity-On-Node (A-O-N) network orientation in the development of our model. This orientation is depicted in Figure 4, where {i} represents the set of predecessors to phase [j], and {k} represents the set of successors to phase [j].

$$\{ i \} \rightarrow [j] \rightarrow \{ k \}$$

Figure 4: A-O-N Network Orientation

Precedence

Under the traditional finish-to-start (FS) precedence relationships, the precedence constraints would be expressed as:

$ES(j) \geq ES(i) + T(i)$, for all {i} where: $ES(j)$ = early start time for activity (j)

$LF(j) \leq LF(k) - T(k)$, for all {k} $LF(j)$ = late finish time for activity (j)

$LF(j) \geq ES(j) + T(j)$, for all [j] $T(j)$ = duration of activity (j)

However, in the CE approach, which incorporates overlapping activities, a subsequent activity may start BEFORE its predecessor(s) is (are) completed. The generalized precedence constraints for this scenario can be expressed as follows:

$$ES(j) \geq ES(i) + D(i,j) \quad (1)$$

$$ES(i) + T(i) <= D(i,j) + T(j) + 1 \quad (2)$$

$$D(i, j) \geq B(i,j) \quad (3)$$

where

$D(i,j)$ = the interval of time elapsing from the start of activity (i) to the start of activity (j)

$B(i,j)$ = the minimum interval (or threshold) required between the start of activity (i) and the start of activity (j); usually a percentage of $N(i)$

Changes in Scope and Duration

We assume that reducing the scope of an activity will decrease its duration, and that expanding the scope will increase its duration. These possibilities can be modeled as follows:

$$T(j) = N(j) - S^-(j) + S^+(j) \quad (4a)$$

$$S^-(j) \leq M^-(j) \quad \text{and} \quad S^+(j) \leq M^+(j) \quad (5)$$

where

$N(j)$ = normal duration of activity (j)

$S^+(j)$ = increase in duration of activity (j) resulting from scope expansion
$S^-(j)$ = decrease in duration of activity (j) resulting from scope reduction
M(j) = maximum (±) change in scope for activity (j)

We further assume that reducing/expanding the scope of one activity will reduce/expand the scope of related activities. This relationship can be expressed as follows:

$$T(j) = N(j) - Y^-(i, j) + Y^+(i, j) \qquad (4b)$$

where

$$Y^-(i,j) = \sum_{i \in p(j)} [I^-(i,j) * S^-(i)] \quad \text{and} \quad Y^+(i,j) = \sum_{i \in p(j)} [I^+(i,j) * S^+(i)]$$

and

$I^-(i,j)$ = the impact factor relating a reduction in scope for activity (i) to a reduction in scope (and/or duration) for activity (j)
$I^+(i,j)$ = the impact factor relating an expansion in scope for activity (i) to an expansion in scope (and/or duration) for activity (j)

Finally, we assume that the amount of work remaining to complete activity (i) when activity (j) is started [T(i) – D(i,j)] will have an direct impact on the increase in the duration of activity (j) because of the increased uncertainty regarding the final deliverables (specifications, etc.) from activity (i). This relationship can also be expressed as an inverse function of D(i,j).

$$T(j) = N(j) + Z(i,j) \qquad (4c)$$

where

$Z(i,j) = F(i,j) * [T(i) – D(i,j)]$ and F(i,j) is a factor relating the amount of time remaining to complete activity (i) to an increase in the duration of activity (j).

Objective

We have the expectation of a certain amount of profit if the NPD project can be completed at the target product release date (TPRD). Therefore, our first objective is to minimize the cost of completing the NPD project at the TPRD. However, additional profits will likely be accrued if the project is completed prior to the TPRD, or losses incurred if it is not feasible to complete the project by the TPRD, so multiple objectives will be investigated.

Our first objective can be expressed as follows:

$$\text{MIN } Z = \sum C^+(j) [S^+(j) + Y^+(i,j) + Z(i,j)] - \sum C^-(j) [S^-(j) + Y^-(i,j)] \qquad (6)$$

where

$C^+(j)$ = marginal cost associated with expanding the scope of activity (j)
$C^-(j)$ = marginal savings associated with reducing the scope of activity (j)

An alternative objective can be expressed as follows:

$$\text{MAX } Z = Q_1 d^- + \sum C^-(j) [S+Y+Z] - Q_2 d^+ - \sum C^+(j) [S+Y] \qquad (7)$$

where

Q_1 = marginal change in revenues caused by releasing product to market before TPRD
Q_2 = marginal change in revenues caused by releasing product to market after TPRD

$d^- =$ difference between actual (early) release date and target release date

$d^+ =$ difference between actual (late) release date and target release date

and

$$LF(n) = TPRD - d^- + d^+ \quad (8)$$

When the concurrent engineering approach is employed in the new product development process, the following model can be utilized to schedule the phases of the NPD process. The model is comprised of an objective function (6) or (7) subject to constraints (1) - (5) & (8).

New Product Development Scheduling Model

$$MIN\ Z = \sum C^+(j)\,[\,S+Y+Z\,] - \sum C^-(j)\,[\,S+Y\,] \quad (6)$$

or

$$MAX\ Z = Q_1{*}d^- + \sum C^-(j)\,[\,S+Y+Z\,] - Q_2{*}d^+ - \sum C^+(j)\,[\,S+Y\,] \quad (7)$$

subject to:

$$ES(j) \geq ES(i) + D(i, j) \quad (1)$$
$$ES(i) + T(i) <= D(j, k) + T(j) + 1 \quad (2)$$
$$D(i, j) \geq B(i, j) \quad \text{and} \quad D(i, j) <= T(i) \quad (3ab)$$
$$T(j) = N(j) - S^-(j) + S^+(j) + Y^+(i, j) - Y^-(i, j) + Z(i,j) \quad (4)$$
$$S^-(j) \leq M^-(j) \quad (5a)$$
$$S^+(j) \leq M^+(j) \quad (5b)$$
$$LF(n) = TD - d^- + d^+ \quad (8)$$

CONCLUSIONS

The NPD model can be used to profile the tradeoffs and determine the "cost optimal" starting point for subsequent phases in the new product development process. By using both objective functions an "envelope" of possibilities can be created.

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