DYNAMIC MODELS OF CONCURRENT ENGINEERING PROCESSES AND PERFORMANCE

by

FARINA BHUIYAN

Department of Mechanical Engineering

McGill University, Montreal

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**DYNAMIC MODELS OF
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Abstract

Mathematical and stochastic computer models were built to simulate concurrent engineering processes (CE) in order to study how different process mechanisms contribute to new product development (NPD) performance. Micro-models of various phenomena which occur in concurrent engineering processes, such as functional participation, overlapping, decision-making, rework, and learning, were included, and their effects on the overall NPD process were related to process span time and effort. The study focused on determining under what conditions CE processes are more favorable than sequential processes, in terms of expected payoff, span time, and effort, as dependent variables of functional participation and overlapping, and the corresponding trade-offs between more upfront effort versus span time reduction.

MODÈLES DYNAMIQUES DES PROCESSUS CONCURRENTIELS ET LA PERFORMANCE

Résumé

Des modèles mathématiques et informatiques ont étés développés pour analyser les processus d'ingéniérie simultanés. La recherche vise à étudier la contribution des charactéristiques des processus au performance de développement de nouveaux produits. Des micro-modèles de phénomènes prennant place dans les processus d'ingéniérie simultanés, tel que le travail d'équipe, la mise en parallèle des étapes, le processus de la prise de décisions, les perturbations, et l'apprentissage, ont étés étudiés. Les effets de ces micro-modèles sur l'espérance de la valeur utile maximale, les délais, et l'effort requis pour complèter le processus du développement de nouveaux produits ont également fait l'objet de la recherche. L'étude vise à définir les conditions dans lesquelles les processus d'ingéniérie simultanés sont plus performants que les processus d'ingéniérie séquentiels.

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1.0 INTRODUCTION

With the advent of factors such as globalization, time-based competition, and changing consumer tastes, the importance of introducing quality products onto the marketplace in a timely manner is emphasized. In response to current business conditions, product innovation is increasingly being used as a competitive strategy. The management of new product development (NPD) processes is a continual challenge facing organizations that develop complex, innovative products.

While market trends are forcing shorter product development times in order to meet time-to-market (TTM) goals, companies are trying to develop mechanisms to streamline their NPD processes. One approach that has provided much success towards achieving shorter TTM is concurrent engineering (Winner *et al.*, 1988; Clark and Fujimoto, 1991; Blackburn, 1991; Wheelwright and Clark, 1992; Smith and Reinersten, 1991). Concurrent engineering (CE) can broadly be defined as the integration of inter-related functions at the outset of the product development process in order to minimize risk and reduce effort downstream in the process, and to better meet customers' needs (Winner *et al.,* 1988). Multi-functional teams, concurrency of product/process development, integration tools, information technologies, and process coordination are among the elements that enable CE to improve the performance of the product development process (Blackburn, 1991).

The traditional NPD process suffers many setbacks. This process evolves in a sequential fashion, where phases follow one another serially, each one dominated by a single functional role. There is little or no cross-communication among various functions, and information generated from one activity gets handed off to the next only after its completion. The commonly encountered problems with this type of process are increased downstream effort, process span time, i.e., the start to finish time of the process, and costs.

CE, demonstrated in many cases to overcome the obstacles faced in the sequential process, considers the inherent interdependencies that exist between product and process design (Winner *et al.,* 1988; Tian *et al.*, 1998). CE uses two main mechanisms to manage the process: functional participation, which is increased information sharing from the start of a project and is described by the degree to which the representatives of the business and technical functions contribute time commitments to a new product development team, and overlapping of activities, which describes the degree to which the project's activities are executed in parallel (Blackburn, 1991). As such, CE converts the sequential process into a more cooperative/participative one, thus creating interdependencies between activities (Liker *et al.*, 1996). Though it becomes more challenging to coordinate such a process, the potential benefits can be considerable. Reduced effort (measured in person-hours) and span time (measured as the process start to finish time) are among the outcomes. While more effective management of interdependencies does lead to shortened span time, at times the price can be a higher cost of effort.

New product development is a critical, competitive component in many industries, and as such, effective management of the process is crucial. The challenge in implementing CE lies in organizing activities and functions in a highly interdependent process without adversely affecting performance. To this end, much research has been done to understand the benefits of CE, and how to achieve them through the coordination of information and activities. Although the results of these efforts are insightful in many respects, most address the problem within a limited context. The studies either focus only on a subset of the overall process, or on very few features of the process, and they provide an analysis of the local phenomena that take place in product development. Given that the development process is a large set of interconnected activities, managing the whole is much more complex. This calls for the development of a systematic framework that studies the essential features of product development processes dynamically to understand how key factors affect performance, and to evaluate the relative merits of various process structures (Tian *et al.*, 1998).

This thesis approaches the stated problem using both a mathematical and computer modeling methodology. An information processing view of organizations, and thus of product development, is assumed in this thesis. From this perspective, the product development process must go through a set of decision-making processes to transform information inputs into information outputs, which are used to develop tangible outputs, i.e., the end product(s) (Clark and Fujimoto, 1991; Galbraith, 1973). Therefore, the focus of the models is on the flow of information as it evolves from the beginning to the end of the development process, making the relationships between development activities more readily apparent.

1.1 OBJECTIVES OF THE RESEARCH

This thesis investigates and suggests policies for managing and coordinating a CE process, and assesses when the benefits of CE outweigh the costs as compared to a sequential process. The key factors that contribute to the performance of NPD processes are studied, and their relative impact on performance is analyzed in an attempt to uncover insights on how to manage activities within a given context. The study of functional participation and overlapping are the main concerns in this research, and these are analyzed through the theories of utility, probability, decision-making, and computer modeling. The objectives of the thesis are stated as follows:

- To introduce a new approach using an existing mathematical technique called the expected payoff method, which is the basis of decision theory, for studying and evaluating the performance of NPD processes. Payoff is defined as the usefulness that a decision has for an individual, and the expected payoff combines the value of the payoff and the probability of taking that decision. Interaction, which is defined as the degree to which a change in one action affects another, and overlapping are the key features of the model. The effect on the expected payoff is studied.
- To develop computer models of the overall development process, both sequential and CE, appropriately conceptualized while including as much detail as necessary, and representing the key process features.
- To study how changes in the key variables of the models affect span time and effort, both individually as well as systemically. The variables that are the main contributors to process performance are functional participation and overlapping.
- To determine under what conditions CE processes are more favorable than sequential processes, in terms of span time and effort, as dependent variables of functional participation and overlapping.

A number of mechanisms have been developed which allow the models to reflect the dynamic interactions that take place in NPD. Various process settings study how the models are affected in terms of span time and effort. A case study provides real-world data that makes the models more realistic, giving them the ability to be predictive and to provide a diagnostic for real-world situations. General guidelines or policies are developed and process improvement techniques are suggested.

Results of the mathematical model demonstrate that a CE process is more valuable than a sequential process, in terms of the expected payoff, when the level of interaction between team members is high, i.e., when the actions of one team member influences those of another.

Results of the computer simulations show that a sequential process with no functional participation always yields the poorest performance as compared to all other processes, in terms of span time and effort. However, a sequential process in which there is functional participation reduces span time. Although more information sharing in the early phases of the process increases upstream effort, it helps to reduce the total amount of effort required to perform development activities. Sequential processes are acceptable under conditions of low uncertainty, when the information that is required by team members is available to them, but with a low to moderate level of functional participation, and at a low cost of effort. Under conditions of high uncertainty, when information is incomplete, sequential processes with high levels of functional participation are preferable over overlapped CE processes.

For CE processes, overlapping without functional participation lessens process performance. A combination of functional participation and overlapping is the best strategy for reducing span time, although often at the expense of a high cost of effort. Under conditions of low uncertainty, a high level of overlapping with a minimum level of functional participation is preferred. Under conditions of high uncertainty, a high level of functional participation is always beneficial, though at the cost of high effort, while overlapping should be avoided.

1.2 APPROACH

Mathematical and stochastic computer modeling methodologies are used to study NPD processes. The models' structure, parameters, and properties are all introduced. The first part of the thesis studies the CE process mathematically. However, it becomes readily apparent that the mathematical approach requires too many simplifying assumptions, thus resulting in gross approximations to the problem. The second part of the thesis therefore takes a simulation approach, which, in this case, turns out to be a more effective method to study the problem at hand.

1.2.1 Expected Payoff Method

The expected payoff method is the basic principle of decision theory, and is presented in this thesis as a new application of an existing methodology for studying development processes, using probabilistic, decision theoretic models to evaluate performance. Under this framework, the mathematics which describe the micro-processes, such as information sharing between team members and overlapping of activities, and their relationships with the macro-process performance in terms of expected payoff (where the macro-process is the overall development process), are described. Network diagrams are presented as a formalism for expressing product development processes.

The fundamental concept of the model is based on the premise that team members make decisions or choose actions that maximize the payoff (utility or usefulness) that their actions bring to the team. Team members must obtain, process, and communicate information to one another to make decisions that will optimize their performance.

The network diagrams that depict teams, their organization, and their actions and interactions, are developed, mathematically described, and evaluated through the 'expected payoff' method. This is introduced through a simple application to a sequential and a CE process. CE is studied in terms of functional participation, i.e. interaction, and overlapping of activities.

1.2.2 Stochastic Computer Modeling Method

The second part of the thesis studies product development processes through stochastic computer models to examine how span time compression and reduction in effort can be achieved. This approach was introduced to overcome some of the limitations presented in the mathematical approach, and it allows for a more detailed analysis. A case study provided much of the data used to develop the models. Insight is gained concerning favorable conditions for using CE by studying how functional participation in early phases of the process and overlapping of activities help to reduce span time and effort.

1.2.3 Organization of Thesis

The thesis is organized in eight chapters as follows. Chapter 2.0 discusses the existing literature, and highlights the contributions of the thesis. Chapter 3.0 explains the characteristics of NPD processes. In Chapter 4.0, the expected payoff method is described and the results of the mathematical analysis are presented. Chapter 5.0 shows how the NPD processes described in the third chapter are translated into the computer models. The results of the computer simulation are detailed in Chapter 6.0, and Chapter 7.0 discusses research and managerial implications. Finally, in Chapter 8.0 of the thesis, conclusions and paths for future research are presented.

2.0 LITERATURE REVIEW

In this chapter, an extensive review of the relevant theoretical and analytical research is presented. In all approaches, an information processing view of product development processes is taken, where information is transformed and communicated among organizational participants who execute development activities in order to meet organizational objectives (Clark and Fujimoto, 1991).

In the existing literature, three types of information dependencies among activities have been identified: independence, sequential dependence, and mutual interdependence (Krishnan *et al.*, 1997). *Independence* refers to activities that are capable of being completed on their own without the need to obtain information from other activities. *Sequential dependence* refers to a one-way transfer of information between activities. For example, in the case of two activities, A and B, B depends on A to obtain information that will allow activity B to begin, but A can be executed independently of B. Finally, *mutual interdependence* refers to the case when activities reciprocally depend on one another for information.

Various analytical approaches to studying CE processes have been developed; most have been evaluated through the development of micro-models of the development process, consisting of an upstream activity A, and a downstream activity B, and they describe the information exchange patterns between the two activities. Significant contributions in this area will be discussed in the following sections.

2.0.1 Evolution and Sensitivity

Krishnan *et al.* (1997) developed a deterministic model based on properties of the design process that help to determine when and how two development activities should be overlapped (Figure 1). These properties are defined as 'upstream information evolution' and 'downstream iteration sensitivity'. The former is the rate at which upstream information converges to a final solution, and the information is modeled as an interval that gets refined over time. Sensitivity describes how vulnerable the downstream activity is to any changes in the upstream information, and is defined by the time needed by the downstream activity to incorporate the changes, which represents rework. Different patterns of information exchange between two activities, represented by the arrows in the diagram, are studied.

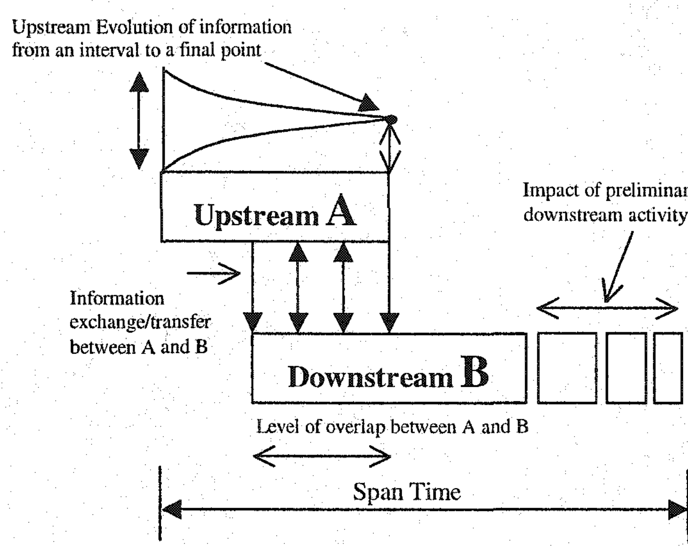


Figure 1 Krishnan *et al.*'s model.

The authors address the overlapping problem by studying how values of the two properties determine the extent to which overlapping is appropriate between the dependent activities, A and B, and consequently how the span time is affected. Various overlapping policies between the upstream and downstream activities are examined based on varying the values of these two properties, and an integer program is developed to minimize span time.

In practice, evolution and sensitivity are not always easy to define quantitatively. The authors have therefore developed a conceptual framework to address the problem of overlapping, where qualitative inputs provide insights on how to overlap activities. This framework consists of a two-by-two grid which considers four combinations of evolution (slow or fast) coupled with sensitivity (low or high). Each case results in a separate overlapping scheme, each of which involves different trade-offs and has different performance outcomes. It is up to the user of the framework to decide upon which outcome is more or less important. At all times, project-specific needs must be carefully assessed.

2.0.2 Communication and Uncertainty of Information

Loch and Terwiesch (1998) have developed an analytical model of CE that considers the overlapping of two sequentially dependent activities, an upstream product design activity, and a downstream process design activity. The authors study the trade-offs between the downstream activity using upstream preliminary information to overlap activities, and the corresponding delay this might cause in terms of downstream rework. They suggest that when engineering changes (EC) arise during the product design, this poses the risk of redoing the overlapped work of the downstream activity, and this can be significant if the dependency between the two activities is high. They propose that communication during overlapping can reduce rework effects, but at the cost of communication time. They also use the concepts of evolution and sensitivity.

The authors developed a model that results in an optimal overlapping policy combined with an optimal communication policy under conditions of uncertainty. Uncertainty is conceptualized as the average rate of EC's, modeled as a nonstationary

Poisson process, occurring during product design. They contend that the later the EC's arrive in the process, the more difficult it is to deal with them, and that communication can help to reduce them. Uncertainty reduction takes place through communication in the form of meetings, while evolution represents how quickly this uncertainty is reduced. A communication policy is described by communicating upstream modifications as quickly as possible to the downstream activity to reduce the effect the change can potentially have on the downstream work.

2.0.3 Decision and Risk Analysis

Yassine *et al.* (1999) have studied the CE problem of overlapping activities through a decision analytic framework. Using a probabilistic model consisting of an upstream activity and a downstream activity, their methodology finds the optimal overlapping policy based on the study of independent, dependent, and interdependent activities, described as the information structure of a process. A schedule of when to transfer information based on the information structures can fall under one of three categories: sequential, partial overlapping, and concurrent. Sequential transfer of information takes place for dependent activities. Partial overlapping can take place for either dependent or interdependent activities. In both cases, however, the information exchange/transfer must appropriately minimize the risk of downstream rework in the event of a change in the upstream activity. A concurrent schedule can take place when the activities are independent; since neither requires information from the other to proceed, they may be executed in parallel.

The information structure and its associated schedule describe how activities will be executed and overlapped. The information exchange/transfer should minimize the risk of downstream rework in the event of a change in the upstream activity. A combination of each structure with each schedule is studied, and the risk involved in the process for each case is probabilistically modeled. The authors conclude through a case study that in order to reduce span time, a high cost is required in terms of effort if a completely concurrent strategy is used, but a partial overlapping strategy can help reduce time at a lower cost. Depending on the project budget, a corresponding overlapping strategy can be found.

2.0.4 Progress Reviews

Ha and Porteus (1995) developed a simple model that proposes the optimal policy for the frequency and timing of progress reviews in an overlapped process. The authors study two overlapped, interdependent activities, an upstream design activity and a downstream process activity. In contrast to sequentially dependent activities, the nature of interdependent activities requires team members to communicate frequently.

They develop a dynamic program that shows that, in order for overlapped activities to be beneficial, the design activity must be accompanied by progress reviews to minimize the risk of downstream rework and thus span time, and to improve quality. However, these gains are only achieved at the expense of the time and cost spent on communication. Therefore, the frequency of communication or progress reviews must be balanced with the value gained from having them. The optimal policy of reviews minimizes span time by providing sufficient information at the right time, helping to identify potential design problems early.

2.0.5 Simulation

Finally, Clermont and Aldonando (1999) choose simulation to study overlapped processes. Their study focuses on three activities which are composed of three steps each. Each step in an activity has an equal unit of time and a unit cost associated with it. The authors study various levels of overlapping, and the corresponding effects on span time and cost by summing up the units of time and cost. They find that in the absence of rework, parallel activities have the same cost as sequential activities, but shorter span time. When rework of an activity in the upstream activity is required, any overlapped activities must be started over. They find that overlapped activities are always shorter in terms of span time, but at times at the expense of higher costs.

2.0.6 Summary of Approaches

Different methods to address the problem of overlapping have been suggested in the literature. Each approach contributes valuable insights about when overlapping activities is appropriate. All authors focus on the study of an upstream activity, representing the product design stage, and a downstream activity, representing the corresponding process design stage (except for Clermont and Aldonando, who study three activities). Each study investigates the use of overlapping based on the downstream activity making use of preliminary information generated from the upstream activity, and how overlapping can be achieved to minimize the risk of reworking the downstream activity, should a change take place during product design.

2.1 CONTRIBUTION OVER EXISTING WORK

This thesis contributes in many ways to the existing work just described. First, from the literature review, it is obvious that one of the reasons previous authors limited their work to the analysis of two activities (micro-model) is the computational burden that accompanies the study of the entire development process (macro-model). Only Clermont and Aldonando (1999) have studied a bigger portion of the process (three activities), but their model does not include many essential features of product development processes. The effect of varying levels of overlapping on span time is studied for all studies, and it is much simpler to limit the analysis to an upstream and a downstream activity. Thus, activities are viewed within a limited context, and the effects are discussed, but these results are not coupled with the potential time compression for the overall development process.

The thesis makes use of computer simulation to study an overall development process. The macro-models developed in the present research extend the efforts of previous authors by studying the entire NPD process, consisting of a full range of phases and activities that are involved in product development. Not only do the models incorporate many essential features of product development processes simultaneously, which is complex to accomplish mathematically, but they also have the ability to study processes from a dynamic point of view. The goal is to understand which features of the NPD process contribute to overall performance rather than just to local performance.

Teamwork, or functional participation, is an essential part of CE processes. In the models from the literature, teamwork is only implicitly assumed. Only Yassine *et al.* consider this feature in one instance, but in a limited way. Explicitly considering the potential effects of teamwork can provide further insights to the CE problem. The thesis explicitly considers functional participation in the computer models.

Uncertainty is conceptualized in a new way in this thesis. Whereas it has been conceptualized analytically in the form of engineering changes, or downstream sensitivity to changes upstream in previous work, it is represented in the computer models through the concept of completeness of information. The lower the completeness of information available to a team member to perform work, the higher the uncertainty involved. Chapter 5.0 discusses this in detail.

Rework of activities is modeled very realistically in the thesis' computer models. Rework indicates that there may be a need for several iterations to complete an activity. With each iteration, the duration of the activity decreases by a certain amount, while its probability of success increases. This models the effect of learning, or knowledge accumulation, which only one of the authors above has considered.

Finally, this research also contributes to the existing work by introducing a methodology based on decision theory to study the performance of processes. The expected payoff method is an analytical method chosen to analyze sequential and CE processes, described in Chapter 4.0.

Table 1 summarizes the features described in the literature review, comparing each to those included in the models in the thesis.

Table 1 Comparison of model features.

	Deterministic /Stochastic	Functional Participation	Over-lapping	Evolution	Sensitivity	Progress Reviews	Rework	Learning
Thesis' Computer models	Stochastic	✓	✓	✓	✓	✓	✓	✓
Krishnan *et al.*	Deterministic		✓	✓	✓			
Loch and Terwiesch	Stochastic		✓	✓	✓	✓		
Yassine *et al.*	Stochastic	✓	✓				✓	✓
Ha and Porteus	Stochastic		✓			✓	✓	
Clermont and Aldonondo	Stochastic		✓				✓	

3.0 DESCRIPTION OF NPD PROCESSES

This chapter provides a description of generic product development processes as an abstraction of the real world system that is under consideration in this thesis.

An information processing view of organizations has been widely adopted by organization theorists in order to study knowledge-based processes (Galbraith, 1973; Tushman 1988). This view has also been assumed in this research, whereby the activities in a product development process within an organization are thought of as entities that create, retrieve, use, transform, and disseminate information. Thus, information inputs are transformed into information outputs that are used to make the final product (Emmanuelides, 1993). Coordination describes the way that activities are organized based on how information is communicated between actors. The movement of information occurs through information flows, which link activities in the NPD process. These flows are defined by the frequency and the direction in which information is transferred or exchanged between two or more organizational participants.

Uncertainty has been defined as the difference between the amount of information available to complete an activity and the amount required to complete it (Galbraith, 1977). The wider the difference, the greater the amount of information processing capacity will be required. Thus uncertainty determines how much information processing is required, and the amount of uncertainty present makes it difficult to plan product development activities in advance. Since uncertainty inevitably exists when developing new products, reducing the level of uncertainty is a key issue. One approach to reducing uncertainty is to study information requirements among activities to determine how best to organize a process.

Activity characteristics can affect uncertainty through the extent to which each activity depends on another for information. This dependency is determined by the information requirements among activities. Two types of activity dependencies are considered in this study: sequential dependence and mutual interdependence.

As previously discussed, *sequential dependence* between activities entails a one-time, uni-directional flow of information between activities. For example, in the case of an upstream phase A and a downstream B, B depends on A for information, but A and can be executed independent of B (Figure 2). Thus, information flows take the form of complete, finalized information, sent to a downstream phase only at the end of the upstream phase. This is a sequential process where there is no uncertainty, since all required information is available, which is one of the reasons why a sequential process can be attractive. However, the drawbacks are the delays in waiting for this information, and the potential dangers of not appropriately communicating information with downstream phases.

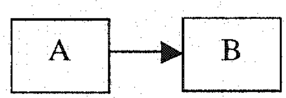


Figure 2 Sequential dependence.

Mutual interdependence, or reciprocal interdependence, between activities, refers to the case when activities depend on one another for information. In this case, A and B mutually depend on one another for information in order to proceed with their work, and as such, are closely linked through a frequent exchange of messages (Figure 3). There is more uncertainty involved in organizing activities in this way, since the downstream activity is working with incomplete information, but the potential benefits can be significant. In this case, information flows must be carefully examined.

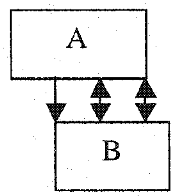


Figure 3 Mutual interdependence.

These activity dependencies form the basis of how processes are studied in this thesis. The case of independent, parallel phases was not considered in this study.

3.1 NEW PRODUCT DEVELOPMENT PROCESS

Product development can be defined as the process of undertaking all the activities and processing the information required to develop a concept for a product up to the product's market introduction.

NPD processes may vary from one organization to the next, and as such, there is no one standard process agreed to by all. However, the general steps required in a product development process are fundamentally similar (Ulrich and Eppinger 2000). The NPD process defined in this study is a generic one which outlines the major steps in product development. It is a summary of the common phases and activities used in many instances in the literature as well as in the case study, and as such, it is a reasonably accepted approach to representing the product development process (Schilling and Will, 1998; Nihtila, 1999; Eastman, 1980).

The NPD process, shown in Figure 4, begins with the development of a concept for a marketable product (Phase A). In this phase, market requirements are determined, new ideas are generated, screened for economic and technical feasibility, and one is selected. In Phase B, 'Definition', a set of specifications to make the product is defined, and the product architecture is developed. Phase C, 'Development', consists of detailed design, physical prototyping, and testing. Finally, in Phase D, 'Implementation', the product volume is ramped up in manufacturing and launched onto the market.

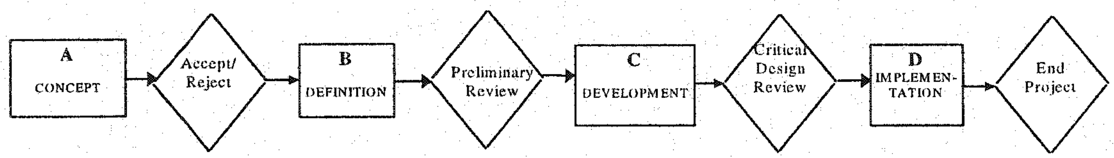


Figure 4 A schematic diagram for a general stage-gate process with Phases A, B, C, D.

Each phase (or stage) is made up of lower level activities that are implicit in Figure 4. These activities consist of exploring, analyzing, and finalizing the phase, and they will be discussed in Chapter 5.0. Typically, there are gates, or major milestones, at the end of each phase to review progress, as shown by the diamonds.

3.1.1 Sequential Development Process

Figure 4 is an example of the traditional NPD process, where the phases are performed sequentially one after the other. Between phases, a one-way dependence is assumed, that is, the downstream phase depends on information generated by the upstream phase, but not vice-versa. This is represented by the uni-directional arrows between phases.

The sequential process is highly functionally segregated, i.e. different functions have responsibility for different phases, with planned communication between the functions occurring at the end of each phase (at the gates, or the milestones) when one function hands off its work to the next. Typically, the functions responsible for the various phases are: Marketing personnel for the Concept Phase, Design engineers for Definition Phase, Design and Test engineers for the Development Phase, and Manufacturing personnel for the Implementation Phase.

Although there is little risk in terms of information transfers, since all functions make use of information in its finalized form, it nevertheless tends to have a long span time, large effort and high costs. This is due to the significant rework generated downstream that is characteristic of such a process, which arises from the lack of early cross-functional communication. There is little need for upstream coordination in a sequential process, however much *unplanned* downstream coordination is likely required to deal with rework. Despite the fact that activities in the development process may be inherently interdependent, the sequential process often ignores these and proceeds as if they are sequentially dependent.

3.1.2 CE Development Process

In an NPD process, the relationship between product and process design is mutually interdependent (Tian *et al.*, 1998). This means that the information generated by one or more functions poses contingencies for others, thus, the parameters of the product and the process should be considered simultaneously (Adler 1995). Therefore a higher degree of coordination is required to manage more people collaborating on interdependent activities. In a sequential process, this interdependence is ignored; a dependent relationship is assumed, and this leads to unplanned coordination downstream. While better management of interdependencies does lead to shortened span time as compared to the sequential process, the price is higher cost of upstream effort.

CE uses two main mechanisms to reduce the span time for NPD processes: 1) increased information sharing from the start of a project (functional participation), and 2) overlapping of phases and activities. In a CE process, functional participation takes place through the formation of a team consisting of a representative from each of the functions that contribute to the development of a product. The goal is to make downstream activities easier to perform by releasing preliminary information to them early in the process to allow for overlap of activities. However, due to uncertainty in the early stages of an NPD process, the release of incomplete information to downstream functions may potentially introduce the need for rework should there be a change in upstream information. Thus, potential risks must be carefully examined to ensure that added time and effort are kept to a minimum (Krishnan *et al.*, 1997).

Compared to a sequential approach, CE can decrease span time at the expense of increased interdependencies between activities (sequential to reciprocal). To handle the increased interdependencies, close intensive coordination is required through functional participation. However, this may increase effort.

Figure 5 shows an overlapped CE process. Note that information flows are more frequent than in the sequential case, and they are also bi-directional. Major milestones exist at the same gates as before, and each phase is made up of activities, not shown in the figure.

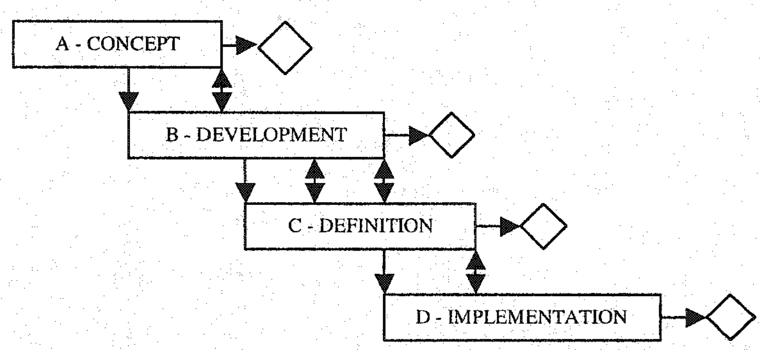


Figure 5 CE development process.

3.1.3 Summary of Theoretical Background

An abstraction of the real world system (the NPD process) that is being studied in this thesis was presented. It is viewed from an information processing perspective, whereby the stakeholders of the project must develop a product through the way they receive, process, and communicate information to achieve their goals. Product development processes can be divided into four generic phases, the Concept, Definition, Development, and Implementation phases, each of which in turn is composed of activities that explore, analyze, and finalize the phase. The main features of the development process are identified as functional participation and the level of overlapping. In the thesis' models, these are chosen as the inputs to the process, while effort and span time have been identified as the key performance indicators, the dependent variables. The thesis compares two models of the product development process, the sequential process and the CE process.

4.0 EXPECTED PAYOFF METHOD

In this chapter of the thesis, a mathematical approach is described to measure the performance of processes, namely, sequential and CE processes, through the study of macro- and micro-variables. The macro-variable is the expected payoff, while the micro-variables are team interaction and level of overlap. The concepts of information processing and decision-making are presented as the basis of this framework.

An information processing view is assumed, so that processes are studied through the way in which several team members perform activities such as acquiring, communicating, and processing information in order to make decisions, which in turn organizes the way activities are executed. Processes and corresponding team activities are modeled via networks of interconnected elements. These elements transform inputs into outputs, and represent people, machines, or other real-world objects. Each network realizes an output which is a measure of process performance, and is used to evaluate and compare processes.

The methodology is based on the expected payoff method, a technique used in decision theory. It is applied in the calculation of a simple model of both a sequential and a CE process, and the results are compared. Further theoretical and analytical work is being developed in this area (Kong and Thomson, 2001). The sections that follow discuss the methodology's background, the methodology itself, a simple application, and finally, potential for future work.

4.1 BACKGROUND

The principle of the expected payoff method has been applied mainly in the field of economics, management science, and in certain areas of artificial intelligence, with respect to decision-making. In this field, economists study 'the best use of available (limited) resources' (Marschak and Radner, 1972). There has been no use of this method in the evaluation of CE in new product development processes. In an organizational environment, teams are also concerned with making the best use of alternatives or limited resources. The interested reader can find several readings in the literature on the principle of utility theory and its various applications (Marschak and Radner, 1972; Fishburn, 1970; Marschak, 1959; Marschak, 1954; von Neumann and Morgenstern, 1943). The framework developed in this part of the research will compare a simple model of a sequential process to a CE process, and evaluate the two in terms of the total expected payoff.

4.2 METHODOLOGY

The approach assumes that individuals in a team work towards achieving common goals with common interests and beliefs, within the constraints of their work, all of which guide their behavior. Given the complexities of such a situation, the problem is allocating appropriate information at the right time, such that team members can make the 'right' decisions which serve to accomplish their common goals (Marschak and Radner, 1972). This chapter will describe the means by which the activities of teams can be described, as well the mathematical analysis which can evaluate team performance, namely, through the use of the *expected payoff method.*

The expected utility or payoff of an action measures the usefulness that an action brings to a person. By combining this with probability theory, decision theory helps a person determine that the action which maximizes his or her expected payoff over all possible actions (from this point forward, for simplicity, the term 'his' will be understood to include 'his/her'). The development of the expected payoff function will be described in detail.

Processes can be explicitly represented through network diagrams that illustrate the activities that team members must perform, the inter-relatedness of activities through information requirements, and the communication required among team members (Figure 6). A network realizes a response function, or outcome function, which is based on the actions of the individuals in the organization, and these actions affect the outcome or expected payoff. Among various possible network configurations, the network with the greatest expected payoff is considered optimal.

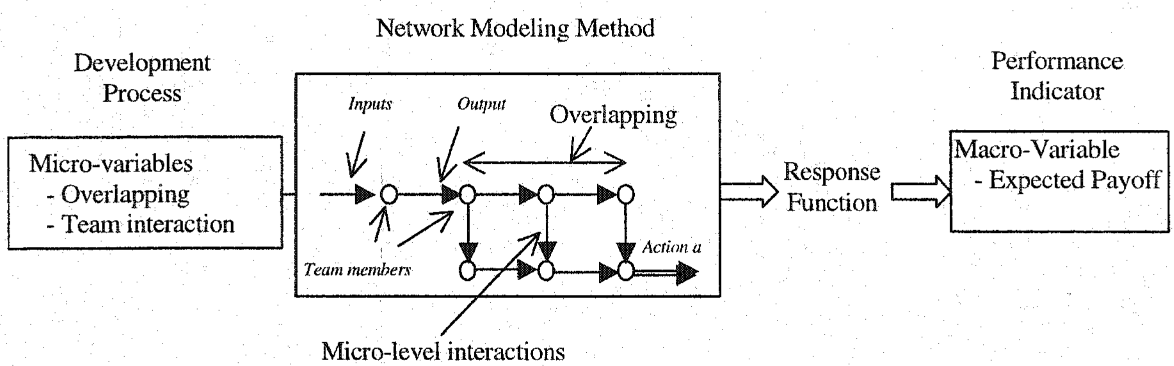


Figure 6 Expected payoff conceptual model.

Section 4.5 describes how network diagrams are constructed, as well as the mathematical tools which compute and evaluate the networks to obtain the total expected payoff.

4.3 MATHEMATICAL MODEL: DEFINITION OF FUNDAMENTAL QUANTITIES

In the following sections, the fundamental quantities of the expected payoff model are defined mathematically.

4.3.1 Actions and Outcomes

Faced with a set of alternatives, the decision made by the decision-maker is called his action, a. An action, or decision, can have more than one outcome (or result or consequence). This is denoted as $r = \rho\ (a)$, where ρ is the outcome function of the action taken. The possible outcomes also depend on external factors out of the decision-maker's control, which can be called the environment, represented by the variable x. Since an outcome depends on both the action taken and the environment, the outcome function can now be expressed as $r = \rho\ (x, a)$. Because x is uncertain, the outcome variable r given a is also said to be uncertain. The decision problem now is made up of a set X of alternative states of the environment x, a set A of all possible actions a, a set R of all possible outcomes r, and an outcome function ρ from X x A to r, giving the outcome of each state-action pair, $r = \rho\ (x, a)$.

4.3.2 Decision Rules

The problem of choosing among alternative actions can be generalized by saying that individuals choose among *rules of actions* or strategies, rather than from a set of possible actions alone. In an organization, rules of action play a very big role in contingency planning, where team members must decide in advance how they will respond to incoming information. This is obviously important in making economic decisions because individuals must be ready to act as soon as they can (e.g. stock brokers). In the context of an engineering firm, if a task is to design and develop a new product and get it to market as quickly as possible, the designers make use of incoming information as soon as they receive it, and they must additionally decide upon how much of it should be transferred to downstream functions, and when.

An action can now be described as $a = \alpha\ (y)$, where α is the decision function, and y is the information which will be obtained in the future. It should be noted that the information y is not the same as the variable x, the state of the environment, which describes information already received. The expression says that an action a depends upon the information y received.

4.3.3 Information

Information can be generated and obtained by team members through various means, such as through observation, communication, and/or computation. There are two sets of information available to the decision-maker: one is the set X of all possible states of the environment, and the other is the set Y of all possible information signals. An information signal y is a partition of the environment X. The information structure η is the partitioning of X into different signals of y. Therefore, a signal y will correspond to each x in X. An information structure is thus defined as $y = \eta\ (x)$. Any partition of X can be viewed as a way to describe the states of the environment.

As an example, suppose a marketing manager can offer a customer a product in small, medium, or large. The customer wants either small or medium. The marketing manager must make a decision about which size to choose, which will impact the design of the product, and the information relevant to his decision is the size small or medium. The set X of all possible sizes is thus partitioned into one subset, small, and another subset, medium, and this partitioning defines the information structure, η.

4.4 EXPECTED PAYOFF

The expected payoff method is based on the premise that every individual has preferences as to how to prioritize a list of alternatives due to personal beliefs or interests (assuming that the individual is consistent). Preferences can be described by the ranking of alternatives according to some subjective probability distribution, consistent with what the person believes will happen. Under uncertainty, each of the alternatives is an action which may result in one or more outcomes, as discussed.

In this sense, the term 'utility' refers to the usefulness an action brings to an individual. For the order of preference given to all actions, each position can be assigned a single number representing the utility of each, or a person's desirability of the occurrence of an event, thus capturing his preferences. The probability of each action occurring is represented by the subjective probability assignments. The expected utility of an action is therefore the sum of the utilities of its various possible outcomes, weighted by the probability of each outcome's occurrence.

Given these basic definitions described in the previous section, for a set R of alternative outcomes $r_1 \ldots r_N$, if $Z_i(a)$ denotes the event that an action a results in the outcome r_i (since $r_i = \rho\,(x, a)$), then the "expected utility" Ω for an action a is:

$$\Omega\,(a; \rho, \pi, \upsilon) = \Sigma\, \upsilon(r_i)\, \pi\,[Z_i(a)], \qquad (1)$$

where:

π = subjective probability function

υ = utility function.

The left-hand side of the expected utility function in (1) shows that the expected utility depends only on the decision-maker's action, given the functions ρ, π, and υ, which describe the factors which are out of his control. The individual's actions are under his control, and his goal is to choose the action which maximizes the corresponding expected utility. In the utility function $\upsilon\,(r)$ in (1), r can be replaced to obtain the new payoff function ω: $\upsilon(r) = \upsilon[\rho(x, a)] \equiv \omega(x, a)$. The expression in (1) can be further simplified by stating that, given the set X of alternative states of the environment x, the probability of the state x can be written as $\Phi(x) = \pi(\{x\})$, where Φ is the probability density (or mass) function, and x is assumed to be a random variable that is normally distributed. This expression is, in other words, the probability of the set X consisting of the single element x denoted by $\{x\}$. The expected utility function in (1) can be re-written as:

$$\Omega(a; \omega, \Phi) \equiv E\,\omega(x, a) = \Sigma\,\omega(x, a)\,\Phi(x) \qquad (2)$$

The expression in (2) can now be called the *expected payoff* of the action a, where the expected utility depends on the decision-maker's action only, and where ω and Φ describe the factors uncontrolled by the decision-maker. Though the utility and the probability functions may be thought of as being controllable, it is assumed for simplicity that they are not, and that they are treated as givens of the problem.

By replacing the actions by decision rules, and introducing the information structure into the equation, the payoff function can be re-written as:

$$\omega(x, a) = \omega[x, \alpha(y)] = \omega[(x, \alpha(\eta(x))] \qquad (3)$$

From this, the expected payoff becomes:

$$U = \Sigma\,\omega[(x, \alpha(\eta(x))]\,\Phi(x) \equiv \Omega(\eta, \alpha; \omega, \Phi) \qquad (4)$$

The expected payoff now depends on the decision function α and the information structure η, and on the factors over which the decision-maker has no control, namely ω, and Φ. The information structure η is assumed to be under the control of the team member; each member has the ability to observe and partition the information into the subsets needed for his activity. The individual has more than one pair (η, α) available, and he will choose the one that maximizes U. This expression is the measure that describes the performance of the various processes through the evaluation of actions under uncertainty. It is used to evaluate the process network diagrams to be developed in upcoming sections. The optimal process structure will be that which maximizes the expected payoff of the network under certain conditions, given the probability distribution of the states of the environment.

4.4.1 Expected Payoff as a Quadratic Function

The payoff function can be expressed as a quadratic function of the team action variables. Although this is an approximation, it is useful. The quadratic function is one that has been used to describe many real-life phenomena, such as in economics for the law of diminishing returns. The concave quadratic function describes the expected payoff function in that there is a point that is optimum, i.e., the maximum point, and before and after this point, the value of the payoff decreases. The use of functions of orders higher than two is very complex and difficult to solve, and a linear function is neither sufficient nor appropriate to describe the present phenomena in detail since it is not expected that the payoff function continuously increases or decreases. Also, since the goal here is to make comparisons between two process structures, the relative comparisons do not require the payoff function to be exact.

Taking the case of two members in a team, 1 and 2, where each must make a decision, then the quadratic payoff function can be chosen as:

$$u = -a_1^2 - a_2^2 + 2Q\, a_1 a_2 - 2\eta_1(x)\, a_1 - 2\eta_2(x)\, a_2 \qquad (5)$$

(the use of functions of x will be suppressed for simplicity in the future).

This particular form of the quadratic function is similar to the one used by Marschak and Radner (1972), with some of the coefficients chosen to simplify calculations. In the above expression, Q measures the interaction between a_1 and a_2, the action variables of team members 1 and 2, respectively, and must be between zero and one. The interaction is one of the micro-variables of the process model. For M action variables, if the second derivative of the expected payoff function exists, then a measure of the interaction between the action variables i and j is $\partial^2\omega / \partial a_i \partial a_j$. In other words, it measures "the degree to which a change in action j influences the effect of a change in action i on the payoff for given values of the other action variables and of *x*" (Marschak and Radner, 1972, p.101). The functions $\eta_1(x)$ and $\eta_2(x)$ are related to the information structure.

Properties of Probability Distributions

The assumption that the payoff is quadratic gives meaning to the variances and the correlations of the information variables. Here, a few parameters of probability distributions will be reviewed. For all distributions:

- the mean $m_i = E[x_i]$,
- the variance $s_i^2 = \Sigma E(x-m_i)^2$, for random variable x_i, (the summation is replaced by an integral for continuous distributions); for the present analysis, *x* is assumed to be a continuous random variable, normally distributed over all real numbers, and the mean of this distribution is the desired target,
- and the correlation coefficient $r = r_{ij} = E[(x_i-m_i)(x_j-m_j)/s_i s_j]$, and in the case of two random variables x_1 and x_2, $r = r_{12} = E[(x_1-m_1)(x_2-m_2)/s_1 s_2]$.

Normal distributions are fully described by their means and variances. The variance can help gauge uncertainty, as it takes the difference between the maximum and minimum values of *x*. For multivariate distributions, the correlation coefficient describes the degree of statistical interdependence between variables (above, r describes the correlation between two variables). Due to the interdependencies in processes, it is often important to understand how one variable affects another. Whether this is the correlation between action variables or the environment variables, it is reasonable that these correlations may affect the information structure and/or probability of occurrence chosen by the organizer.

Another simplification is the normalizing assumption, where each variable is considered to be measured from its mean, so that m = 0, and E (m) = 0. There is no loss of meaning since this is simply a coordinate transformation. In this case, the correlation coefficient becomes:

$r = r_{12} = Ex_1x_2/s_1s_2$, or

$Ex_1x_2 = r * s_1s_2$.

These properties of probability distributions will be useful in solving the expected payoff functions and determining the macro-variables of interest, discussed in upcoming sections.

4.4.2 Multi-person Teams

For *n* members in a team, then there will also be *n* information structures and *n* decision rules. Each member i chooses an action a_i from set A_i of all possible alternatives. The payoff function can be written as:

$u = \omega (x, a_1, a_2 \ldots)$

where *u* is now the utility to the team (and to each of its members). Although a_i is the action variable controlled by the ith member, a_i itself can be an m-tuple of many distinct variables, each controlled by the ith member. If there is no interaction among the action variables, then the payoff is said to be *additive*, and the form of the expression becomes:

$\omega (x, a) = \Sigma\, \omega_i (x, a_i)$

If, however, there are interactions among action variables, then the quadratic function must include an extra term to express this interaction, namely Q, as before.

4.4.3 Team Decision Functions and Information Functions

In a single person team, the person's action is related to the decision function through $a = \alpha(y)$. For a multi-person team, there are now n decision functions, $\alpha = (\alpha_1 \dots \alpha_n)$ and $a_i = \alpha_1(y_i)$. The same decision rules as before can be applied for a team. The joint action of the team members is $a = (a_1, \dots a_n)$, and $y = (y_1, \dots y_n)$ is the team information, so there are n decision functions, and the team decision rule can then be denoted as $\alpha = (\alpha_1, \alpha_2, \dots \alpha_n)$. The same expression for an action $a = \alpha(y)$ for a single person team is also applicable for teams, keeping in mind what each term means individually. The information structure for each team member can be expressed as $y_i = \eta_i(x)$, and for the team, the information structure is $\eta = (\eta_1, \dots \eta_n)$. Then, for $y = \eta(x)$, and $a = \alpha(y)$, $a = \alpha[\eta(x)]$ applies for the team action. The payoff of the team can be written, as before:

$$u = \omega(x, a_1, a_2, \dots) = \omega(x, \alpha_1[\eta_1(x)], \dots \alpha_n[\eta_n(x)]) = \omega(x, \alpha[\eta(x)],$$

and the expected payoff of the team is:

$$E(u) = \Omega(\eta, \alpha) = E(\omega(x, \alpha[\eta(x)]) \qquad (6)$$

4.4.4 Consideration of Time

All the discussion up until now has involved the static case of the team decision problem, but time can be incorporated into the various concepts. If one team member's action at time t ($t = 1, \dots T$) is $a_i(t)$, and x(t) is the state of the world at time t, then the team action variable becomes:

$$a = [a_1(1), \dots a_n(1), \dots a_n(T)],$$

and the state of the world is:

$x = [x(1), \ldots x(T)]$.

For $y_i(t) = \eta_i(x, t)$, the action variable becomes:

$a_i(t) = a_i[\eta_i(x, t), t]$.

An important assumption of this situation is that for actions that are spaced apart in time, the larger the time difference, the less the interaction between those actions. Therefore, it is assumed for simplicity that the actions that are distant in time need less coordination than those that are closer together. The payoff function with no interaction is thus additive in time, and can be expressed as:

$\omega(x, a) = \Sigma\, \omega_t [x, a(t)]$ (for t=1,…T).

4.5 DESIGN OF NETWORK MODELS

Networks can be used as a powerful tool to represent and evaluate the structure of a process, and more specifically, the structure of information flow and work patterns in a team. A network can be defined as a system of interconnected elements, all of which work together to produce a desired output. A network consists of the following basic components:

- *element* (represented by a circle): the component which has the function of transformation of information. An element can represent a human being, a machine, a communication tool, etc., in the process of performing an activity.
- *input(s)* (represented by an arc into the element): required for each element. These inputs are various types of information (e.g. information or actions coming from the previous element's output, noise from the environment, team members' personal knowledge or expertise, etc.).

- *output(s)* (denoted by an arc leaving the element): the result of each element. This can be in the form of 1) processed information, 2) a simple relay or distribution of information, or 3) an action being sent out as a result of the transformation process, either to another element or to the environment.

Each element in a network has an input which is transformed into or transferred as an output; the message of this output then feeds into one or more downstream elements. Elements are connected to one another through the input and output arcs, which carry information messages to and from elements. Messages coming from the environment (i.e., external to the organization) are called observations. Messages from one element to another are communication, while messages going out into the environment are called actions. In the context of an organization, networks can be used to represent processes from an information processing point of view. Once all intermediate elements have been completed, a final action(s) is issued, which signals project completion. Networks can be organized according to time structure.

4.5.1 Connections Between Elements

The connections between elements in a network can be described in the form of a square array. For each element i and j, the set of all possible messages that can be sent from i to j, is denoted by B_{ij}. Any messages that come from outside, that is, from the environment, are described by the set Z_i, and E_i which denotes the set of all possible values of noise coming from the environment to element i. This noise can be information that is observed from outside the organization, such as customer input, best practices, etc. The messages sent out to the environment are defined as the action variables, a = $(a_1, \ldots a_n)$, for n actions, where *a* is the team action variable.

The set B_{i0} denotes the set of all possible messages from element i to the environment. This set will consist either of the Cartesian product of some sets A_j, where for each j, A_j is the set of all possible values that action variable a_j can take, or it will be empty since not all elements will have an action as an output.

The set B_{0i} is symmetric to this set, and it represents the set of all possible messages from the environment outside to an element i, which is the Cartesian product of Z_i and E_i. Therefore, the set B_i of possible alternative output messages of element i is denoted by $B_i = \Pi B_{ij}$ (j=0...m). For *m* elements, the set B_i' of combined messages from other elements to i is given by $B_i' = \Pi B_{ki}$ (k=0...m). The transformation of each element i is expressed through the *task function* $\beta_i = (\beta_{i0},..., \beta_{im})$, which transforms each input message into an output message. The set B_{ii} is empty as it is assumed that messages will not be sent from an element to itself.

Figure 7 below shows an example of a simple network diagram. The corresponding square array consisting of the sets B_{ij} in Table 2 illustrates message transfers between elements in the figure. The symbol Φ denotes an empty set.

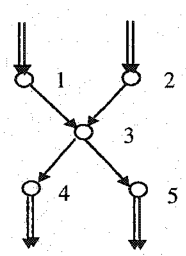


Figure 7 Simple network diagram.

	0	1	2	3	4	5
0	ϕ	B_{01}	B_{02}	ϕ	ϕ	ϕ
1	ϕ	ϕ	ϕ	B_{13}	ϕ	ϕ
2	ϕ	ϕ	ϕ	B_{23}	ϕ	ϕ
3	ϕ	ϕ	ϕ	ϕ	B_{34}	B_{35}
4	B_{40}	ϕ	ϕ	ϕ	ϕ	ϕ
5	B_{50}	ϕ	ϕ	ϕ	ϕ	ϕ

Table 2 Information dependencies.

The time distribution and spatial distribution of members in a team must be separated. For teams in a dynamic environment, networks are divided into time periods by several elements based on the structure of information flow, which is illustrated by elements broken down into intermediate stages or actions. Figures 8 and 9 show the network diagrams of possible sequential and CE processes.

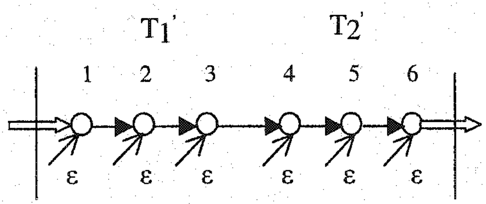


Figure 8 Sequential network diagram.

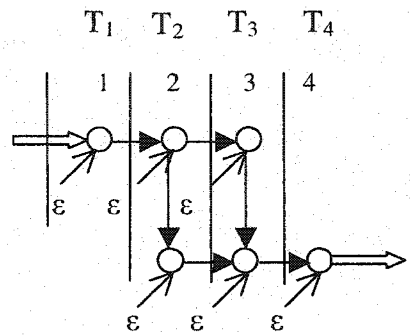


Figure 9 CE network diagram.

In the context of NPD processes, as an example, an element i can be a designer who receives information ε from the environment, say from the customer. An action *a* can be the release of design specifications from the designer to another element, say the manufacturing resource. This resource then uses information from this action as well as information from observations through personal experience and/or company databases for example, transforms the new combined information, and takes an action, such as manufacturing the product. This action is sent out to the environment, i.e., the customer.

4.6 APPLICATION TO MODELS

A simple model is designed in this section using network diagrams and its evaluation using the expected payoff method will be studied. The main purpose here is to compare the relative differences between process structures in terms of the expected payoff. In the evaluation that follows, the expected payoff function is equation (5), repeated here:

$$u = - a_1^2 - a_2^2 + 2Q\, a_1\, a_2 - 2\eta_1\, a_1 - 2\eta_2\, a_2 \quad (5)$$

Recall that the coefficient "Q" in (5) denotes the interaction, specifically in this case between two overlapping activities occurring in the same time period. This function evaluates every step of performing work, and also evaluates the different processes as a whole (i.e., each intermediate step is evaluated using this function, as well as the overall structure of the network).

4.6.1 Assumptions of the Model

Some simplifying assumptions are made for the model. They are discussed below.

4.6.1.1 Model Inputs

In order to compare the two processes at the same level, some assumptions must be made to ensure consistency. First, both of the processes begin with the same input information variable η_1 which is a random variable dependent upon x. Thus, the first member of each process begins by observing the same information that is coming from the environment.

Another assumption in the model is that the members inside the organization not only receive information from other sources (i.e., other elements or the environment), they also contribute to the processing of their work through the use of their own expertise, which is denoted in the models by ε as an input into each element (Howard, 1966). However, this is considered as being a special state of the set X of information from the environment despite the fact that it comes from the element itself. Therefore, during the evolution of the activity, not only does the information that a member receives get processed, but also because each member is contributing his own knowledge and expertise, this pooled information adds value to the activity, which results in an increase in the expected payoff.

4.6.1.2 Quadratic Form of Payoff Function

Earlier, it was mentioned that the choice of the payoff function as a quadratic equation is appropriate since a quadratic function has a maximum point. This assumption is important and must be re-stated. Furthermore, since the expected payoff is the measure being used to compare relative process performance, an absolute measure is unnecessary, so the problem of defining a specific and accurate form of the function can be avoided.

4.6.1.3 Network Cost

The cost of a network is not considered in the models. Marschak and Radner (1972) did not include this important factor explicitly in their decision functions, although they acknowledge its importance. There is a cost associated with decision-making, with how information is obtained, with team organization, etc. In the context of this research, cost was not chosen as a parameter of the models, however, since cost can help in assessing the trade-offs of one process design over another, this is being explicitly considered in on-going research (Kong and Thomson, 2001).

4.6.1.4 Payoff Functions Additive in Time

The sequential and CE process networks are created as sequences of single-period decision problems (see Figures 11 and 12), where the interaction between periods is assumed to be zero, i.e., Q=0, as previously discussed in Section 4.4.4. Thus, interaction is assumed to be zero across periods, though there is interaction within time periods. Therefore, it is assumed that the total payoff function is additive in time. In each time period, optimal decisions are made. This difference in interactions addresses the case for which the sum of the maximum expected payoffs is equal to maximum of the sum of expected payoffs. In other words:

Max Σ E ω (x, a) = Σ Max E ω (x, a) = Σ E ω_{max} (x, a).

Thus the maximum expected payoff is calculated in each period, which are the added up to give the total maximum expected payoff. In other words, the expected value of the maximum payoffs is equal to the total maximum expected payoffs for each period.

4.6.1.5 Rework

Rework is not modeled in either the sequential or CE process. Though this is a simplifying assumption not characteristic of most NPD processes, the model is presented in basic form, with the intent of bringing out some essential features of the expected payoff method.

4.6.2 Networks and Best Decision Functions

The simple network shown below in Figure 10 will be defined here to illustrate how a network diagram is evaluated in terms of its gross expected payoff ('gross' since the cost of a network is not considered). The network is assumed to be in one time period, reflecting a single action. In cases when there is more than one element, each element in the network can be evaluated separately in terms of its expected payoff, and the total expected payoff is simply the sum of the individual ones. Actions taken at different times can be considered to be corresponding to different team members.

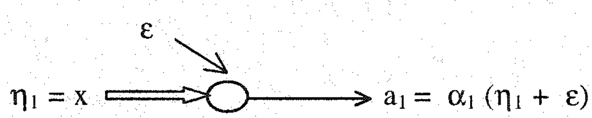


Figure 10 Action taken in one time period.

Figure 10 illustrates an action. Element 1 has η_1 = x as input variable, where η_1 is a random variable dependent upon the state of nature x (which is suppressed). The state variable observed by the team member at element 1 is processed, which also receives some information ε from outside (qualified as information such as team member's personal expertise), which, for simplicity, is considered to be a constant. This information is processed, and an action a_1 is taken, which is a function of the inputs to the element. The information ε combined with the information μ_1 is additive. With a single action, the payoff function is chosen as a quadratic in one input variable, in the form:

$$\omega = -a_1^2 + 2a_1x \qquad (6)$$

Taking the derivative of (6) with respect to a_1 and setting it equal to zero gives:

$\omega'(a_1) = -2a_1 + 2x = 0$, and solving for a_1 gives the best decision function, denoted by $\acute{\alpha}$:

$$\acute{\alpha}(x) = x \qquad (7)$$

which is the optimal decision. The second derivative of (6) is negative (-2), ensuring a maximum point, so plugging (7) back into (6) and taking the expected value of the payoff gives the following expected value of the maximum payoff:

$$\mathbf{\Omega = E\,(x + \varepsilon)^2 = s^2} \qquad \mathbf{(8)}$$

where s^2 is the variance of x. The decision function in equation (7) has a distribution of possible decisions, which implies that multiple choices can be made. Assuming that this distribution is normal, then, equation (8) shows that the payoff is equal to the variance. This means that in making a decision, i.e., reducing possible choices to a single value, the payoff is equal to the value of the reduction of uncertainty of information. It is reasonable to conclude that the larger the variance, i.e., the more uncertain the decision, then, the more benefit (payoff) there is in making a decision.

4.6.3 Sequential Engineering Network Diagram

The sequential engineering network diagram is illustrated in Figure 11, and consists of six time periods, T_1 to T_6, which represent the division of the sequential work done by six different functional team members. Team member 1 receives complete information represented by the state variable x, and then uses this information, along with his own expertise represented by ε, to complete his activity. At the end of his activity, he sends complete information to the downstream activity, which is again processed by the second team member. The output of this activity is a message sent to the next team member, and so on.

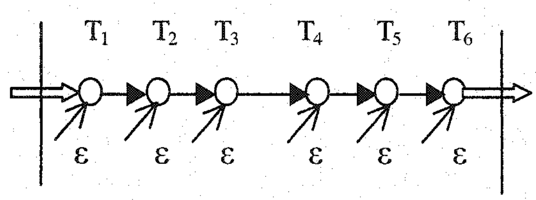
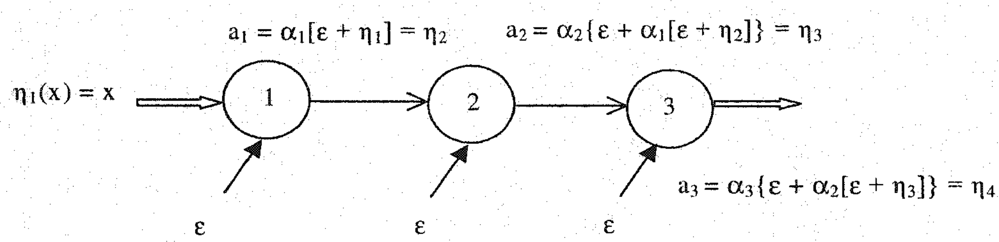


Figure 11 Sequential network diagram.

Because of the assumption of no cross-functional communication in a sequential process, there is no interaction between team members, and the communication of information is assumed to be 'over-the-wall', thus even if there is some interaction, it is assumed to be so weak that it is negligible.

Evaluation of the Network

1) First Period T_1:



Similar to the example above, team member 1 receives complete information, and every member within the network contributes his special technical knowledge to the flow, denoted by ε. As before, the payoff function is (6) and the expected payoff is (9):

$$\omega = -a_1^2 + 2a_1x \qquad (6)$$

$$\mathbf{\Omega_1 = s_0^2} \qquad \mathbf{(9)}$$

where $s_0^2 = E(x + \varepsilon)^2$.

2) Second Period T_2:

As in time period 1, member 2 receives output x from element 1, giving the payoff:

$$\mathbf{\Omega_2 = s_1^2} \qquad \mathbf{(10)}$$

where $s_1^2 = E(x + \varepsilon + \varepsilon)^2$.

A similar procedure as above applies to each time period, up until time period six.

Total Expected Value of the Maximum Payoff:

$$\Omega = \Sigma\,(i = 1\ldots6)\,\Omega_i = \Omega_1 + \Omega_2 + \Omega_3 + \Omega_4 + \Omega_5 + \Omega_6$$

$$= s_0^2 + s_1^2 + s_2^2 + s_3^2 + s_4^2 + s_5^2$$

If it is assumed for simplicity that the variance for each information structure is the same, then the total expected payoff becomes:

$$\mathbf{\Omega_{TOT} = s_0^2 + s_1^2 + s_2^2 + s_3^2 + s_4^2 + s_5^2 = 6s^2} \qquad \mathbf{(11)}$$

4.6.4 Concurrent Engineering Network Diagram

The concurrent engineering diagram shown in Figure 12 is an appropriate modification of the sequential engineering network. It takes into account the two teams of three members each, but this time with a few added features. The two teams' activities are now overlapping in time periods T_2 and T_3. These two teams now are also communicating with each other through the transfer of information denoted by the arrows between overlapped activities. There is interaction between the two members from both teams in the same two time periods. Since rework is not modeled, overlapping part of the six time periods in the sequential process gives the resulting four time periods in the CE process. The main comparison of interest at this point is the difference between expected payoffs.

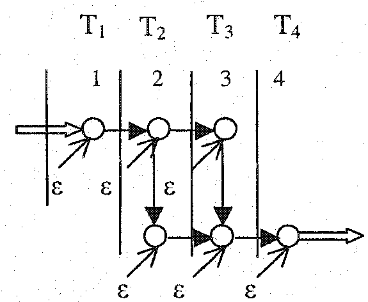
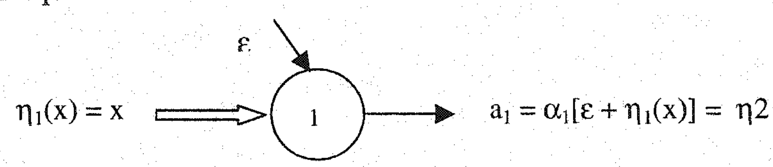


Figure 12 CE network diagram.

Evaluation of the Network

1) First Period T_1:



Again, it is assumed that member 1 obtains complete information x, that is the information structure $\eta_1(x)=x$. Also, every member within the network contributes his special technical knowledge to the processing and transferring of information. The output $\alpha[x] = a_1$ is determined as before. Choosing $u_1= \omega(x, a_1) = -2a_1^2 + 2a_1[x + \varepsilon]$, the best decision function is:

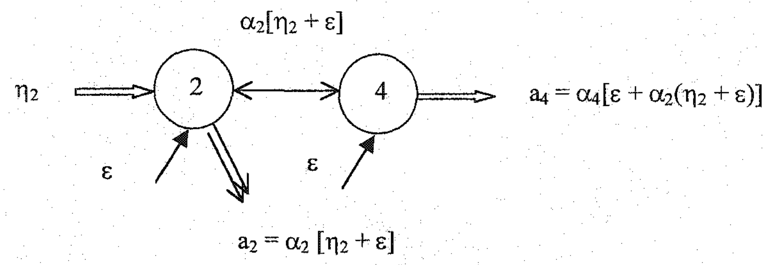
$\acute{\alpha}[x] = x + \varepsilon$

and the expected value of the maximum payoff for the first time period is:

$$\Omega_1 = s_0^2 \qquad \textbf{(12)}$$

where $s_0^2 = E[x + \varepsilon]$

2) Second Period T_2:



The payoff function is:

$$\omega(x, a) = -a_2^2 - a_4^2 + 2Q\, a_2\, a_4 - 2\, \eta_2\, a_2 - 2\, \eta_4\, a_4 \tag{13}$$

Taking the first derivative of the payoff function first with respect to a_2 and a_4 setting each equal to zero:

$$\delta\omega/\delta a_2 = -2a_2 + 2Q\, a_4 \; - 2\, \eta_2 = 0 \tag{14}$$

$$\delta\omega/\delta a_4 = -2a_4 + 2Q\, a_2 \; - 2\, \eta_4 = 0 \tag{15}$$

gives the following system of equations:

$$- a_2 + Q\, a_4 = \eta_2 \tag{16}$$

$$Q\, a_2 \; - \; a_4 = \eta_4 \tag{17}$$

Solving for a_2 and a_4 yields the following best decision functions for T_2 period actions:

$$\acute{\alpha}_2 = [-1/(1-Q^2)] * \eta_2 + [-Q/(1-Q^2)] * \eta_4$$

$$= [-1/(1-Q^2)] * [x + \varepsilon + \varepsilon] + [-Q/(1-Q^2)] * [x + \varepsilon + \varepsilon + \varepsilon] \tag{18}$$

$$\acute{\alpha}_4 = [-Q/(1-Q^2)] * \mu_2 + [-1/(1-Q^2)] * \eta_4$$

$$= [-Q/(1-Q^2)] * [x + \varepsilon + \varepsilon] + [-1/(1-Q^2)] * [x + \varepsilon + \varepsilon + \varepsilon] \tag{19}$$

Plugging (18) and (19) into (13) gives the payoff for time period T_2:

$$\omega = [\eta_2^2 + 2Q\,\eta_2\,\eta_4 + \eta_4^2] / [1-Q^2], \tag{20}$$

and the expected payoff is:

$$\mathbf{\Omega_2 = E\omega = [s_1^2 + 2Qr_{12}\,s_1\,s_2 + s_2^2] / [1-Q^2]} \tag{21}$$

where:

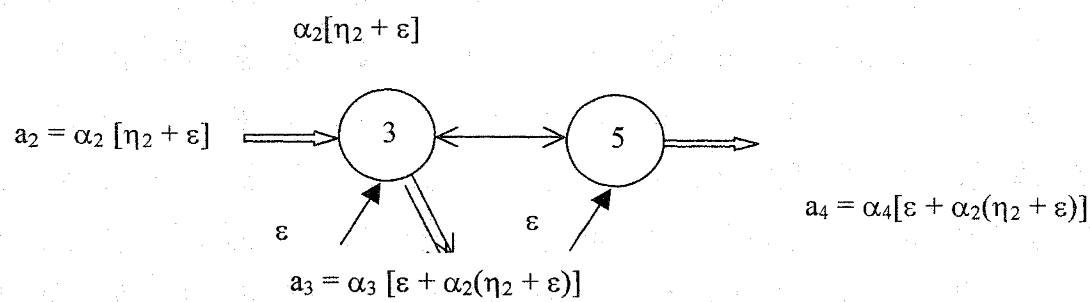
$$s_1^2 = E\,[x + \varepsilon + \varepsilon]^2$$

$$s_2^2 = E\,[x + \varepsilon + \varepsilon + \varepsilon]^2$$

$$r_{12} = [E\,(x + \varepsilon + \varepsilon)(x + \varepsilon + \varepsilon + \varepsilon)] / s_1\,s_2$$

where r_{12} is the correlation coefficient and Q is the interaction.

3) Third Period T_3:



The payoff function is:

$$\omega = -a_3^2 - a_5^2 + 2Q\,a_3\,a_5 - 2\,\eta_3\,a_3 - 2\,\eta_5\,a_5 \tag{22}$$

where:

$$\eta_3 = \varepsilon + \acute{\alpha}_2 = [-1/(1-Q^2)] * [x + \varepsilon + \varepsilon] + [-Q/(1-Q^2)] * [x + \varepsilon + \varepsilon + \varepsilon] + \varepsilon \tag{23}$$

$$\eta_5 = \varepsilon + \acute{\alpha}_2 = [-Q/(1-Q^2)] * [x + \varepsilon + \varepsilon] + [-1/(1-Q^2)] * [x + \varepsilon + \varepsilon + \varepsilon] + \varepsilon \tag{24}$$

Performing the same calculations as in T_2 gives the following best decision functions:

$$\acute{\alpha}_3 = [-1/(1-Q^2)] * \eta_3 + [-Q/(1-Q^2)] * \eta_5$$

$$= [-1/(1-Q^2)]\ \{-1/(1-Q^2)] * [x + \varepsilon + \varepsilon] + [-Q/(1-Q^2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon\} +$$

$$[-Q/(1-Q^2)]\ \{-Q/(1-Q^2)] * [x + \varepsilon + \varepsilon] + [-1/(1-Q^2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon\} \qquad (25)$$

$$\acute{\alpha}_5 = [-Q/(1-Q^2)] * \eta_3 + [-1/(1-Q^2)] * \eta_5$$

$$= [-Q/(1-Q^2)]\ \{-1/(1-Q^2)]\ [x + \varepsilon + \varepsilon] + [-Q/(1-Q^2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon\ \} +$$

$$[-1/(1-Q^2)]\ \{-Q/(1-Q^2)]\ [x + \varepsilon + \varepsilon] + [-1/(1-Q^2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon\ \} \qquad (26)$$

The expected payoff is:

$$\boldsymbol{\Omega_3 = [s_3^2 + 2Qr_{34}s_3\, s_4 + s_4^2]/\ [1-Q^2]} \qquad \mathbf{(27)}$$

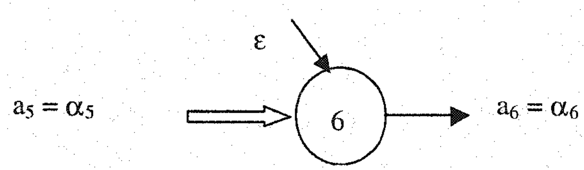
where:

$$s_3^2 = E[-1/(1-Q^2)\ [x + \varepsilon + \varepsilon] + [-Q/(1-Q^2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon]^2$$

$$s_4^2 = E[-Q/(1-Q^2)\ [x + \varepsilon + \varepsilon] + [-1/(1-Q^2)] * (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon]^2$$

$$r_{34} = E[\eta_3\ \eta_5]/\ s_3\ s_4$$

4) Fourth Period T_4:



The payoff function is chosen as:

$$\omega = -a_6^2 + 2a_6\, \eta_6 \qquad (28)$$

where:

$$\eta_6 = \varepsilon + \acute{\alpha}_5$$

$$= (-Q/(1-Q^2)\ \{[-1/(1-Q^2)]\ [x + \varepsilon + \varepsilon] + [-Q/(1-Q^2)]\ (x + \varepsilon + \varepsilon + \varepsilon + \varepsilon) + \varepsilon] + \varepsilon$$

$$+ (-1/(1-Q^2)\ \{[-Q/(1-Q^2)]\ [x + \varepsilon + \varepsilon] + [-1/(1-Q^2)]\ (x + \varepsilon + \varepsilon + \varepsilon) + \varepsilon] + \varepsilon\} \qquad (29)$$

The best decision function is:

$$\acute{\alpha}_6 = \eta_6 \qquad (30)$$

Therefore the expected value of the maximum payoff is:

$$\mathbf{\Omega_4 = s_5^2} \qquad \textbf{(31)}$$

where:

$$s_5^2 = E\,[\varepsilon + \acute{\alpha}_5]^2$$

Total Expected Value of the Maximum Payoff:

$$\Omega = \Sigma\,(i = 1 \ldots 4)\,\Omega_i = \Omega_1 + \Omega_2 + \Omega_3 + \Omega_4$$

$$= s_0^2 + [s_1^2 + 2Qr\, s_1\, s_2 + s_2^2]/\,[1-Q^2] + [s_3^2 + 2Qr_{34} s_3\, s_4 + s_4^2]/\,[1-Q^2] + s_5^2$$

$$= [s_0^2 + s_5^2] + [s_1^2 + s_2^2 + s_3^2 + s_4^2]/\,[1-Q^2] + [2Q(r_{12}\, s_1\, s_2 + r_{34} s_3\, s_4]/\,[1-Q^2]$$

$$\mathbf{\Omega_{TOT} = A + B/[1-Q^2] + CQ/[1-Q^2]} \qquad \textbf{(32)}$$

where the coefficients A, B, C are:

$$A = s_0^2 + s_5^2$$

$$B = s_1^2 + s_2^2 + s_3^2 + s_4^2$$

$$C = 2(r_{12} s_1\, s_2 + r_{34} s_3\, s_4)$$

4.7 RESULTS

From the calculations in the previous section, the total expected payoffs are summarized below for each of the two processes:

Sequential: $\mathbf{\Omega_{TOT} = s_0^2 + s_1^2 + s_2^2 + s_3^2 + s_4^2 + s_5^2}$ **(11)**

CE: $\mathbf{\Omega_{TOT} = A \;+\; B/[1-Q^2] \;+\; CQ/[1-Q^2]}$ **(32)**

where the coefficients A, B, and C are as before. The equation for the expected value of the maximum payoff for the sequential process is a constant with respect to Q, while for the CE process it is polynomial in Q. If it is assumed for simplicity that all variances are equal and the correlation coefficients are equal to zero, i.e., the information variables are independent, then Figure 13 depicts the resulting curves for each process.

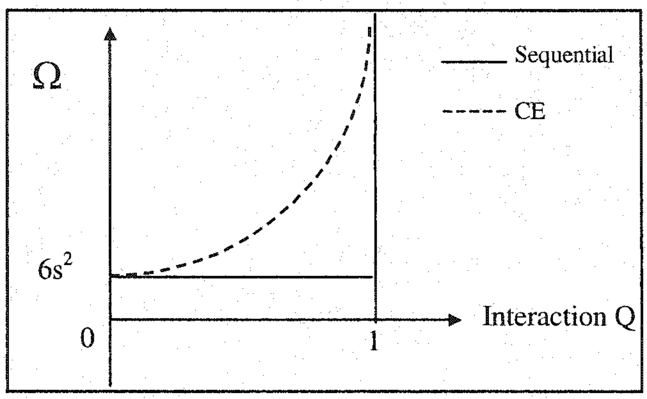


Figure 13 Expected payoff vs interaction.

This analysis shows that a CE process is always better than a sequential one in terms of expected value of the maximum payoff. This is contradictory to practical observations of both processes. This is due to the fact that the analytical model oversimplifies the sequential process, whereby it is assumed that there is virtually no interaction between phases, and that information is 'thrown over the wall' from one function to another. Under this assumption, there is no interaction, which naturally results in an expected payoff that is independent of the interaction, Q, thus giving a constant. Additionally, it is also assumed in the modeling process that the contribution of each member's specialized information is the same for both the sequential and CE processes. This results in the total expected payoff for the sequential process being always lower than that of CE. Again, this assumption is not consistent with practical observations. In order to make the analysis more meaningful, some further assumptions should be made with regards to team members in a sequential process as compared to a CE process.

In some practical situations, a sequential process can be better than a CE process (Krishnan *et al.,* 1997). When this is true, in the modeling process it is reasonable to assume that for a sequential process, every team member's knowledge and information is sufficient to allow him to finish his activity independently. In fact, it may even be argued that in a sequential process, the amount and types of information that functional members must possess is greater than members in a cross-functional team, which allows them to finish their activity independently. They must possess not only information about their own specialization, but they must also have, to some extent, information about other functions as well. After all, a designer will not design a product which requires milling if the company does not own a milling machine. In contrast, in a CE process, it can be assumed that members on a cross-functional team do not need to possess as much information about other functions since sharing of information will occur naturally as a consequence of teamwork, in which case it is reasonable to assume that more work is required to obtain information. Therefore, the variance of knowledge and information measured by s^2 is assumed to be larger for members in a sequential process than for the same members who would work in the overlapped periods in a CE process. This implies that the lack of information or knowledge by members in a CE process can be compensated by the exchange of information in the overlapped periods.

Given this assumption, the straight line in Figure 13 would move up the y-axis, while the CE curve would remain the same. This would create a point of intersection between the two curves, indicating that, for a given point of interaction, one process will be superior to the other in terms of expected payoff. For simplicity, it is assumed that for the CE process, all variances are equal to 1, and that the correlation coefficients are equal to 0. It can be further assumed that team members 2, 3, 4, and 5 in a sequential process have a variance that is slightly higher than the same members in a CE process, who, as explained above, exchange information during the overlapped periods. For simplicity, the variance for the sequential members' information is taken to be one-quarter higher than that of the CE members' information i.e., s_i^2 (sequential) = 1.25 s_i^2 (CE). Plugging these values back into 11 and 32, the total expected payoffs are:

Sequential: $\Omega_{TOT} = 8.25$

CE: $\Omega_{TOT} = 2 + 4/[1-Q^2]$

This analysis is now illustrated in Figure 14.

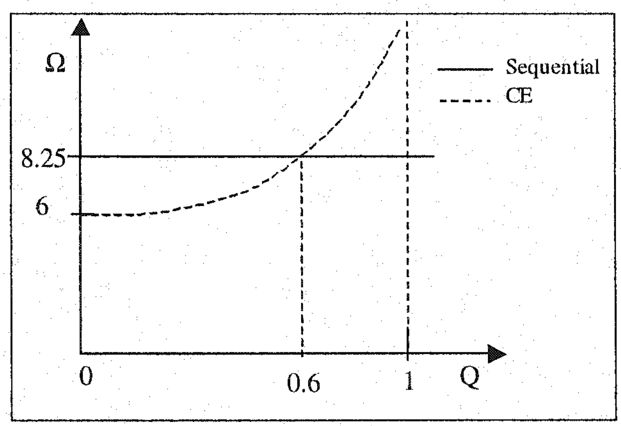


Figure 14 Expected payoff vs interaction.

The curve for the CE process shows how the expected value of the maximum payoff changes with interaction, showing that as team interaction increases, the expected payoff increases as well. For this particular case, it was found that a sequential process has a higher expected payoff when the interaction is lower than 0.6, and a CE process has a higher payoff for values of interaction greater than 0.6. In other words, the results show that when actions in a CE process highly influence one another, i.e., the interaction is higher than 0.6, then a CE process is more valuable in terms of expected value of the maximum payoff. If the interaction between action variables is not strong, i.e., less than 0.6, then the sequential process is sufficient, and superior in terms of expected payoff.

In conclusion, the expected payoff method from decision theory provided some initial results in the comparison of a sequential and CE process. From the mathematical derivation presented in this chapter, comparing equation (11) to (32) shows that a CE process is always more valuable than a sequential process in terms of expected payoff. In most instances in reality, however, a sequential process has some benefit. Under the conditions when this holds true, the sequential process has a higher total expected payoff when the interaction intensity is low, while CE is better than a sequential process for high interaction.

4.8 LIMITATIONS OF THE MODEL AND FUTURE WORK

The expected payoff method is presented here as a very simple introduction to studying NPD processes. A more elaborate and detailed development is in progress (Kong and Thomson, 2001), the results of which are expected to provide a major contribution to the existing body of work in studying organizational processes and their coordination.

4.8.1 Interaction

In the comparison of sequential and CE processes, it is assumed that there is no interaction between team members in the sequential process, thus emulating the 'over-the-wall' approach, where team members throw information over an invisible wall. In practice however, there exist interactions among members (or departments) of a team, though they may be very weak. Future work should consider this.

4.8.2 Goals

At the start of the chapter, it was stated that the expected payoff method assumes that individuals in a team work towards achieving common goals with common interests and beliefs within the constraints of their work, all of which guide their behavior. For a CE team, this is conceivable in the sense that any 'team' usually works together to achieve some goal, and a cross-functional team, ideally, works towards the common project goals of being on time, and within budget. However, in practice there is tension between meeting project and functional goals, as team members have project-specific goals, but also have departmental obligations to fulfill.

The same assumption is debatable for a sequential process, where functional teams in different activities tend to have differing goals. For example, in isolation, a designer's goal is to create a product design without much concern for the production process that will build it. Similarly, a marketing manager's goal is to get customers to buy the company product without much concern for how the product will be made. This is partly due to the fact that functional goals are tied to functional rewards. Taking into account this divergence of beliefs would require further analysis into economic and organization theory where individuals' actions are based on self-interest.

4.8.3 Time and Interaction

A more detailed description of the influence of time on the payoff function must be developed. Presently, it is assumed that interaction between action variables at different times is weaker the farther apart they are in time. However, if there is interaction between actions at different times, the payoff function will not be additive in time. The sequential process will have constraints which link actions that are distant in time, and can no longer be evaluated as a series of single-period problems, in which interaction is so weak that it does not exist.

4.8.4 Rework

Most activities are not deterministic in a product development process. In fact, many situations arise where a stochastic relation between activities apply. A commonly occurring phenomenon is the failure of one or more activities, which consequently require rework. Rework loops in the network diagrams must be expressed to incorporate this very important characteristic of development processes. The function of rework in a network is to prevent the expected payoff from reaching a maximum when an activity is reworked, though a maximum can be reached after a few iterations but at a greater cost.

4.8.5 Cost

The measure of the expected utility of a network has always been considered in its gross form, that is, without any consideration for the cost of the network. In reality, obtaining information can be very costly, and though one network may be superior to another in terms of the expected payoff, the cost of that network may not justify its use. This concept should also be incorporated into the models.

5.0 STOCHASTIC MODELS

Simulation was chosen as a method to study development processes because analytical techniques are not only difficult to develop, but also difficult to solve, especially in the case of complex, dynamic systems. Valid simulation models can describe reality effectively, and experimentation with the models can be performed readily. Because the objective of this thesis is to study the performance of interdependent activities, simulation makes it possible to study alternate scenarios with relative ease. The next sections of the thesis describe the methodology and development of the models.

5.1 METHODOLOGY

This portion of the thesis uses a computer modeling and simulation methodology. The simulation is based on a stochastic model. The purpose of computer modeling here is to simulate the micro-level actions and interactions among actors in a product development process, and to study the corresponding macro-level effects on sequential and CE processes. Span time and effort were chosen as the dependent variables of the model inputs, functional participation and overlapping. Models of both sequential and CE processes were built using a commercially available process modeler called FirstStep™., which is a discrete event simulation software package based on object-oriented programming. The software maps the processes, simulates them, and performs quantitative analyses. FirstStep™ is a product of Interfacing Technologies Inc., Montreal.

The broad steps required in building the computer models are illustrated in Figure 15. From analysis and data collection, an abstraction of the real world system brought about the generic product development process, from which a conceptual model was developed. This model was then translated into a computer model; computer simulations were then run to obtain results. The results of the simulation runs were then analyzed.

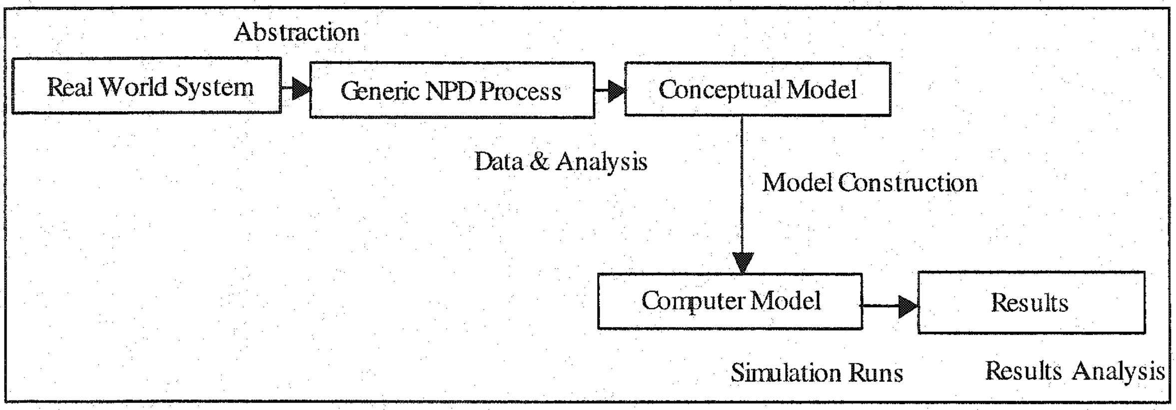


Figure 15 Broad steps in creating a computer model and running simulations.

5.2 DEFINITION OF PROCESS MODELS

The abstraction of the real world system, the generic product development process, was presented in Chapter 3.0. In the following sections, the conceptual model is discussed. A number of important parameters and features of product development processes were identified, and these were translated into computer models. Before discussing these, a key assumption in the construction of the models is discussed first, which is the information processing view of NPD. This is established as a theoretical basis for building the models.

5.2.1 An Information Processing View of the NPD Process

In previous chapters, a discussion was presented on the information processing view of product development. In this view, the activities in a product development process can be thought of as entities that create, retrieve, use, transform, and disseminate information. Thus, ideas for products, knowledge, experience, market and technology data, and other information (information inputs) are transformed into a knowledge base (information outputs), which is used to make the product (Emmanuelides, 1993). Based on this view, the models are made up of *processes*, within which *actors* execute *activities* in order to generate information. *Actors* disseminate information, and link activities to one another through *information flows,* and based on information available to them, they make *decisions*. The movement of information in a development process determines the organization of activities.

Figure 16 gives an overview of the conceptual model, which consists of the following components, each of which will be discussed in upcoming sections:

- *Inputs:* functional participation, overlapping;
- *Process model:* actors execute activities within phases, transforming inputs into outputs through information flows and decision-making processes;
- *Outputs:* span time, effort, as dependent variables of the model.

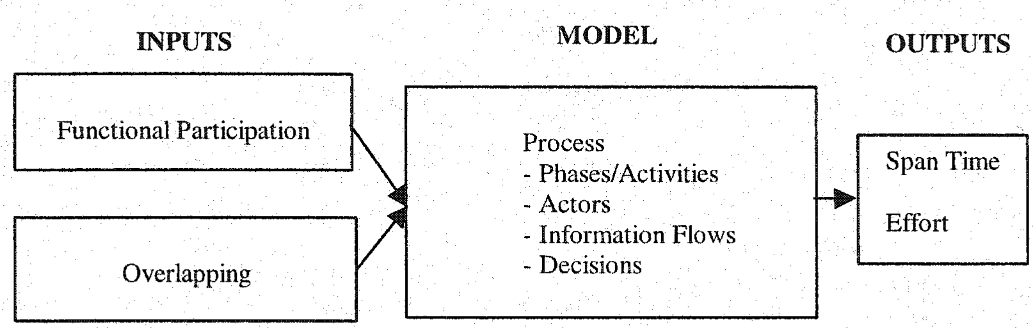


Figure 16 Overview of conceptual model.

Once the conceptual model was built, a set of rules was developed to describe the functional relationships between the variables and the mechanisms in the models. The probability distributions at decision points were also defined. Each of the rules governing the behaviour of the relationships and the distributions were developed based on assumptions found in the literature and on case study findings. In the sections that follow, the outputs will be discussed first, followed by the inputs, and finally, the model.

5.2.2 Outputs of the Model

The main dependent variables of the model, which are product development performance measures, are span time and effort. Effort reflects development cost, since this is typically the major component. Rework is considered as a part of total effort and is thus implicitly considered in the model.

5.2.2.1 Span Time

One of the leading indicators of product development performance is time to market or span time (Emmanuelides, 1993, p365). Span time is the total calendar time elapsed between the initiation of the project until the introduction of the product onto the market. In this study, this corresponds to the time between the start of the initial phase to the end of the final phase. Span time measures the ability of an organization to transform intangible information inputs into a knowledge base that produces a tangible output, and as such, is a very important parameter, particularly in today's time-based environment.

Studies show that managers are more concerned about span time than cost, therefore, cost was not seen a primary parameter of interest (Bozarth and Chapman, 1996). However, in most development projects, effort is the main cost driver, so that cost can be determined if the amount of effort is known. In a global survey of 1,300 manufacturing executives, between 82% and 93% of executives cited that the ability to introduce new products quickly was very important, and many are willing to incur added costs (effort) to achieve this goal (Bozarth and Chapman, 1996).

5.2.2.2 Effort

The nature of interdependence in product development using CE is such that there is an increased need for effort very early in the development process. This interdependence is ignored in the sequential process, and as a result, effort increases downstream in reaction to imperfect information from upstream activities. However, the intent of CE is to reduce *overall* effort by minimizing downstream rework as a result of better upstream communication of information with downstream activities. Effort is measured as the sum of total person-hours from the start of the initial phase to the end of the final phase. Clearly, there can be a tradeoff between effort and span time. Achieving shorter span time may be at the expense of increased effort. These trade-offs are studied in this thesis.

Rework is another important measure of product development performance, and it is defined as the effort required to redo work. As such, it is a component of the overall measure of effort. In the models studied here, variations in effort are due to variations in rework (Section *5.2.4.1.2* has further details).

5.2.3 Inputs of the Model

The factors that influence span time and effort are discussed in this section. Functional participation and the level of overlapping of activities are most often cited as being the strongest factors which contribute to performance in CE processes (Blackburn, 1991; Clark and Fujimoto, 1991). They were chosen as the input variables of the models.

5.2.3.1 Functional Participation

One of the main CE drivers for achieving shorter span times is functional participation, which is the collaboration of individuals from different functions on a team (Blackburn, 1991). The early involvement in the development process by downstream functions holds the promise of less rework in the overall NPD process, since there is a greater chance of getting specifications 'right' the first time. The participation by someone from a downstream activity in an upstream one is expected to reduce rework for both activities. However, this does increase the amount of effort that takes place upstream as a result of early cross-functional teamwork. In practice, the amount of work that has to be done later by individuals downstream, i.e., the effort required to perform downstream activities, should also be reduced, however, only the reduction of downstream rework is modeled.

5.2.3.2 Overlapping

Another important element of CE is the overlapping of product development activities or phases. Recall that the sequential development process progresses in a serial fashion, where finalized information generated from one phase gets handed off only after its completion to the next phase. In contrast, partial information is transferred at many points during the execution of two overlapped phases in a CE process. Because the information is partial and incomplete, the potential risks must be carefully examined to ensure that added span time and effort are kept to a minimum (Krishnan *et al.*, 1997).

Increased levels of overlap guarantee earlier message exchange or transfer between two phases. The goal is to freeze acceptable specifications in Phase A early in the process, so that B can then make use of them to start phase overlap. However, there is a tradeoff between early message exchange and the corresponding risk of imperfect information. Since there is a relatively high degree of uncertainty in the early stages of a CE process, the earlier B starts with respect to A, the more uncertain is the information B receives. Thus, in the case of a change in A, B risks rework; however, by increasing cross-phase communication through the form of progress reviews, the probability of downstream rework decreases.

5.2.4 Process Model

The process models developed in this study include the elements shown in Figure 17.

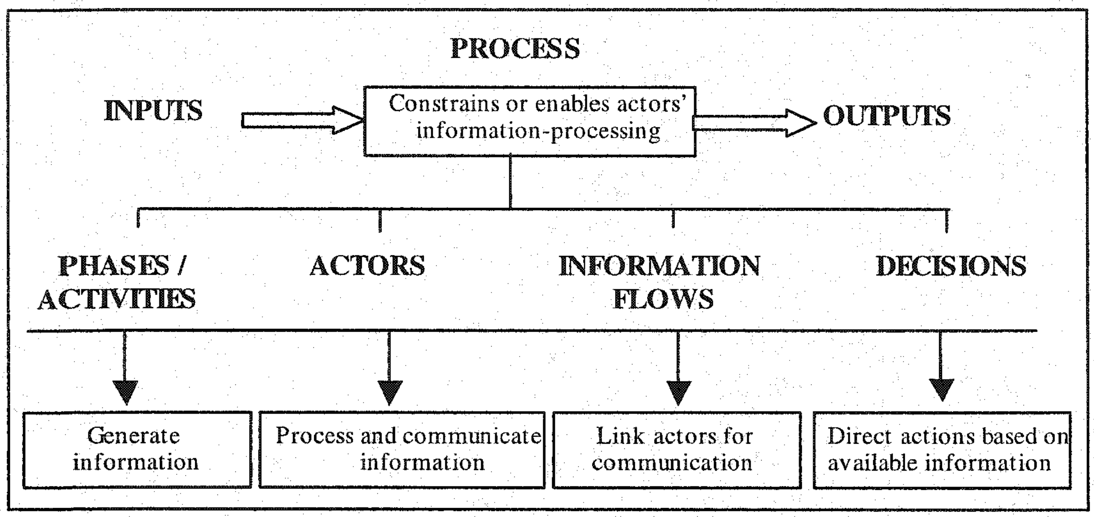


Figure 17 Model composed of four key conceptual components.

The key conceptual components of the models are:

- A process (e.g., sequential or CE), which is made up of phases (Concept, Definition, Development, and Implementation), which in turn are composed of activities (e.g., design work or coordination activities);
- Actors, (Marketing personnel, Designers, Test engineers, Manufacturing personnel);
- Information flows that govern how information links actors (describing dependence relationships among activities);
- Decisions which direct actors' actions based on the information that is available to them (e.g., decisions to accept work, to rework, etc., i.e., progress reviews).

The sequential and CE process models are built on precedence requirements. Each process is semi-structured, wherein "all process steps can be identified but only a partial order of the execution sequence is *a priori* known" (El Mhamedi and Vernadat, 1998, p.264). In other words, alternative routings of the process are left open and routing decisions take place at run time depending on state variables.

5.2.4.1 Sequential Process Model

The sequential process model is presented first. The model is made up of the following components, as discussed above: phases, activities, actors, information flows, decisions, and progress reviews.

5.2.4.1.1 Phases

The process is made up of four sequential phases A, B, C, and D (Figure 18). As described in Chapter 3.0, the four phases correspond to: A – Concept, B – Definition, C – Development, and D – Implementation. At the end of each phase is a progress review or process gate (illustrated by the diamonds). The outcome of the reviews indicate the success of work to date, and thus, a move forward to the next phase, or failure, and thus, rework of one or more phases, i.e., a new design version is created.

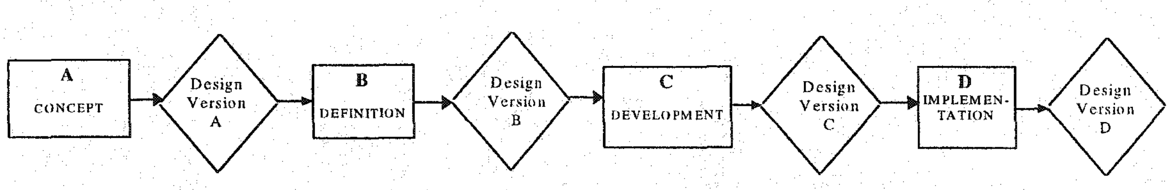


Figure 18 Sequential process model.

5.2.4.1.2 Activities

Each phase consists of three sequential activities, e.g., A1, A2, and A3 for Phase A (Figure 19). These activities are generically named "Explore", "Analyze", and "Finalize" respectively, for each phase. "Explore" was chosen to describe the initial investigation that occurs at the start of a phase. "Analyze" describes the in-depth study of the problem, and "Finalize" refers to the completion of the phase, and can include such things as writing up final reports, completing the design, etc.

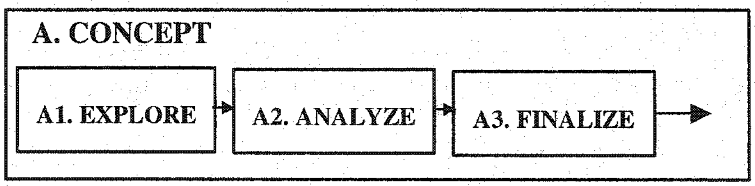


Figure 19 Activities within a phase.

Activities are the main unit of study in the process and they can represent value-added production work, where a set of information inputs is transformed into a set of information outputs or coordination work, which is required to communicate information or to have activities work together. Production work is based on specifications of the product, and it directly adds value to the process. Coordination work consists of decision-making and communication, which facilitates production work, but does not add value to the process.

Activities have the properties of duration and processing time. The duration of an activity is a component of the span time, i.e., it is the start to finish time of the activity, while the processing time is a component of effort, i.e., it is the person-hours required to complete the activity. Activities' durations are partly deterministic, and partly stochastic (Figure 20). Durations are fixed in terms of initial execution time; this portion is deterministic. The randomness takes place in the decision-making process. At decision points at the end of certain activities, alternatives exist which are tagged with a probability of execution, representing possible rework of one or more activities. The randomness or uncertainty is reflected through iterative activities.

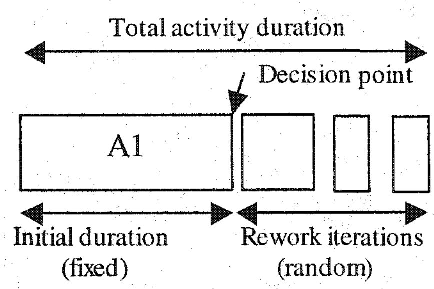


Figure 20 An activity with rework iterations.

In the absence of rework, the processing time (effort) is the person-hours required to execute the activity, and the duration required to perform an activity is strictly taken as the fixed time of the activity. When rework takes place, the increased effort and duration are added to the initial fixed duration. Initial activity durations were estimated to be approximately equal to average cycle times for general, complex NPD processes, based on findings in the literature and on a case study. Since they are used for relative comparison purposes, they need not be exact.

5.2.4.1.3 Actors

Actors are the resources that represent the functional roles required to perform activities, and describe the experts responsible for the new product development process. These resources execute the production work, make decisions, and communicate information. Resources are defined by skill type, i.e., Marketing, Designer, Test engineer, or Manufacturing personnel, and allocable time, i.e., the time during which they are available to work, which is constrained by regular working hours, as well as by other activities they may be already working on.

One of the critical constraints in any enterprise is the number of resources available to execute the processes. The present study assumes a limited resource capacity level, which realistically captures the effect of time delays due to resource constraints. It is also assumed that an actor's skills match the activity requirement, that is, each resource assigned to an activity is qualified to perform that activity.

In the sequential model, the Marketing (MK) is responsible for the Concept Phase (A), the Designers (D) execute the Definition Phase (B), Test engineers (T) and Designers who perform the Development Phase (C), and finally, Manufacturing (MF) is responsible for the Implementation Phase (D).

5.2.4.1.5 Information Flows

Recall that activities are linked to one another through information flows. Actors take incoming information, transform them during activity execution, and transfer the output information to the downstream activity. The sequential model assumes dependent activities, ignoring the interdependencies that exist between product development activities. As such, all information flows are uni-directional and they take place at the end of completed activities and phases. In this way, downstream phases make use of complete information in its finalized form.

Figure 21 illustrates the information flow for Phases A and B of the sequential process; the arrows indicate the points in time that transfers of information take place and the direction of the message for the dependent case. Note that progress reviews, or design versions, have been omitted from this diagram for simplicity.

Figure 21 Information flows in sequential model.

5.2.4.1.6 Decisions

Clark and Fujimoto (1991) view the information processing perspective of product development as an integrated set of problem-solving cycles. As such, a number of decisions must be made throughout the process. A decision process begins with a problem for which a plan of action is developed, consisting of alternative strategies formulated to solve the problem. These strategies are evaluated, and a decision is made. The action taken is then appraised, and this may result in the need for rework.

All decision alternatives in the models are assigned a probability of occurrence. In this study, probability assignments were made based on the literature, and on case study findings. The user of the models can assign different probability distributions to model various levels of uncertainty across alternatives, based on intuition and/or experience, and depending on the situation being modeled.

Actors must often make decisions with respect to the progress of their work, and the work of others, given the information available to them. This is represented at various points in the process models as decision points, which provide alternative routings, each assigned a probability of success. In the sequential model, major decision points exist at the end of phases.

Design Versions

At the end of each phase, there is a progress review, or a gate, where an approval is required in order for the next phase to proceed (shown by the diamonds in Figure 22). These gates are called design versions, and they involve decisions on the need for rework at formal reviews at the end of each phase. As they affect entire sections of the specifications, they contribute significantly to overall span time and effort. At the end of Phases B, C, D, a decision must be made to move forward to the next phase or back to the beginning of the same or a previous phase for rework. For modeling simplicity, it is assumed that Phase A is always successful initially, but later in the process, it may be start from the beginning if a design version is required.

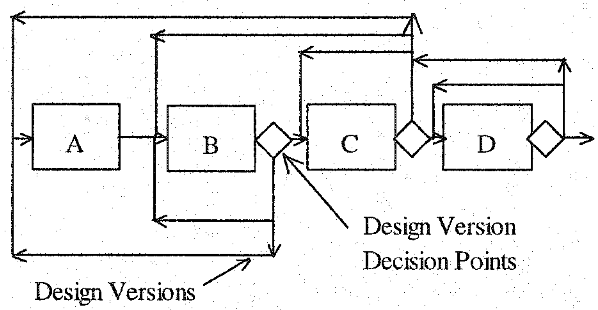


Figure 22 Design versions.

At each design version, there exist probabilities for each possible alternative path that can be chosen. These decision points exhibit a high probability of rework, as expected in a sequential process.

- *Iterations and Learning*

In many practical cases, when rework is required, error correction is achieved only after repeated attempts through multiple rework loops. Each iteration is characterized by a reduced rework duration and increased probability of activity success using learning curves, which capture the effect of knowledge accumulation for activities within a phase. In the models, this is accomplished through a feature built into the simulation software that dynamically updates the model; rework inputs are identified, and decision probabilities and resulting activity durations are adjusted accordingly.

With each iteration in a multiple rework loop, the probability of success of a phase increases and the duration of the phase decreases through the use of an effort multiplier, which is a fraction which multiplies the initial duration of each activity in the phase. To calculate the multiplier, the following learning curve equation is used:

$T_n = T_1 \times n^b$ where:

n = iteration number
T_n = effort multiplier for iteration n
T_1 = effort multiplier for the first iteration, i.e., the initial activity execution, = 1
b= ln learning curve percentage/ln 2

For the sequential model, a 90% learning curve has been chosen, which indicates the following effort multipliers for the second and third iterations, respectively:

$T_2 = 1 \times 2^{\ln 0.9/\ln 2 = 0.9} = 0.9$
$T_3 = 1 \times 3^{\ln 0.9/\ln 2 = 0.9} = 0.846.$

These fractions then multiply the initial duration of the activity if rework is required. For example, if an activity has a duration of 5 days, and it must be reworked, then, if the initial activity takes 5 days, the second iteration is 5 x 0.9 = 4.5 days, and the third iteration is 5 x 0.846 = 4.23 days. This exhibits the situation of high rework in a sequential process, and reflects the fact that not a great deal of learning takes place due to the lack of cross-functional communication, as consequent iterations are not much lower in duration than the initial activity duration.

5.2.4.2 Sequential Process Model with Functional Participation

Up until now, the model discussed is the baseline model, representing a traditional sequential process in which there is no teamwork, and as such, it is called the baseline sequential process. The sequential model can also include concurrency in the form of functional participation or multi-functional teams. The process structure remains sequential, that is, the phases and activities are executed one after the other, with no overlapping, but teamwork takes place within the phases.

5.2.4.2.1 Modeling Functional Participation

In the baseline sequential process, where there is no functional interaction between activities, it was assumed that each phase is executed by only one function: Marketing is responsible for the Concept phase; Design Engineering for the Definition phase; Test engineering for the Development phase; and finally, Manufacturing for the Implementation phase. By introducing functional participation as an input to the model, a cross-functional team is created by including one of each of these resources to participate in all activities. Thus, in a given phase, the four actors work together.

To model functional participation, activities are further broken down into sub-activities. Each activity is composed of the following three sub-activities (Figure 23).

- *Work*: a value-added activity representing production work, made up of parallel sub-activities, performed by the functions Marketing (MK), Designers (D), Test engineers (T), and Manufacturing personnel (MF).
- *Communicate*: a non-value-added activity representing the work needed to coordinate activities through the transfer of information, and
- *Feedback*: an activity completion decision that indicates activity success and moving ahead, or activity failure and the need for rework of *work* sub-activities.

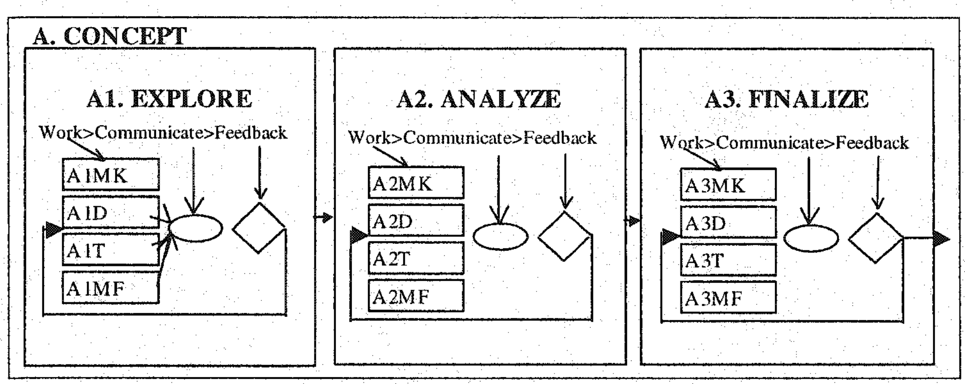


Figure 23 Work-communicate-feedback model for Phase A.

Functional participation is measured as the percentage of time that an actor participates in an activity, and can be varied at different levels of effort. It is modeled by assigning each team member who is presently in a non-traditional activity (i.e., an activity in which he would not participate in a baseline sequential process), to a percentage of the actual duration of the activity. For example, say a design activity has a duration of 5 days, and each non-traditional function participates 25% of the time in the activity. Then the designer participates during the entire length of the activity (5 days), while the remaining functions devote only 25% of their time (1.25 days). For modeling simplicity, it is assumed that all functions begin simultaneously, and each works full-time until their activity time expires. The percentage of participation in an activity is explicitly defined in each model, and can take on a value of 0%, 25%, 50% or 100%. The case of 100% functional participation refers to a dedicated team, where team members devote all of their time to a single project.

In the work-communicate-feedback module, feedback is a new decision point in the model, and has a particular significance. The participation by someone from a downstream activity in an upstream activity is expected to reduce the amount of downstream rework that has to be done later by the individual downstream. However, this does increase the amount of informal changes, termed 'churn', that take place upstream as a result of increased cross-functional teamwork. By introducing functional participation in the sequential model, there is an increase in churn and a corresponding decrease in design versions. The following sections discuss the importance of churn and design versions. The reasons for which rework takes place are not a part of this study, as the two types appear probabilistically.

5.2.4.2.2 Churn

Churn involves making changes early in the process when the design has not yet been solidified, reflecting a proactive approach to work. These changes take place prior to the formal adoption of the specifications, thus they occur early in the process after the completion of an activity. Churn represents a lower amount of rework compared to design versions, where significant change downstream affects span time and effort.

At the feedback unit of each work-communicate-feedback module, shown in Figure 23, a decision must be made to move forward to the next activity or churn. For example, in the case of activity A1, this means move forward to the next work-communicate-feedback cycle in A2, or do rework in the same cycle in A1.

- *Probability of Churn*

The alternatives at the decision points at the end of each activity are to move forward or to have churn; each alternative is tagged with a probability. These probabilities depend on the level of functional participation input into the model. The probability of churn increases as functional participation increases (Figure 24, dashed curve).

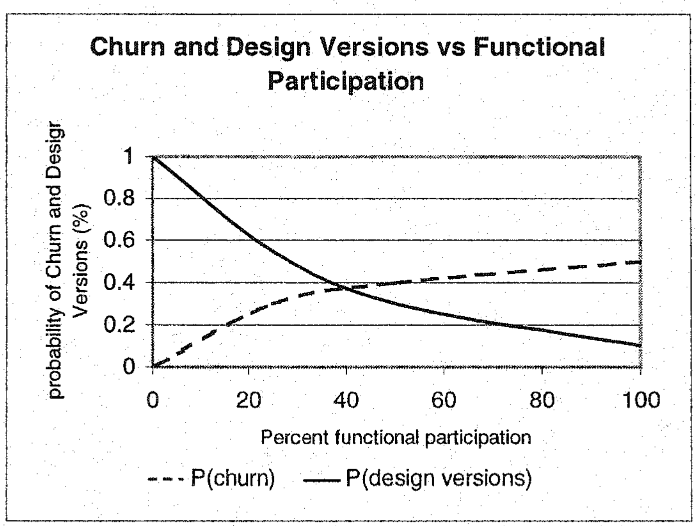


Figure 24 Churn and design versions vs functional participation.

The premise is that as more information sharing takes place among multi-functional team members, more informal changes take place in the activity.

5.2.4.2.3 Design Versions

Recall that design versions involve major rework decisions at formal reviews at the gates in the phase-gate process (Figure 18). These gates have characteristics that exhibit a level of uncertainty and a probability of rework which is dependent upon the level of functional participation. Design versions are more likely to occur in sequential processes with lower levels of functional participation.

- *Probability of Design Versions*

The alternatives at the decision point at the end of the phases are to either move forward or to have design versions, and each alternative is given a probability. In the cases where there is functional participation in the sequential process, the probability of design versions decreases with increasing functional participation (Figure 24, solid curve). In other words, as team members work together more, they are increasing the probability of having informal changes early in the process (churn), but they are also decreasing the probability of having significant downstream iterations (design versions) through better preparation upstream.

5.2.4.2.4 Learning and Functional Participation

As functional participation increases, it is assumed that learning also increases because more information is being shared among team members due to cross-functional interaction (Figure 25). Hence, the learning coefficient or multiplier is lower and results in lower effort for the activity. For example, if functional participation is 25%, from Figure 25, this corresponds to a 70% learning curve, which means that for the second iteration of an activity, the initial activity duration is multiplied by 0.7. Recall that the first iteration is the initial activity execution. If functional participation is 50%, the initial activity duration is multiplied by 0.6 to obtain the duration of the second iteration. With higher functional participation, there is a higher degree of learning taking place.

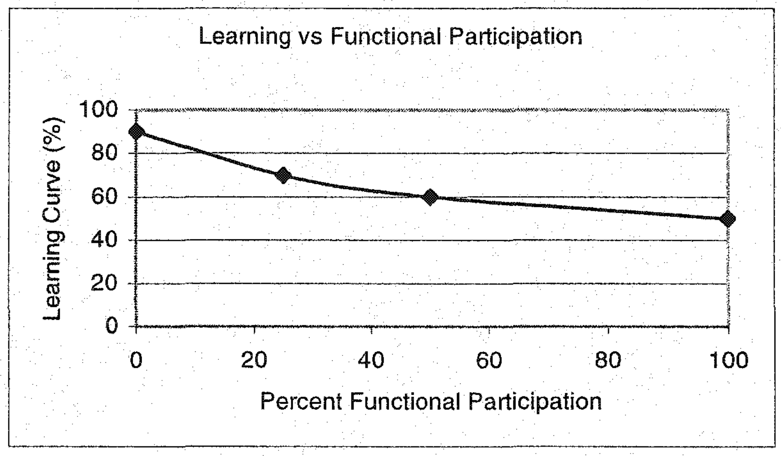


Figure 25 Learning vs functional participation.

5.2.4.2.5 Overview of the Sequential Process Model

Figure 26 shows an overview of the sequential process model, consisting of four phases, each phase composed of three sequential activities. Activities are characterized by duration and processing time (person hours), and the sum of each measure over all activities, from the start of Phase A to the end of Phase D, gives the performance indicators of span time and effort, respectively (effort is implicit in the diagram). Phases A, B, C, and D are carried out in series, and each phase is executed by one function, Marketing (MK), Designer (D), Test engineer (T), and Manufacturing (MF), respectively.

Information flows that link activities are uni-directional, represented by the thin single-headed arrows, indicating dependent relationships. At the end of Phases B, C, and D, there are decision points (diamonds) representing the decision points for design versions. The arrows at the end of a phase, going back from the design version decision points, show the possible starting points for subsequent design versions. When design versions take place, multiple iterations are possible: with each one, the learning effect takes place, resulting in reduced activity duration and increased probability of success in subsequent decisions for rework.

When functional participation is introduced as a model input, a work-communicate-feedback module is created to represent teamwork within each activity. As such, a new feature of the model results called churn. The probability of churn, the probability of design versions, and the learning coefficient are parameters which depend on functional participation.

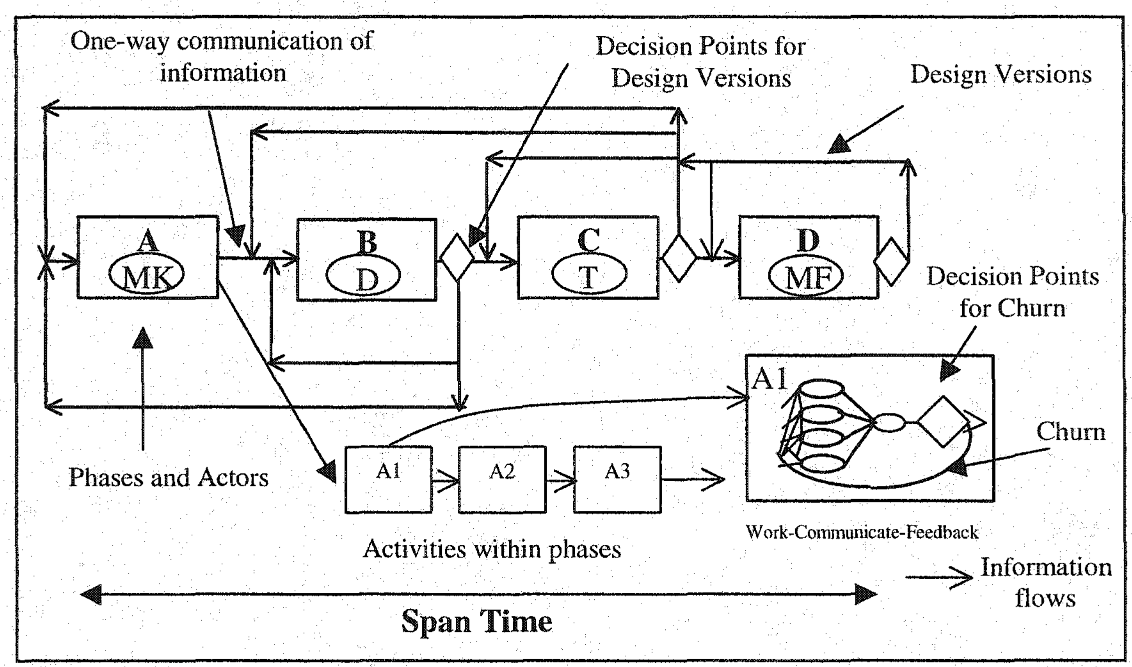


Figure 26 Overview of sequential process model.

5.2.4.3 Concurrent Process Model

The concurrent process model consists of the same basic building blocks as the sequential model, i.e., phases, activities, and sub-activities, which require actors, information flows, decisions and progress reviews. It also includes churn, design versions, and learning as parameters of the model, which are determined by the inputs of functional participation and overlap. Overlapping is introduced as a new input variable in the CE model, which causes the process structure to differ from the sequential process. Modeling overlapping necessitates some changes to the sequential model, which will now be discussed.

5.2.4.3.1 Phases

In the CE model, the same phases exist as in the sequential model (Figure 18). In the model, these phases are overlapped at two possible degrees of parallelism. Figures 27 and 28 respectively show levels of overlapping at 33% and 66%. The new diagonal arrows in the process diagrams depict information flows across phases which create overlap. Though in the real world, overlap can exist without them, they are necessary for modeling purposes. All decision points are suppressed in the diagram for simplicity.

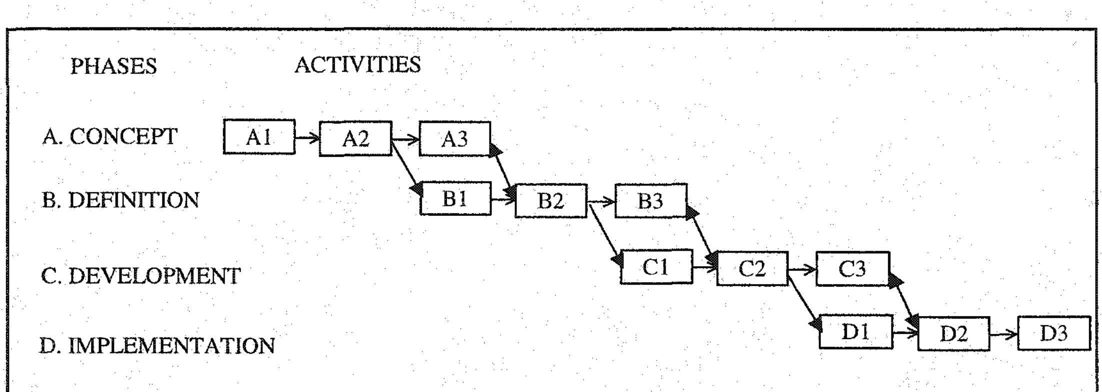


Figure 27 Top-level phase-activity model: 33% overlapping.

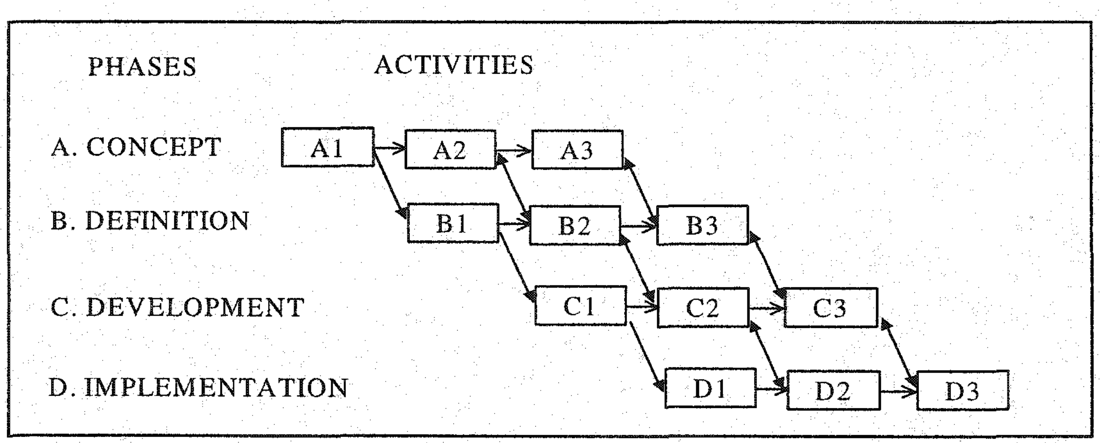


Figure 28 Top-level phase-activity model: 66% overlapping.

5.2.4.3.2 Activities and Sub-activities

Within each phase, once again there are three generic activities, "Explore", "Analyze" and "Finalize", as shown in the Figure 29. These activities remain sequential within each phase. The same properties described for activities in the sequential model, i.e., duration and effort, apply to the CE model. Again, the initial activity duration is deterministic, while the rework portion is probabilistic.

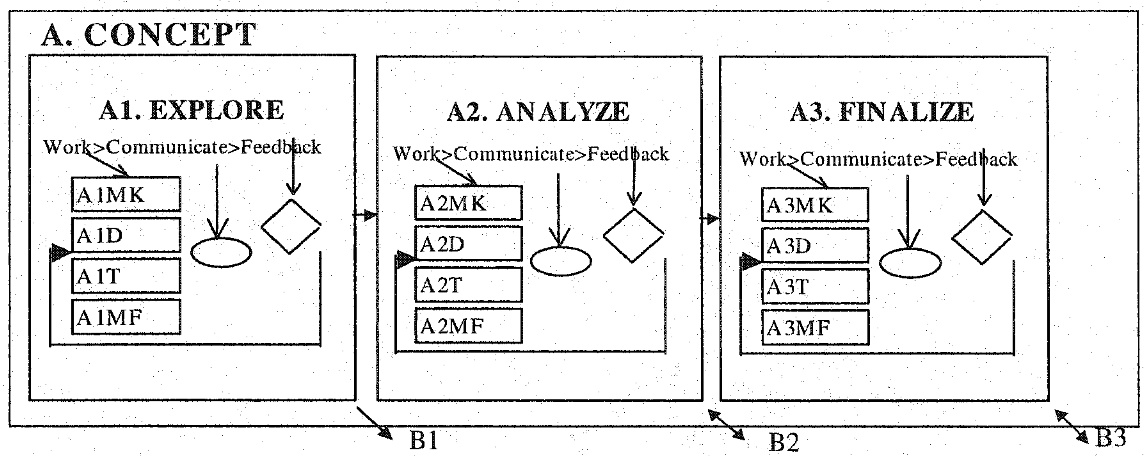


Figure 29 Activity-work-communicate-feedback model for Phase A.

The CE model also consists of sub-activities, which model functional participation as before except for the special case when there is overlapping without any functional participation. The sub-activities again consist of the work-communicate-feedback module (Figure 29). In the CE model, in contrast to the sequential one, information is sent not only to the subsequent activity in the same phase, but also to activities in the downstream phase.

5.2.4.3.3 Actors

Recall that in the sequential model, Marketing is responsible for the Concept phase, Design engineering for the Definition phase, Test engineering for the Development phase, and finally, Manufacturing for the Implementation phase. In the CE model, the possibilities range from single-function teams, where overlap takes place without any functional participation, to cross-functional teams created by including one of each of these resources to take part in all activities at various levels of participation.

5.2.4.3.4 Information Flows

As in the sequential model, activities are linked through information flows; actors use, transform, and disseminate information to downstream activities. In contrast to the sequential model, the CE model acknowledges mutual interdependencies between product development activities in different phases, and as such, information flows must be organized differently. With overlapping, information flows must be bi-directional between activities in successive phases, and they must take place more frequently. For example, if Phases A and B work concurrently, both mutually depend on one another for information to support overlap. A and B are therefore closely linked with a frequent exchange of messages.

Figures 27 and 28 illustrate the information flows for the interdependent cases for Phases A and B at both 33% and 66% overlap, respectively. These are depicted by the arrows which indicate the points in time that a transfer takes place as well as the direction of the messages. The flow remains uni-directional between sequential activities within a phase (indicated by the single-headed arrows), but bi-directional between successive phases indicated by the two-headed arrows, representing information exchange. The initial point of transfer from the upstream phase must be uni-directional since the downstream activity has not yet begun and it is assumed that there is no information to share (A2, B2, C2, and D2 for Figure 27, and A1, B1, C1, and D1 for Figure 28).

5.2.4.3.5 Decisions

The CE model has the same decision points as the sequential one; that is, the design version and churn decision points, as well as two additional important decision points. These are discussed below.

- *Modeling Overlap: Sufficiency of Information*

The decision of whether or not to transfer information from an upstream activity to a downstream activity in order to overlap phases is set in the model using a decision point based on the sufficiency of information available to the decision-maker. At the end of the upstream activity, a decision point exists to determine whether the downstream phase can begin early. The outcome at this decision point can result in overlapping of activities or sequential execution of activities. If there is enough information, the subsequent activity within the same phase *and* in the downstream phase can proceed, thus creating an overlap of activities. Otherwise, the upstream activity will continue, and no overlap takes place.

For example, as shown in Figure 30, at the end of activity A1, some information is generated as an output. This output is input into a decision point, the diamond, which represents a point where this information is either 1) deemed sufficient so that activity B1 of Phase B can begin concurrently with A2, thus 66% overlap takes place (follow dashed arrows), or 2) deemed insufficient, so A2 begins, and B1 waits for further information (follow solid arrows). In Case 1), the output of B1 enters a new decision point, where the overlapping decision must be taken for C1 of Phase C (follow double solid arrow). In Case 2), when A2 is completed, the same decision must be taken again, and if the information generated from A2 is sufficient for B1, 33% overlap takes place (follow double-dashed arrow). Otherwise, B1 waits again for A3 to finish (follow thin solid arrow), and it becomes a sequential case.

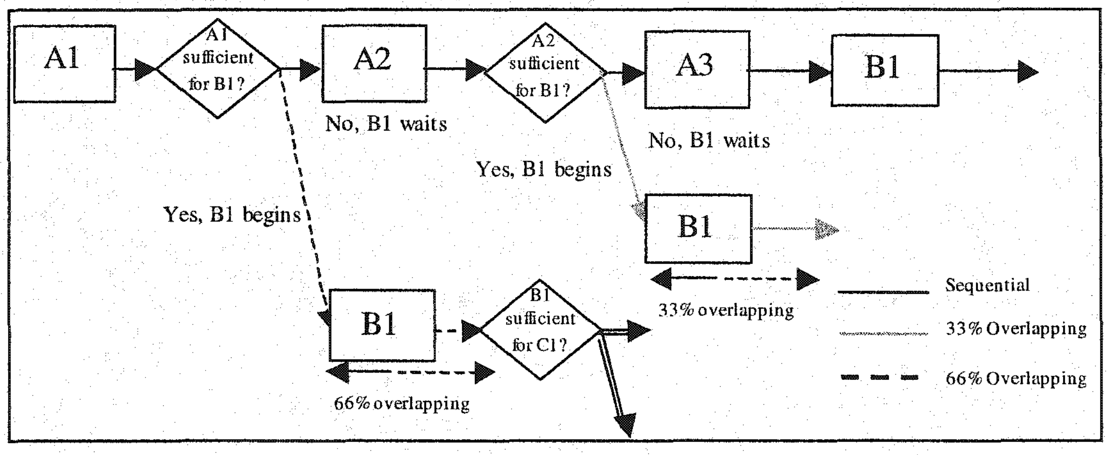


Figure 30 Overlapping of activities.

Each decision point for sufficiency of information requires a probability assignment for the possible alternatives. When a specific level of overlap is desired, the decision points are directly set to achieve the desired level of overlap. For example, suppose in Figure 30, it is desired to study the effects of 66% overlap. The first decision point "A1 sufficient for B1?" has two possible outcomes, and the outcome "Yes, B1 begins" is assigned a probability of 100%. This ensures that 66% overlap will take place.

- *Acceptance of Information*

At the end of overlapped activities, decisions are made on the acceptance of work. Acceptance of information relates to whether information exchanged and transformed during overlap is satisfactory for one or more downstream activities to begin or continue their work (Figure 31).

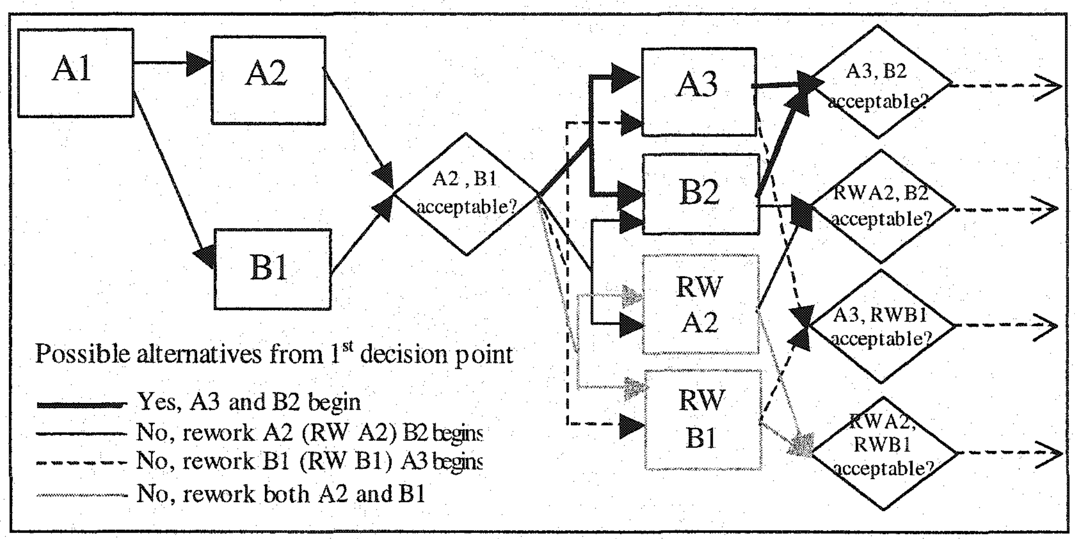


Figure 31 Progress reviews for overlapped activities.

As shown in the figure, if the information exchanged between A2 and B1 is acceptable, subsequent activities within the same phase *and* in the downstream phase can proceed (i.e., A3 and B2 respectively). However, if the information is unacceptable, there is partial or complete rework of one or both of the activities involved. If only one of the two overlapped activities requires rework, then the other activity must wait for the completion of the rework before *its* subsequent activity can begin. For example, if A2 is acceptable but B1 is not, then A3 cannot begin until B1 has been reworked successfully (activity RW B1). In the case where the upstream activity has reached phase end, for example, A3, then in the case where B2 needs rework, the gate for Phase A cannot take place until B2 has been successfully reworked (activity RW B2). The decision for acceptance takes place every time two activities are overlapped. Note however that the acceptance decisions do not replace the decisions for churn, which take place within an activity box. Similarly, the acceptability decision does not replace a gate at the end of a phase: it takes place after two overlapped activities are successfully completed.

Probabilities assigned to the alternatives are always equal, so that each alternative has the same probability of occurrence.

5.2.4.4 CE Model with Functional Participation and Overlapping

In the CE model, functional participation is an input along with overlapping. The various levels of functional participation are again explicitly defined in each model, and can be set at 0%, 25%, 50% or 100%. Various scenarios can be modeled by combining both levels of overlap with any level of functional participation. Note that when there is 0% overlap and any level of functional participation, this is considered under the sequential model. The case of 0% functional participation and any level of overlap is a special case. All possible combinations are shown in Figure 32:

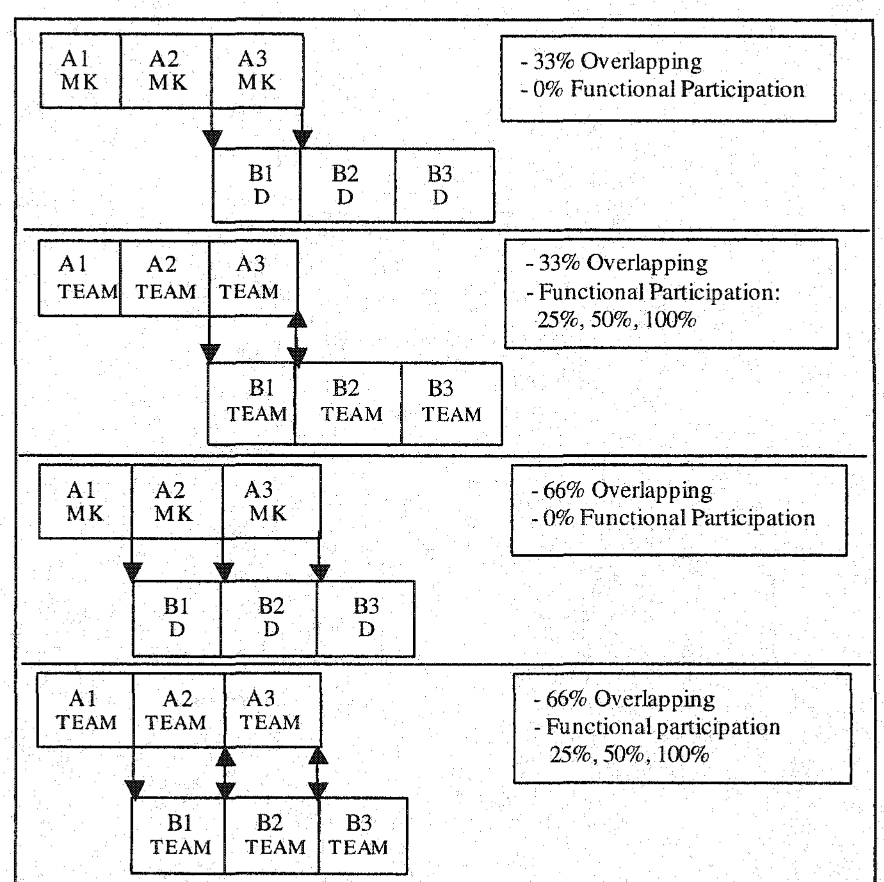


Figure 32 Combination of overlapping and functional participation scenarios.

5.2.4.4.1 Effects of Input Variations

When the input variables, functional participation and overlapping, are adjusted, either individually or simultaneously, there is a corresponding effect on the behaviour of the model. These effects will be discussed as they are related to the probability of churn and design versions.

- *Increasing Overlap*

In the cases where there is overlapping in the process without any functional participation, there is no effect on the probability of design versions, because the only form of information flow among team members is a one-way transfer to the subsequent (adjacent) phase. (Recall there is no churn when there is no functional participation). This scenario has the same characteristics as the baseline sequential scenario, only the phases are overlapped.

The result is that increasing levels of overlap introduce a higher risk of re-doing entire activities with almost the same duration and effort as the first iteration (recall that at 0% functional participation, the learning curve is 90%). This implies wastage of resource time and increasing resource cost without the benefit of having significantly increased learning. For example, if Phases A, B, and C are overlapped at 33%, and Phase B undergoes a design version, then the overlapped portion which included activities A3 and B1 must be repeated, in addition to the remaining activities of Phase B. Additionally, since B3 is overlapped with C1, C1 could also be repeated. In a baseline sequential process, only Phase B would be repeated. Increased effort is a highly increased possibility with overlapping of activities. As compared to the sequential process, more activities are likely to be affected when phases are overlapped without functional participation.

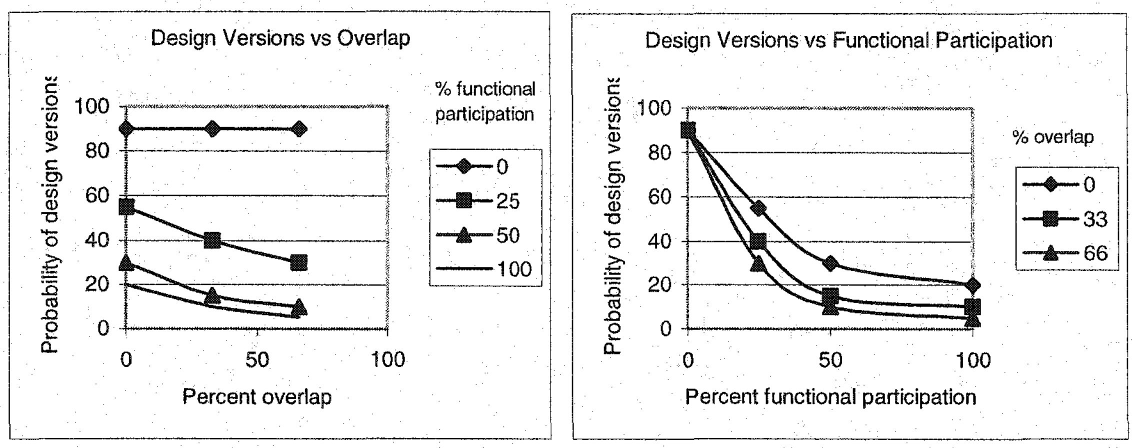
- *Increasing Functional Participation and Overlap*

In the cases where there is increasing functional participation *and* overlapping, there is an effect on the probability of churn and design versions. However, a distinction must be made between the effects of increasing each.

First, there is an internal communication among team members in an activity represented by functional participation. As this teamwork activity increases (i.e., functional participation increases), there is more communication and teamwork, and therefore, more churn, as previously discussed.

Second, as phases are simultaneously overlapped, there is an exchange of information *across phases* in order to mitigate the risk of overlapping. In other words, the team is working on the activity in the upstream phase, and periodically, it exchanges information among team members so that the activity in the downstream phase may begin in parallel. Through the reviews of acceptability, the team members working on the two overlapped activities stop and communicate their work with each other to verify whether they can move ahead, or whether they must go through some more churn before finalizing their solution. If the decision is to rework a portion of either/or both of the overlapped activities, then, there is more churn.

This cross-phase communication results in an increase in churn due to an increase in the number of activities affected, but the *probability* of churn does not change as overlapping is increased. Since more communication is required with overlap, a decrease in the probability of design versions also takes place because more frequent checks are made as to the acceptability of overlapped work. This is shown in Figure 33, in the left graph, which shows that when there is functional participation, the probability of design versions decreases as the level of overlap increases. The graph on the right in Figure 33 shows that the probability of design versions decreases with increasing functional participation at all levels of overlap.



Figures 33 Probabilities of design versions vs overlap and functional participation.

The higher the degree of functional participation, it is assumed that, in general, there is more potential for overlap.

5.2.4.4.2 Iterations and Learning

In the cases when design versions or churn take place, activities may undergo a number of iterations before moving on. In the cases when they do, learning curves are again used to model knowledge accumulation. Recall that learning depends on functional participation, and the function shown in Figure 25 applies to CE models as well. In the CE model, due to functional participation, there is a higher degree of learning taking place that result in a lower coefficient of learning. A higher coefficient of learning (less learning) is used for sequential processes.

5.2.4.4.3 Overview of the CE Process Model

Figure 34 shows an overview of the CE process model. Phases A, B, C, and D, each composed of three sequential activities, are carried out with the introduction of an overlapping variable to allow for either 33% or 66% overlap.

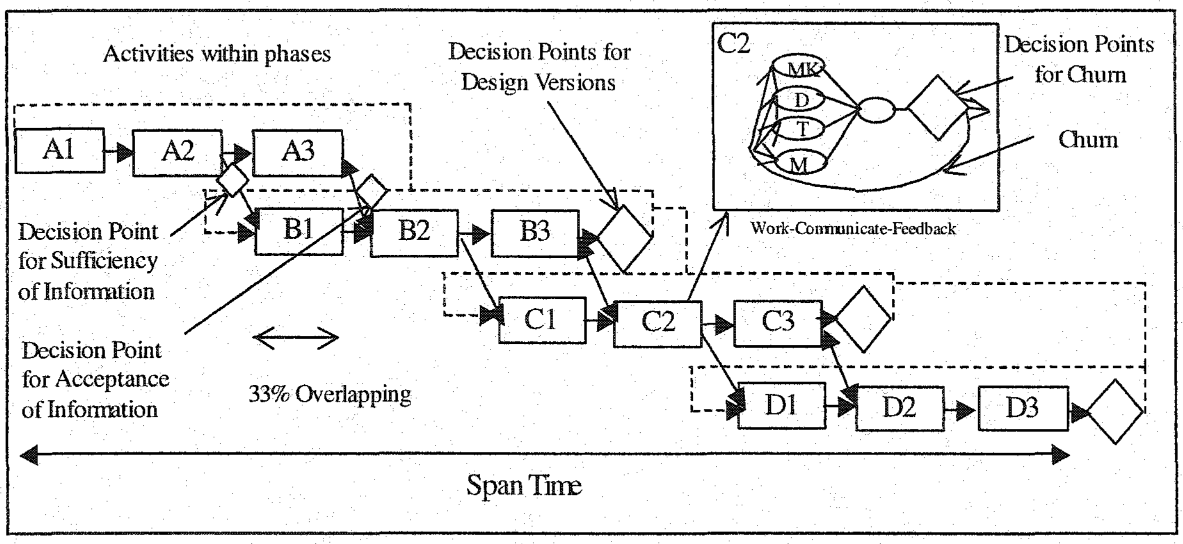


Figure 34 CE process model (33% overlap).

When functional participation is an input to the model, the work-communicate-feedback module is created to represent teamwork within each activity. Each phase is executed by a cross-functional team consisting of one of each of the following functions: Marketing (MK), Designer (D), Test engineer (T), and Manufacturing (MF), represented in each activity by the work-communicate-feedback module.

Information flows between phases and activities are represented by solid-headed arrows. Uni-directional arrows which are sent from an upstream activity to the start of a downstream phase represent the point at which overlap is set through the sufficiency of information decision point. Bi-directional arrows indicate interdependent relationships between overlapped activities, where acceptability of information decisions take place.

The decision points for sufficiency and acceptability of information are shown upstream only by the small diamonds in Figure 34, and are suppressed in the rest of the diagram for clarity. The flow of information remains sequential within phases.

Churn, design versions, and learning are model parameters which are dependent on the two main variables, functional participation and overlapping. Churn takes place within each activity box, each of which contains a work-communicate-feedback module. Overall span time is again measured from the start of Phase A to the end of Phase D, while total effort is the sum of the processing times of all activities.

Table 3 summarizes the comparison of the characteristics of the sequential and the CE model. When text in the table is followed by a question mark, this implies that the answer is known when results are obtained from the simulation runs.

Table 3 Comparison of sequential and CE models.

	SEQUENTIAL MODEL	**CE MODEL**
SPAN TIME	Overall?	Overall?
EFFORT	Little or none upstream Higher effort Overall?	Higher effort upstream Lower effort Overall?
FUNCTIONAL PARTICIPATION	Varying levels (0%, 25%, 50%, 100%)	Varying levels (0%, 25%, 50%, 100%)
OVERLAPPING	0%	Two levels (33%, 66%)
REWORK Churn Design Versions	 No churn, unless functional participation is an input High level of design versions in baseline scenario Overall?	 High churn upfront Low level of design versions Overall?
PROCESS	Sequential	Overlapped
ACTIVITIES	Same in both models	Same in both models
ACTORS	Same actors form different teams (single function teams)	Same actors form different teams (multi-functional teams)
INFORMATION FLOWS	One-time flow of information at end of phases	Frequent transfer of information flows during phases
DECISIONS	Few progress reviews, mainly in form of phase reviews	Frequent reviews of progress throughout process
LEARNING	Little knowledge accumulation across phases	High knowledge accumulation across phases

5.3. SPECIAL FEATURES OF THE MODELS

Some of the concepts introduced in the models were compared to the study done by Krishnan *et al.* (1997). Their study is used to establish a theoretical framework for the present models, and is discussed to justify the selection of some functional relationships which were discussed in the previous sections. A brief description of Krishnan *et al.*'s model was given in Chapter 2.0. It is revisited in this section.

In addition to Krishnan *et al.*'s quantitative analysis, the authors have developed a conceptual framework to address the problem of overlapping. In practice, the design properties identified in their mathematical model (evolution and sensitivity as two parameters of the design process) are not always easy to define quantitatively. Their conceptual model describes a framework which can take qualitative inputs and provide insights on how to overlap activities. This framework consists of a two-by-two grid which considers four combinations of evolution of information (slow or fast) coupled with downstream sensitivity (low or high). Each case results in a different type of overlapping scheme, each of which involves different trade-offs and has different outcomes on performance. In contrast to the mathematical model, the conceptual model can be applied to more than two activities or even phases.

In the context of this research, upstream and downstream have slightly different meanings than in Krishnan *et al.*'s work. In the latter, the authors deal with only two development activities, A and B, where A is the upstream *activity* and B is the downstream *activity*. Recall that in the computer model, A and B represent phases with many activities. Since the whole development process is studied in the present research, upstream is defined relative to downstream. In this context, evolution refers to how quickly information is finalized in an upstream phase relative to a downstream phase, and similarly downstream sensitivity is the probability of design versions occurring in phases downstream to the current phase.

5.3.1 Evolution and the Probability of Churn

In Krishnan's study, evolution of information is defined as the rate at which information in an upstream activity finalizes to a complete solution, and can be qualified as being either slow or fast. In the computer models here, the concept of evolution is represented by churn.

One important point to be made is that Krishnan uses evolution to help determine *when* CE is appropriate, thus taking evolution as a given. In contrast, in the present models, evolution is affected by the input variable, functional participation. Nevertheless, the two concepts are similar and can be broadly compared. In what follows, the two cases of evolution, slow and fast, are discussed in more detail.

- *Slow evolution: High Probability of Churn*

Slow evolution, as compared to fast evolution, takes place when information is incomplete. This represents a high degree of uncertainty, so that the amount of churn required to complete an activity is higher compared to fast evolution. In other words, more work must be done to accomplish goals as compared to when the completeness of information is higher (Figure 35). For example, the development of an innovative product design requires designers to generate ideas and create new information. In such a case, only a *low degree of functional participation* upfront should be necessary to speed up the overall development process since it is assumed that downstream functions can only contribute so much at the initial stages of innovation.

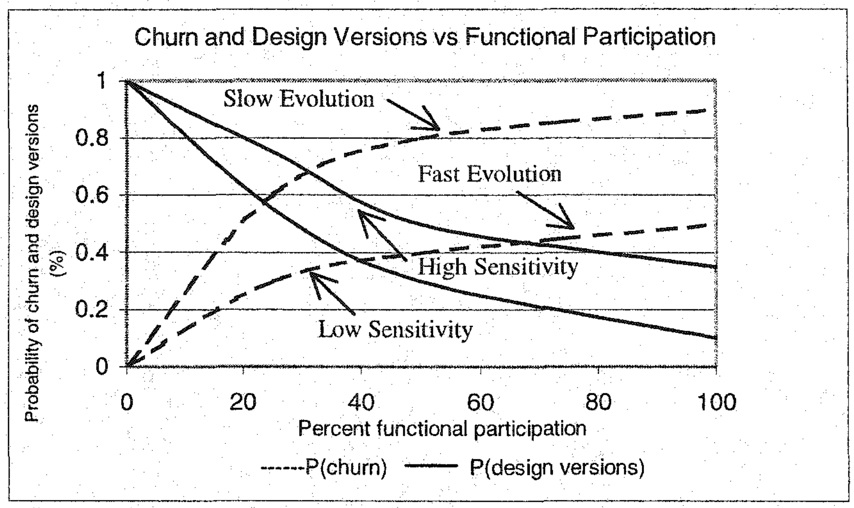


Figure 35 Probability of churn and design versions for different levels of evolution and sensitivity.

- *Fast evolution: Low Probability of Churn*

Fast evolution, as compared to slow evolution, takes place when information becomes complete rapidly. Therefore, a solution is finalized relatively quickly which results in lower churn (Figure 35). A *high level of functional participation* can help to reduce span time. Due to completeness of information, designers can confidently share their information with process and test engineers, get feedback, and act accordingly.

5.3.2 Sensitivity and the Probability of Design Versions

Krishnan defined downstream sensitivity to information transfers as the impact of changes in upstream activities on downstream activities, measured by the duration required to incorporate the changes, and qualified as being either low or high. The analogy to this concept in the computer models is the use of design versions.

- *Low Sensitivity: Low Probability of Design Versions*

Low sensitivity means that the downstream impact due to changes upstream is low, and thus, the probability of design versions is low (Figure 35). This implies that it is acceptable, and even advantageous, to have *high overlap*. If a downstream activity is started early, and if a change occurs upstream, the time needed to incorporate that change is negligible in comparison to the time gained from overlap.

- *High Sensitivity: High Probability of Design Versions*

High sensitivity means that the downstream impact due to changes upstream is high, so the probability of design versions is high (Figure 35). This impacts heavily on overall performance in terms of time and cost of effort. In this case, it is preferable to *avoid overlapping*. If a downstream activity is started early, and if a change in an upstream activity requires time for the downstream activity to incorporate the change, this can not only waste what had been accomplished due to the overlap period, but also increases effort. However, if a suitable level of functional participation accompanies the overlap, then, communication within and across phases should help to mitigate the impact.

5.3.3 Completeness of Information

Uncertainty was defined earlier as the difference between the information available to complete an activity and the amount required to complete it. When less information is available upstream, there is more uncertainty involved in the process. The probabilities of churn and design versions imply the degree of completeness of information for any level of functional participation. When the probability of churn is high and the probability of design versions is high, this implies a high level of uncertainty. In other words, the less information is available upstream, it is assumed that the higher the expected rework (both churn and design versions) (Figure 36).

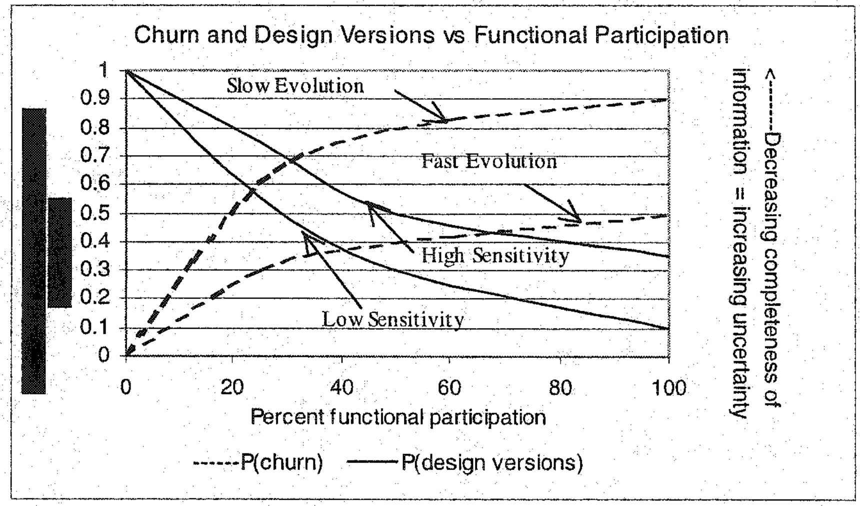


Figure 36 Probability of churn and designs versions versus functional participation and completeness of information.

Recall that solid curves represent the probability of design versions, while the dashed ones represent the probability of churn. The right side of the graph shows that as the completeness of information decreases for a given amount of functional participation (moving up along the vertical axis), the probability of design versions increases, as does the probability of churn. In other words, there is a greater uncertainty due to incompleteness of information. Thus, the new dotted curves represent a scenario of less complete information and a higher level of uncertainty compared to the solid curves.

Each curve in Figure 36 also represents a level of evolution or sensitivity, and pair-wise combinations of evolution and sensitivity can be made. Four possible conditions exist: slow evolution, low sensitivity (SL); fast evolution, low sensitivity (FL); slow evolution, high sensitivity (SH); and fast evolution, high sensitivity (FH). Pairs of curves are input into the models, so that a certain degree of completeness of information is implied. The following section discusses these conditions in detail.

5.3.4 Coupled Phenomena – Conditions of Uncertainty

The previous section described the probability of churn (evolution) and design versions (sensitivity) as they relate to completeness of information, and it discussed their effect on the process if they are considered in isolation. Each curve in Figure 37 has a specific expected effect on performance, but the coupled effect of two curves at a time may produce different sets of outcomes. The curves in Figure 37 show the four combinations of completeness of information, which are categorized as different conditions of uncertainty, as per Figure 36.

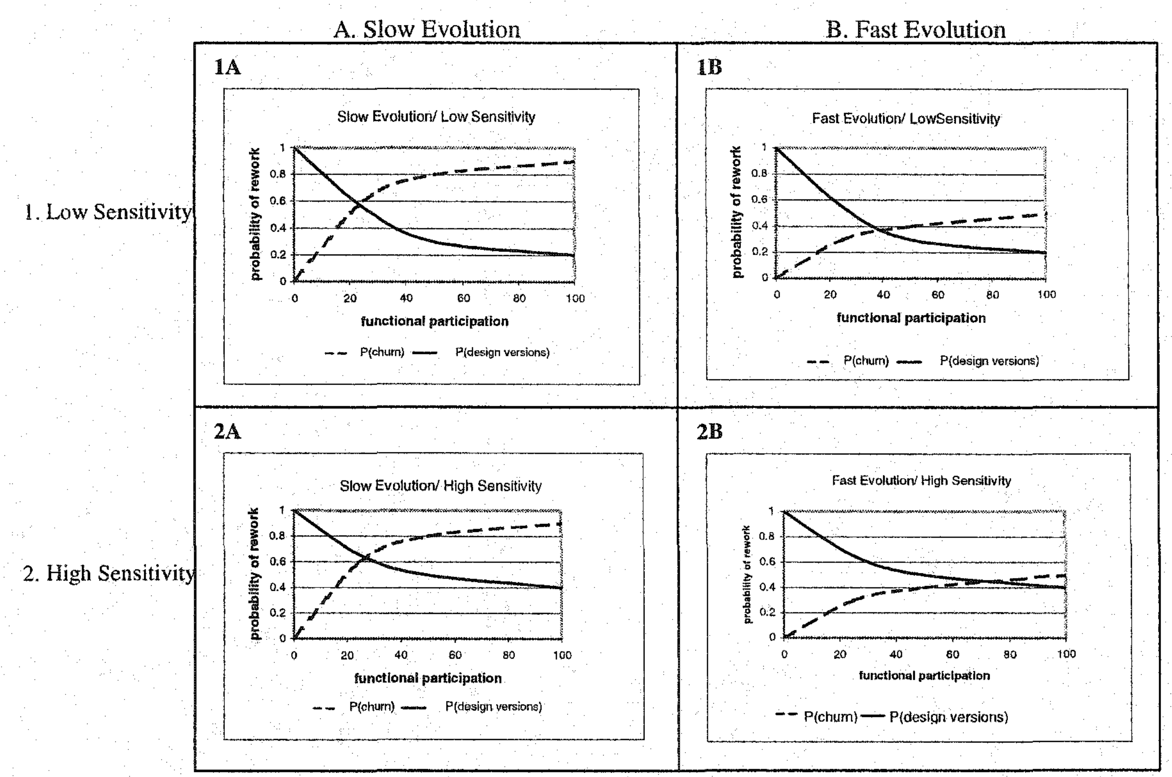


Figure 37 Probability of churn and design versions for the four cases of combined evolution and sensitivity.

All sequential and CE scenarios described earlier in the chapter were studied under each of the four conditions shown above, which are discussed in detail below.

i) If information is relatively complete, this is a condition of low uncertainty and the probabilities of both churn and design versions are low (fast evolution and low sensitivity, respectively, Figure 37 1B).

ii) If information is relatively incomplete, this is a condition of high uncertainty, where the probabilities of both churn and design versions are high (slow evolution and high sensitivity, respectively, Figure 37, 2A).

These describe the extreme cases of uncertainty. Two intermediate cases are also possible:

iii) It may be possible in some cases that although information is relatively incomplete (so the probability of churn is high), the probability of design versions is low (slow evolution and low sensitivity, respectively, Figure 37, 1A). This is possible if downstream activities are relatively straightforward, so even if a lot of changes take place upstream, there is little risk of serious downstream penalties.

iv) It may also be possible in some cases that although information is relatively complete (so that the probability of churn is low), there may be a high probability of design versions (fast evolution and high sensitivity, respectively, Figure 37, 2B). For example, if manufacturing process technology is new and unproven, even if the design is simple, a design change may not be supported by process capability and may result in considerable downstream work.

Consider the example of the scenario involving 25% functional participation and 66% overlapping. For this scenario, from Figure 37, under the conditions of slow evolution and low sensitivity (1A), there is a 60% probability of churn and a 55% probability of design versions. For fast evolution and low sensitivity (1B), there is a 30%

probability of churn and a 55% probability of design versions. For slow evolution and high sensitivity (2A), there is a 60% probability of churn and a 65% probability of design versions. Finally, for fast evolution and high sensitivity (1A), the probability of churn is 30% and the probability of design versions is 65%.

5.3.5 Expected Model Outcomes

In the following sections, the expected results for scenarios under each of the above conditions of uncertainty are discussed in detail, and comparisons are made to Krishnan *et al.*'s conceptual framework. Recall that their model did not explicitly account for functional participation. Their model uses the term concurrency in a generic sense. While information is transferred between activities, they do not make any assumptions about actors and teamwork, only that communication somehow takes place. In what follows, the coupled effect of churn and design versions is discussed. The suggested levels of functional participation and overlapping are based on the expected outcomes proposed in Sections 5.3.1 and 5.3.2.

1A. High Churn – Low Design Versions: Slow Evolution – Low Sensitivity

Krishnan *et al.*'s conceptual framework suggests that iterative overlapping is required under this condition of uncertainty. Under iterative overlapping, the downstream activity can begin before the end of the upstream activity, and any upstream changes are incorporated into the downstream activity though a number of iterations.

In the present models, it is suggested that if design versions are low (downstream sensitivity is low) and churn is high (evolution is slow), then, it is beneficial to have a low level of functional participation and high level of overlap to reduce span time. Effort is expected to be low as well since functional participation is not too high.

The premise for this statement is that some functional participation can reduce uncertainty by allowing downstream functions to help designers answer process-related questions early, and therefore reduce span time. Overlapping should also help reduce span time since the downstream sensitivity is low. Although there is a high possibility of frequent changes occurring upstream, the changes should not have any major negative impact on span time since downstream impact is low.

1B. Low Churn – Low Design Versions: Fast Evolution– Low Sensitivity

Krishnan *et al.*'s conceptual framework suggests that a high level of overlapping can help reduce span time. This is called distributive overlapping, where the downstream activity can make use of preliminary information, and the exchanged upstream information can be precipitated to its final form. Bi-directional exchange of information takes place, and the effect of overlapping is distributed between the upstream and downstream activities.

In the computer models, if design versions are low (low downstream sensitivity) and churn is low (fast evolution), then it is proposed that a high level of functional participation and a high level of overlapping reduces span time and effort.

When information is complete, there is a low degree of uncertainty, and information evolves quickly to a final solution. This situation is similar to a strategy of incremental innovation, where a product or a product line is improved in small steps. In this case, since all required information is soon available in the development process, high functional participation should help to speed up the process and should nevertheless keep effort low due to the ability to make correct decisions quickly. The low uncertainty of information allows team members to make decisions quickly and is conducive to making downstream commitments early in the process, thus overlapping should not entail a high risk of design versions occurring.

2A. High Churn – High Design Versions: Slow Evolution – High Sensitivity

Under Krishnan *et al.*'s conceptual framework, it is recommended that, unless activities can be disaggregated into independent components, overlapping should be avoided under these conditions.

In the present study, if design versions are high (downstream sensitivity is high) and churn is high (evolution is slow), then overlapping should be avoided, and a low level of functional participation should help to reduce span time and effort.

Due to high uncertainty, it is assumed that downstream functions can contribute to the evolution of a design in only a limited way. Overlapping may be harmful due to the uncertainty of the information being sent downstream. The effort and span time for this condition should be longer than that of a case where uncertainty is lower.

2B. Low Churn – High Design Versions: Fast Evolution – High Sensitivity

In Krishnan *et al.*'s conceptual framework, preemptive overlapping can reduce development time; since information evolves rapidly, the finalized form (which is precipitated) is sent downstream early. In this case, however, there is no change in upstream information since it is finalized, so that, although downstream risk is high, no downstream changes will be required to accommodate upstream changes.

In this study, if design versions are high (downstream sensitivity is high) and churn is low (evolution is fast), then, it is suggested that high functional participation and low overlap can help to reduce span time, though effort may be high due to high functional participation.

Fast evolution of information should allow high functional participation to reach a solution quickly. Additionally, with high sensitivity downstream, high levels of integrated teamwork can help mitigate the risk of design versions. Although according to Section 5.3.2, high sensitivity warns that overlapping should be avoided, because evolution is fast, it should be acceptable to transfer preliminary information downstream early allowing for some overlap. This is because it is assumed that exchanged information is certain and complete, so that there is a low expectation of upstream changes. Since information is evolving quickly, high levels of overlap may produce negative effects on the amount of effort and span time; changes may occur rapidly, and frequent changes may cause downstream activities to rework too often. Any overlapping should be coupled with functional participation so that communication reduces the risk of downstream rework. This is different than in Krishnan *et al.*'s model, where they suggest precipitating, or accelerating, the information into its *final* form before overlapping.

Figure 38 summarizes the characteristics of the coupled phenomena described above. A high level of churn or design versions is defined by the probability curve involved, as shown in Figure 37. A description of each variable is defined according to the following scale.

Variable	***Low***	***Moderate***	***High***
Functional Participation	25%	50%	100%
Overlap	0%	33%	66%

	A. Slow Evolution	B. Fast Evolution
1. Low Sensitivity	**1A** **Analogy** A. High level of *churn* relative to B • information finalizes relatively slowly due to incompleteness of information 1. Probability of *design versions* is low • Downstream impact is relatively low **Implications:** - Low level of functional participation. - High overlap.	**1B** **Analogy** B. Low level of *churn* relative to A • information finalizes relatively quickly due to completeness of information 1. Probability of *design versions* is low • Downstream impact is relatively low **Implications:** - High level of functional participation. - High overlap.
2. High Sensitivity	**2A** **Analogy** A. High level of *churn* relative to B • information finalizes relatively slowly due to incompleteness of information 2. Probability of *design versions* is high • Downstream impact is relatively high **Implications:** - Low level of functional participation. - Overlapping should be avoided.	**2B** **Analogy** B. Low level of *churn* relative to A • information finalizes relatively quickly due to completeness of information 2. Probability of *design versions* is high • Downstream impact is relatively high **Implications:** - High functional participation. - Moderate overlap.

Figure 38 The expected outcomes with the four cases of coupled phenomena.

6.0 EXPERIMENTAL DESIGN AND RESULTS

From the description of the conceptual models in Chapter 5.0, it can be readily seen that many situations in product development processes are worth studying. In both the sequential and the CE models, the key features and conditions under which they can be adjusted provide a variety of experiments to analyze. This chapter begins with a description of how the simulation experiments were designed, set up, run, and analyzed. Following this is a discussion of the simulation results.

The possible scenarios studied in the thesis consist of all of the sequential and CE models at varying levels of functional participation and overlapping, each tested under the four conditions of uncertainty, which are a combination of probabilities of churn (evolution) and design versions (sensitivity). In the context of this study, a strategy was defined as the choice of using various levels of functional participation and overlapping; the choice of each level indicates whether it is a sequential or a CE process. An example of a strategy is the choice of using 25% functional participation and 33% overlap, which is a CE process. A scenario would be this strategy under the condition of high uncertainty, i.e., slow evolution and high sensitivity.

The strategies tested were: the baseline sequential process (0% functional participation, 0% overlap); a sequential process (0% overlap) with three levels of functional participation (25%, 50%, 100%); a CE process with two levels of overlap (33%, 66%) and no functional participation (0%); and a CE process with two levels of overlap (33%, 66%) combined with three varying levels of functional participation (25%, 50%, 100%). This gives a total of 12 strategies, each of which was tested under the four conditions of uncertainty, for a total of 48 scenarios. For each scenario, a sample of five simulations runs was executed, for a total of 240 simulation runs. Each result from a single run consisted of effort, measured in person-days, and span time, i.e., process start to finish time, measured in calendar years.

To ensure that this sample was not too small, various descriptive statistics were computed, such as the standard deviation and confidence intervals for each sample, to express the uncertainty in the quantities being estimated, and it was found that means began to stabilize after two or three runs. Results were relatively stable over the samples. The effects of any experimental deviations in results due to the sample size are analyzed in Section 6.1.4, following the results.

Recall that the output parameters of interest are span time and effort, which are dependent upon the inputs, functional participation and overlapping, for sequential and CE processes. Graphs of effort versus span time were plotted for each sample of each scenario, and analysis of the graphs showed the relationships, if they existed, between input variables and the dependent variables. Specifically, the relationships investigated were: functional participation and effort and span time; overlapping and effort and span time; and the combination of functional participation and overlapping with effort and span time. The goal was to find the tradeoffs between effort and span time at different levels of functional participation and overlapping, under all conditions of uncertainty.

6.1 RESULTS

Since different strategies are expected to yield different results, a baseline was established against which they could be all be compared. The sequential process with no functional participation was chosen as the baseline. The sequential model with functional participation and the strategy of overlap without any functional participation are also discussed in the initial analysis. All analyses are made in relative and not absolute terms. In all graphs, the following legend applies: LS is Low sensitivity and Slow evolution; LF is Low sensitivity and Fast evolution; HS is High sensitivity and Slow evolution; and HF is High sensitivity and Fast evolution.

6.1.1 Sequential Process Models: Functional Participation

Since the goal of the thesis is to verify under which conditions a CE process is preferable to a sequential process, a discussion of the sequential process model is appropriate at this point. The baseline sequential scenario (no overlapping or functional participation) and the sequential scenarios (no overlapping) with the various levels of functional participation, all under the four conditions of uncertainty, are discussed in this section. The results are shown in Figure 39. N.B. for Figure 39: by tracing each curve from right to left, each of the four points represents a level of functional participation, starting from 0%, to 25%, to 50%, and finally to 100%.

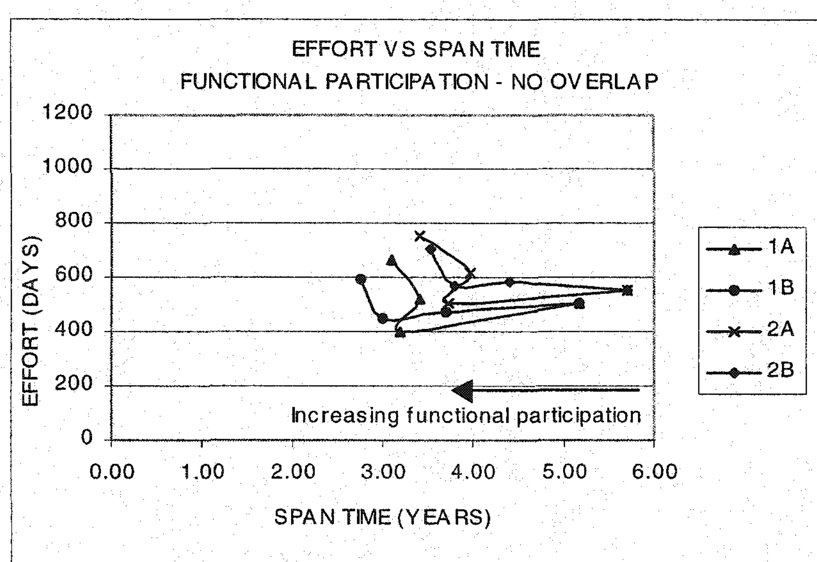


Figure 39 Effort vs Span Time – Sequential Models.

For all four conditions, the baseline sequential process with no functional participation yields the poorest results in terms of span time (the four points furthest to the right; note that the points for Condition 1A and 1B are superimposed, while the same is true for 2A and 2B). Similarly, for all four uncertainty conditions, the shortest span time can be achieved with 100% functional participation, i.e., a dedicated team, though at a high cost of effort. However, for scenarios with slow evolution (1A and 2A), though span time is minimized, slightly lower span times can be achieved at a much lower cost of effort. The minimum point of effort for all scenarios under all conditions of uncertainty is between 25-50% functional participation.

More specifically, Figure 39 shows that for conditions 1A and 2A, both of which have slow evolution, an increase in functional participation from the baseline scenario decreases span time significantly, while effort also reduces. As further functional participation is added, both span time and effort increase. Finally, further increases reduce span time but continue to increase effort. For Conditions 1B and 2B, both of which have fast evolution, increasing functional participation from the baseline consistently reduces span time, while changes in effort are negligible, except for 100% functional participation, where effort rises sharply.

These results are similar to the expected outcomes that were suggested in Chapter 5.0. The graphs show that when evolution is slow, only a low degree of functional participation (25%) is needed to minimize span time and effort. When evolution is fast, a moderate to high (50% to 100%) level of functional participation will minimize span time, although a dedicated team has a high cost of effort.

6.1.2 CE Process Model: Overlap Only

In these scenarios, overlapping was tested without any functional participation. The main purpose for conducting this test was to analyze the results of overlapping activities without any changes in team design. Figure 40 shows the results of simulations of the scenarios with 0% functional participation with overlap. In the figure, the results for Conditions 1A and 1B are superimposed (curves on the left); likewise, the results for Conditions 2A and 2B are also superimposed (curves on the right). N.B. for Figure 40: as the curves are traced from bottom to top, overlapping is increased from 0% for the bottom-most points, to 33%, to 66% for the top-most points.

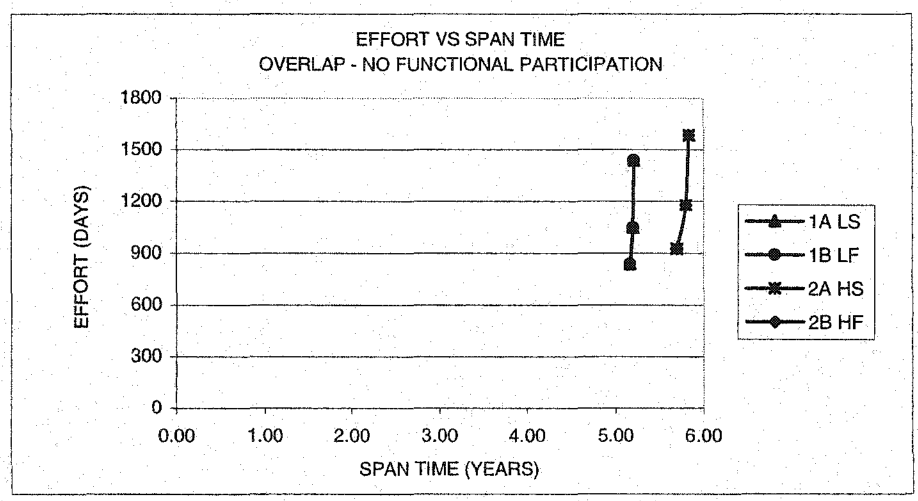


Figure 40 Effort vs Span Time – CE: Overlap Only.

As can be seen from these scenarios, overlapping without any functional participation can be harmful. In all cases, as overlap is increased, effort increases while span time either increases slightly or remains unchanged. Effort and span time are significantly higher for conditions 2A and 2B (the two superimposed curves on the right), where downstream sensitivity is high. Clearly, overlapping without any functional participation is not recommended.

For all results that follow, the relevant results from the sequential scenarios will be repeated to compare to results found in the CE scenarios.

6.1.3 Combined Results: Functional Participation and Overlapping

In the sections that follow, results are given for the various strategies under the four conditions of uncertainty, by varying functional participation and overlap. The graphs therefore have four dimensions: effort, span time, functional participation, and overlap, in contrast to the previous section, where functional participation and overlap were each varied independently, one at a time. Again, for each curve in each graph, by tracing the curves from right to left, functional participation is increasing. This pattern holds true for all upcoming graphs. The scale in Table 4 is used to describe the variables.

Table 4 Variable scale.

Variable	***Low***	***Moderate***	***High***
Functional Participation	25%	50%	100%
Overlap	0%	33%	66%

1A: High Churn – Low Design Versions: Slow Evolution – Low Sensitivity

Figure 41 shows that as functional participation is increased from 0 to 25%, span time decreases considerably, for any value of overlap. After a certain point, as functional participation is further increased, the cost of effort increases without being coupled with any gains in span time, for any value of overlap. On the other hand, as overlap is increased, span time decreases consistently after 0% functional participation.

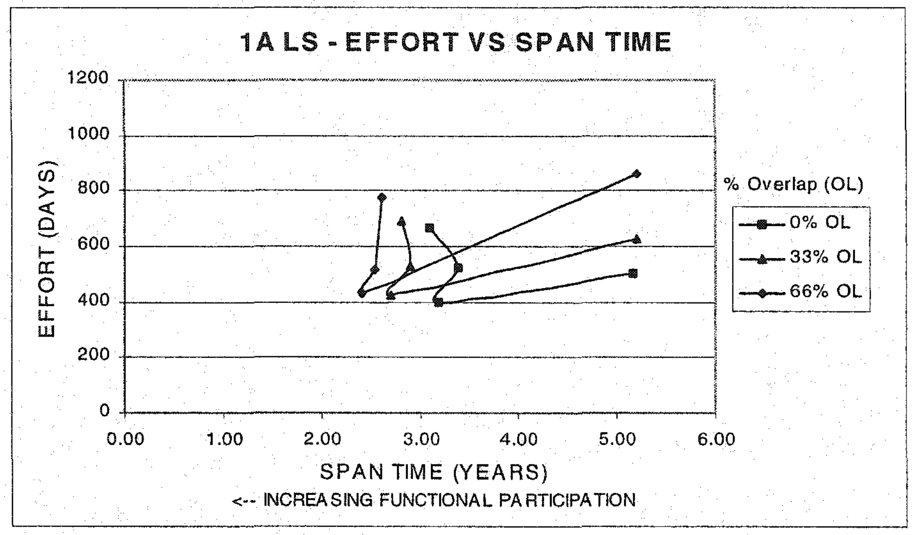


Figure 41 Effort vs Span Time – Model 1A.

It can be concluded that span time reduction is sensitive to increases in overlap, while changes in functional participation, after 25%, increase effort but have no positive impact on span time. The best strategy in this scenario is 25% functional participation and 66% overlap. However, since 33% overlap and 25% functional participation is very close to this point, and due to experimental deviation, this strategy should also be considered. From the graph, the average of the two strategies results in a span time of about 2.5 years, and a little over 400 days of effort. The comparable sequential scenario is 25% functional participation and 0% overlapping, which resulted in 3.2 years for span time and 400 days of effort. The CE scenario is 22% lower in terms of span time, and relatively unchanged in terms of effort.

According to the scale in Table 3 then, this results in ***low functional participation and moderate to high overlap.*** This is in agreement with the proposed expected outcomes in Chapter 5.0, which suggested that low functional participation and high overlap would be beneficial under this condition. With slow evolution, information evolves slowly to a final design due to the complexity or difficulty of the activity at hand. Although this activity requires some knowledge of the manufacturing and test processes, it is mostly design -intensive. Some teamwork can help speed up the process, but too much involvement from downstream functions can slow down the process through excessive churn, as well as waste the opportunity for downstream activities to be involved in other value-added activities, such as other projects in the organization. Low downstream risk allows for overlapping.

1B Low Churn – Low Design Versions: Fast Evolution– Low Sensitivity

Figure 42 shows that an initial increase in functional participation from 0 to 25% (for any value of overlap) significantly decreases span time and effort. Increasing functional participation from 25% to 50% (for any value of overlap) reduces both span time and effort, while going to 100% (for any value of overlap) quickly increases effort with no notable effect on span time, except for the sequential scenario, where it is reduced. Again, there is a reduction in span time as overlap increases, with no noteworthy changes in effort after 0% functional participation.

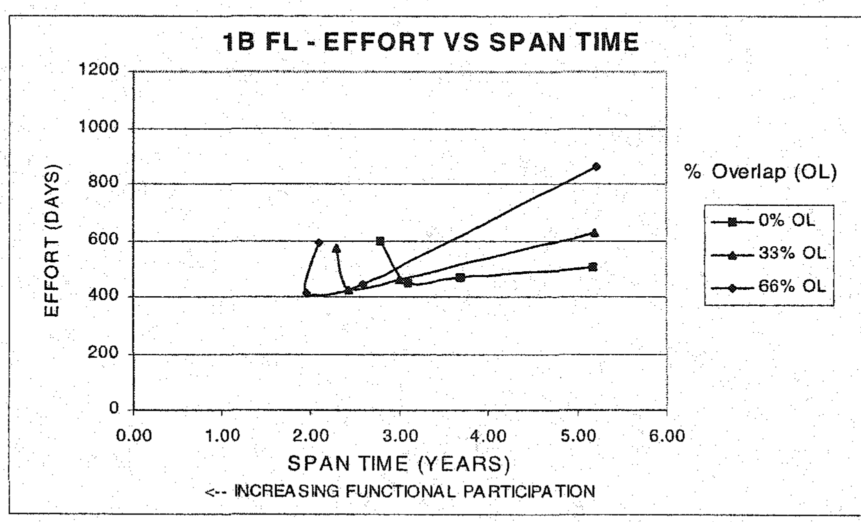


Figure 42 Effort vs Span Time – Model 1B.

The conclusion for the low uncertainty condition, where information is relatively complete, is that a dedicated team, i.e., 100% functional participation, is not necessary to reduce span time since the cost of effort is steep, unless a sequential process is preferred, however span time is much longer than a CE process. The best strategy in this case is 50% functional participation and 66% overlap. By observing the graph, this strategy results in an approximately 2-year span time and approximately 400 days of effort. The equivalent sequential scenario is 50% functional participation and 0% overlapping, which resulted in a span time of 3.1 years and 450 days of effort. The CE scenario is 35% lower in terms of span time, and 11% lower in terms of effort.

Therefore, it can be stated that a ***moderate level of functional participation can help to reduce span time and effort, while a high level of overlap has a big impact on time, with little change in effort***. In Chapter 5.0, it was proposed that high functional participation and high overlap would be beneficial under this condition. Though high functional participation generally yields good results, it would seem that with low uncertainty, moderate functional participation is sufficient. Additionally, because of the low downstream sensitivity, increasing overlap consistently reduces span time.

2A High Churn – High Design Versions: Slow Evolution – High Sensitivity

Figure 43 illustrates that increasing functional participation significantly decreases span time (for any value of overlap), eventually at the cost of high effort. Increasing overlap has the effect of increasing effort, with negligible effect on span time.

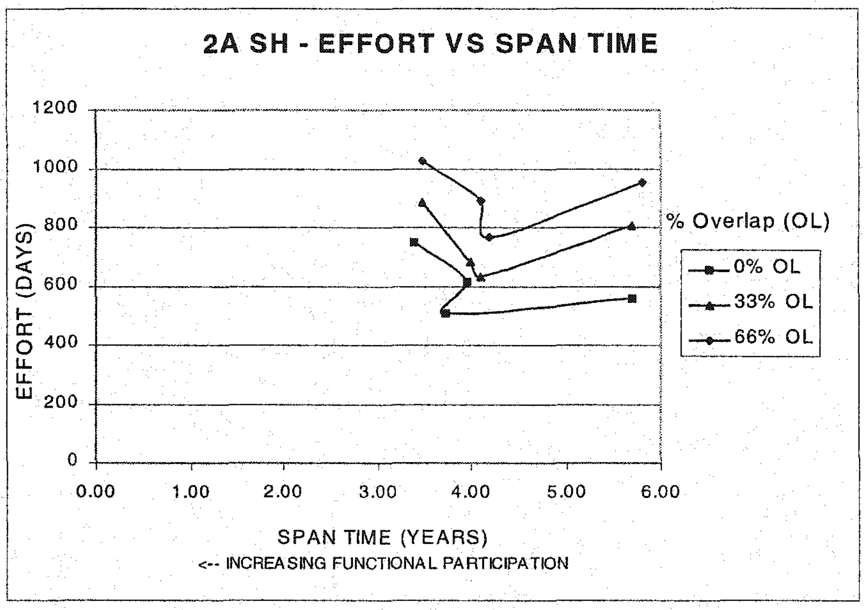


Figure 43 Effort vs Span Time – Model 2A.

The strategy of 100% functional participation and no overlap, gives the lowest span time, though effort is high. This is approximately a span time of 3.4 years and 750 days of effort. The comparable CE scenario is 33% overlapping and 100% functional participation, which resulted in 3.5 years span time and 880 days of effort. The CE scenario is 3% higher in terms of span time, and 17% higher in terms of effort. If the cost of effort is too steep, then 25% functional participation (no overlapping) is the preferred strategy in terms of effort. This strategy has almost 3.7 years of span time and about 500 person-days of effort. The comparable CE scenario is 25% functional participation and 33% overlapping, which resulted in a span time of 4.1 years and 630 days of effort. The CE scenario is about 11% higher in terms of span time, and 26% higher in terms of effort.

It can be concluded that ***a high level of functional participation can help to reduce span time at a high cost of effort, while overlapping should be avoided. If the cost of effort is too high, low functional participation reduces effort.*** In Chapter 5.0, it was also suggested that overlapping be avoided, but that low functional participation was sufficient. This holds true if the cost of effort must be kept low. When span time reduction is a priority, this can be explained by likening the high uncertainty condition to a breakthrough innovation, i.e., the development of a new product, where brainstorming activities can generate ideas and solutions more quickly than in a baseline sequential scenario. Furthermore, information is relatively incomplete and uncertainty is high, with frequent changes expected upstream. With a high potential impact downstream of using preliminary information early, overlapping is risky since any change in this information has a significant impact on the work done downstream.

2B Low Churn – High Design Versions: Fast Evolution – High Sensitivity

Figure 44 shows that as functional participation is increased, span time is continuously decreasing in all cases, with a decrease initially in effort (except for 0% OL, where effort is stable), and then an increase in effort going from 50% to 100% functional participation (for any value of overlap). As overlap is increased, initially span time decreases (except at 0% FP), and after 33% overlap, span time stabilizes, although effort increases.

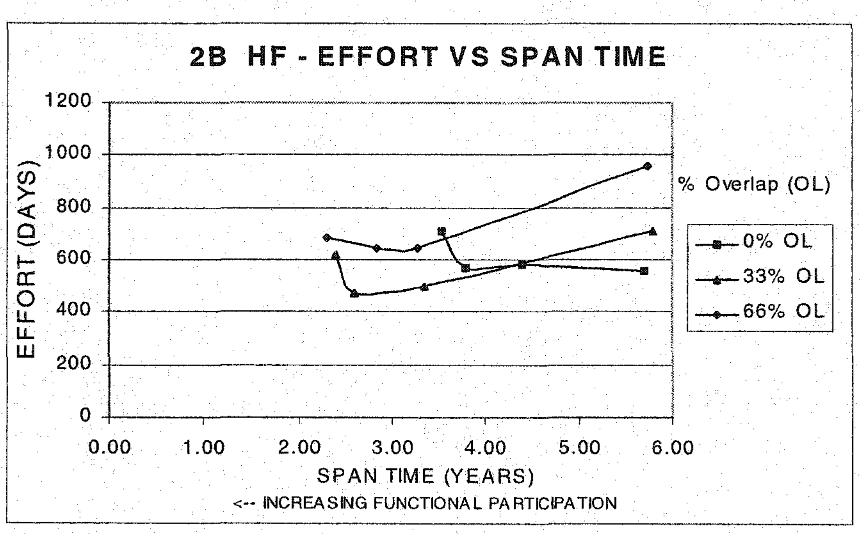


Figure 44 Effort vs Span Time – Model 2B.

In this scenario, the strategy of 100% functional participation and 66% overlap gives the shortest span time, with 100% functional participation and 33% overlap close behind, but effort is high for both cases. This gives an average of approximately 2.3 years in span time and about 650 days of effort. The comparable sequential scenario is 100% functional participation and 0% overlapping, which resulted in 3.5 years span time and 700 days of effort. The CE scenario is 34% lower in terms of span time, and 7% lower in terms of effort. If the cost of effort is too high, then 50% functional participation and 33% overlap yields the preferred strategy. This strategy has a span time of about 2.6 years, but with an effort of approximately 470 days. The comparable sequential scenario is 50% functional participation and 0% overlapping, which resulted in a span time of 3.8 years and 570 days of effort. The CE scenario is 32% lower in terms of span time and 17% lower in terms of effort.

It can therefore be concluded that span time reduction is more sensitive to increasing functional participation. ***A high level of functional participation accompanied by a moderate to high level of overlap, is beneficial for span time reduction. Conversely, a moderate to high level of overlap can reduce span time only if it is accompanied by a moderate to high level of functional participation. A dedicated team entails a high cost of effort.*** In agreement with these results, in Chapter 5.0 it was proposed that high functional participation and moderate overlapping would be suitable for this condition. In this situation, information becomes complete quickly, but the risk of using preliminary information on the downstream activities is high. Early cross-functional teamwork can help reduce the risk. This, along with the fact that information is complete, can make overlapping beneficial for span time reduction.

6.1.4 Experimental Deviations

Studying experimental deviations in the simulation results allows for the investigation of whether the findings are reliable. As mentioned earlier, descriptive statistics were used to analyse the data, namely means, standard deviations, and confidence intervals. To test for the effects of sampling error in the sample means, the 95% confidence intervals were plotted for effort and span time, and graphed on the results curves. Uncertainty Condition 2B was chosen as a sample illustration based on Figure 44. Each of the three curves under this condition represents all levels of functional participation (FP), i.e. 0%, 25%, 50%, and 100%, at a given level of overlapping (OL), i.e., 0%, 33%, and 66%.

In Figures 45, 46, and 47, the deviations for span time (horizontal bars) and effort (vertical bars) range from approximately 5% to a maximum of 20% of the means, with most landing between 0% and 10%. More importantly, these deviations overwhelmingly show that even if the true means fall on the extreme points of the bars, the trends in the graphs and subsequent conclusions would not change. If the bars do overlap, the conclusions have acknowledged the potential effects of the deviations on results.

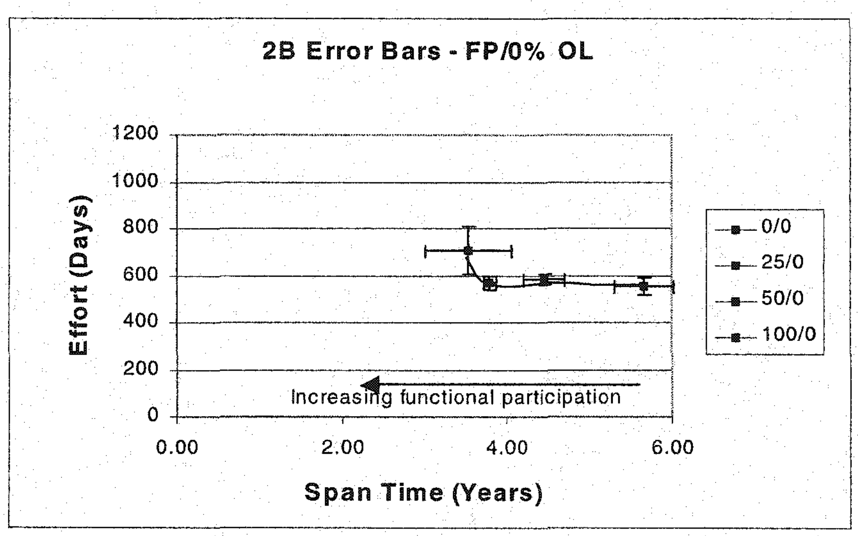


Figure 45 2B 95% confidence intervals - FP/0% OL.

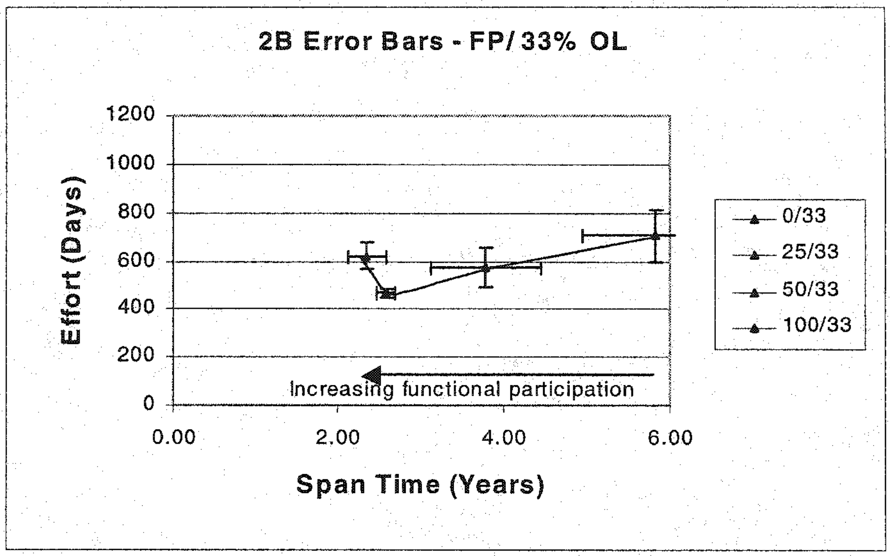


Figure 46 2B 95% confidence intervals - FP/33% OL

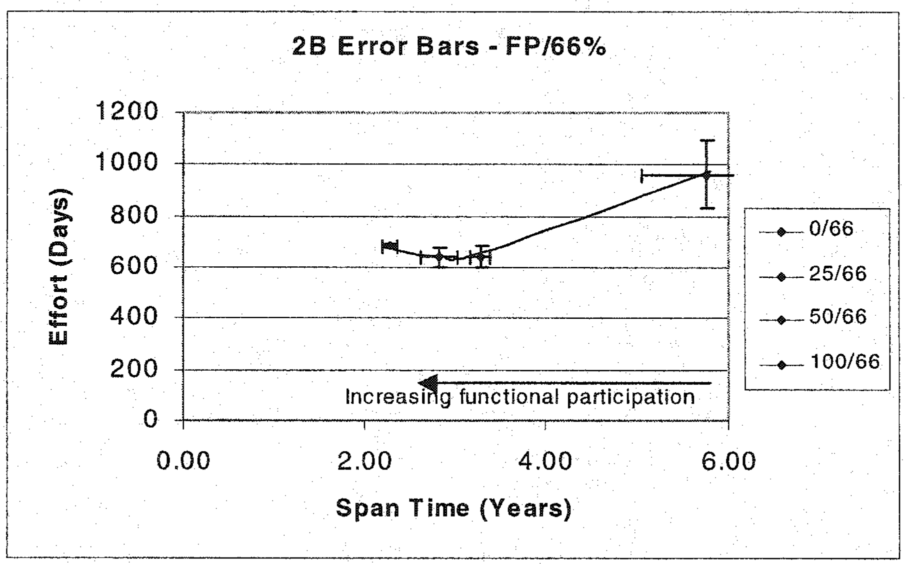


Figure 47 2B 95% confidence intervals - FP/66% OL

For example, the left-most point in Figure 45, i.e., 100% functional participation at 0% overlapping, has the largest deviations for both effort and span time. Results show that the best scenarios under this condition are those of 100% functional participation with either 33% overlap (Figure 46) or 66% overlap (Figure 47). These remain the best points even if the true mean falls at the larger end of the bar, for span time and effort.

Recall that when any increase in effort is undesirable, the scenario with 50% functional participation and 33% overlap is preferred. Again, comparing possible extreme values of the means with the scenario of 100% functional participation and 0% overlap, the former scenario still is preferable.

As another example, in Figures 46 and 47, the first points on the right (0% functional participation and 33% overlap, and 0% functional participation and 66% overlap, respectively) have large deviations for span time; however, since these points are not even close to the best results, these deviations have no bearing on the conclusions and can therefore be dismissed.

This type of analysis was performed on all curves to ensure that results are robust enough to support the conclusions. In all cases, statistical deviations are sufficiently small that all conclusions are valid, as shown in Figure 48, where the range of deviations for all scenarios falls between 0% to 21%, with the majority falling between 5% to 9%. Tables containing the descriptive statistics for all data can be found in Appendix A.

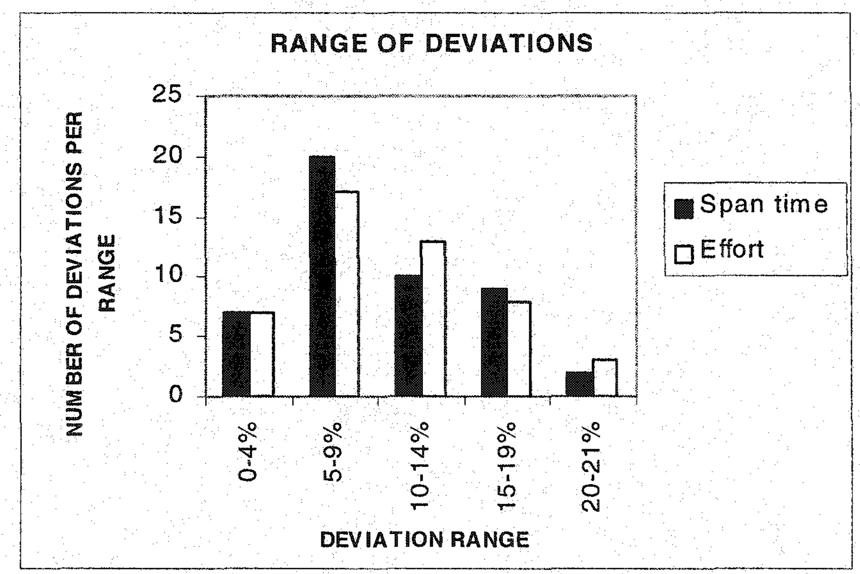


Figure 48 Range of deviations for all scenarios.

6.1.5 Summary of Results

Table 5 summarizes the simulation results, comparing the best scenarios of each model (sequential or CE) to the corresponding scenarios of the other model for the four conditions of uncertainty. For each condition, the scenario with the best span time and effort is indicated. It turns out that for three out of the four conditions, the CE scenarios yield the best results in terms of both span time and effort. In cases where there is not one clear best result in terms of both span time and effort, the trade-offs are indicated. The percent difference between sequential and CE results are also shown. In the table, FP stands for functional participation, while OL stands for overlapping.

Table 5 Summary of results.

Uncertainty Condition	**1A**	**1B**	**2A**		**2B**	
Best CE Scenario*	**25% FP; 33-66% OL**	**50% FP; 66% OL**	**100% FP; 33% OL**	**25% FP; 33% OL****	**100% FP; 33-66% OL**	**50% FP; 33% OL****
Span Time	2.4 yrs	2.0 yrs	3.5 yrs	4.1 yrs	2.3 yrs	2.6 yrs
Effort	400 days	400 days	880 days	630 yrs	650 days	470 days
Comparable Sequential Scenario	**25% FP 0% OL**	**50% FP 0% OL**	**100% FP 0% OL**	**25% FP 0% OL****	**100% FP 0% OL**	**50% FP 0% OL****
Span Time	3.2 yrs	3.1 yrs	3.4 yrs	3.7 yrs	3.5 yrs	3.8 yrs
Effort	400 days	450 days	750 days	500 days	700 days	570 days
Percent Difference						
Span Time	- 22%	- 35%	+3%	+11%	- 34%	- 32%
Effort	0%	- 11%	+17%	+26%	- 7%	- 17%

* N.B. The experimental deviation for all results falls between 5% and 20%.
** When the cost of effort is too high, this scenario yields the next best results.

The results of the simulations produced a general pattern of convex curves of effort versus span time, except for the scenarios of overlapping with no functional participation. In all cases, there is a minimum point of effort in the curves where there is a balance between reducing downstream rework and increasing churn. Knowing this point is important in that it should be a stable point for the NPD process for which span time should be more predictable. Knowing the shape of the effort versus span time curve is also important since it shows whether more concurrency in terms of functional participation and/or overlap can reduce span time further for a modest increase in effort.

The results can be summarized according to condition of uncertainty. In no case is the baseline sequential scenario with 0% functional participation ever a preferred strategy, as it always yields the longest span time and highest effort. The results summarized in Table 5 are translated into the following conclusions.

Uncertainty Condition 1A

- Moderate to high overlapping with a low level of functional participation is conducive to reducing span time and effort.

Uncertainty Condition 1B

- High overlapping with moderate functional participation reduces span time and effort.
- A minimum of 25% functional participation is necessary for span time reduction, while going beyond 50% is not advisable unless a sequential process is preferred, since the cost of effort is steep with minimal, if any, gains in span time. A sequential process does not however provide good span time benefits as in a CE process.

Uncertainty Condition 2A

- Overlapping should be avoided.
- Sequential processes with a high level of functional participation are best suited for this condition.
- A dedicated team minimizes span time, though the cost of effort is highest.

Uncertainty Condition 2B

- Moderate to high overlapping is beneficial only if accompanied by a moderate to high level of functional participation.

- Highly overlapped processes are costly in terms of effort.
- Functional participation reduces span time in all cases, for both sequential and overlapped processes.
- Again, a dedicated team minimizes span time at the cost of effort.

Scenarios characterized by high uncertainty, i.e., high sensitivity and slow evolution (2A) generally have the longest span time and highest level of effort, as compared to other uncertainty scenarios.

Some important points can be made with regards to these findings. First, other authors have found that overlapping should be avoided under conditions of high uncertainty; their analysis is based purely on overlapping strategies without the explicit consideration of functional participation. This study shows that overlapping under conditions of high uncertainty should indeed be avoided when evolution is slow and sensitivity is high (for case 2A). However, it is beneficial when evolution is fast and sensitivity is high (in the case of 2B) *as long as* it is accompanied by functional participation. The cost of effort can be high, so the trade-off between span time and effort must be considered.

Second, as a result of this point, there is a risk involved in making recommendations based on span time alone without considering the accompanying effort required to achieve the reduced span time. In many cases, there is a preferred strategy that yields the shortest span time. However, in many of those instances, the cost of effort is significant, and this may deter the selection of one strategy over another. The trade-offs that are involved are important and must be considered; as well, without an understanding of the investment in terms of the resources required to achieve desired results, an important indicator of performance remains hidden.

Another important finding of this study are the independent effects that functional participation and overlap have on the development process. In all cases, when only functional participation is an input, i.e., no overlapping, increasing functional participation reduces span time. A dedicated team, i.e., 100% functional participation, always yields the lowest span time, but usually has the highest cost of effort. Varying overlap alone without any functional participation is detrimental to process performance. Effort is increased with no gains in span time. This is logical since bi-directional information sharing is necessary for interdependent processes. This result demonstrates an important point, which is that if overlapping is used to reduce span time, then it is beneficial only when it is accompanied by functional participation, often at the expense of high effort.

While previous authors have studied only overlapping without explicit consideration of functional participation, their results cannot lead to any recommendations about sequential processes. In their models, they compare sequential to CE processes, but not sequential scenarios to one another. In contrast, this study *can* address the problem of sequential processes in isolation, where functional participation as the input variable is changed, and comparisons are made on the performance of one sequential scenario over another. Results show that if overlapping is not desirable or is not an option, then sequential processes should always be accompanied by a minimum of 25% functional participation. The higher the functional participation, in general, the better the opportunity to reduce span time. Effort generally decreases as well, or remains stable, except for a dedicated team, (100% functional participation). Though a dedicated team always yields the shortest span time, it produces the highest effort.

The experimental deviations in the simulation results were estimated using descriptive statistics. Future work should involve conducting a detailed statistical analysis that tests the independent and/or interaction effects of the input variables under the various conditions of uncertainty, on the output variables. This would provide further insights in measuring the relative contribution of functional participation and overlap to span time and effort as well as the amount of interaction, for each uncertainty condition.

6.2 VERIFICATION AND VALIDATION

Verification and validation are important elements of a simulation study. Although there is no definitive method of verifying and validating a model, there are many facilitating techniques. Generally speaking, verification and validation should be performed to test the accuracy of the model representation of real world systems (Figure 49).

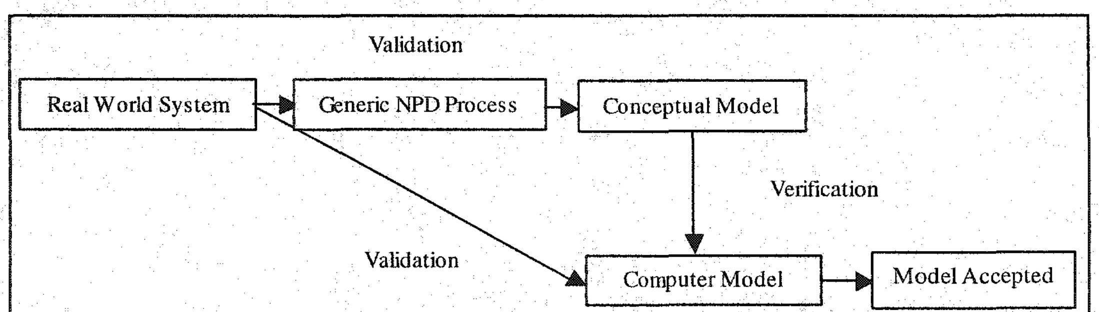


Figure 49 Verification, validation, and credibility of models.

The first step is *verification*, which checks if the simulation models do what the conceptual model intends for them to do. It should answer the question of whether the system is being built 'right'. This can be done using a variety of techniques, such as testing portions or modules of the computer models, instead of the entire models, and by changing input parameters in order to verify if resulting outputs behave as intended.

The second step is to *validate* the models, which is done by comparing them to what is generally accepted as the real system. It should answer the question of whether the 'right system' is being built. In this case, validation of the computer models is required to ensure that the simulations are appropriate representations of real-world product development processes. This can also be done by comparing the models to those represented in the literature where some validation has already been done.

Verification and validation are both necessary to ensure that the relevant concepts of this system are correctly conceptualized and realistically represented. This was accomplished a) through a thorough analysis of features and characteristics underlying NPD processes, b) by ensuring that the process modeling purpose had been met realistically through the concepts that were developed, and c) through a case study. These are all described in the next sections.

6.2.1 Verification

The verification process involved determining if the conceptual model has been correctly translated into the simulation models. Several steps were followed.

6.2.1.1 Debugging

The first step in verification was to test and debug the models. This was done in modules for some tests, since it was very difficult to debug the entire model due to its size and simulation run time.

A 'work-communicate-feedback' module was created in isolation to test the effect of the probability of churn (Figure 50). The goal was to ensure that rework iterations were executed properly, and that the effort multipliers captured the effect of rework. Results were expected to show that when an activity required churn, that it would loop back and start over, and that the duration of the next execution would be reduced by the amount prescribed by the effort multiplier.

The module acted as a stand-alone model, replicated exactly as any module in the model. For purposes of this experiment, the specific module used is not of importance since all modules are structurally similar with only the input values differing, so details will be omitted. Recall that the feedback point consists of the decision point with alternative courses of action that could result in churn or in moving forward to the next activity. The probabilities of churn were removed from this point so that there was no possibility of churn occurring. Thus the module became deterministic. Results of this run were compared to results in which the module included probabilities. Simulations were run until the module underwent churn five times, and the resulting outputs were checked, confirming that the churn feature functions as expected.

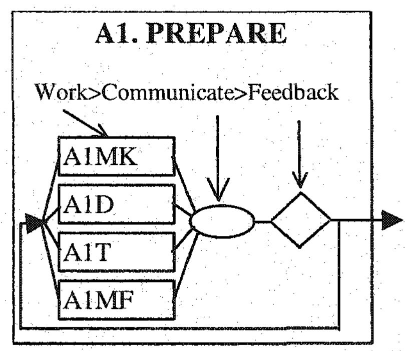


Figure 50 Work-communicate-feedback module for activity A1.

The same module was used to test functional participation to ensure that the teamwork effect was captured as described in Chapter 5.0, i.e., the modeling of four functions in the four parallel work sub-activities, as seen in Figure 50. This test involved varying levels of functional participation for the various resources, at 0%, 25%, 50%, and finally 100%. The probability of churn was omitted from these test modules so that the differences in terms of duration and effort of the module could be detected for each level of functional participation. Simulations were run five times for the module for each level of functional participation to check that activities were properly executed at the preset levels of functional participation. In other words, each resource in each activity should have been working for the duration and effort prescribed. The simulation results confirmed that they were.

6.2.1.2 Structured Walkthrough

The next step in the verification process was to conduct a 'structured walkthrough', which involved meeting with people in educational institutions and in industry who are experienced in NPD, and with developers and professional users of the simulation software. The walkthrough involved analyzing the models in detail by going through all the key concepts and input data and ensuring that they were realistically captured in the computer models.

6.2.1.3 Input Analysis

Next, the input parameters of the models were varied to ensure that the models behave as expected when input conditions are changed. First, the models were verified to ensure that the effect of learning was taking place by removing the learning. This was accomplished by changing the learning curve effort multiplier in all scenarios to 1, so that if and when rework is required in any activity or phase, the total duration of the activity/phase would be executed again in full, rather than at a fraction of the initial duration. The set arbitrarily chosen for this analysis consisted of the scenarios with 50%

functional participation at all levels of overlap. Recall that the learning curve for 50% functional participation is a 60% learning curve. In other words, the comparison was made between scenarios with a learning curve of 60% (indicating a high level of learning), and 100% (indicating a situation in which no learning has taken place).

Each scenario was run five times. As expected, the results of the analysis show in Figure 51 that the adjustment in the learning curve does have a big effect on process performance. The curve with no learning (curve with triangular points) lies above the original results, which has 60% learning (curve with diamond-shaped points). This shows that the effort has increased considerably when no learning takes place. The span time has also increased, as seen by the shift towards the right of the top curve. This suggests that the learning effect is a significant feature in the study.

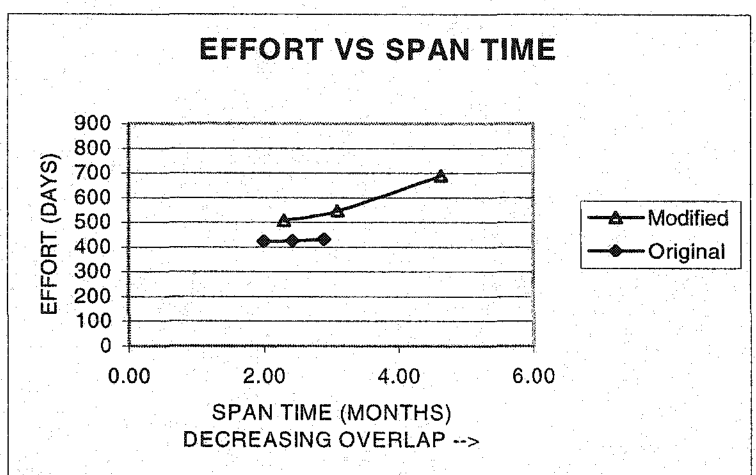


Figure 51 Verification of effect of learning curves on outcomes.

6.2.1.4 Output Analysis

Another step in the verification process was to observe the simulation runs carefully. The output files of the runs were studied to check if the process models were producing expected outputs. Each simulation output report provides a number of results of interest to the verification process; they are activity execution patterns, activity duration, and activity processing time (effort). Through several simulation runs, each report was checked for these outputs.

First, a check was made on the activity execution pattern to verify that the routing of activities were logical, i.e., that activity precedence requirements were obeyed. This was done simply by reading through the report and following the sequence in which activities were executed. Next, recall that initial activity durations in the model are deterministic, while the need for rework is stochastically determined. Where no rework is required, the activity duration could easily be checked against the results. Where multiple rework loops are executed, the expected value of the duration was manually calculated and checked against results.

6.2.2 Validation

The process of checking the validity of the models and the results was performed by comparing the models to what is generally accepted as the abstraction of the real world system, that is, the product development process. Validation of the models was difficult as there is not a standard model to which it can be compared. Validation of the models' structure was accomplished through a case study, while results were validated through a comparison of published results from an empirical study. These are both discussed in the following sections.

6.2.2.1 Validation of Models: Case Study

Much of the data used in the design of the models was collected at a company site. The case study was undertaken at a medium-sized Canadian telecommunications company (due to confidentiality agreements, the company name will remain anonymous) to investigate the use of CE in their NPD process. It is a high-tech company which designs and manufactures printed circuit boards for telecommunications systems. The impact of CE on the NPD process was observed in terms of span time, development cost, and quality. These performance indicators were chosen by top managers in the company, and were seen as being the leading indicators of product development performance for the company.

New product development at the company is a very critical part of the business, and as such, the company was concerned about improving the process. Prior to the study, the company informally experimented with CE on several projects. Ad hoc approaches to implementing CE took the form of undertaking various levels of functional participation and overlapping of activities, and the use of design simulation tools and other information technologies to make the availability and transfer of information more seamless.

The company was interested in evaluating how well its CE approaches were faring in comparison to their existing NPD process. Hence, its existing sequential NPD process for the development of circuit board assemblies was compared to the various CE approaches.

6.2.2.1.1 Data gathering

Data for the study was gathered through the analysis of six historical projects, tracking of an ongoing development project, company documentation, observation of the manufacturing process and product samples, in-depth interviews of key individuals and groups, surveys handed out to project team members, attendance at project meetings, and numerous informal discussions with project team members, over a period of two years.

Each set of information was collected from the appropriate departmental personnel in the company. For example, top managers and directors provided the high-level process. More detailed information on specific activities in specific phases came directly from documentation, and from the stakeholders in a project, such as hardware and software designers, test engineers, and the respective program and project managers. The data gathered formed the basis for the computer models. It includes the following:

- Detailed description of the design and development processes;
- Activities, and their corresponding durations and probabilities of rework, such as the development of hardware specifications and the integration of hardware and software;
- Resources that perform the activities, such as hardware and software design engineers who design the systems, test engineers who write the test applications, and process engineers who develop the manufacturing processes.

Probability distributions for rework, average durations for activities and phases, and resource requirements were all determined from observations at the company and through model assumptions. Company team members were then consulted for feedback and validation of the information gathered. For example, probability distribution curves were initially created based on assumptions about the process. These assumptions were in turn based on the observations and data obtained during the study. The distributions were then shared with project team members, who helped fine-tune the data to be more accurate reflections of the situation at the company.

The multiplicity of data sources, such as formal documentation, meetings with top managers and directors, and the results of surveys, facilitated gathering reliable information. Additionally, the various data used in the models, such as activity durations, and probability distributions were confirmed as being relatively accurate through consultations with program directors, project managers, and design engineers.

The study, which lasted for two years, provided considerable experience, insights, and knowledge about how business firms deal with development process issues, such as team organization, project management, tools and techniques used for design and information sharing and communication.

Though the models used in this thesis were built within the context of the telecommunications industry, they can be applicable to any other industry with minimal changes. As stated in an early chapter of the thesis, the development process modeled is generic, so it would require slight changes to reflect a particular company's process. Activity durations, probabilities at all decision points, and learning can easily be modified manually, and functional participation reflecting various team styles can also be adjusted with minimal effort. If fewer phases, or activities within a phase, are required, this is easily fixed. If more phases or activities must be added, some time-consuming changes would be needed to the structure of the models. Hence, though the models are built based on NPD in a telecommunications company, they are applicable to many companies.

6.2.2.1.2. Case study findings

The case study showed that increasing functional participation and overlapping were beneficial in achieving shorter span time, but to a limit. As more current projects attempted to increase both functional participation and overlapping, a lack of a formal communication structure for the team members by management (certain project stakeholders, such as mechanical designers, or certain support groups, were not always kept updated on the status of the project), planning (resource requirements were inadequately planned), and a number of external factors out of the control of the project team (e.g., key engineers leaving the company, training programs which forced team members to temporarily abandon the project), increased both span time and effort.

Resource planning was seen as one of the critical issues that needed to be dealt with. Planning was being done through estimates based on experience, and this tended to produce a plan that underestimated the quantity and timing of human resources required for a given project. Project team members admitted that more effective planning of resource requirements would have greatly assisted in avoiding delays a project suffered.

These findings and the difficulties faced by the company helped to provide a focus for the computer models. It seemed important to understand how levels of overlapping and functional participation could be determined for a NPD project, which in turn would help plan resource requirements.

6.2.2.2 Validation of Results

Simulation results were validated through analyses of NPD processes, both from the literature and from practice. The output variables, span time and effort, were validated by comparing sequential scenarios with functional participation to CE scenarios for each condition of uncertainty, and then by comparing *all* scenarios to the baseline scenario (the exceptions in these calculations are scenarios of 0% functional participation with 33% and 66% overlap; these were omitted from the analysis since these results always produced the poorest performance in terms of effort and span time, and they were deemed to be unrealistic in practice and not comparable to the other scenarios). Since the results from these can be fairly well predicted, generally speaking, the outputs should reflect the expectations.

Based on many findings, sequential processes are expected to result in overall longer span times and higher effort than CE processes, though for conditions of high uncertainty, it is expected that CE processes will yield longer span times (Winner *et al.*, 1988; Clark and Fujimoto, 1991). This phenomenon was verified by taking an average of the effort and span time values for all sequential processes, and comparing them to average values for CE processes under the various conditions of uncertainty. Table 6 summarizes these comparisons.

This was also checked by graphically illustrating the results for all sequential and CE scenarios, each under the four conditions of uncertainty, as shown in Figure 52. Recall that each of these scenarios relate to different levels of uncertainty, based on completeness of information (Section 5.3.3). Each point in the graph represents the result of a single simulation run, measured in effort and span time. An ellipse indicates the results of simulations under one of the four conditions of uncertainty, which are slow evolution, low sensitivity (1A); fast evolution, low sensitivity (1B); slow evolution, high sensitivity (2A); fast evolution, high sensitivity (2B). Note that observations about all aggregated results are meant to show general trends.

Table 6 Aggregate comparisons of sequential versus CE models.

Condition of Uncertainty	Average Values*	Sequential Model	CE Model	Percent Difference
1A Slow evolution, Low sensitivity	Span Time Effort	3.2 years 530 days	2.7 years 560 days	- 16% + 6%
1B Fast evolution, Low sensitivity	Span Time Effort	3.2 years 505 days	2.4 years 485 days	- 25% - 4%
2A Slow evolution, High sensitivity	Span Time Effort	3.7 years 630 days	3.9 years 813 days	+ 5% + 30%
2B Fast evolution, High sensitivity	Span Time Effort	3.9 years 620 days	2.8 years 590 days	- 28% - 5%

* N.B. The experimental deviation for all results falls between 5% and 20%.

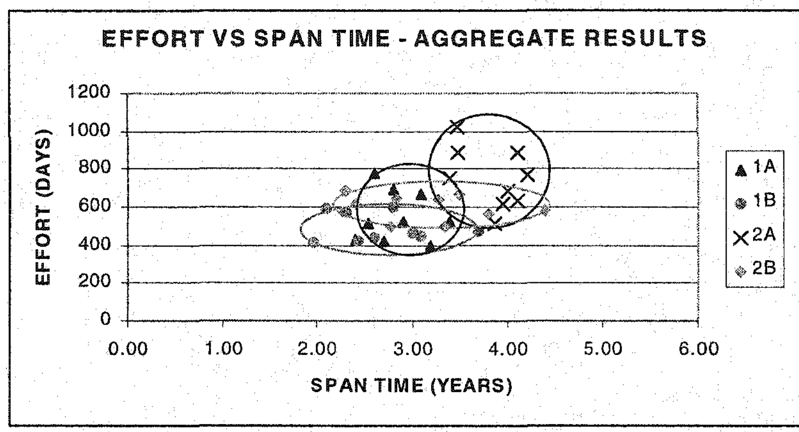


Figure 52 Aggregation of results.

Table 6 shows that, under each of the three Conditions, 1A, 1B, and 2B, sequential processes are much longer in span time and slightly lower or the same effort compared to CE processes. Only in 2A do the sequential processes fare better than CE. Overall effort is generally slightly lower for CE processes, but further analyses would undoubtedly show that the distribution of effort is different for the two models, such that it would be higher downstream for sequential processes, and higher upstream for CE.

Figure 52 shows that in general, the shortest span time and lowest effort are achieved with scenarios in 1B, which are the low uncertainty scenarios, while the high uncertainty scenarios in 2A generally yield the longest span time and the highest effort. Scenarios in Condition 1A give results in between, while Condition 2B has a wide variation in span time and a short range in effort.

By aggregating results for all strategies under all conditions of evolution and sensitivity, (including the sequential strategies with functional participation), and comparing these to the baseline sequential strategy (no functional participation or overlapping) under all conditions of evolution and sensitivity, some broad conclusions can be made about span time and effort. In computing the averages, equal weight was given to all scenarios. Although this may distort the overall conclusions somewhat, the idea was simply to measure the trend to make a generalized comparison. Note that this comparison is different from previous comparisons made in this chapter as it takes an average over *all* scenarios, comparing them to the baseline sequential scenario. Overall, an average of 13% increase in effort was found for all scenarios over the baseline scenario. The comparison also suggests that an average span time reduction of 43% can be achieved.

6.2.2.3 Comparison of Model Results

The results of the simulations were compared to actual CE process performance in a number of projects which were studied in a published field study, and were found to be closely related to some observations and conclusions. The study was done by a group of authors on five companies that had used CE and had been successful in terms of meeting goals of span time, product cost, and design quality (Swink *et al.*, 1996). Two goals of their study were to investigate functional participation and overlapping in CE processes. Some of the practical results they obtained were compared to the computer model results.

6.2.2.3.1 Comparison of Results to a Published Field Study

The five companies chosen in the study were Boeing Company (Commercial Aircraft Division-777 project), Cummins Engine Company (heavy-duty diesel engine project, HDD), Red Spot Paint and Varnish Company (thermoplastic olefin automotive coating, TPO), Texas Instruments (TI) (airborne vehicle forward-looking infrared night vision system, AVFLIR), and Thomson Consumer Electronics (digital satellite system, DSS).

The companies were chosen for their experience with NPD, the complexity of their products, and their use of CE, among other reasons. The projects chosen from the respective companies entailed technically moderate to complex products. Table 7 summarizes the level of priority each company placed on different performance indicators, where the only one comparable to the simulation results is product introduction speed. The others are mentioned to reconcile possible differences in results.

Table 7 Company priorities.

Company Priorities	**Design quality**	**Product Cost**	**Product introduction speed**
Boeing	High	Moderate	Moderate
Cummins	High	Moderate	Moderate
Texas Instruments	Moderate	High	Moderate
Thomson	Moderate	Moderate	High
Red Spot	Moderate	Low	High

In order to make a comparison to the results of the simulations, each company's project was categorized according to its uncertainty condition, that is its degree of evolution and sensitivity. This was assessed through the descriptions provided for each company's project. Because detailed descriptions were unavailable, these assessments are based on certain assumptions to be explained. The field study also provided information on the level of functional participation and overlapping used for each project. Functional participation was assigned based on Table 2 in Swink *et al.*'s study (1996, p. 238). This table indicates the "primary" functions interacting with the designers in each company, that is functions having heavy participation in the projects. The table also includes the type of communication that took place. These two measures were used to assign functional participation in the study, and were compared to the level of functional participation in the computer models.

In the same table in the study, for each project, the level of overlap was given in terms of low, moderate, or high. These were then compared to the simulations study's values of functional participation and overlapping for the same uncertainty condition.

The following sections describe how evolution, sensitivity, functional participation, and overlapping were defined for the field study.

Boeing 777

Evolution is considered to be fast for the Boeing 777. First, this project was only moderately innovative, since it used many existing systems. Second, Boeing used three-dimensional digital design technology that was able to foresee and rectify design problems before the parts were produced.

Sensitivity is assumed to be high, since a change in the design of a single subsystem could affect entire systems in an airplane. Given that the authors state that Boeing was said to have taken an enormous financial risk in producing this airplane, it was assumed that every measure had to be taken early to ensure no design versions took place, especially since the time and cost associated with a design version for an airplane can be substantially high. Extensive testing was undertaken for example. To conclude, Boeing was found to fall under Condition 2B, that of fast evolution and high sensitivity.

For the Boeing 777, a high level of functional participation occurred. Both marketing and manufacturing were primary groups interacting with designers. Communication was also emphasized as co-location took place. According to the study, a moderate level of overlapping was used in this project.

Cummins

The Cummins HDD project is assumed to have undergone fast evolution. This project was also only moderately innovative, and made use of mostly proven technologies.

Sensitivity is assumed to be high since it is said that the production of manufacturing hardware before the design freeze could be very costly if design versions took place. To mitigate this risk, Cummins used extensive testing and experimentation, and manufacturing personnel were required to work with the designers in all phases. However, design problems could occur and might necessitate expensive tooling changes. Thus, Cummins was categorized under Condition 2B, fast evolution and high sensitivity.

Similar to Boeing, Cummins also used high functional participation. Again, marketing and manufacturing were primary groups interacting with the designers. Communication was also high as co-location took place. The study indicates that a moderate level of overlapping was used in this project.

Texas Instruments

For the Texas Instruments (TI) AVFLIR project, evolution is assumed to be fast. The level of innovation on this project was low. TI was developing a product for which the design requirements were almost complete at the start of the project, and no new technologies were used. It was simply an incremental redesign, and there was no pressure to develop the product quickly.

Sensitivity is assumed to be low since no new technologies were being used. For these reasons, this was seen as a project of low uncertainty, falling under Condition 1B, fast evolution and high sensitivity.

Functional participation was moderate for the TI project. Manufacturing was a primary interactor with designers. This function was co-located and therefore participating 100% of the time. This meant a high level of communication took place. Marketing, however, was not a primary interactor with design. Note that this situation in which the level of functional participation is higher for manufacturing than for marketing does not exactly correspond to the definition of 'moderate' functional participation in the computer models. In the latter case, both marketing and manufacturing are assigned the same level of 'moderate' functional participation through the number of hours they work. Nevertheless, manufacturing had heavy participation with the designers in this project, and this is a closer measure of functional participation than the number of functions that participate. A high level of overlapping was used in this project.

Thomson

Evolution is assumed to be slow for Thomson's DSS project. Thomson was developing a highly innovative new product with many new components. Furthermore, new production technologies were used, which might cause the design to evolve slowly if, for example, new production requirements were not yet clear or were complex.

Sensitivity is assumed to be low for Thomson. Although new production technologies were being used, these were bought early and set up during design. Since Thomson was able to build manufacturing facilities very early in the process, the new technologies were being installed and set up in tandem with the design. Product samples were periodically being sent to manufacturing to ease this transition in order to reduce uncertainty downstream. This distinguishes Thomson from the other projects where new technologies were being used, since Thomson went well out of its way to avoid last minute problems by starting the manufacturing processes early. This made Thomson fall under Condition 1A, slow evolution and low sensitivity.

Low functional participation was assigned, since marketing and manufacturing were not primary interactors with designers. According to the study, a high level of overlapping was used in this project.

Red Spot

The TPO project is assumed to have slow evolution. A highly innovative, new product and application were developed. Additionally, a new process was being used, and the company had little experience with the new material being used in the product.

Sensitivity is assumed to be high for the same reason, i.e., a new process was being used, and the company lacked experience with the new material. This led to the conclusion that the project fell under Condition 2A, slow evolution and high sensitivity.

At Red Spot low functional participation was assigned, since marketing and manufacturing were not primary interactors with designers. A moderate level of overlapping was used in this project.

Summary

Table 8 summarizes the assignments of uncertainty conditions, functional participation, and overlapping to projects. The qualifiers (low, moderate, high) for functional participation and overlapping for the computer models results are taken from Section 6.1.3. In the cases where there are two rows for the computer model results, the first row indicates the best results for span time (with high effort), while the second indicates the next best results for span time (with lower effort).

Table 8 Comparison of Computer Models and Swink *et al.*'s Study

					Field Study		**Computer Models**	
Company	Goal: Speed	Evolution	Sensitivity	Uncertainty Condition	Functional Participation	Overlap	Functional Participation	Overlap
Boeing	Mod	Fast	High	2B	High	Mod	High	Mod-High
							Mod	Mod
Cummins	Mod	Fast	High	2B	High	Mod	High	Mod-High
							Mod	Mod
TI	Mod	Fast	Low	1B	Mod	High	Mod	High
Thomson	High	Slow	High	1A	Low	High	Low	Mod-High
Red Spot	High	Slow	High	2A	Low	Mod	High	None
							Low	None

6.2.2.3.2 Comparison of Results

Table 8 compares the projects to the computer models, highlighting the similarities and differences between the field study and the simulation results, each of which are discussed below. The scale in Table 4 from Chapter 6, shown again as Table 3 below, is used to describe the results from the simulations. Based on the best (and sometimes the next best) results found in the simulations, functional participation and overlapping in each condition of uncertainty is assigned a qualifier (low, moderate, high), shown in Table 8.

Table 9 Variable scale.

Variable	***Low***	***Moderate***	***High***
Functional Participation	25%	50%	100%
Overlap	0%	33%	66%

Boeing 777

The field study's results for Boeing are similar to the simulations' results. Boeing exhibited high functional participation and moderate overlap, while the simulation had either high functional participation and moderate to high overlap (best span time results), or moderate functional participation and moderate overlap (next best span time results). Boeing's goals were high design quality and moderate speed (and moderate product cost), while the goals for the computer models are low effort and high speed. This suggests that for Uncertainty Condition 2B (fast evolution, high sensitivity), the simulation's results are valid even when the goals are quality and speed.

Cummins HDD

Once again, the results for Cummins HDD project are similar to the simulation results. Cummins made use of high functional participation and moderate overlap. The best span time results for the simulations are the same. The next best span time results yield moderate functional participation and moderate overlap. For the HDD project (as with Boeing) design quality had high priority and speed had moderate priority (and moderate product cost), as compared to the goals of low effort and high speed for the computer models. This reinforces the assertion that under Uncertainty Condition 2B the results also apply when quality and speed goals are present goals.

Texas Instruments AVFLIR

The results for the TI project are a moderate level of functional participation and high overlap, the same as the best results in the simulation. The priority on speed was moderate for the AVFLIR project, with higher emphasis placed on product life-cycle cost (and moderate design quality), compared to low effort and high speed goals for the computer models. The authors explain high overlap by the need to reduce product cost, which forced design engineers to work with process engineers early in the process. For this low uncertainty condition (fast evolution, low sensitivity), the comparison implies that the simulations' results are also valid when cost and speed goals exist.

Thomson DSS

Thomson's DSS project resulted in the same outcome as the simulations. The DSS achieved successful results with low functional participation and high overlap, while low functional participation and moderate to high overlap give the best results in the simulations. Thomson had speed as a high priority, with moderate priority on quality and cost. As was suggested in Chapter 5.0, when evolution is slow, only a limited level of functional participation is needed from downstream functions to help designers answer process-related questions early. Overlapping reduces span time due to low downstream sensitivity. Although there was a high possibility of frequent changes occurring upstream in this case, the changes were not expected to have any major negative impact on span time due to the early set-up of manufacturing processes.

Red Spot TPO

The results for Red Spot's TPO project did not coincide with the simulation results. Red Spot achieved successful results with low functional participation and moderate overlap. In the simulation results, a high level of functional participation and no overlapping gave the best span time results, and a low level of functional participation and no overlap yielded the next best span time results. Red Spot had speed as a high priority, with moderate priority on quality and low priority on cost. Red Spot was investigating a few technical alternatives for TPO paints in order to avoid losing their competitive position in the auto coatings industry. While still in discussions with customers about the requirements of the product, Red Spot engineers independently and rapidly designed and tested various samples in parallel, which helped them win a contract for the project. In this case, the definition of overlap used in the computer study is not the same as Red Spot's definition of overlap, and the high level of parallelism at the innovation stage can explain the difference in model results.

6.2.2.3.3 Summary of Comparisons

The comparison between the field study and the simulation study show that results are generally comparable. In terms of both functional participation and overlap, there is very good agreement. The exception is Red Spot, and discrepancies in this result are explained by their different use of overlapping compared to the definition used in the computer models. Results also imply that when at least certain of a company's goals for a project are different than the goals of the computer models, for a given condition of uncertainty, the levels of functional participation and overlapping that provide the best results in the computer models are still valid.

6.2.3 Summary of Verification and Validation

The verification and validation of the models confirmed that relevant concepts related to product development processes are properly represented in the computer model. Key features of the models, such as the probabilities of churn and design versions and learning, were tested through various procedures. An industry case study was instrumental in providing data to create and populate the computer models. Comparison to a field study validates the simulation results, at least as a minimal test of comparison.

6.3 SENSITIVITY ANALYSIS

Sensitivity analysis involves testing how model parameters and assumptions, such as probabilities, impact the model outcomes. In the previous section, the inputs of the models were varied and the models were observed in order to ensure the models behaved as expected. In this section, the inputs were also varied, but the purpose was to observe the effects of these adjustments on the outputs in order to determine their sensitivity to the changes, and to note the extent to which input variations affect outputs.

Sensitivity analysis was performed by adjusting the probabilities of design versions and churn. The outputs of the simulations were expected to be susceptible to changes in these values, especially since these were estimated based on the literature and on a case study. In this case, unlike in the previous section, the outputs of the models were not predictable. The set chosen for sensitivity analysis consisted of the scenarios with 50% functional participation at all levels of overlap, and under the conditions of low sensitivity and fast evolution (Condition 1B). These scenarios will be referred to as the 'original' scenarios, as compared to when they become 'modified' scenarios when changes are made.

6.2.1.4.1 Design version probability

The probability of design versions was varied in each of the scenarios. In the original scenarios, i.e., the scenarios each with 50% functional participation, and 0%, 33%, and 66% overlap, the probability of design versions is 0.30, 0.15, and 0.10, respectively. Each of these probabilities were varied from their original value, and increased by up to 0.20. For example, for the scenario with 50% functional participation and 0% overlap, the probability of design versions was incrementally increased from 0.30 to 0.50. With small changes, the results remained relatively stable, with a change occurring only at the upper limit (i.e., at 0.50), where results increased by approximately 20% for both span time and effort, as shown in Figure 53. In other words, each point in the modified scenarios (top curve in Figure 53) increased by approximately 20% as compared to the points in the original scenarios (bottom curve). This indicates that small changes do not change the trend in the results nor the conclusions. The model is insensitive to small changes in the probability of design versions.

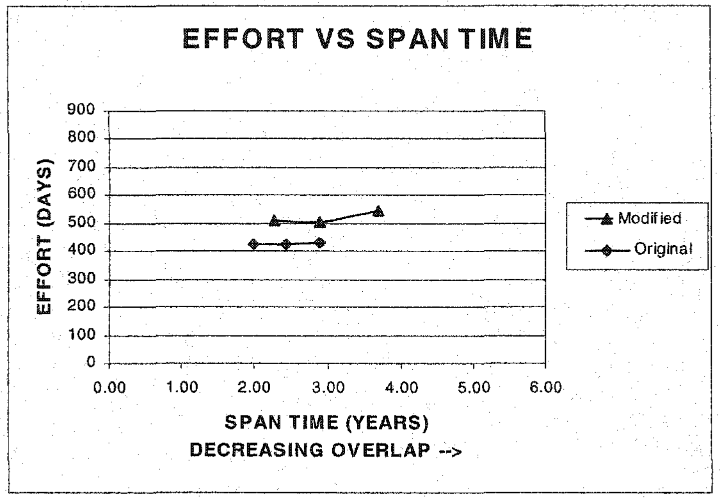


Figure 53 Sensitivity analysis results for probability of design versions.

6.2.1.4.2 Churn probability

The next part of the sensitivity analysis consisted of changing the probability of churn. The probability of churn is the same for all of the original scenarios since they are all at 50% functional participation (recall that the probability of churn is a function of functional participation). This original value was 0.40, and was varied in increments up to 0.70. At a probability of churn of 0.7, the results of the analysis showed an increase of approximately 10% in both span time and effort, as shown in Figure 54. Therefore, it can be concluded again that the results were insensitive to small changes in the probability of churn.

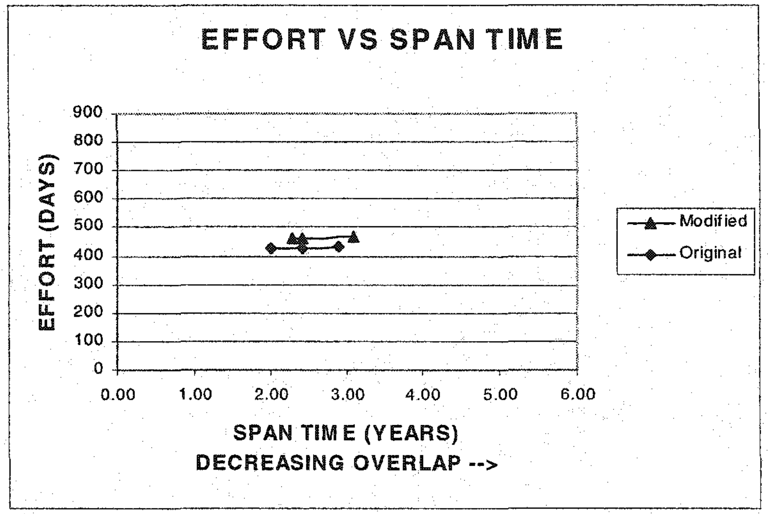


Figure 54 Sensitivity analysis results for probability of churn.

Sensitivity analysis on these two key parameters indicates that the models are relatively robust and are effective at modeling the phenomena being studied. Thus, the model results would occur even if probabilities were slightly different, and there would be no significantly change in the trends in the results or in the conclusions.

7.0 DISCUSSION AND IMPLICATIONS

Many qualitative and quantitative studies have been performed over the last two decades in a search for the core requirements and the essential practices that lead to success with CE. In this thesis, both a mathematical analysis and computer simulation were used to study and compare sequential and CE processes. The comparisons discussed in this chapter will be related to the computer models.

This chapter begins with a brief overview of the results. It then discusses the research implications, comparing the computer models presented in this thesis to existing models, first in terms of model findings, and then in terms of model design. These comparisons will highlight the contribution of this study over existing work. It concludes with the managerial implications of the thesis findings.

7.1 OVERVIEW OF RESULTS

At the start of the thesis, the stated objectives were to study how changes in the key variables of the models, functional participation and overlapping, affect span time and effort, both individually and systemically, and to determine under what conditions CE processes are more favorable than sequential processes.

Results of the simulation study suggest that NPD processes can be designed by controlling levels of functional participation and overlapping, given a level of uncertainty, to achieve span time reduction and to minimize the level of effort. The models show that, in general, an increase of effort upstream (churn) results in a decrease of more burdensome rework (design versions), thus shortening span time (Figure 55). This implies that teams should be designed and formed early, and despite the increase in effort required upstream, the benefits are reaped downstream.

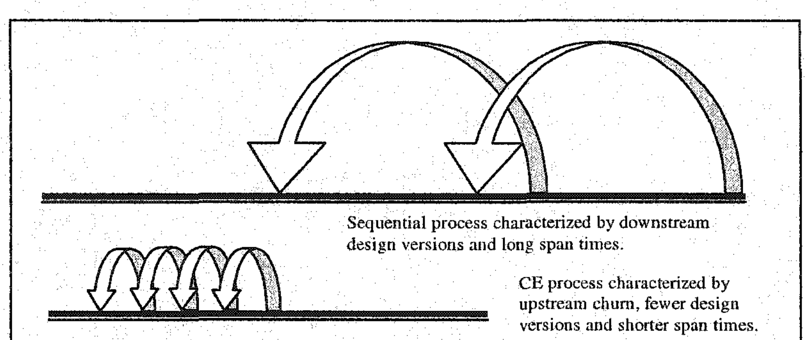


Figure 55 Sequential and CE processes characterized by design versions and churn.

The following generalized prescriptions are offered for the design of a process through the manipulation of the two key inputs.

7.1.1 Functional Participation

The use of functional participation generally reduces span time and often effort. The results of the simulations show that as functional participation increases, span time decreases and there is a corresponding decrease in effort up to a minimum point. As functional participation increases further, decreases in span time can be achieved in certain situations, at the expense of a high cost of effort. In general, at least a low level of functional participation is required to reduce span time for CE and sequential processes, under any condition of uncertainty. Increased levels of functional participation benefit situations that exhibit high uncertainty.

7.1.2 Overlapping

Overlapping without at least a minimum level of functional participation should be avoided. As the results show, not only does effort increase considerably, there are no benefits in span time reduction either. Increasing overlapping requires increased functional participation, which means more frequent exchange of information, and more frequent progress reviews to validate information sharing and to mitigate the risk of rework due to overlapping.

When the probability of design versions is high (high downstream sensitivity) and evolution is slow, overlapping should be avoided. With high downstream sensitivity and fast evolution, overlapping is beneficial only if it is accompanied by functional participation. The use of dedicated teams involves a high cost of effort. When the probability of design versions is low (low downstream sensitivity), high overlap can help reduce span time considerably, for both fast and slow evolution.

7.2 COMPARISION OF MODEL FINDINGS

In this section, findings from existing studies will be compared to results in this thesis in terms of overlapping, functional participation, and uncertainty. Some of the important findings of the thesis are concerned with the nature of the effects that functional participation and overlap independently have on the development process. Sections 7.2.1 and 7.2.2 examine simulation findings in which the effects of overlapping or functional participation on performance occur independently of the other. Some of these effects occur for all of the uncertainty conditions, or for pairs of conditions, and in this sense, they are overall effects. Section 7.2.3 first compares studies that look at the effects of the two inputs together, for each condition of uncertainty. The section concludes with a look at the effects of the two inputs in combination under all conditions of uncertainty. In any of these sections, an overall simulation effect (i.e., occurring in all four uncertainty conditions) is typically compared to a study in which the overall results have not been separately analyzed by uncertainty condition. This is necessary as so few studies have been broken down in this manner.

7.2.1 Independent Effects of Functional Participation

While most studies involving mathematical models provide recommendations on when overlapping is beneficial, they do not explicitly include functional participation in depth. Only empirical studies have done so to date. Based on the results of the computer study, it is suggested that explicit consideration of functional participation is important.

For all uncertainty conditions, it was found in this study that the baseline scenario in which there is no functional participation is always the least desirable in terms of effort and span time results. However, a minimum of a low level of functional participation in sequential scenarios reduces span time.

In accordance with the above findings, Crawford and Rosenau (1994) state that functional participation is a requirement for achieving low span time. Based on empirical studies, Gupta *et al.* (1990) and Trygg (1993) view functional participation as the most effective way to reduce span time.

Under Conditions 1B and 2A, i.e., when evolution is slow, only a low level of functional participation reduces span time and effort. Under Conditions 1A and 2B, i.e., when evolution is fast, a moderate to high level of functional participation reduces span time and effort. More specifically, the simulation models find that a dedicated team (100% functional participation) minimizes span time but at the cost of increased effort, for all uncertainty conditions, but the benefits are greatest when evolution is slow.

Smith and Reinersten (1991, p. 143) equally state that team members must be dedicated in order to reduce span time. They suggest that phasing team members out of a project at various points in the process can adversely affect performance since there remain many details that need to be attended to by the team throughout. Similarly, empirical work indicates that projects with dedicated team members are completed faster than projects with part-time team members (Scott, 1997).

To summarize, simulation results obtained for scenarios with functional participation alone are consistent with current thinking. Results suggest that functional participation should be applied in any situation. Additionally, if span time reduction is a priority, then assuming the cost of a dedicated team is recommended, especially when evolution of information is fast, for either high or low sensitivity. One implication of these results is that when CE is not a desired strategy, sequential processes can be beneficial if the appropriate level of functional participation is implemented.

7.2.2 Independent Effects of Overlapping

The results of the simulation study show that overlapping without functional participation increases a CE process' span time and effort for all conditions of uncertainty. As the level of overlap is increased, effort consistently increases for all uncertainty conditions, while span time increases slightly. This indicates that overlapping without any exchange of information between functions will not only not decrease span time, but also substantial effort may be wasted in the process.

In Yassine *et al.*'s (1999) models, in their consideration of interdependent activities, they compare a sequential and a partially overlapped process without functional participation. Their partially overlapped strategy, which is overlapped at 33%, resulted in a span time decrease and an increase in effort over the sequential one. In contrast, in the computer models, for 33% overlap without any functional participation and under all conditions of uncertainty, there is a slight increase in span time over the baseline sequential scenario, while effort increases sharply.

The results differ, and one reason for this may be because Yassine *et al.* study only two activities, while in the computer models, an entire development process is studied. With high levels of rework possibly occurring for many activities in many phases, the implication is that the ratios of span time to effort for two activities cannot be extrapolated for an entire development process. Additionally, a two-activity process cannot differentiate between churn and design versions which are a major part of the present analysis, i.e., qualitatively different types of rework.

AitSahlia *et al.* (1995) found that a partially overlapped CE process (without functional participation) is faster than the sequential process, though with the same cost (effort), which is different from the simulation results. One of the reasons for the differences may be due to the way rework is modeled. In AitSahlia *et al.*'s study, rework can only take place for the current, failed activity, i.e., rework cannot extend back to any previously completed activities. More than one iteration can take place for that activity with the same probability of success for each trial, and with the same duration. In contrast, the computer models have the ability to revisit any previously completed phase, and this recursive effect can occur a number of times. Thus, in the partially overlapped simulation scenarios, there is more potential for redundant work, especially for increased levels of overlap, which would explain the higher levels of span time and effort.

In the computer models, for Conditions 2A and 2B, both of which have high sensitivity, span time and effort are considerably higher than Conditions 1A and 1B, when downstream sensitivity is low. However, the trends for the two sets of conditions are similar with respect to increases in span time and effort as overlap is increased.

Terwiesch and Loch (1999) found that overlapping reduces span time only if uncertainty is low as compared to high. The simulation results also show that span time is lower for low uncertainty (1B) than high uncertainty (2A).

In summary, the results of the simulation study do not coincide with existing mathematical work, but does agree with empirical work. Simulation results warn against attempting to speed up the process just by overlapping, while mathematical studies suggest that overlapping without functional participation is beneficial for span time reduction, though effort may increase or remain stable. It is suggested that the study of the overall process, as well as added features that are significant in NPD, make the computer models more realistic than existing analytical models, and that the absence of a comprehensive study may lead to recommendations that may be inappropriate for real-life applications. The simulation results seem to hold better than less comprehensive approaches for practical situations.

7.2.3 Combined Effect of Functional Participation and Overlap

This section studies the effects of functional participation and overlap combined, at all possible values, for each condition of uncertainty. It should be noted again that the baseline scenario, i.e., the sequential scenario with no functional participation, always has the lowest process performance of all scenarios. Furthermore, there are no results in the literature specifically for this scenario, i.e., 0% functional participation and 0% overlap, that are compared to CE scenarios under the various conditions of uncertainty, and therefore the baseline will not be included in the discussion below.

For all scenarios, clearly uncertainty in new product development has an important effect on performance. This is evident through the different sets of curves that result from the simulation runs for each of the four conditions of uncertainty. The two extreme cases of uncertainty, i.e., high and low uncertainty, warrant special attention since other studies have also focused on these conditions in particular.

7.2.3.1 1A Slow Evolution – Low Sensitivity

In the computer models, a moderate to high level of overlap with a low level of functional participation is conducive to reducing span time and effort.

Krishnan *et al.*'s (1997) conceptual framework suggests that iterative overlapping is required under this condition of uncertainty, whereby overlapping can take place, and upstream changes are incorporated into the downstream activity through a number of iterations. This result implies a high level of overlap is possible, similar to the thesis findings. Recall that comparisons to Krishnan *et al.*'s study can only be made in terms of overlapping, since the authors did not explicitly consider functional participation.

7.2.3.2 1B Fast Evolution– Low Sensitivity (Low Uncertainty)

For the condition of low uncertainty, a moderate level of functional participation and a high level of overlapping is recommended to minimize both span time and effort.

In their conceptual framework, Krishnan *et al.* suggest that a high level of overlapping can help reduce span time, but at the expense of increased effort, in contrast to the simulation's results where both span time and effort are minimized. While both studies prescribe a similar level of overlapping, simulation results show that the modeling of functional participation as an input contributes to minimizing effort.

In an empirical study, Eisenhardt and Tabrizi (1995) compare two models that companies use to reduce span time. Whereas the compression model, which emphasizes planning, is appropriate for low uncertainty conditions, the experiential model deals with high uncertainty conditions, and thus relies more on experience. For the compression model in Eisenhardt and Tabrizi's study, which is comparable to low uncertainty scenarios in the thesis, functional participation and overlapping reduced span time. This is in accordance with the simulation results. They also suggest that overlapping can reduce span time only when uncertainty is low as compared to when it is high, and found that functional participation was linked to successful overlap, both of which are in agreement with the simulation results.

7.2.3.3 2A Slow Evolution – High Sensitivity (High Uncertainty)

In the simulations, results emphasize that, for the condition of high uncertainty, a high level of functional participation and no overlapping are best suited to minimize span time, though the cost of effort is high.

Krishnan *et al.* also recommend that overlapping should be avoided under this condition, similar to the simulation results. Eisenhardt and Tabrizi's (1995) experiential model is comparable to scenarios under high uncertainty in the thesis. They also found that overlap should be avoided under conditions of high uncertainty.

For Eisenhardt and Tabrizi's experiential model (related to high uncertainty), the authors found that functional participation reduces span time, similar to the findings presented in the thesis. Souder *et al.* (1998) suggest that under conditions of high technical and market uncertainty, a high level of functional participation is required between research and development (R&D) and marketing personnel in order to reduce span time. This is comparable to the simulation results. Griffin (1997) empirically studies how product newness and product complexity affect span time, two variables closely linked to uncertainty. Griffin finds that the higher they are, i.e., the higher the uncertainty, the more functional participation reduces span time, again in agreement with the simulation results.

Though a high level of functional participation reduces span time according to the simulation results, the cost of the effort is high. Results further suggest that if this cost is too high, a low level of functional participation minimizes effort, but at the expense of higher span time. Johne and Snelson (1988) suggested that a high level of functional participation might be too costly under conditions of high uncertainty, as the simulation results have shown.

The computer models not only recommend that sequential scenarios (no overlap) be used with functional participation for the condition of high uncertainty, they also identify what trade-offs are involved between span time and effort. No studies have focused on studying sequential processes alone. The ability to suggest how to design sequential processes based on the level of functional participation has not been considered in other studies, and is therefore an important contribution of this thesis.

Finally, the results of the simulations in the thesis showed that all scenarios under the condition of high uncertainty have overall longer span times and effort, as compared to all other scenarios in other uncertainty conditions. Griffin (1997) found that the higher the uncertainty, the longer the span time, in accordance with the simulation results.

7.2.3.4 2B Fast Evolution – High Sensitivity

Simulation results show that moderate to high levels of overlap can minimize span time as long as a high level of functional participation is used, though the cost of effort is high.

Krishnan *et al.* recommend that preemptive overlapping can reduce development time. In preemptive overlapping, since information evolves rapidly, it can be precipitated to its finalized form and sent downstream early. Although downstream risk is high, since upstream information is finalized early, no downstream changes will be required. This agrees with the simulation results.

7.2.4 Combined Effect of Functional Participation and Overlap for All Conditions of Uncertainty

When all uncertainty conditions are compared, it was found that at least a low level of functional participation reduces span time and effort for all scenarios.

Clark and Fujimoto's (1991) suggestion that overlapping requires intensive communication between upstream and downstream activities in order to be beneficial is in agreement with the simulation results. Similarly, Smith and Reinersten (1991, p. 162) state that because overlapping means team members are using partial information, the effective use of this information must be achieved through high levels of functional participation in order to succeed. In an empirical study undertaken by Zirger and Hartley (1996), the authors found that adding more functional participation with overlapping significantly reduces span time by cutting the time needed to prepare reviews, make presentations, and for rework. They also found that earlier involvement of functions also helps to address and resolve issues sooner in the process.

Additionally, in most CE scenarios in the thesis, a dedicated team yields the lowest span time, though at the cost of high effort. Similar to the simulation results, Zirger and Hartley (1996) found that dedicated projects (in which functional participation is 100%) are completed faster than projects with part-time team members.

In conclusion, the proper use of overlapping combined with functional participation can be an effective way of reducing span time and effort of the development process, as suggested both by the simulation results and empirical evidence.

7.2.5 Summary of Comparisons

In summary, the main conclusions can be stated for the conditions of high and low uncertainty. If minimizing span time is a priority, then under the condition of high uncertainty, the use of high levels of functional participation is recommended, and overlapping should be avoided. Otherwise, a low level of functional participation can reduce effort, though span time is higher. Under the condition of low uncertainty, a high level of overlapping combined with moderate functional participation will minimize span time and effort.

For any condition of uncertainty, all scenarios benefit from at least a low level of functional participation, while the baseline sequential scenario (no overlap) is never beneficial compared to all other scenarios. These results are in general agreement with existing research findings. It can be confirmed that uncertainty conditions play an important role in determining how to design a process.

The simulation's results are mostly consistent with empirical findings, though often do not agree with the mathematical studies. The reason for this may be attributed to the fact that the computer models study the overall development process, with more features included than the existing models. Thus, they are presumably more comparable to practical situations, which is what the comparisons to studies in companies suggest. This indicates that the study of the overall development process is an important contribution to the existing research. For example, the modeling of functional participation throughout the process has a significant effect on the recommended level of overlapping.

Similarly, the computer models make an important distinction between two types of rework, rework that occurs upstream called churn, and rework that occurs downstream called design versions. A two-step model cannot adequately perform an analysis on the relationship between these two types of rework, and their relation to functional participation and overlapping. Future studies in this area should be focused on the overall process, and should explicitly consider more features that are important contributors of product development performance.

7.3 COMPARISONS OF MODEL DESIGN

In this section, the characteristics of the model design will be compared to models in the literature. The computer models presented in this thesis incorporate a broad range of characteristics of product development processes that are dealt with individually in other studies. The computer models also take a more unified, holistic approach to the problem of managing the NPD process. Although a few studies were done on an overall process, they did not cover as much detail as the present study (AitSahlia *et al.*, 1995, Clermont and Aldanondo, 1999).

In the next sections, the characteristic features differentiating the computer models from existing work will be discussed, starting with the input variables, continuing with the overall process model, and followed by the features of the models themselves.

7.3.1 Model Characteristics

Table 10 summarizes the differences between existing models and the computer models in terms of their characteristics. Each of these will be discussed in the sections that follow.

Table 10 Comparison of model characteristics.

Model Characteristics	Computer Models	Existing Models
Functional participation	Various levels explicitly considered	Not explicitly considered
Overlapping	Overlapping between four phases	Mainly overlap between two activities or phases
Type of process	Dynamic	Dynamic and static
Development process	Overall process (phases & activities)	Upstream & downstream activity or phase
Rework	Churn and design versions	Planned iterations, rework loops
Learning	Effort multipliers	Knowledge accumulation curves
Progress Reviews	Progress reviews (within/across phases)	Progress reviews (in activities or phases)
Uncertainty	Completeness of information	Market/technology-driven, resolution

7.3.1.1 Functional Participation

The consideration of functional participation is an essential part of studying CE processes. In the literature review, though many studies found optimal overlapping policies based on information sharing, there was no explicit consideration of functional participation in any of the models except for one study.

Most of the models use the term concurrency in a generic sense and do not speak about functional participation. While information is transferred between activities they do not make any assumptions about actors and teamwork, only that communication happens in some way. Therefore, it is difficult to make any comparison between the models except around the concept of overlap. Only Yassine *et al.* (1995) consider it in one instance of their study (for 100% overlapped activities) by adding the amount of effort equivalent to the number of team members involved, averaging the percent functional participation to a certain percentage throughout the upstream design activity.

The concept of functional participation directly means that different people are working on activities together. In the computer models, this is explicitly modeled in an attempt to understand how changes in this variable affect effort and span time. The computer models can also represent functional participation in a sequential process. Results show that sequential processes can be improved considerably in terms of span time by increasing functional participation. So even if overlapping is considered too risky, functional participation can be highly beneficial in a sequential process. Work done to date focuses on information exchanged between activities or phases, not within them, so at best, recommendations can be made for overlapped activities or phases.

With the absence of explicitly modeling functional participation in overlapping studies, analyses may be overlooking an important aspect of the problem, possibly distorting results, or missing potentially significant impacts on process performance. The computer models in this thesis explicitly consider the effect of varying levels of functional participation, both with and without overlapping. This demonstrates the appropriate levels of effort and span times required when activities are being overlapped under various conditions of uncertainty in terms of completeness of information.

7.3.1.2 Overlapping

The problem of overlapping has been the primary focus of the existing models in the literature. However, in most of these models, overlapping is applied to only an upstream and downstream activity or phase. In contrast, in the computer models, the level of overlap can be varied across many activities in multiple phases, all the while including the features of the micro-processes of the existing models. Additionally, through the work-communicate-feedback modules, parallel sub-activities can be studied. The benefit of the design of the computer models is that by varying overlap, different process structures can be analyzed.

Overlapping was considered as a separate input, as well as in combination with functional participation. Along the lines of what was said earlier, the results expose the risks of overlapping without considering functional participation, showing how results can change with the introduction of functional participation as an input variable. The results provide a general demonstration of when overlapping is acceptable (reduced span time), and at what cost in terms of effort by comparing scenarios at varying levels of overlapping and functional participation, under different conditions of uncertainty.

7.3.1.3 Dynamic, Stochastic Processes

Dynamic, stochastic processes change with time and involve randomness, as for example, a product development process. Though mathematical techniques are often the choice of methodology, the design of such models is limited in terms of the number of process features they can study at a time. Attempts to study further details become not only very complicated and computationally burdensome, but any models developed would be difficult to solve. Additionally, the dynamic nature of processes further complicates the analytical methods.

Product development processes are continuously changing over time, and original project plans are subject to constant fluctuations and uncertainty. This limits the ability of a static, deterministic model to reflect the highly volatile nature of processes. It has been stated that the "study of the dynamic characteristics of concurrent engineering processes remains as a difficult problem" (Tian, 1998 p.514).

Krishnan *et al*'s (1997) mathematical model is deterministic. Loch and Terweisch (1998), Ha and Porteus (1995), and Yassine *et al.* (1999) have all considered stochastic processes, and specifically, they apply a nonstationary Poisson process, dynamic programming, and probabilistic modeling, respectively, to study overlapping. Though their models are dynamic and/or stochastic, they only handle the analysis of a limited process model. The authors have restricted their analysis to only an upstream activity and a downstream activity or phase.

This research uses dynamic, stochastic simulation to study the flow of information during the execution of an NPD process. The models use a process network of activities to mimic the flow of information among the actors during product development. During simulation, the initial variables of functional participation and overlap change the way that the process is executed. Changing these inputs changes the probabilities of churn and design versions, which simulate the variability in the information flow. This in turn governs the actual path of activities executed through the process network during simulation, making the simulation dynamic and stochastic.

The advantage of using stochastic computer modeling in this study is the ability to demonstrate the dynamics of CE processes from the point of view of the overall development process, while simultaneously studying a broad range of features.

7.3.1.4 Overall Development Process

New product development consists of a large network of activities that are interconnected. The complexity involved in managing such a process is a challenge. Developing models to approach the problem of CE is therefore a difficult task, and as such, most models developed to date can focus only on a limited portion of the process. In the most significant research works done to date, the analyses deal with an upstream activity or phase A, representing product design, and a downstream activity or phase B, representing process design. This type of analysis has the benefit of deriving important insights due to the simplicity of the models, but does not account for the many other interdependent activities that contribute to product development. Furthermore, there is no relation considered between the micro-processes being modeled and macro-performance of the overall process.

Krishnan *et al.* (1997), Loch and Terweisch (1998), Ha and Porteus' (1995), and Yassine *et al.* (1999) study overlapping, but their models consider only an upstream and a downstream activity. Clermont and Aldanondo (1999) consider three activities made up of three steps each, but their work is limited to the study of overlapping and rework, with no other features of product development. AitSahlia *et al.* (1995) examine a development process as a simple *m*-phase model with breakdown of phases into two activities, and with no detail such as functional participation, communication, or learning incorporated. Their models use simple probabilistic analysis to compare a sequential process to partially and 100% overlapped processes, in terms of costs and span time.

In this study, insights can be gained with respect to the macro-process in addition to micro-processes. Four generic phases of product development are studied, each of which is composed of three activities. The actual events occurring in micro-processes are due to changes in the input variables, functional participation and overlapping, which in turn affect the outcomes of the macro-process. For example, a change in a micro-process downstream, say, the occurrence of rework within an activity, can end up having a recursive impact reaching upstream work, resulting in the need to redo all work done to date. Through micro-processes, an evaluation of overall performance can be gauged. This is an advancement over studies done to date, where micro-processes are considered in isolation from other factors in the overall process.

From the comparison of findings in the last section, it is obvious that micro-process performance is not similar to macro-process performance, and that studying the overall development process does make a difference over studying only two or a few development activities. Due to the sheer number of activities and phases involved in the full development process, not to mention the particular characteristics of each phase, it is reasonable to expect that conclusions about local performance cannot be projected for global performance. In order to study NPD processes further, the development of macro-process models is essential to understanding the broader implications of CE features on NPD.

7.3.1.5 Rework

CE is often called an iterative process, but the danger of accepting too many changes early in the process is that upstream changes increase span time as opposed to reducing it. Although it is evident that a "certain number of extra design changes must be accepted if advance engineering information is to be used" (Eastman, 1980, p.39), the issue is to determine what is 'acceptable'. The computer models show that adding functional participation increases churn upfront. The level of functional participation that is recommended for a particular situation has a corresponding probability of churn that is associated with it. In the models, this is what is considered to be acceptable in order to achieve benefits of span time and effort reduction.

Krishnan *et al.* (1997) did not consider any downstream rework in their sequential model. They assumed that no changes are made in the upstream information, and therefore, no downstream changes are required. Additionally, for overlapped processes, downstream iterations are planned, that is, the user of their model chooses the number of iterations to perform and when to start them. Thus, there is no room for unplanned work, which is the nature of rework.

In Ha and Porteus' (1995) model, they assume that flaws can only be detected by the product designers (design engineers), and that once a flaw has been detected and corrected, there is no possibility of any further flaws arising in the process. The simulation models include the probability of rework as an important parameter of the process, modeled through multiple possible loop-backs in churn and design versions in all phases. Any team member can detect potential flaws at any point in the process, and rework can take the form of fully or partially reworking one or more activities, or one or more phases. Additionally, the probability of flaws in the authors' model is independent in each stage, while in the computer models, these probabilities depend on previous phases through the probability distribution curves discussed in Chapter 5.0.

In AitSahlia *et al.*'s (1995) model, when an activity fails, only it can be reworked; there is no recursion back to activities that have already been executed.

In Yassine *et al.*'s (1999) model, if rework is required, both the upstream and downstream activity must be reworked; there is no possibility of reworking only the downstream activity.

The computer models presented in this thesis explicitly consider rework, both upstream and downstream, making a distinction between frequent, minor changes upstream (churn) versus time-consuming, costly rework loops (design versions). The level of acceptable churn is not always clear, and the computer models help to identify the point after which the trade-off between churn and reduced design versions becomes unfavorable towards span time and effort reduction.

In analytical models, it is difficult to model rework, and when it is, it is modeled as rework for a single instance, as opposed to being an iterative process. In computer modeling, it is easier to model this recursive effect. The computer models have the advantage of demonstrating the trade-off between upstream versus loop-back rework.

7.3.1.6 Learning

Little work has been done to consider the effect of learning in the development process (Yassine *et al.*, 1999). In Ha and Porteus' (1995) model, in contrast to the present models, it is assumed that 100% learning takes place after reworking once, with no possibilities of making mistakes again, while in the computer models, several iterations can take place. Yassine *et al.* incorporate learning through a knowledge accumulation curve, in which the percentage of knowledge accumulated is a function of the duration of the activity. One minus this percentage is the probability that the downstream activity has rework.

The computer models presented in the thesis represent learning as a function of the level of functional participation. This has the advantage of capturing the work reduction due to increased information sharing, and because it is applied when rework takes place, which is iterative by nature, each iteration incorporates the learning effect. It was previously mentioned that sensitivity analysis on the learning parameter demonstrated that learning has a very positive effect on process performance, suggesting that a process can benefit from the learning curve effect; in other words, if means can be found to improve learning processes, then span time and effort reduction can be achieved. Because of the potentially big difference in outcome by including the learning parameter, it seems that this is an important aspect in the study of product development processes, especially from a managerial point of view.

7.3.1.7 Progress Reviews

The implementation of progress reviews can simplify the overlapping process through the arrangement of meetings, the increased use of approval points along the process, and the reduced reliance on major design meetings to accept work progress.

Ha and Porteus (1995) consider the effect that progress review meetings have in a concurrent process. Similar to their notion of these reviews, the present work integrates progress reviews throughout the process.

Several decision points simulating progress reviews exist in the models: meetings to examine the possibility of moving forward based on completeness of information, meetings to communicate and send information downstream, approval and acceptance meetings to move forward or rework, as well as design meetings at phase completion. The computer models show that the increased implementation of progress reviews has the potential for allowing increased overlapping. Further informal communications surely occur in organizational settings, and although these are not explicitly modeled, they can only serve to improve performance in real processes.

7.3.1.8 Uncertainty

Uncertainty in new product development has an important effect on performance. Most research defines uncertainty in different ways, which may be a source of variations in outcome.

Krishnan *et al.* (1997) conceptualize uncertainty resolution through evolution. The more uncertainty is involved, the slower the evolution of information to a final solution. Eisenhardt and Tabrizi (1995) conceptualize uncertainty as being market-driven. This thesis proposes a new way of conceptualizing uncertainty. In the computer models, the measure of uncertainty is represented through the 'completeness of information', which is described by the probability of churn and design versions, i.e., rework. Thus, in an environment of high uncertainty, the level of churn and design versions is expected to be higher than in an environment with low uncertainty, all other things being equal. Since analyses in this thesis are all relative, the qualifier of high and low is defined for a given scenario relative to another.

There are advantages in depicting evolution and sensitivity in terms of churn and design versions. First of all, it is more practical in the sense that all that is needed is to choose different probability distributions for rework (churn and design versions) in order to test various scenarios. This can be done based on experience, or through estimates, thus setting a 'perceived' level of uncertainty. The exact measure of uncertainty can be avoided due to the fact that relative comparisons are being made. This is significant as the measurement of uncertainty is difficult (Souder *et al.*, 1998). Furthermore, a conservative approach can be taken during process design (or vice versa) by choosing high probability distributions for rework and observing the impact on performance. Various scenarios can be tested, and the results can assist in evaluating how to tailor the process based on the representation of uncertainty.

7.4 RESEARCH IMPLICATIONS

The results from this thesis support the findings of statistical studies and some mathematical studies, and also add to the current research in NPD and CE by showing how two key aspects of NPD processes, functional participation and overlapping, are related to two measures of product development performance, span time and effort, under various conditions of uncertainty. Some important research implications emerge from the relationships studied between the input and output variables. To begin with, results show that clearly, there is no one prescriptive method that works for all situations. Despite this, there may be some clear lessons and directions that can be taken for various situations, each of which will likely require some level of customization.

Contributions of the thesis can be said to be three-fold: 1- determining *when* CE is beneficial, i.e., under what conditions of uncertainty, 2- *how* the process should be designed, in terms of functional participation and overlapping, to achieve benefits, whether in a CE or sequential process, and 3- *what* trade-offs are involved between span time and effort. Results support the well-known fact that CE accelerates span time for NPD processes. More importantly, the condition under which this is not the case is identified (specifically, the condition of high uncertainty). The levels of functional participation and overlapping needed to achieve both low span time and effort are predicted for certain uncertainty conditions (1A and 1B), while alternate solutions are provided for conditions in which one performance indicator must be traded off for the other (2A and 2B). Results also show that CE has a more significant impact on span time reduction than effort.

The implications of using functional participation, overlapping, and uncertainty, are now discussed. Functional participation has been shown to be a key feature, central to studying CE. Existing empirical studies that show that increasing functional participation reduces span time are supported. Though the cost of effort at times is high, the study does not take into account potential gains that may be accrued by introducing the product on the market quickly. A link to this and other financial benefits of a project will allow exploration of whether it is worthwhile to invest in CE for the project.

Overlapping has also been identified as an important aspect of CE. Consistent with other studies is the result that overlapping can reduce span time, but functional participation and the level of uncertainty must be considered. The results showing that overlapping reduces span time are supported for conditions of low uncertainty.

Uncertainty plays a significant role in determining how a process should be designed. Results in this thesis were found under various conditions of uncertainty that were preset, and recommendations were made on how to organize a process given a condition. Future research should be focused on determining specifically how uncertainty can be reduced. As just one example, Thomke (1997) showed that uncertainty could be reduced using simulation and experimentation. However, as a start, the definition and measurement of uncertainty needs to be standardized, as so many authors have conceptualized uncertainty in different ways (Souder, *et al.*, 1998).

This study is one of the first, if not the first, to study the conditions under which CE processes are preferred to sequential processes by stochastically modeling a full development process. Most work to date focused on studying CE between two product development activities or phases. Krishnan (1997) recognized the need to extend the study to deal with interactions over more product development phases, but did not follow through. To properly analyze CE in NPD, future research in this area must focus on the full development process to observe the effects on overall process performance, not just on micro-process performance. Furthermore, explicit consideration of more key features needs to be included in the analysis of macro-processes, and the effect of these on product development performance should be studied.

Though the results prescribe levels of functional participation and overlapping to achieve low span time and effort, it is obvious that successful implementation of the methods suggested in this thesis is also necessary to achieve the desired benefits. Even in practical situations, cross-functional teams may not have the desired effect if the 'right' people are not participating (Clark and Fujimoto, 1991, p. 105). Often departmental representatives (called 'liaison' engineers) are chosen to be part of the team, and they simply communicate the needs of the project to the actual working members and vice-versa. For certain functions, the direct contributors of product development should be identified and be made part of the team. On the other hand, liaisons may be necessary for certain stages of the process. Gerwin (1993) suggests that "functional liaisons be generalists" in the strategic phases of NPD, while specialists are required for collaboration for CE. Zirger and Hartley (1996) found that the degree of cross-functional representation in a team, i.e., the number of functions included, had a significant impact on span time reduction. This study does not vary the number of functions on a team other than from a single function in a sequential process, to four functions in a CE process. These are deeper issues involved in team formation, and understanding how to effectively create and implement teams is an area that calls for further research.

7.5 MANAGERIAL IMPLICATIONS

Managing the key contributing factors for NPD success has been an ongoing concern for managers, who are often apprehensive of the added costs that come along with the use of practices such as CE to reduce span time (Smith and Reinersten (1991, p. 204). Many studies have been done to date to explore this issue.

The computer models can be used to compare various process strategies, and results can demonstrate cost-benefit analyses of CE and sequential processes, possibly helping to get managerial support for resources when the benefits are shown to be clear. When a particular strategy is attractive in terms of one performance indicator, for example span time, but costly in terms of the other, i.e., effort, whether or not it is worthwhile to invest is left up to the manager, who must consider what the implications of being quicker to the market are for the company.

It has already been well established that functional participation and overlapping are two elements that are central to success using CE (Blackburn, 1991). The difficulty remains in knowing how to customize the development process such that the trade-offs involved in terms of span time and effort are well understood. This study has shown how to design the process under various conditions of uncertainty by tailoring levels of functional participation and overlapping. From a managerial perspective, it is important to note that CE processes reduce span time more significantly than effort. The following sections suggest recommended practices for NPD processes in light of some major findings of the thesis.

7.5.1 Uncertainty of Information

The uncertainty of information is directly related to the completeness of information available for design decisions. The use of incomplete information downstream has the risk of causing rework. The results of computer simulations prescribe the level of upfront functional participation and process overlap that would help to mitigate the downstream impact. This allows managers to anticipate the potential effect of overlapping, and can help better plan activities and resources by understanding the repercussions to downstream functions, which in turn helps manage risk. By setting the parameters of the model, and identifying the ideal level of functional participation and overlapping, managers can decide on how to deal with releasing incomplete information.

In what follows, managerial implications of the findings are discussed under the four conditions of uncertainty, providing recommendations on how to deal with the parameters discussed above.

1A Slow Evolution – Low Sensitivity

When downstream sensitivity in the process is low, span time reduction is more sensitive to increases in overlapping than to functional participation. Increases in overlapping causes span time to decrease, except when it is increased without any functional participation. With an increase in functional participation over the baseline scenario (from 0% to 25%), span time initially decreases considerably, but is relatively insensitive to further increases in functional participation.

When evolution is slow, effort is sensitive to increases in functional participation; effort increases with no span time benefit after an initial decrease when functional participation is increased (from 0 to 25%). Except for the scenarios in which overlapping is considered without functional participation, effort is generally insensitive to increases in overlapping.

The results imply that with slow evolution, only a limited level of functional participation can reduce uncertainty by allowing downstream functions to help designers answer process-related questions early. Since information is being obtained slowly, too much functional participation will increase effort, as downstream functions cannot contribute too much to the design. Overlapping reduces span time since the downstream sensitivity is low. Despite the high probability of frequent changes occurring upstream, the changes do not have a major negative impact on span time reduction.

1B Fast Evolution– Low Sensitivity

Once again, with low sensitivity downstream, span time reduction is more sensitive to overlapping than to functional participation. Except for the case of overlapping with no functional participation, overlapping helps to reduce span time. With only a minimum increase in functional participation over the baseline scenario, span time is significantly reduced.

Effort is a little less sensitive to functional participation under this condition: as functional participation increases, effort stays relatively stable while span time is reduced, except with a dedicated team (100% functional participation), in which case effort is high with little span time benefit.

Due to completeness of information, team members can make decisions quickly, so some functional participation reduces span time, while a dedicated team is unnecessary. With low downstream sensitivity they can make downstream commitments early in the process so that overlapping reduces span time.

2A Slow Evolution – High Sensitivity

When downstream sensitivity in the process is high, span time reduction occurs for increases in functional participation, but not for increases in overlapping.

Effort is highly sensitive to increases in overlapping; it increases with no span time benefit. At a low level of functional participation (25%) effort reaches a minimum point. Span time can be decreased for a high level (100%) of functional participation, but at the cost of higher effort.

Results suggest that functional participation can help to reduce span time. Overlapping is harmful due to the uncertainty of the information being sent downstream, and as such, should be avoided.

2B Fast Evolution – High Sensitivity

Under this condition, span time reduction is highly sensitive to increases in functional participation, while it is generally insensitive to overlapping.

Effort generally increases with increasing overlapping, and except for the case of a dedicated team, (100% functional participation), increasing functional participation reduces effort.

With high sensitivity downstream, high levels of integrated teamwork can help mitigate the risk of design versions. Under this condition, it is acceptable to transfer preliminary information downstream early allowing for some overlap even if the downstream sensitivity is high. Since exchanged information is certain and complete, there is a low expectation of upstream changes. However, since information is evolving quickly, high levels of overlap should be coupled with functional participation to reduce the risk of rework; otherwise, frequent changes may cause downstream activities to be reworked too often.

When either span time or effort minimization is a priority, a certain level of functional participation and overlapping can achieve the goal. Table 11 summarizes the level of each input that is needed to minimize an output; therefore no trade-offs are indicated in the table. For example, for Condition 2B, if the goal is to reduce span time, at the cost of high effort, then a high level of functional participation with a high level overlapping can achieve this goal. On the other hand, if the goal is to minimize effort and accept a longer span time, then a low level of functional participation and a moderate level of overlapping can achieve this goal. Note that in all cases, at least a minimum of a low level of functional participation is required, regardless of the goal, and also, in all cases, whenever overlapping is used, a minimum level of functional participation is necessary.

Table 11 Required inputs for individual output minimization.

	Condition of Uncertainty							
	1A		1B		2A		2B	
Outputs / Inputs	Span Time	Effort	Span Time	Effort	Span Time	Effort	Span Time	Effort
Functional Participation	Low	Low	Moderate	Moderate	High	Low	High	Moderate
Overlapping	High	High	High	High	None	None	High	Moderate

From a managerial perspective, under conditions of low uncertainty, overlapping is significant as it contributes more to span time reduction for a given level of functional participation, while under conditions of high uncertainty, functional participation is more important to implement than overlapping. Since overlapping and functional participation can consume much of an organization's resources, the benefits of CE beyond those suggested in this thesis must be investigated, as mentioned at the start of the chapter. When the cost of effort is high, for example, unless a company has high market power, in which case span time reduction is critical, it may not be a worthwhile investment. In such cases, it would be recommended to spend more time on a sequential process, perhaps to focus on quality, for example.

7.5.2 Learning

Learning is a partially controllable factor in any organization. Though every individual has a skill set, a certain level of experience, and a body of knowledge and intelligence from which to innovate, managers can exert some influence in this respect. To increase learning, a number of managerial practices may be useful, such as training or teamwork, i.e., functional participation. In this study, learning was assumed to be a function of functional participation. The learning coefficients were chosen based on certain assumptions of teamwork impacts. Sensitivity analysis on the learning parameter showed that there is a relatively big difference in outcome between a process in which there is learning and one in which there is not. This implies that a process can benefit from the learning curve effect by reducing rework and promoting effectiveness, and that to some degree, learning can and should be improved or controlled.

7.5.3 Resource Requirements

A common problem managers have is knowing *when* to ramp up on resources, and often, the problem lies in ramping up too late. Projects often get overstaffed with resources with the belief that this is necessary for CE implementation. The simulation results show that this is not always necessary, and that there is not always a gain in increasing effort. Results show that under Conditions 2A and 2B, a high level of functional participation is required to achieve low span time, and therefore, increasing effort is beneficial. On the other hand, under Conditions 1A and 1B, only a limited amount of functional participation is necessary, and results show that increasing effort has no impact on span time reduction. Additionally, anytime overlapping takes place, a minimum level of functional participation is required (at least 25% in all cases).

Although there is a tendency for functional managers to limit the participation of their subordinates in projects (Gerwin and Moffat, 1997), the results of the present study show that putting in the effort early can have long-term benefits. For example, post-production repair, fieldwork, and maintenance can be minimized, and engineering change orders can be reduced. The benefit of the computer models is that they give managers a better understanding of the staffing needs for projects. By varying the input levels, the corresponding results help to identify the trade-offs between span time reduction and cost of effort.

7.5.4 Progress Reviews

The models implicitly show that, in general, as the process moves more towards an integrated, concurrent environment, as opposed to a sequential one, increased communication provides better performance. Managers should set up formal progress reviews periodically for overlapped activities. The reliance on design reviews for project progress, which are few and far between, should be minimized. Though informal communications take place all the time, this was not modeled explicitly, and this can potentially demonstrate further benefits if modeled. Further studies should be able to show at what point the effort involved in conducting progress reviews is simply not justifiable in terms of the cost and effort involved.

7.5.5 Summary of Research and Managerial Implications

The computer models contribute to the existing body of work by encompassing many features of the product development process into one model, including dynamic, stochastic processes, the overall development process, functional participation, overlapping, decision-making, rework, learning, progress reviews, and uncertainty.

Additionally, a new representation of uncertainty of information is conceptualized through the completeness of information. Combinations of the probabilities of churn (evolution) and design versions (sensitivity) correspond to different levels of completeness of information, representing different conditions of uncertainty. As information is less complete, a higher degree of uncertainty is involved.

Knowledge of the level of uncertainty involved in the development of a new product is necessary to get an accurate prediction of results. Describing uncertainty can be subjective or objective. It can be translated into probability distributions that broadly estimate the probability of upstream work needed, and the corresponding probability of rework. The representation in the form of probability distributions is useful for comparative purposes. As long as the relative differences are correct, exact measures of uncertainty can be avoided. With this conceptual definition, various levels of overlapping and functional participation can be tested in an effort to compare different process designs and to evaluate the relative merits and trade-offs involved in each.

Overall, the computer models simultaneously account for a variety of features that characterize product development processes. A more holistic view of detailed processes in dynamic form provides insights from a broader perspective, allowing for a more in-depth study of CE.

Managers can achieve desired outputs in terms of span time and effort, to a certain degree, by choosing the appropriate levels of functional participation and overlapping. Functional participation alone can considerably improve span time, more than effort under all conditions of uncertainty, although at times this involves a high cost of effort. Overlapping can have a greater negative impact on span time and more so on effort if it is considered in isolation from functional participation, than if functional participation is considered alone.

The implication is that more careful attention needs to be paid to overlapping, as more risk is involved. In one case, a company was said to have lost several million dollars worth of tooling due to a highly overlapped process which resulted in major commitments made in downstream phases, where subsequent upstream changes proved to be extremely costly (Bhattacharya *et al.*, 1997). The level of overlap must absolutely be weighed against the sensitivity to rework. In cases when downstream sensitivity is too high for overlap, the use of functional participation alone in a sequential process can be highly beneficial.

Finally, results suggest that functional participation is always recommended, with levels varying depending upon the conditions of uncertainty. Results further suggest that when span time is a top priority, managers should emphasize the use of high overlapping with high levels of functional participation, sometimes at a high cost of effort. However, if high uncertainty exists, overlapping, but not functional participation, should be avoided. If cost is a concern, there are many instances in which lower levels of overlapping and functional participation can still be beneficial.

8.0 CONCLUSIONS

This chapter concludes the dissertation by summarizing the main findings and contributions. The chapter also discusses the limitations of the models and presents avenues for future research. It closes with a discussion of the significance of the thesis findings.

8.1 SUMMARY OF CONTRIBUTIONS

This thesis explored important features of new product development processes in an attempt to identify how and to what extent they affect product development performance. Both a mathematical and a computer modeling methodology were presented to study the performance of new product development processes in terms of effort and span time. Comparisons were made specifically between sequential and CE processes. In addition, the conditions under which one process outperforms the other were investigated. The thesis has both theoretical and methodological implications.

8.1.1 Contributions to Theory

This thesis contributes to theory in two ways, both based on the modeling methods chosen to study NPD processes.

8.1.1.1 Expected Payoff Method and Results

First, the thesis applies the expected payoff method of the economic theory of teams from decision theory to compare sequential and CE processes. It was found that as the interaction among team members increases in the CE process, the expected payoff increases. Beyond a certain point of interaction, a CE process is preferable to a sequential process in terms of expected payoff. Further research in this area should provide additional insights.

8.1.1.2 Computer Modeling Method and Results

Second, a computer modeling methodology allowed for the study of dynamic processes from a broad perspective. The product development process was treated as a system and as such, the full process was mapped. This is presumably the first study using computer models to analyze the overall NPD process in detail. This was done based on practical observations of organizational processes and on findings from the literature, using an information processing view of organizations. While many of the findings are intuitive, some are counter-intuitive. For example, in practice, managers may decide that overlapping will reduce span time, but overlook the fact that functional participation must also occur to benefit from overlapping. The results show that when processes are overlapped with no functional participation, the effect is a high increase in effort with no benefit due to span time reduction at all. On the other hand, because results are intuitive, this indicates that the models are accurate representations of the real-world system.

Computer modeling also conveniently incorporated many of the key features of NPD processes. The two key features of NPD, teamwork and parallel processing of activities, were conceptualized using functional participation and overlapping as input variables to the models. Additionally, relevant features such as rework, decision-making processes, and learning, were explicitly included in the models. The models also implicitly considered communication through progress reviews, interaction between succeeding phases, and the effects of sharing information at various points in the process. Uncertainty is conceptualized in a new way, represented by the completeness of information based on the probability of churn and design versions. Various combinations of the probabilities allow for the study of scenarios under four conditions of uncertainty. This thesis is the first to integrate all of these features into one study.

Given the broader scale on which NPD is studied, the simulation models can be tailored to a given project within a company by modifying the number of phases and activities, by changing the durations required to perform activities and the corresponding probabilities of rework, by adjusting the learning curve coefficients, by changing the number of actors involved in a team, and by adding costs.

In terms of results, the study provided an analytical tool that is able to simulate a range of scenarios and provide resulting performance indicators in terms of span time and effort, giving insights from a system perspective. The results show how the two strategic features of CE, functional participation and overlapping, can be customized to fit the environment of a particular project based on the uncertainty involved. The research produced the following significant results, categorized under the uncertainty conditions.

1A Slow Evolution – Low Sensitivity

For scenarios falling under Condition 1A, a CE process is preferable to a sequential process. A low level of functional participation and a moderate to high level of overlapping minimize both span time and effort.

1B Fast Evolution– Low Sensitivity

Under the condition of low uncertainty, a CE process is again superior to a sequential process. High levels of overlapping with a moderate level of functional participation minimize both span time and effort.

2A Slow Evolution – High Sensitivity

Under the condition of high uncertainty, sequential processes are recommended. A high level of functional participation, more specifically, a dedicated team, is beneficial for span time reduction, although this comes at a high cost of effort. When the latter is considered too high, a trade-off must be made. A sequential process with low functional participation will achieve span times that are longer than with a dedicated team, but the cost of effort is greatly reduced.

2B Fast Evolution – High Sensitivity

For scenarios that fall under Condition 2B, once again, a CE process is preferable to a sequential process. A dedicated team with moderate to high overlap minimizes span time at a high cost of effort. When the cost of effort is too high, it can be lowered at the expense of longer span times by using only a moderate level of overlapping coupled with a moderate level of functional participation.

The above summarizes the main results of the simulations. It can be concluded that, except under high uncertainty (Condition 2A), CE processes are preferable to sequential processes, though the characteristics of CE processes may vary from one condition to the next. In other words, when CE prevails, depending upon the level of uncertainty involved, a certain level of functional participation and overlapping is recommended either to minimize both span time and effort, or to make trade-offs between the two. CE processes have a much greater effect on span time reduction than on effort reduction.

The findings of the computer models generally agree with empirical results. As such, they seem to provide a reasonable prediction of performance and can therefore be considered to be a good managerial tool to help design a process in terms of functional participation and overlapping, and to determine trade-offs between span time and effort.

Comparing the simulation results to the mathematical models developed in existing research showed that results are not always in agreement. It is suggested that the study of the full development process has a strong influence over the discrepancy in results. Studying the overall process allows for the flexibility of testing a number of features simultaneously, giving the models the ability to tie micro-process performance to macro-process performance, and therefore make them more realistic. This is difficult to do in a study limited to only a portion of the process. This is presumably one of the first studies to focus on the overall development process, and future work in this area should do the same, as recommendations based on a portion of the process may be limited and not applicable to real-world situations.

8.1.2 Contributions to Methodology

Contributions to methodology include the use of the expected payoff method for evaluating NPD processes. The mathematical model was introduced as a simple approach to investigating the problem of evaluating the performance of CE. As the basic principle of decision theory, it presumably has not been applied to research in NPD. The thesis demonstrates how to describe a process in terms of a network diagram by incorporating actions of team members and their corresponding utilities, how to design the payoff function, and how to obtain a response function for the network, which evaluates the process in terms of the expected payoff. Although only a basic version of this method is used, the potential for future research promises a new mathematical framework for determining NPD process performance (Kong and Thomson, 2001).

Contributions to methodology also include the use of computer models to study NPD. The use of stochastic, computer models provided great insight into the operation of CE processes. Not only did these models allow for the inclusion of the dynamic properties of NPD processes, they were also instrumental in broadening the scope of the study of development processes, which was limited when using the expected payoff technique. As a result, one of the most significant contributions of this thesis is that the outcomes of micro-process activities could be tied to macro-process performance in a product development model, showing where trade-offs between span time and effort exist. Whereas most models in the existing literature have produced important findings about micro-processes in CE, the computer models integrate these process characteristics into more comprehensive models, which, though by no means exhaustive, are detailed enough to draw some meaningful insights that past studies have not been able to do.

8.1.3 Summary of Theoretical and Methodological Contributions

The study of CE processes was the main focus of the thesis, with the objective of determining when CE was preferable to sequential processes. The expected payoff method was introduced as one means of studying product development processes. Initial results indicate when CE is favorable over sequential processes, but the model is very basic; future work should provide further insights.

Choosing computer simulation as a methodology allowed for the study of several features of an overall NPD process at once. Results were found for a range of scenarios under four conditions of uncertainty, and have indicate that CE processes outperform sequential processes in terms of span time and effort under all but one condition of uncertainty, high uncertainty, where a sequential process is clearly better.

The results produced a general pattern of convex curves of effort versus span time. These curves can indicate how a process should be organized by identifying how much functional participation and overlapping would be required to achieve certain span time and/or effort benefits. Knowing the shape of the effort versus span time curve is important since it shows whether more functional participation and/or overlap can reduce span time further for a modest increase in effort. The minimum point in the curves reveals the point beyond which additional increases in both functional participation and overlapping force trade-offs in terms of span time and effort.

Given the results this study has produced, there exist broader research implications. First, it is important to note that practical situations require more than just the determination of levels of functional participation and overlapping to design a process. There is no guarantee that product development performance will be optimized by simply following the recommendations outlined in the thesis, since there are many other practical considerations involved. For example, the best mix and number of functions that should participate on a team must be determined, and which functions should spend more or less time than others must also be understood. In other words, careful implementation of the recommendations presented in this thesis is required.

Next, the importance of uncertainty has been clearly demonstrated in this study. As such, future studies should focus on how to standardize a definition of uncertainty, and then on how uncertainty can be reduced. Finally, future empirical studies focusing only on the elements studied in this thesis would be useful for comparison of results.

8.2 LIMITATIONS AND FUTURE WORK

This section begins by discussing limitations of both the mathematical and computer models, and concludes with areas of research that are potentially viable for future work using both methods.

8.2.1 Limitations and Future Work of the Mathematical Models

The limitations and future work of the expected payoff method were presented at the end of Chapter 4.0, and they will be briefly revisited here.

8.2.1.1 Interaction

The sequential process model was built under the assumption that no interaction takes place between different functions when work from one phase is handed off to the next. In practice, there is always some form of communication, and modeling this would require the inclusion of an interaction variable in the sequential model.

8.2.1.2 Goals

The models assume that all team members share common goals in a project, for both sequential and CE processes. Though this may be true to some extent in a CE process, in a sequential process, functional teams tend to have goals that differ from one another.

8.2.1.3 Time and Interaction

The present models assume that the farther apart activities are in time, the weaker the interaction, thus payoff can be additive in time. However, this is often not true, and time and interaction would thus need to be developed further in the models.

8.2.1.4 Rework

Rework was not included in the process models. As such, there is only a one-time execution of activities. In reality, rework is a very common occurrence in NPD activities, and must therefore be considered in future work.

8.2.1.5 Costs

Finally, the cost of obtaining and communicating information was not represented in the expected payoff method. Though a network may prove to be more valuable for one process as compared to another in terms of the expected payoff, the actual cost of designing and managing that network may or may not be worth the cost, and this is an important parameter to be included in future work.

8.2.2 Limitations of the Computer Models

Although the computer models encompass more features of product development processes than previous research in this area, they still have some limitations.

8.2.2.1 Number of Scenarios

Though a large number of scenarios were studied in this thesis, more scenarios should be studied in the future. A greater number of levels of functional participation and overlapping should be studied so that the minimum point of effort in the resulting curves can be more precisely defined for the various scenarios. By increasing the levels of either or both functional participation and overlapping, this point may or may not change significantly. However, in order to study varying levels of overlap, the models need to be structurally adjusted. Although functional participation is easily adjusted, overlapping is more complex, as it involves allowing the phases to be overlapped to different degrees.

8.2.2 Structure

The structure of the model cannot easily be modified. If additional activities or phases need to be added, the structure has to be redefined, which is time-consuming. Further refinement and simplification of the model should help make it easier to manipulate.

8.2.3 Team Behaviour

No attempt is made to include team behaviour or attitudes in the model. It is simply assumed that team members are cohesive, however imperfect behaviour distorts real performance. However, this aspect needs an in-depth consideration before implementing or rejecting it.

8.2.4 Delays

No time delays have been included in the models. For example, delays due to external factors, such as new customer requirements or suppliers' late deliveries, have not been accounted for. Furthermore, information transfers between actors is assumed to be seamless, and take no time to be delivered from one actor to another. Adding these delays can allow for a more realistic setting of development processes.

8.2.2 Future Work

There are a number of opportunities that exist to extend the work presented in this thesis to allow the computer models to be more comprehensive, as well as to develop new areas of research. Avenues for future work are now discussed.

8.2.2.1 Design and Communication Technologies

Modeling the use of various technologies would undoubtedly affect the trade-offs presented in this thesis. The design process using computer-aided design or rapid prototyping tools, for example, could be studied either in a CE environment or in the traditional sequential design process, and may possibly change results and recommendations. Considering the growing use of such technologies, future work should not ignore their roles and impact on process performance.

Similarly, the communication medium for transmitting information was not considered in this study, i.e. faxes, electronic mail, telephone etc. This study assumes that availability of appropriate communication media is already embedded in the organization. This simplifying assumption is expected to have a negligible effect on the outcome since differences in communication time are not expected to be substantial with respect to production time, i.e., the value-added time required to perform activities. On the other hand, it may be useful in the future to focus on communication in NPD processes, in which case, modeling the effect of technologies such as shared databases would be useful and necessary. Making use of such technologies might minimize the need to coordinate people, and may even show how sequential processes can be successfully designed.

8.2.2.2 Costs

"A surprisingly negative and disruptive side to new styles of small-team management sometimes appears. It can boost people costs" (Crawford, 1992). This was cited as a hidden cost of speeding up development processes. Although the results showed that the cost of effort in using CE teams could at times be steep, future analyses could consider the potential reduction in various other costs as well as the increased revenue that could offset the cost of effort. For example, some of the costs that might go down as a result of fewer design versions are the costs of: materials (due to building fewer prototypes), scrap and defective parts, field repairs, maintenance, and smoother manufacturing ramp-up.

It has been suggested that when the opportunity cost of delaying a product's introduction to the market is high, the speed of development should be prioritized, presumably over cost reduction (Swink *et al.*, 1995, p.235). A study done on high-technology products found that products that were late to market by six months but within budget earned 33% less in profits over a period of five years. On the other hand, projects that went 50% over budget but got out to market on time resulted in only a 4% loss in profits (mentioned in Eisenhardt and Tabrizi, 1995).

The implication here is that investing in the added cost of effort during development may be more than balanced by significant savings during implementation and sales, due to the minimization of waste (rework, materials, etc.), or because of increased profits due to early entrance to the market. Further research could significantly contribute to understanding just how much savings result from using CE. The present model can be modified to incorporate costs, though research would be required to evaluate the cost of resource time, materials, and communication.

8.2.2.3 Quality

Process quality was implicitly considered through rework in this thesis. Future work could consider that one of the possible dangers of speeding up a process is rushing through it at the expense of product quality. This may actually end up costing the company in terms of warranty or product liability costs, for example. Functional diversity (i.e., the number of functions that are on a cross-functional team) is said to reduce technical quality because too many people from varying backgrounds working on the same thing creates difficulties in integrating ideas (Scott, 1997, p.99). Krishnan *et al.* (1997) did include quality in their qualitative analysis, suggesting the trade-offs between span time, effort, and quality. In an empirical study, Hauptman and Hirji (1996, p. 161) found that CE achieves budget goals without negatively affecting quality, cost, or schedule. Trygg (1993), Gupta *et al.* (1990), and Griffin (1992) found that functional participation increases speed while maintaining quality.

Additional research would help to verify some of the findings of other authors' previous work. The effect of variations in functional participation and overlapping on product quality could be studied, and the relationships to span time and effort can be established.

8.2.2.4 Supply Chain

In the future, the external stakeholders that are involved in the NPD process could be considered in the models. The development process could include the participation of actors such as suppliers, vendors, and customers who play an integral part in the development of a product, many of whom may be closely interconnected with the development team.

Since supply chain management (SCM) deals with information coming from the external environment, as it evolves from the raw material suppliers to the end users, it can affect communication patterns in NPD processes as well as how information is coordinated. Modeling this interdependence with the external environment would involve adding activities and actors, and possibly new features as well. The models would reflect more realistic NPD processes, and might potentially contribute to existing research in SCM.

Once a supply chain model is created, further research can be developed that follow along the lines of the present research. The use of preliminary information exchange may also take place in SCM. For example, in a string of companies within a supply chain, each company places orders from its immediate upstream partner. The commonly occurring bullwhip effect takes place when information is not shared in a timely manner between the upstream and downstream companies, and distorted demand propagates upstream across the entire supply chain in an amplified form. As a way to reduce this effect, decisions about orders may be taken before complete information is available, creating a virtual overlap of information. In some cases, placing orders based on uncertainty, or incomplete information may be more risky than others. Many of the concepts presented in this thesis can provide an alternate means of studying this problem.

8.2.2.6 Multiple Project Interaction

The present models consider only one project within an organization, though, in actuality at any given moment, there may be other projects that may interact with it. Each project is vying for the limited resources within the organization, which places constraints on all of them (Scott, 1997). This may result in one project not getting enough resources when other projects are considered, making it difficult to dedicate resources to a project.

From the case study undertaken at the telecommunications company, team members were often being pulled from one project to another. The resulting effect was span time prolongation and effort increase due to the 'warm-up' period required for the team members to start up again where they had left off. This occurrence can seriously constrain a project from achieving low span times and effort. Incorporating it in the model would not only make the model more realistic, it would help to identify the costs involved in such delays, the serious impacts the loss of a team member might entail, and the importance of resource availability to an organization. This can also highlight the difference in performance between projects that have dedicated resources, and those whose team membership is subject to fluctuations.

8.2.2.7 Testing and Iterations

An area of research that has been emerging recently is in the testing activities involved in the development of products. As was discussed in Chapter 3.0, in the sequential process, once the design of a product is complete, a prototype is built and then testing begins. Test results typically go back to the designer(s), who then prepare for the next design-build-test iteration. Being able to identify problems early and speed up this cycle is important in order to be able to minimize costly design versions, and therefore span time.

Because of their importance to the design of a product, some researchers are attempting to identify testing strategies that optimize product development performance (Loch *et al.*, 2001; Thomke and Bell, 2001). W testing activities are overlapped with each other, though span time is reduced, the effect of learning is lost, as compared to testing in series (Thomke, 1998). Eisenhardt and Tabrizi (1995) found that longer testing time reduced span time. Loch *et al.* (2001) suggest that when testing is costly, it should be performed sequentially, and that when the test activity is slow, executing it in parallel with the product design will reduce span time.

Because the simulation study models testing as part of the design process, an opportunity exists to focus on these issues. Learning, rework iterations, costs, durations, and overlapping, can all be readily studied as features and parameters of the design-test cycle. Additionally, uncertainty will play an important role in the development of test strategies. Thus a link between the present study and the growing research in testing has been identified.

8.3 SIGNIFICANCE OF FINDINGS

This thesis set out to investigate policies for managing NPD processes, and to determine when the benefits of a CE process outweigh the costs of a sequential process. Two methods were used to achieve these objectives. First, a mathematical model was built based on decision theory, and then, computer modeling was used to develop more detailed and comprehensive models. In both methods, relationships between the input variables and output variables were analyzed. The results produced in this thesis provide significant insights for NPD processes. Concurrent engineering processes have been shown, in general, to be beneficial for span time and effort reduction; that is, this is not always true. There is a clear demonstration that there are only certain situations in which CE processes are more favorable than sequential processes. These situations were identified for both the mathematical and computer models.

In the first method, a new approach using the expected payoff method was chosen to study and evaluate the performance of NPD processes. Functional participation, or interaction between team members, and overlapping are the key features of the model. An introductory model was presented and results showed that a CE process is more valuable than a sequential process when the interaction intensity is high. This method proved to be a feasible, new way of studying organizational processes, which are represented through network diagrams and evaluated in terms of their expected payoff. Further work is in progress.

Computer models were then developed in order to be able to study NPD processes with more flexibility, and in more detail than the mathematical model. The overall development process, both sequential and CE, was built, each made up of several key process features. A number of mechanisms have been developed which allow the models to reflect the dynamic interactions that take place in NPD. The key contributors of NPD process performance were assumed to be functional participation and overlapping, and their relative impact on process span time and effort was studied.

However, it was also recognized that the design of the development process is highly dependent upon the environment in which it is present, more specifically, the condition of uncertainty it faces. In this regard, the NPD processes were studied under four conditions of uncertainty, each one characterized by how quickly information evolves upstream and how sensitive are downstream activities to changes upstream. The conditions under which CE processes are more favorable than sequential processes were determined, in terms of span time and effort, as dependent variables of functional participation and overlapping. When trade-offs existed between span time and effort, these were also identified.

Results have shown that CE is a significant accelerator of process span time under all but the condition of high uncertainty, though sometimes effort must be invested to achieve this. For each condition under which CE processes are preferred to sequential processes, an appropriate level of functional participation and overlapping is prescribed to minimize span time and/or effort. Results show that the level of functional participation in a process has an effect on the recommended level of overlapping.

Sequential processes are recommended when uncertainty is high, and the appropriate level of functional participation is prescribed. This is significant as sequential processes are often condemned as being a poor way of managing the NPD process. Furthermore, according to the results, the use of functional participation in a sequential process considerably reduces span time over the baseline sequential process.

To improve NPD performance, an investment in effort is required at times, but span time can be reduced. By classifying a process under one of the various conditions of uncertainty, the appropriate amount of overlap and functional participation can be chosen to minimize span time and/or effort. Functional participation alone can considerably improve span time, more than effort under all conditions of uncertainty, although at times this involves a high cost of effort. Overlapping has a negative impact on span time and more so on effort if it is considered in isolation. CE processes with both functional participation and overlapping have a more significant impact on span time reduction than on effort.

The findings of the thesis are significant because they clearly reveal that concurrent engineering, though it is often touted as being the solution to managing NPD, is not a universal solution to all problems. Although this has also been established in other studies, this thesis gives more detail in understanding when and why CE is valuable, and how the process can be designed to obtain results. Furthermore, significant trade-offs between span time and effort are specified. It is also clear that often, more effort is required to truly benefit from the potential outcomes that CE promises.

Though the results of the simulation study prescribe the appropriate levels of functional participation and overlapping, it is obvious that successful implementation of the methods suggested in this thesis is also necessary to achieve the desired benefits. Managers of NPD processes must take into account a number of other factors not considered in the thesis, both tangible and intangible, as for example, available budgets or human issues, that require careful consideration during process design and management.

Furthermore, the results of the thesis imply that there exist other areas that managers can target for improving processes, such as providing means to improve learning in an organization, better management of organizational resources, and improved process control through the implementation of progress reviews. These areas affect how processes are designed using functional participation and overlapping under uncertainty conditions.

To date, no other existing studies have attempted to study NPD processes using the expected payoff method. Furthermore, no existing work has been able to recommend how to design and manage processes in detail under various conditions due to the limited scope of their models. Additionally, this is presumably the first study that has integrated so many important NPD features into one comprehensive study through the use of computer models. Thus, the models developed in this thesis are more comparable to practical situations than previously developed models. The study of the overall development process is therefore a significant contribution to the existing research.

Future work can be valuable in terms of creating more comprehensive models, both mathematical and computer, and by branching out into other areas of NPD research. Also, empirical research focusing on the issues in this thesis would be useful to compare to the models' results. A continued effort towards studying NPD process performance using the methodologies and toolsets presented in this thesis should contribute increasingly to understanding how to successfully manage NPD in order to meet organizational goals.

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APPENDIX A: EXPECTED PAYOFF NOTATION

Symbol	Concept
X	The set of states x of the environment.
x	The state x of the environment.
R	The set of alternatives outcomes of an action.
r	An outcome of an action.
A	The set of all actions a.
a	An action taken by the decision-maker.
Y	The set of all possible information signals.
y	An information signal.
η	An information structure: a function from X to Y.
α	A decision function: a function from Y to A.
ρ	Result or outcome function.
υ	Utility function of r.
π	Probability measure on X.
ω	Payoff function for state x and action a.
Ω	Expected utility of an action a.

APPENDIX B: DESCRIPTIVE STATISTICS OF SIMULATION RESULTS

CONDITION 1A
MODEL %FP/%OL

M10 0/0

	Effort	Span Time
X-bar	501.9	5.168
Standard Deviation	44.40355	0.448464
Confidence Interval	38.92065	0.393088
Lower Limit	**462.9793**	**4.774912**
Upper Limit	**540.8207**	**5.561088**

M11 25/0

	Effort	Span Time
X-bar	402	3.185
Standard Deviation	2.828427	0.021213
Confidence Interval	3.919922	0.029399
Lower Limit	**398.0801**	**3.155601**
Upper Limit	**405.9199**	**3.214399**

M12 50/0

	Effort	Span Time
X-bar	523	3.403333
Standard Deviation	67.84541	0.415492
Confidence Interval	76.77279	0.470164
Lower Limit	**446.2272**	**2.93317**
Upper Limit	**599.7728**	**3.873497**

M13 100/0

	Effort	Span Time
X-bar	667.4	3.1
Standard Deviation	25.36336	0.535164
Confidence Interval	22.23152	0.469082
Lower Limit	**645.1685**	**2.630918**
Upper Limit	**689.6315**	**3.569082**

M20 0/33

	Effort	Span Time
X-bar	628.125	5.2075
Standard Deviation	59.36381	0.305219
Confidence Interval	58.17538	0.299108
Lower Limit	**569.9496**	**4.908392**
Upper Limit	**686.3004**	**5.506608**

M21 0/66

	Effort	Span Time
X-bar	864	5.2
Standard Deviation	149.8449	0.839524
Confidence Interval	146.8451	0.822717
Lower Limit	**717.1549**	**4.377283**
Upper Limit	**1010.845**	**6.022717**

M30 25/33

	Effort	Span Time
X-bar	422	2.665
Standard Deviation	8.485281	0.233345
Confidence Interval	11.75977	0.323394
Lower Limit	**410.2402**	**2.341606**
Upper Limit	**433.7598**	**2.988394**

M31 25/66

Observation	Effort	Span Time
X-bar	432.8	2.35
Standard Deviation	33.08625	0.25387
Confidence Interval	29.0008	0.222522
Lower Limit	**403.7992**	**2.127478**
Upper Limit	**461.8008**	**2.572522**

M40 50/33

	Effort	Span Time
X-bar	528	2.9175
Standard Deviation	32.68027	0.182094
Confidence Interval	28.64495	0.15961
Lower Limit	**499.355**	**2.75789**
Upper Limit	**556.645**	**3.07711**

M41 50/66

	Effort	Span Time
X-bar	513	2.526667
Standard Deviation	47.28636	0.254231
Confidence Interval	46.33971	0.249141
Lower Limit	**466.6603**	**2.277525**
Upper Limit	**559.3397**	**2.775808**

M42 100/33

	Effort	Span Time
X-bar	693.75	2.7725
Standard Deviation	71.15418	0.330794
Confidence Interval	80.51693	0.374322
Lower Limit	**613.2331**	**2.398178**
Upper Limit	**774.2669**	**3.146822**

M43 100/66

	Effort	Span Time
X-bar	765.8	2.652
Standard Deviation	17.99166	0.10616
Confidence Interval	17.63148	0.104035
Lower Limit	**748.1685**	**2.547965**
Upper Limit	**783.4315**	**2.756035**

CONDITION 1B
MODEL %FP/%OL

M10 0/0

	Effort	Span Time
X-bar	501.9	5.168
Standard Deviation	44.40355	0.448464
Confidence Interval	38.92065	0.393088
Lower Limit	**462.9793**	**4.774912**
Upper Limit	**540.8207**	**5.561088**

M11 25/0

	Effort	Span Time
X-bar	469.75	3.7
Standard Deviation	94.95394	0.799875
Confidence Interval	93.05301	0.783862
Lower Limit	**376.697**	**2.916138**
Upper Limit	**562.803**	**4.483862**

M12 50/0

	Effort	Span Time
X-bar	449.25	3.1
Standard Deviation	95.27285	0.637652
Confidence Interval	93.36554	0.624886
Lower Limit	**355.8845**	**2.475114**
Upper Limit	**542.6155**	**3.724886**

M13 100/0

	Effort	Span Time
X-bar	595.6	2.768
Standard Deviation	73.55814	0.380355
Confidence Interval	64.47527	0.333389
Lower Limit	**531.1247**	**2.434611**
Upper Limit	**660.0753**	**3.101389**

M20 0/33

	Effort	Span Time
X-bar	628.125	5.2075
Standard Deviation	59.36381	0.305219
Confidence Interval	58.17538	0.299108
Lower Limit	**569.9496**	**4.908392**
Upper Limit	**686.3004**	**5.506608**

M21 0/66

	Effort	Span Time
X-bar	864	5.2
Standard Deviation	149.8449	0.839524
Confidence Interval	146.8451	0.822717
Lower Limit	**717.1549**	**4.377283**
Upper Limit	**1010.845**	**6.022717**

M30 25/33

	Effort	Span Time
X-bar	462	3
Standard Deviation	46.51881	0.42
Confidence Interval	45.58753	0.411592
Lower Limit	**416.4125**	**2.588408**
Upper Limit	**507.5875**	**3.411592**

M31 25/66

Observation	Effort	Span Time
X-bar	443.3333	2.64
Standard Deviation	92.57609	0.409512
Confidence Interval	81.14491	0.358946
Lower Limit	**362.1884**	**2.281054**
Upper Limit	**524.4782**	**2.998946**

M40 50/33

	Effort	Span Time
X-bar	425.8	2.434
Standard Deviation	51.42179	0.190342
Confidence Interval	45.07229	0.166839
Lower Limit	**380.7277**	**2.267161**
Upper Limit	**470.8723**	**2.600839**

M41 50/66

	Effort	Span Time
X-bar	411.25	1.96
Standard Deviation	16.5	0.146287
Confidence Interval	14.4626	0.128224
Lower Limit	**396.7874**	**1.831776**
Upper Limit	**425.7126**	**2.088224**

M42 100/33

	Effort	Span Time
X-bar	574.5	2.31325
Standard Deviation	38.44043	0.18555
Confidence Interval	37.67087	0.181836
Lower Limit	**536.8291**	**2.131414**
Upper Limit	**612.1709**	**2.495086**

M43 100/66

	Effort	Span Time
X-bar	590	2.145
Standard Deviation	44.24929	0.354636
Confidence Interval	43.36345	0.347536
Lower Limit	**546.6366**	**1.797464**
Upper Limit	**633.3634**	**2.492536**

CONDITION 2A
MODEL %FP/%OL

M10 0/0

	Effort	Span Time
X-bar	554.4	5.6686
Standard Deviation	40.25621	0.409747
Confidence Interval	35.28542	0.359152
Lower Limit	**519.1146**	**5.309448**
Upper Limit	**589.6854**	**6.027752**

M11 25/0

	Effort	Span Time
X-bar	505.25	3.73
Standard Deviation	28.00446	0.208006
Confidence Interval	24.54651	0.182322
Lower Limit	**480.7035**	**3.547678**
Upper Limit	**529.7965**	**3.912322**

M12 50/0

	Effort	Span Time
X-bar	616	3.96
Standard Deviation	22.62742	0.056569
Confidence Interval	31.35938	0.078398
Lower Limit	**584.6406**	**3.881602**
Upper Limit	**647.3594**	**4.038398**

M13 100/0

	Effort	Span Time
X-bar	750.4	3.39
Standard Deviation	39.57651	0.133978
Confidence Interval	34.68965	0.117434
Lower Limit	**715.7103**	**3.272566**
Upper Limit	**785.0897**	**3.507434**

M20 0/33

	Effort	Span Time
X-bar	805.8	5.718
Standard Deviation	170.9717	1.382071
Confidence Interval	149.8603	1.211415
Lower Limit	**655.9397**	**4.506585**
Upper Limit	**955.6603**	**6.929415**

M21 0/66

	Effort	Span Time
X-bar	960.5	5.75
Standard Deviation	133.3426	0.713372
Confidence Interval	130.6732	0.699091
Lower Limit	**829.8268**	**5.050909**
Upper Limit	**1091.173**	**6.449091**

M30 25/33

	Effort	Span Time
X-bar	633	4.113333
Standard Deviation	46.50806	0.268576
Confidence Interval	52.62778	0.303917
Lower Limit	**580.3722**	**3.809416**
Upper Limit	**685.6278**	**4.41725**

M31 25/66

Observation	Effort	Span Time
X-bar	768.25	4.235
Standard Deviation	114.6397	0.649436
Confidence Interval	112.3446	0.636434
Lower Limit	**655.9054**	**3.598566**
Upper Limit	**880.5946**	**4.871434**

M40 50/33

	Effort	Span Time
X-bar	681.6	4.018
Standard Deviation	94.38909	0.575256
Confidence Interval	82.73404	0.504225
Lower Limit	**598.866**	**3.513775**
Upper Limit	**764.334**	**4.522225**

M41 50/66

	Effort	Span Time
X-bar	888.6667	4.073333
Standard Deviation	56.8712	0.200333
Confidence Interval	64.35454	0.226694
Lower Limit	**824.3121**	**3.84664**
Upper Limit	**953.0212**	**4.300027**

M42 100/33

	Effort	Span Time
X-bar	884.25	3.48
Standard Deviation	88.13768	0.359444
Confidence Interval	86.37321	0.352248
Lower Limit	**797.8768**	**3.127752**
Upper Limit	**970.6232**	**3.832248**

M43 100/66

	Effort	Span Time
X-bar	1023.5	3.48
Standard Deviation	72.34409	0.320208
Confidence Interval	70.8958	0.313798
Lower Limit	**952.6042**	**3.166202**
Upper Limit	**1094.396**	**3.793798**

CONDITION 2B

MODEL %FP/%OL

M10 0/0

	Effort	Span Time
X-bar	554.4	5.6686
Standard Deviation	40.25621	0.409747
Confidence Interval	35.28542	0.359152
Lower Limit	**519.1146**	**5.309448**
Upper Limit	**589.6854**	**6.027752**

M11 25/0

	Effort	Span Time
X-bar	581.5	4.455
Standard Deviation	13.43503	0.176777
Confidence Interval	18.61963	0.244995
Lower Limit	**562.8804**	**4.210005**
Upper Limit	**600.1196**	**4.699995**

M12 50/0

	Effort	Span Time
X-bar	569	3.79
Standard Deviation	19.79899	0.056569
Confidence Interval	27.43946	0.078398
Lower Limit	**541.5605**	**3.711602**
Upper Limit	**596.4395**	**3.868398**

M13 100/0

	Effort	Span Time
X-bar	706.6667	3.53
Standard Deviation	75.10215	0.375899
Confidence Interval	104.0842	0.520959
Lower Limit	**602.5825**	**3.009041**
Upper Limit	**810.7509**	**4.050959**

M20 0/33

	Effort	Span Time
X-bar	706.2	5.832
Standard Deviation	122.5528	0.999585
Confidence Interval	107.4202	0.876157
Lower Limit	**598.7798**	**4.955843**
Upper Limit	**813.6202**	**6.708157**

M21 0/66

	Effort	Span Time
X-bar	960.5	5.75
Standard Deviation	133.3426	0.713372
Confidence Interval	130.6732	0.699091
Lower Limit	**829.8268**	**5.050909**
Upper Limit	**1091.173**	**6.449091**

M30 25/33

	Effort	Span Time
X-bar	504.5	3.3525
Standard Deviation	97.65415	0.674111
Confidence Interval	95.69917	0.660615
Lower Limit	**408.8008**	**2.691885**
Upper Limit	**600.1992**	**4.013115**

M31 25/66

Observation	Effort	Span Time
X-bar	641.6	3.284
Standard Deviation	47.88841	0.125618
Confidence Interval	41.97521	0.110107
Lower Limit	**599.6248**	**3.173893**
Upper Limit	**683.5752**	**3.394107**

M40 50/33

	Effort	Span Time
X-bar	468.5	2.585
Standard Deviation	20.5061	0.120208
Confidence Interval	23.20437	0.136026
Lower Limit	**445.2956**	**2.448974**
Upper Limit	**491.7044**	**2.721026**

M41 50/66

	Effort	Span Time
X-bar	641.5	2.835
Standard Deviation	44.54773	0.233345
Confidence Interval	61.73877	0.323394
Lower Limit	**579.7612**	**2.511606**
Upper Limit	**703.2388**	**3.158394**

M42 100/33

	Effort	Span Time
X-bar	619.75	2.355
Standard Deviation	71.07449	0.292859
Confidence Interval	69.65162	0.286997
Lower Limit	**550.0984**	**2.068003**
Upper Limit	**689.4016**	**2.641997**

M43 100/66

	Effort	Span Time
X-bar	681.5	2.29
Standard Deviation	4.949747	0.056569
Confidence Interval	6.859864	0.078398
Lower Limit	**674.6401**	**2.211602**
Upper Limit	**688.3599**	**2.368398**