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Product-Process Development Simulation to Support Specialty Contractor Involvement in Early Design

by

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GRAD. (Technical University, Lisbon) 1992
M.A. (Katholieke Universiteit te Leuven) 1995

A dissertation submitted in partial satisfaction of the
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Abstract

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Nuno António Pires de Almeida Pinho Gil

Doctor of Philosophy
in
Engineering - Civil and Environmental Engineering

University of California, Berkeley

Professor Iris D. Tommelein, Chair

Specialty contractors and suppliers have knowledge to contribute to the early design of architecture-engineering-construction (AEC) products. Lean construction theory advocates such involvement. The practice of involving suppliers in product development and in manufacturing has proven to be highly successful. This dissertation builds on empirical research in the semiconductor industry to study the following research questions: what value does specialty-contractor knowledge bring to early design, and how and when should specialty contractors be involved in early design?

An understanding of the design development process is fundamental to effectively involve specialty contractors early on. This work categorizes the contributions of specialty-contractor knowledge to early design and it provides examples that stem from current practice. It also argues why specialty-contractor knowledge is often ignored in design and it discusses the conditions that AEC organizations need to create for increasing interaction between designers and specialty contractors.

This dissertation describes a product-process model for the design process of high-tech facilities. An implementation of a model excerpt in a computer simulation environment provides the basis for studying the dynamics of design processes in unpredictable environments. Unpredictability means that design criteria are prone to change throughout the development process. Specifically, the study casts light on the impacts of postponing commitments for managing design in unpredictable environments.

Finally, this dissertation integrates the implementation of the design model with a model for the procurement, fabrication, and construction phases of a facility system. This systemic simulation model provides a computer-based framework for sharpening theoretical understanding of alternative systems to deliver projects in unpredictable environments. These systems differ based on when specialty contractors get involved in design and on when construction starts relative to the completion of design.

Simulation results show that earlier contractor involvement and shorter lead times reduce the mean project duration but magnify variability and may significantly increase construction wasted resources, if improperly implemented. A judicious postponement of design commitments can reduce this waste and increase the reliability of the development process. In addition, results lend support to empirical research findings by demonstrating the value of leveraging specialty-contractor knowledge in early design for expediting project development.

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“Words Have Meanings, Nuno”

Iris D. Tommelein

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I. INTRODUCTION

I.1. PROBLEM STATEMENT

The design and building development process of a high-tech facility is extremely complex. This complexity stems from diverse sources. The product definition is technologically complex because it is composed of a variety of interdependent facility systems, such as architectural, structural, mechanical, electrical, and piping systems. These systems need to be flawlessly interwoven so that the facility meets the stringent performance criteria set by the production processes. The window of opportunity within which a high-tech facility is designed and built tends to be also extremely narrow. Practitioners often overlap the engineering, procurement, and construction phases in an attempt to compress the project delivery duration. Such overlap forces practitioners to make downstream design decisions based on incomplete and possibly unreliable upstream information.

In addition, owners seldom have a clear definition of the performance requirements for a high-tech facility when its design development process begins. Owners may therefore need to change the project scope and the design criteria several times during execution of the design-build process. These changes create additional uncertainty in the development process. Consequently, to be effective, design and building specialists have to continuously exchange information and collaborate.

Regrettably, the project delivery system of most high-tech facilities does not lend itself to an efficient handling of such complexity. Specialty contractors—such as mechanical, electrical, and piping contractors—detail the design (occasionally), build, start up, and maintain the facility systems. Suppliers fabricate the major pieces of equipment and specialty items installed in the facility. Specialty contractors and suppliers have a wealth of process and product design knowledge that they have primarily gained through past experience. Most of this knowledge remains essentially tacit, however, because contractors and suppliers seldom express it openly in manuals of practice or in regulatory codes that designers could easily access. Consequently, this knowledge could only be leveraged throughout the design effort by means of interaction between designers, specialty contractors, and suppliers.

Specialty contractors and suppliers are seldom involved when designers make critical decisions about the product definition of a high-tech facility. Instead, they typically get involved in a project by competitively bidding a design solution that has already been committed to (although evidence suggests industry practices are changing). Consequently, losses in efficiency are likely to occur during the fabrication and construction of the design solution. It also becomes more likely that designs are chosen that perform poorly. Frequently, the lack of interaction between designers and builders during early design also triggers a confrontational environment during the subsequent execution phase. Confrontation can consume significant financial resources and, ultimately, can delay the project delivery. Research and observation of current practices indicate that this is a pervasive problem in the project delivery system of most architecture-engineering-construction (AEC) products in the United States and overseas.

I.2. RESEARCH FRAMEWORK

I.2.1. LEAN PRODUCTION THEORY

Baumol and Blinder (1979, p.12) define a theory as "a deliberate simplification (abstraction) of factual relationships that attempts to explain how those relationships work. It is an *explanation* of the mechanism behind observed phenomena."

In the book *Factory Physics: Foundations of Manufacturing Management*, Hopp and Spearman (1996) consolidate a long-term effort to develop a theory that explains manufacturing operations. They focus on "the flow of material through a plant," and thereby emphasize measures such as "throughput, customer service,..., quality, labor costs, and efficiency". Hopp and Spearman (1996, p.7) "seek a science of manufacturing by establishing concepts as building blocks, stating fundamental principles as 'manufacturing laws', and identifying general insights from specific practices".

Within manufacturing, lean production is a management theory based on the work of Taiichi Ohno at Toyota Motor Company in the early 1950s. Ohno's work aimed to streamline the manufacturing process in vehicle plants in Japan. Since this time, lean production has expanded outside Japan and to other manufacturing industries (Shingo 1981, Krafcik 1988, Womack et al. 1990). Lean production theory encompasses the product development and production management processes. Product development consists of conceptualizing and developing a new idea into a product definition. In production management, the product definition acts as the main guideline for the fabrication and assembly of components into a complete product.

Womack and Jones (1996) formalized some of the tenets that guide the implementation of lean production theory. These are: (1) specify value "in terms of specific products with specific capabilities offered at specific prices through a dialogue with specific customers" (p.19), (2) identify the value stream for each product, i.e., "the entire set of activities running from raw material to finished product for a specific product" (pp. 19 and 314), (3) "make the value-creating steps [in the value stream] flow" by redefining "the work of functions, departments, and firms" (p.24), (4) "let the customer *pull* the product from you as needed rather than pushing products, often unwanted, onto the customer" (p.24), and (5) perfection, i.e., "make continuing efforts to improve" (p.26).

The integration of the product development process with the fabrication of components and their assembly in the manufacturing plant is essential in lean production theory, and a principle of lean design (Womack et al. 1990, Clark and Fujimoto 1991, Womack and Jones 1996). The involvement of suppliers—those who fabricate and deliver the components—in the early design effort is an important contributor in such integration. As Womack et al. (1990, p. 60) state, "First-tier suppliers [those who are assigned whole components] were responsible for working as an integral part of the product-development team in developing a product." Moreover, "suppliers are not selected on the basis of bids, but rather on the basis of past relationships and a proven record of performance" (Womack et al. 1990, p.146).

In the lean system, suppliers assign staff members—called resident design engineers—to the development team at the very outset of product development. This involvement aims to (e.g., Womack 1990, Clark and Fujimoto 1991): (1) avoid conflicts between product and process design that stem from lack of understanding and lack of communication among individuals; (2) create conditions that allow for more frequent innovations in product design and manufacturing in order to increase the value of the product to the client; (3) create conditions to start manufacturing without complete product information in order to compress the project duration; (4) avoid meaningless iterations in product development and production in order to reduce waste and to increase the probability of projects being completed on time; (5) leverage the technological knowledge of individuals with production experience in order to develop more efficient solutions in manufacture and assembly; and (6) increase trust and commitment among suppliers, product development groups, and assemblers.

Examples of the means and methods that lean production theory advocates to involve suppliers in product development are: (1) develop long-term relationships between suppliers and manufacturers; (2) promote two-way communication, as well as formal and informal exchanges of information between suppliers and manufacturers; (3) create cross-functional teams which include people with manufacturing knowledge, and make teams commit to what is agreed upon as a group; (4) encourage suppliers to innovate about the product definition and the process development; (5) share the responsibility for the results and the risks; and (6) provide the contractual framework and the incentives to encourage collaboration.

I.2.2. NEW PRODUCT DEVELOPMENT

Literature on new product development has made clearer how industries, such as the multimedia and computer industries, develop products in unpredictable environments (e.g., Eisenhardt and Tabrizi 1995, Iansiti 1995, 1997). In these environments, market conditions fluctuate constantly, project requirements change frequently, and technology evolves rapidly. Because the window of opportunity to develop and market new products may be extremely narrow, firms frequently overlap the product development and implementation phases. To flexibly accommodate design changes as the development process unfolds, practitioners opt for postponing the date when they freeze the concept, as the flexible model in Figure I.1 (b) illustrates. In addition, suppliers and those responsible for design implementation actively participate in the product development effort.

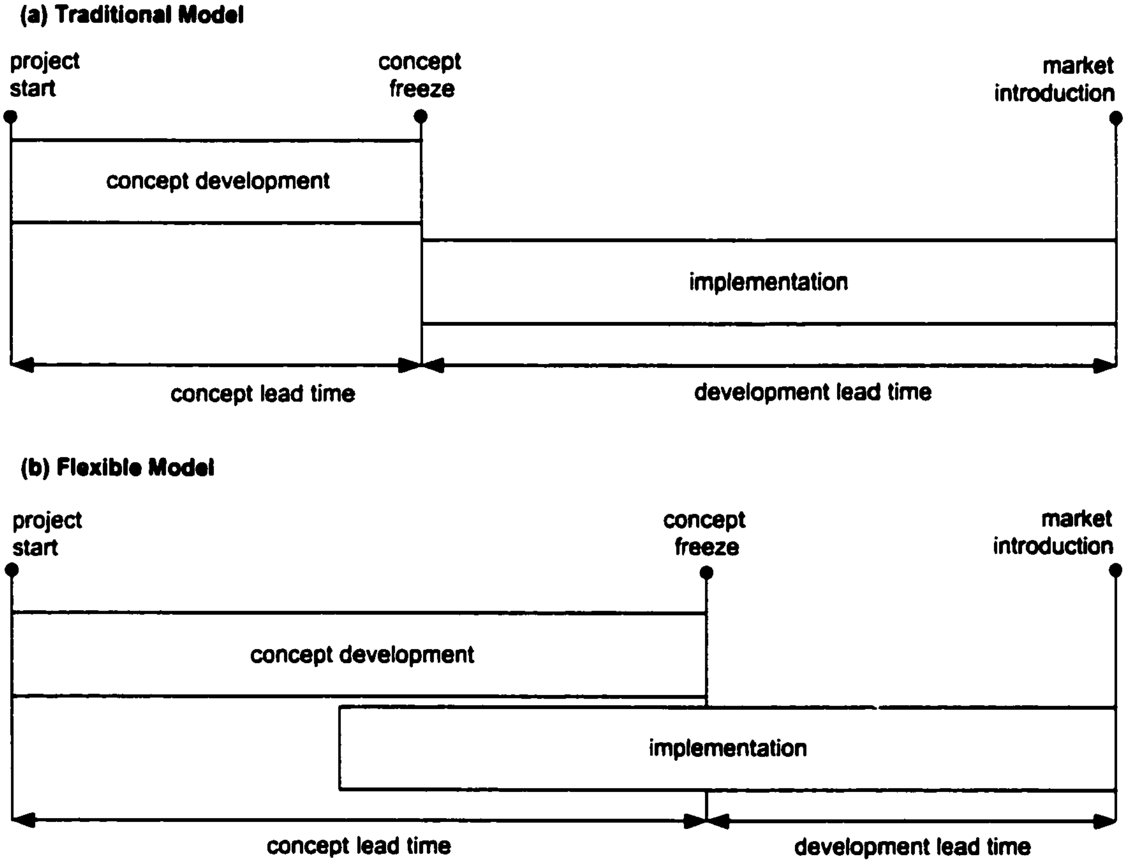


Figure I.1 - Two Models of Effective Product Development (Iansiti 1995)

The airplane industry provides another example of a product development environment in which it is crucial that there be flexibility to accommodate design changes. For instance, the airplane manufacturer BOEING developed diverse software environments—such as the Computer Aided Three-dimensional Interactive Application (CATIA) and the

Electronic Pre-assembly in the Computer (EPIC)—that take advantage of Internet technology to support the airplane design and assembly process (Sabbagh 1996). These computer systems help multidisciplinary teams (bringing together people from design, procurement, operations, customer support, and suppliers) to optimize the design definition and to minimize the process impact of design changes. In addition, these systems also enable airline companies to let customers customize the design definition according to their requirements throughout during the development process, as it is the case with the configuration of interior airplane cabins (Sabbagh 1996).

In addition, a flexible development process is paramount to satisfy the needs of customers in those industries that have evolved towards the delivery of individually customized products. This effort has been termed "mass customization" (e.g., Pine II et al. 1993, Gilmore and Pine II 1997, Thomke and Reinertsen 1998). In these industries, product development and manufacturing processes have to frequently overlap and to be flexible enough to satisfy, in a timely way, the multiplicity of product configurations which result from the needs of individual customers. Simultaneously, these processes have to be lean enough to enable the firms to stay competitive in the marketplace.

I.2.3. LEAN CONSTRUCTION THEORY

Despite many analogies, the uniqueness and temporary nature of an AEC project is seldom found in the product development and manufacturing world. In the AEC industry, the circumstances in which each design-build development process evolves are rarely if ever replicated between projects. Changes between projects typically affect project participants, the product definition, the location of the project, and the project delivery system. The development of physical prototypes that would help project participants refine the product and process design is only exceptionally done. Apparently, physical mock-ups are too costly and time-consuming in practice to be feasible in most circumstances.

Lean construction theory was born out of the seminal work by researcher Lauri Koskela from VTT in Finland, developed during a sabbatical period at Stanford University (Koskela 1992). Lean construction theory embodies the effort to adapt the principles and methods of lean production theory to the product and process design of AEC systems. It advocates a new way of thinking for the AEC industry based on production management principles (e.g., Howell et al. 1993, Tommelein and Ballard 1997, Ballard and Howell 1998, Tommelein 1998a, Choo et al. 1999).

Just as the involvement of suppliers in early design is a fundamental principle in lean production and in new product development, lean construction theory advocates the integration of specialty contractors in the early AEC design effort (Tommelein and Ballard 1997). Specialty contractors have developed and integrated knowledge of design and building practices in order to adapt to the increasing complexity of buildings (e.g., Higgin and Jessop 1965, Crichton 1966). Their task has evolved from artisanship to sophisticated assembly of components (Bennett and Ferry 1990). Specialty contracting work, typically done on-site, has progressively extended off-site. Among other off-site production tasks, specialty contractors create detailed fabrication and installation drawings, select vendors, procure materials, and expedite their delivery (Tommelein and Ballard 1997). However, current practices in the AEC industry, such as partnering and design-build procurement, often leave specialty contractors and suppliers out of these agreements, as Figure I.2 illustrates.

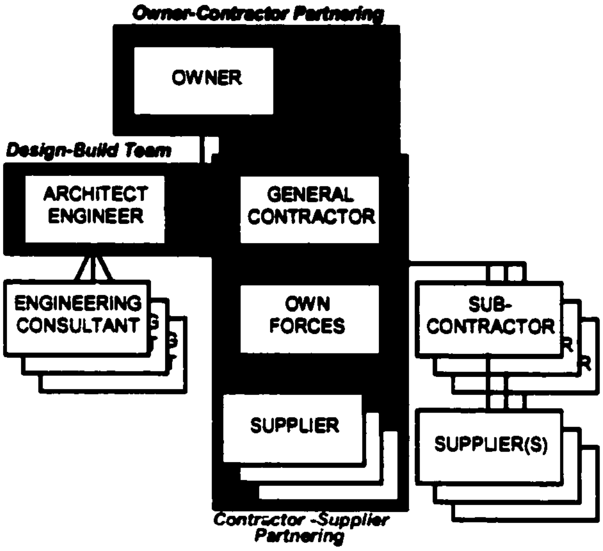


Figure I.2 - Traditional AEC Contracting Relationships and Cross-Functional, Cross-Organizational Alliances (Tommelein 1998b)

The assumption in lean construction theory that the specialty contractors' role in the AEC industry is equivalent to that of suppliers in product development and in manufacturing is the basis for the research questions that follow.

I.3. RESEARCH QUESTIONS

There is a need to better understand the value of involving specialty contractors in early design, to devise alternative project delivery systems that account for their early involvement, and to determine which performance variables can help to compare the different systems. It is also important to understand which tools can best support this involvement. My research is therefore based on the following questions:

1) What contributions would specialty-contractor knowledge bring to the early design effort?
2) Which performance variables could be established to evaluate the impact of these contributions to the design development process, to the manufacturing of facility components, and to the construction process?

3) In what ways could the involvement of specialty contractors in early design create value for the owner?
4) In what ways could this involvement affect the performance quality of the design definition?
5) How should specialty contractors be involved in the design development process?
6) How could this involvement differ (e.g., regarding timing and contribution) for different design specialties and for different specialty contractors?
7) What tools could be developed to support the involvement of specialty contractors in early design?

I.4. RESEARCH METHOD

This dissertation builds on empirical research that focused on the semiconductor industry. This research consisted of conducting a series of one-on-one interviews with practitioners involved in the design-build development processes of semiconductor fabrication facilities.

First, I interviewed designers to understand the critical decisions they make in early design, the information they prefer to have on hand before making those decisions, the sequences and durations of design tasks, and the exchanges of information between designers. In the process of interviewing designers, I progressively synthesized and validated a product-process representation for the design development of high-tech facilities.

Second, I interviewed people working for electrical, piping, and mechanical specialty contractors in the semiconductor industry. Through these interviews, I aimed to better understand the value of involving specialty contractors early in design and to find specific instances of such value. Third, I interviewed owner representatives to understand what factors they value most in the project delivery process and to learn more about the unpredictable nature of the semiconductor industry environment.

Subsequently, I used a computer simulation environment called SIGMA (Schruben and Schruben 1999) to further explore the research questions on the value of involving specialty contractors early in design. Thus, I first implemented a generic excerpt of the design development model with SIGMA to better understand when to make design commitments in an unpredictable environment. Then, I integrated the simulation model for the design development process of one facility system with a model of the following procurement, fabrication, and construction phases. I implemented a set of performance variables in this systemic model for evaluating the consequences of involving specialty contractors as early as in concept development. Practitioners validated the product-process simulation model, its results, and its usefulness.

I.5. DISSERTATION STRUCTURE

I structured this dissertation as follows. Chapter I introduces the research problem, framework, and method, and states the research questions that provided the foundation for this work. Chapter II presents a review of the literature on how different schools of thought have addressed the role of specialty contractors in the AEC industry. It also discusses the usefulness of specific tools that these schools have developed for supporting the management of specialty contractors' work. Chapter III characterizes the industry domain in which the empirical research was conducted—the design-build development processes of semiconductor fabrication facilities. Appendix I presents a technical synopsis of semiconductor fabrication facilities as a complement to this chapter.

Chapter IV focuses on the contributions of specialty-contractor knowledge to the early design effort. This chapter builds on empirical research to categorize these contributions and to illustrate them by means of examples that stem from current practice. It gives reasons for the fact that specialty-contractor knowledge is often ignored in design development practice. This chapter also discusses the conditions that organizations need to create for increasing interaction between designers and specialty contractors.

Chapter V introduces the product-process model for the design development of high-tech facilities. The model captures the critical decisions designers make and tasks they perform for concept development. In addition, this chapter explains why the computer simulation environment SIGMA was chosen. Appendix II, a complement to Chapter V, characterizes the design development model for five distinct facility systems.

Chapter VI presents the implementation of a generic excerpt of the design development model with SIGMA. Simulation results yield insight into the effectiveness of postponed commitment strategies for managing the design development process in an unpredictable environment. In addition, Chapter VI discusses the validation of the simulation model's inputs, rationale, and results.

Chapter VII presents the integration of the design development model for one facility system with a model for the following fabrication, assembly, and construction phases. This systemic simulation model delivers proof-of-concept of a computer-based framework that aims to help managers evaluate alternative project delivery systems in unpredictable environments. Chapter VII illustrates the usefulness of the model by contrasting diverse project scenarios, such as scenarios in which the contractor is involved in early design decisions in relation to scenarios that lack such involvement. In addition, it extends the discussion of the model validation, initiated in Chapter VI, in what specifically concerns the integrated design-construction model.

Finally, Chapter VIII synthesizes the contributions to knowledge of this dissertation and it establishes directions for future research.

II. LITERATURE REVIEW

II.1. INTRODUCTION

Early research on the role of specialty contractors in the architecture-engineering-construction (AEC) industry adopted a transaction cost economics perspective (e.g., Eccles 1981a, b, Reve and Levitt 1984, Usdiken et al. 1988, Winch 1989). Subsequent research focused on contracting practices (e.g., Bennett and Ferry 1990, Uher 1991, Hinze and Tracey 1994, 1995). More recent, research has addressed the role of specialty contractors from a product design perspective (e.g., Jaafari 1997, Kalay et al. 1998). Little research has been conducted to date, however, regarding the role of specialty contractors from an operations management perspective.

Operations management pertains to the process of applying and managing resources (capital, materials, technology, and human skills/knowledge) to the production of goods and services (e.g., Hopp and Spearman 1996, Nahmias 1989). Operations management comprises product and process management. Product management focuses primarily on the performance of the design product whereas process management focuses more on how the product can be developed efficiently.

Figure II.1 charts some schools of thought according to the way these have addressed the role of specialty contractors in the design-build development process. Each model is positioned along the categories of process and product management. Within product management, I distinguish formal from informal models. Formal models articulate methods and means that leave records. Examples of formal models are AEC product models, Critical Path Method (CPM) networks, and meeting minutes. Informal models articulate methods and means that do not necessarily leave a record. Examples of informal models are a phone conversation or a one-on-one meeting.

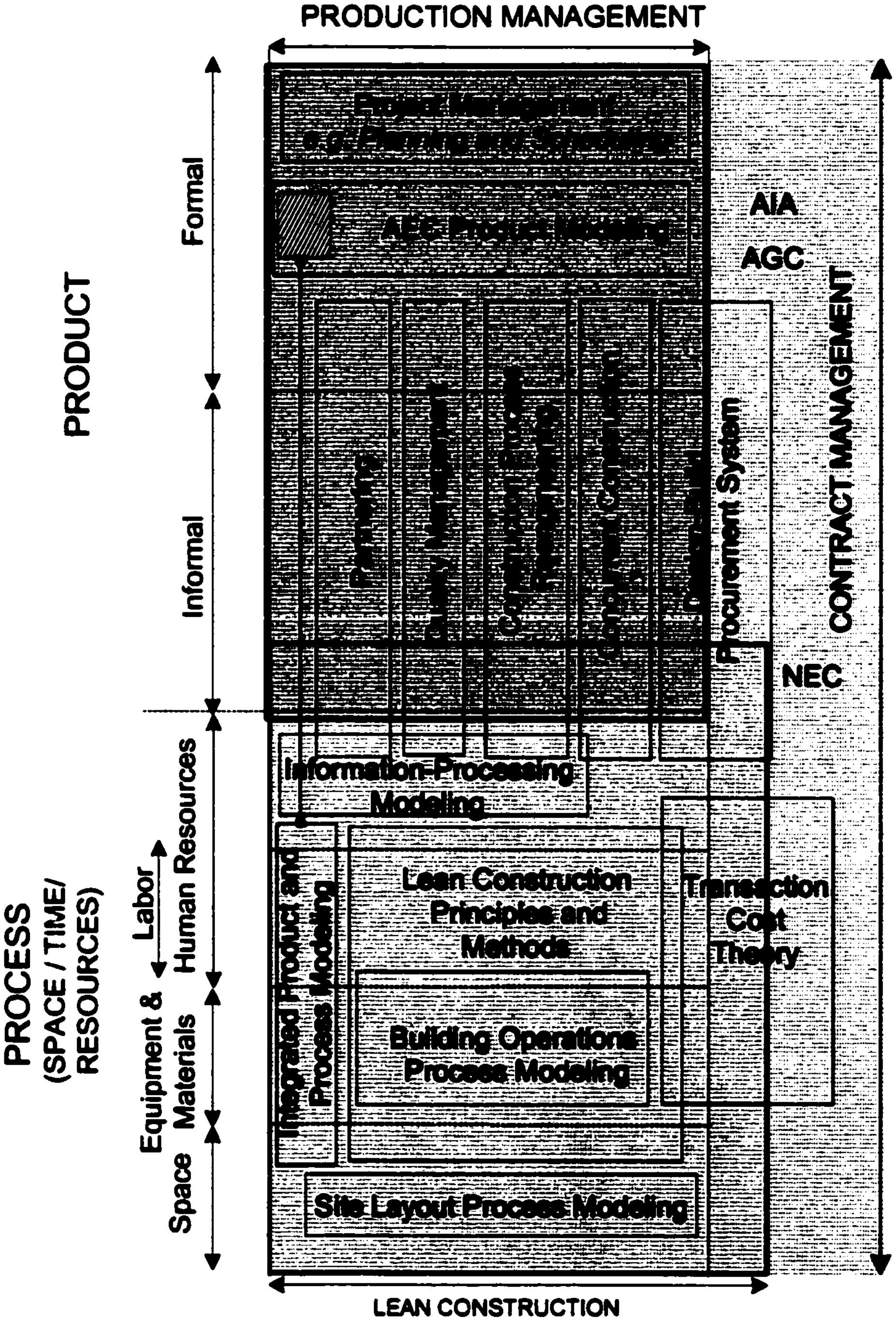


Figure II.1 - Qualitative Mapping of Various Schools of Thought Regarding the Role of Specialty Contractors, Charted by Product and Process

Within process management, I organize models according to whether their focus is on human resources, equipment and materials, or space. I represent contract management adjacent to operations management to express the fact that some schools of thought span the two fields in the way they address the role of specialty contractors. In the following sections, I traverse Figure II.1 and discuss the viewpoints of these schools of thought regarding the role of specialty contractors in AEC projects. I also discuss specific tools researchers within these schools have developed to support that role.

II.2. TRANSACTION COST THEORY

Transaction cost theory draws on the work of Williamson (1975). Williamson argues that the characteristics of the transactions between firms and of the effort to minimize the costs incurred with those transactions determine the structures that govern firms as well as the boundaries between them. Williamson (1975) characterizes transactions in terms of asset specificity, uncertainty, and frequency. Transaction costs comprise the cost of searching, contracting, monitoring, and enforcement (Dyer 1997). Markets and vertically integrated structures (or hierarchies) are two major organizational structures in Williamson's work. Market transactions tend to be nonspecific and can be either occasional or recurrent. Hierarchy transactions tend to be specialized and recurrent. In conditions of uncertainty, firms tend to find intermediate governance structures to lessen opportunism and to infuse confidence between transacting parties (Williamson 1975).

Transactions between specialty contractors and the contracting party—the owner, the design-build consortium, the design firm, or the general contractor—tend to be specific to each project and not necessarily recurrent. Most often, design-build consortia invite specialty contractors to competitively bid the work. Subcontracting through bidding provides design-build consortia the flexibility to cope with uncertainty in future demand. Subcontracting also satisfies their needs of specialization and risk sharing (e.g., Eccles 1981a, b, Krippaehne et al. 1992, Bresnen and Fowler 1994, O'Brien et al. 1995). However, bidding does not offer many incentives for project participants to share information, build trust, and collaborate.

Observation of current practices shows that contractors primarily rely on informal communication to satisfy their needs for information and coordination (Pietroforte 1997). These informal practices of collaboration are the basis of the clan model that has been used to characterize the AEC industry (Reve and Levitt 1984, Lansley 1994). A clan is an appropriate kind of organization when parties have somewhat similar objectives but their performance is hard to evaluate (Ouchi 1980). Clans promote long-term relationships and mutual trust. Recurrent transactions help to build trust, lessen opportunism, and ease coordination because they enable parties to get to know each other better.

Despite the fact that long-term relationships and trust ease collaboration, they take time to build and do not guarantee success. Clans are not necessarily effective in exchanging information either because they are not specifically structured in that way. Because clans remain informal structures, they are also vulnerable to turnover in organizations. By contrast, a production management theory advocates more formal governance structures. As Womack et al. (1990 p.155) point at: "The relationship between suppliers and assemblers in Japan is not built primarily on trust, but on the mutual interdependence enshrined in the agreed-upon rules of the game."

Production systems force organizations to formalize information exchanges between project participants in terms of content and of the timing of their occurrence.

Formalization helps to preserve the knowledge of individuals within the organizations where that knowledge has evolved (Bohn 1994). Formalization also helps individuals to learn faster what they are supposed to learn when they move from one project to the next.

In addition, studies in the manufacturing industry indicate that production systems help to reduce transaction costs between suppliers and manufacturers (Dyer 1997). To the best of my knowledge, however, no research in the AEC industry has yet quantified the transaction costs of subcontracting.

Transaction cost theory combines with contracting law. Contracts project an exchange into the future. Their purpose is to facilitate those exchanges (Macneil 1974). Frequently, however, construction subcontracts contribute to creating adversarial relationships between specialty contractors and the other contracting parties. Much research in construction has focused on subcontracting contracts.

II.3. CONTRACT MANAGEMENT

Contracts do not accurately indicate working relations as they occur in reality. To be effective, however, contracts must provide at least a rough description of the way the working relations occur (Macneil 1974). In the AEC industry, subcontracting contracts often spell out unfavorable terms and conditions to specialty contractors. Major complaints from contractors concern terms of payment, extensions of time, liquidated damages clauses, and cost of delays (e.g., Birrell 1985, Beardsworth et al. 1988, Uher 1991, Hinze and Tracey 1994, 1995, Borg 1995, Haltenhoff 1995). These terms and conditions do not encourage collaboration between specialty contractors and the general contractor. Some terms and conditions might not even be enforceable in practice (Bennett and Ferry 1990). Tommelein and Ballard (1997) illustrate the latter point with the third article of the Associated General Contractors of America (AGC 1990) Document No. 600 entitled 'Subcontract for Building Construction':

> SCHEDULE CHANGES. The Subcontractor recognizes that changes will be made in the Schedule of Work and agrees to comply with such changes.
>
> PRIORITY OF WORK. The Contractor shall have the right to decide the time, order and priority in which the various portions of the Work shall be performed and all other matters relative to the timely and orderly conduct of the Subcontractor's work. The Subcontractor shall commence its work within ___ days of notice to proceed from the Contractor and if such work is interrupted for any reason the Subcontractor shall resume such work within two working days from the Contractor's notice to do so (AGC 1990).

Alternatively, in the U.S.A., some contractors use the subcontractor's form developed by the American Institute of Architects (AIA 1987), referred to as AIA Document A401. AIA fails to acknowledge the conditions of uncertainty in which the construction work evolves. AIA acknowledges neither the involvement of specialty contractors in design nor the effort required from subcontractors to coordinate the work among themselves. Instead, AIA is written as if the building product development is divisible into discrete activities with well-defined responsibilities and temporal boundaries (Pietroforte 1997).

From a contract law perspective, many construction subcontracts fall in the category of contract transactions defined in Macneil's (1974) two-way classification system. Contract transactions involve only economic exchanges. They are appropriate to support most market transactions that involve commodities, are short, and of limited scope. In contrast, Macneil introduces the concept of contractual relations. Contractual relations include economic exchanges, personal relations, extensive communication, and elements of non-economic personal satisfaction.

Contracting relationships between specialty contractors and the owner or the general contractor typically are of a long-term nature. Because the scope of the work frequently changes during the contracting period, parties continuously exchange information to clarify methods of execution, propose alternative solutions, adjust the construction sequence, etc. In addition, parties negotiate the impacts of those changes on the cost and on the duration of the work. Contracting relationships may recur if the owner or the general contractor promotes additional contracts with the same specialty contractors. Personal relations get established between individuals working for the contracting parties. Contractual relations, therefore, are more appropriate to support contracting relationships with specialty contractors.

The New Engineering Contract (NEC 1995), which is used in the UK, takes some steps in this direction (Broome and Perry 1995, Tommelein and Ballard 1997). The first clause in its Engineering and Construction Subcontract prescribes: "Contractor and subcontractor shall act in a spirit of mutual trust and cooperation". The omission of this statement in the contract is considered enough reason for the Project Manager not to accept the contract. NEC states that the subcontractor program should provide for each operation a method statement that identifies the conditions in which the subcontractor should carry out the work. NEC recognizes the right of the general contractor to change the timing of any subcontracted work but it figures these situations as compensation events. NEC is, however, not clear to what extent it acknowledges the role of specialty contractors in design development.

Altogether, contracting is but a means to the ultimate objective of the design-build organization, which is to get the project built. Contracts alone cannot build trust, that is, they cannot make parties confident in each other's intentions and abilities to honor promises, collaborate, and share information. Contracts cannot guarantee on their own that the work will be efficiently executed.

II.4. PROJECT MANAGEMENT

Project management is an application of knowledge and different techniques to project activities to meet or exceed expectations from a project (PMBOK 1996). Project management provides planning and scheduling tools that are the basis of most software used in current practice to plan the work of specialty contractors.

At the heart of the scheduling tools lies the Critical Path Method (CPM). The CPM represents the construction process as a sequential network of activities with precedence relationships between them. Construction activities in the CPM schedule typically express the effort to build different components of the building product. CPM schedules are, however, not production management tools. Despite their popularity, researchers have long stressed the inadequate way AEC practitioners use CPM schedules (e.g., Higgin and Jessop 1965, Crichton 1966, Laufer and Tucker 1987, Laufer and Howell 1993, Tommelein 1998a). Among common criticisms, the following are particularly relevant to the role of specialty contractors:

- CPM schedules model the construction process in terms of sequences of construction activities. They do not model the flows between activities, such as those of information, space, materials, and equipment (Tommelein et al. 1999).
- CPM schedules reflect poorly the way work is executed because schedules are

imposed on specialty contractors rather than developed jointly with them and developed to a level of detail suitable to the uncertainty teams face.

- The way CPM schedules are used in practice fails to acknowledge the interdependencies that exist between the work of different specialty contractors.

Other work on planning and scheduling tools to support project management—such as on tools to expedite the generation of schedules (Hendrickson et al. 1987, Winstanley and Hoshi 1993)—has not expanded much the capabilities of CPM from a production standpoint. The criticism of the use of CPM schedules in current practice have remained valid for more than four decades.

II.5. INDUSTRY PRACTICES FOR IMPROVING PROCESS EFFICIENCY

II.5.1. PARTNERING

Partnering is a set of practices to promote common goals, build trust, and ease the understanding of each other's individual expectations in the construction process (e.g., Woodrich 1993, Abudayyeh 1994, Matthews et al. 1996). The term was coined by the Army Corps of Engineers in 1987 to describe a concept that had been developing since the early 1980s (Dyer 1997). Partnering promotes coordination meetings and the development of a charter for every project that sets the goals for all project participants.

Partnering creates opportunities for people to meet and get to know each other better. This initiative works in the sense that it helps to prevent conflict, it improves relationships between people, and it fosters communication. These all are common attributes of early stages of socialization in temporary organizational systems (Bryman et al. 1987). Partnering propositions and methods stay, however, rather informal. Partnering promotes meetings among project participants. However, meeting participants are not necessarily selected in function of the specific production tasks that must be accomplished for the project to succeed. Specialty contractors may not even be invited to these meetings. Many times, the objectives of the meetings tend to remain vague despite the effort of facilitators to focus the discussion on specific topics. Partnering has to start anew whenever project participants change during the project cycle or between projects.

Moreover, because partnering does not formalize any specific means and methods, its success depends on the perceptions, personal experiences, needs, rewards, and goals of everyone in the meeting room. Partnering, like other informal systems, remains vulnerable to conflict, ambiguity, and opportunistic behavior (McCann and Ferry 1979, Bryman et al. 1987, Liu and Walker 1998, Li and Love 1998).

II.5.2. QUALITY MANAGEMENT PROGRAMS

Quality management programs for the AEC industry should be differentiated between those primarily concerned with product performance and those primarily concerned with process quality. Product quality methods have existed for long in the AEC industry, mainly in the form of institutional and professional regulations, and quality control tests. Design regulations have set criteria to guarantee the reliability of the product design performance. Other regulations have provided guidelines—such as step-by-step methods for placing concrete and driving piles—to instruct builders how to consistently execute the design so that the product quality will conform to that prescribed in the drawings and specifications. Quality control methods—such as tests to evaluate the strength of hardened concrete—have helped to ensure the conformance of the built product to the design product specifications.

In contrast, process quality methods entered into the AEC industry only in the early 1990s. Process quality methods have primarily aimed to guarantee the consistency and reproducibility of the building development process between projects. Some quality programs have implemented ISO 9000 standards (e.g., Moatazed-Keivani et al. 1999) whereas others have implemented techniques of the Total Quality Management (TQM) philosophy (e.g., Burati et al. 1992). ISO 9000 is a series of standards, created in 1987 by the International Standardization Organization (ISO), that promote the formalization of procedures (ISO 1999). As Cole (1999 p. 152) argues, "the ISO 9000 standards are aimed at ensuring the consistency in the production of a product or service.... Thus, ISO 9000 certification does not measure the quality of a product or service but simply confirms whether a company has fully documented its quality control procedures, whatever they are, and whether they [the company] are adhering to it".

TQM aims to improve the quality of the product. TQM proposes a set of mostly informal practices that emphasize methods such as continuous improvement, teamwork, and closer relationships with suppliers (Powell 1995). Recent research on the application of TQM and ISO9000 in the AEC industry reports that quality programs have not succeeded in establishing effective communication channels among participants, even in projects that presumably are successful (Shammas-Toma et al. 1998, Moatazed-Keivani et al. 1999, Winch et al. 1998). The reasons for this failure are not clear. Apparently, the origin of the failure lies in conflicts within the individual interpretation of quality standards.

Nonetheless, quality programs promote awareness of the process as a means to achieve a product of better quality. Organizations have to study their processes in the course of implementing a quality program and this may lead them to remove some process inefficiencies. But quality programs do not necessarily make the production system more efficient because that is not their ultimate goal. Quality programs may promote methods such as long-term relationships with suppliers and cross-functional teams to achieve a product of better quality, but these programs lack a framework to leverage their contribution. Moreover, to the best of my knowledge, neither ISO 9000 nor TQM promotes the establishment of organizations' goals or advocates checking on a regular basis to what extent these goals are being achieved within the organization.

II.5.3. DESIGN-BUILD PROCUREMENT SYSTEM

In recent years, owners have increasingly been using the design-build system to procure their projects (e.g., Akintoye 1994, Songer and Molenaar 1996). The design-build procurement system essentially forces designers and a general contractor to team up in a consortium from the project inception. Industry practitioners have acknowledged that the design-build system enhances collaboration between project participants (e.g., Yates 1995, Friedlander 1998, Rizzo 1998).

However, the way the design-build system is implemented does not necessarily guarantee projects will be more effective than others where design and construction services are procured separately. Specialty contractors seldom participate in design-build consortia. Design-build consortia seldom provide formal mechanisms and incentives to help designers and builders expedite the process and exchange information. In addition, design-build consortia typically bring in construction experts only to comment on the design (at so-called 'value engineering sessions' or 'constructability reviews') after designers have made major decisions. If construction experts then detect clear needs for changes, designers will have to rework the design.

Most research on the design-build procurement system has focused on competitive bidding practices (e.g., Potter and Sanvido 1994, Songer and Molenaar 1996, Pocock et al. 1997). That research has contributed little to the understanding of the design-build development process from a production perspective. Thus, even if design-build creates opportunities to streamline the AEC process and to formalize procedures between firms, these have largely remained unexplored in practice and research, as I discuss in further detail in section IV.3

II.5.4. CONCURRENT CONSTRUCTION AND CONSTRUCTION PROCESS REENGINEERING

Concurrent Construction (Eldin 1997, Jaafari 1997) and Construction Process Reengineering (Mohamed 1997) are recent initiatives that express awareness in the AEC industry of the potential applicability of manufacturing management models. Concurrent Construction (CC) draws from the field of Concurrent Engineering (CE). CE aims to improve the quality of the product while simultaneously reducing the product development time through parallel processing of activities. CE emphasizes, among other methods, cross-functional teams, continuous improvement, and early integration of suppliers in product development (e.g., Swink et al. 1996, Eppinger and Smith 1997).

Construction Process Reengineering (CPR) is based on the principles promoted by business process reengineering (BPR) (Hammer 1990, Hammer and Champy 1993). BPR advocates a radical, top-down redesign of business processes to achieve dramatic improvements in critical measures of performance, such as cost, quality, and speed. The principles of reengineering are (Hammer 1990): (1) organize around outcomes, not tasks, (2) have those who use the output of the process perform the process, (3) subsume information-processing work into the real work that produces the information, (4) treat geographically dispersed resources as though they were centralized, (5) link parallel activities instead of integrating their results, (6) put the decision point where the work is performed, and build control in the process, and (7) capture information once and at the source.

The risk of failure is great when attempts are made to redesign processes from scratch. BPR challenges the organizations to put aside a system that works even if inefficiently, and replace it with something new that is not guaranteed to work. BPR got its recognition for the numerous successes achieved as well as extraordinary failures (Chase et al. 1998, Nahmias 1989).

Concurrent Construction and Construction Process Reengineering express the growing concerns of practitioners and researchers regarding the way AEC projects typically get planned and executed, but they stay largely informal despite the significant changes they advocate.

II.6. PRODUCT MODELING

AEC Product Modeling is the basis of most design representations of building systems. The RATAS work motivated much research on building product modeling (Bjork 1989). Bjork noted that building product models should comprehensively contain information from different design disciplines. He also recommended that product models should be able to expand and accommodate changes along their lifecycle. Following Bjork's work, several product models have evolved into enriched representations of building components such as EDM (Eastman et al. 1993), COMBINE2 (Karstila et al. 1995), and STEP (1999).

Recent work in product modeling reflects concerns for better design collaboration and information sharing among project participants. Some product models aim to capture the design intent in addition to capturing the physical and performance attributes of the design product. SME (Clayton et al. 1999), for instance, is a software prototype that collects information on geometry, topology, and material properties as well as on the function and behavior of product components. EDM-2 is a data model and database implementation that extends the evolution capabilities of EDM to support multi-application views of a centralized building model and to support mapping between these views (Eastman and Jeng 1999).

Other recent work in product modeling aims to automate communication among designers and between designers and builders. P3 (Kalay et al. 1998) is a web environment that fosters knowledge networking among design specialists. P3 takes advantage of the World Wide Web so that designers can share different representations of the product model. IBES (Arnold et al. 1999) is another web environment to automate design interpretation and information exchange between designers and manufacturers.

It is not clear if either any of these recent models is being used in practice. These models aim to automate current practices but they do not propose new ways to streamline the design-build development process. They encourage collaboration among design specialists and contractors but fail to provide incentives to make it happen. Nothing guarantees that people will have the information or that they will be able to find it when they need it. Ultimately, these models risk to overload individuals with information they do not necessarily need, rather than help them to coordinate and execute their work.

II.7. PROCESS MODELING

Work in AEC process modeling has aimed to make explicit the interdependencies among production activities, human resources, work methods, physical materials and equipment, and information flows (Fisher and Yin 1992). AEC process models can be grouped into information-processing models, building operations models, and site-layout process models.

Information-processing models study information flows and tasks. They mimic on individual's ability to exercise their skills when performing specific tasks. Rules and roles are formalized and bounded rationality constrains the agents, that is, agents have limited information and cognitive resources and thus they have limited processing capability. Some information-processing models have been implemented with simulation engines (e.g., Jin and Levitt's VDT 1996, Salazar-Kish's FT-VDT 2001, Baldwin et al.'s model 1998). Information-processing simulation aims at helping managers to replicate the way the work is done for: (1) optimizing the sequencing of tasks, (2) stochastically predicting the duration of projects, (3) doing what-if planning, and (4) gaining understanding of organizational problems and the time people need to process information (Carley 1995). Information-processing has, however, a limited ability to express the process impact of alternative design decisions because it does not capture the content of information exchanges and decisions.

Process models of building operations help planners to choose construction methods, optimize the allocation of resources, detect process bottlenecks, and evaluate time-cost trade-offs. Some models have also been implemented with simulation engines (e.g., Halpin and Riggs 1992, McCahill and Bernold 1993, AbouRizk and Shi 1994, Ioannou and Martinez 1996, Sawhney and AbouRizk 1994, Senior and Halpin 1998). Likewise, site-layout process models help users to solve location problems, or to experiment with different paths for on-site physical flows as a means for evaluating the quality of alternative layouts (e.g., Choo and Tommelein 1999, Akinci and Fischer 2000).

Mostly, process models have proved to be useful in helping design managers optimize the design process and in helping construction managers optimize construction operations. However, when construction managers plan operations they have to consider many constraints that result from decisions and choices made early on in design. Conversely, the information designers do and do not have on construction resources and methods influences their decisions. Process models have limited ability to enhance exchange of information between designers and builders. A need is expressed for integrated product-process models.

II.8. INTEGRATED PRODUCT-PROCESS MODELING

AEC product-process models integrate a representation of the design product with representations of the execution process in order to achieve a more meaningful representation of reality. CIPROS (Odeh 1992, Tommelein et al. 1994) is a computer system that links product and process modeling with discrete-event simulation. CIPROS enables construction managers to choose alternative construction methods and to experiment with their process execution based on product information and activity sequence. The product information derives from drawings and specifications available at the time the construction process is planned.

Other product-process models such as CONSTRUCTION PLANEX (Hendrickson et al. 1987), OARPLAN (Winstanley and Hoshi 1993), 4D-CAD (Fischer and Aalami 1996), BPM (Luiten and Tolman 1997), and Kim et al.'s work (1997) better fit in the category of object-activity-resource models. These models map the different components or objects of the building product to a CPM network of construction activities. Object-activity-resource models inform designers of the impact that alternative designs may have on the construction process. This impact is expressed in terms of choices of construction methods, allocation of resources, and duration and sequence of construction activities.

Object-activity-resource models are, however, not production management tools. Their capabilities are limited by the representation of the construction process in a sequential network of activities. These models cannot help to improve, for instance, the flow of materials and equipment during construction because they do not represent flows. Object-activity-resource models also fail to capture specialty-contractor knowledge on the fabrication of building components and on component's assembly on site. Object-activity-resource models provide limited help in matching the design definition with the building capabilities of specialty contractors.

Other product-process models have taken advantage of postponed commitment strategies to support specialty contractor involvement in design development. Postponed commitment strategies guide designers in keeping track of sets of alternative solutions during the search for a design solution. In contrast, early commitment strategies lead individuals to make decisions and choices earlier in the process. When design teams commit early, they run the risk of later being forced to mutually adjust or rework their design. Early commitment is usually the method of choice for human designers limited by cognitive ability. In contrast, postponed commitment strategies are easier to implement when computers are being used (Tommelein et al. 1991). Lottaz et al. (1999), for instance, present SpaceSolver, a proof-of-concept of an Internet environment that facilitates project participants to progressively refine the space of design solutions without having to commit early on. SpaceSolver brings together designers and builders at design detailing so that they can share information before making design commitments.

A need exists to explore product-process models further and to extend their use. Nonetheless, even integrated process-product tools may not be effective in the complex, time-pressured environment of AEC projects if they are set apart from other project management initiatives. A product-process model should be grounded in production management theory if it hopes to succeed in practice. To deliver proof-of-concept of an innovative product-process simulation environment grounded in a production theory is one of the goals in this dissertation. Accordingly, after describing the environment in which I conducted the empirical research in Chapter III, I discuss the way specialty-contractor knowledge can be leveraged in early design in Chapter IV. I introduce the product-process model of design development in Chapter V.

III. EMPIRICAL RESEARCH ON SEMICONDUCTOR FABRICATION FACILITIES

III.1. REASONS FOR STUDYING SEMICONDUCTOR FACILITIES

Semiconductor fabrication facilities (or fabs) are one kind of high-tech facility. Their purpose is to provide the physical space, environmental conditions, and process utilities for the production of semiconductors. Semiconductors "are the basic building blocks of integrated circuits" or chips. Chips are the "brains of every computing device manufactured today" (Wright 2001, p. 172).

The design-build development process of a fab is extremely complex. Three major sources of complexity are the multitude of decision-making agents, the complexity of the fab design definition, and the dynamic nature of the fab design criteria. The number of fabs each manufacturing organization (the *owner or client* served by architecture, engineering, and construction (AEC) organizations) builds annually varies in a cyclic fashion. At the time of this writing, major manufacturers build on average one fab every four years.

To develop a temporary inter-firm organization that efficiently brings together all parties for the project duration is a complex problem. People from diverse functional divisions of the manufacturer organization, such as procurement, finance, and technology, will participate in the project. They may lack, however, experience and knowledge of the fab design-build process due to the cyclical nature of the industry and due to job turnover. In contrast, design and construction firms specialized in high-tech facilities may design and build three or four fabs every year. Senior designers and trade people working for these firms have a wealth of knowledge on how to go about doing this.

From a technological perspective, fabs are extremely complex AEC products. The chip production process demands stringent performance requirements regarding, for instance, the quality of the air in terms of cleanliness, temperature, and humidity. The tools that produce chips are also complex pieces of equipment in and by themselves. To operate, each tool requires a large number of utilities, process support equipment, stringent vibration control, and specific space requirements. To satisfy these performance requirements, the design-build process of fabs involves a myriad of specialists and construction trades. These AEC participants will make closely intertwined decisions.

In addition, semiconductor projects typically evolve in an unpredictable environment. Unpredictability here means that design criteria change frequently as the design-build development process unfolds. These changes stem from diverse origins. Speed of execution is a critical factor in ensuring a fab project's profitability. The first manufacturers to reach the market with a new product can benefit from higher selling prices, which rapidly decrease once alternative products reach the market (Burnett 1997). Because the window of opportunity for bringing a fab online is extremely narrow, AEC practitioners need to start construction while the fab design is still being developed and while the latest process tools are being fine tuned. In addition, the need for fast execution also forces manufacturers to overlap the chip development process with the fab design-build process. Consequently, the fab design definition will be directly affected by changes in production technology, in tool performance requirements, in tool quantity, or in forecasts of market demand.

Despite the complexity of design-build fab projects and of their already short cycle times, manufacturers continuously challenge AEC practitioners to further compress the fab delivery time. Practitioners are also challenged to deliver fabs under increasingly tight budgets. Consequently, they are constantly looking for innovative practices that let them better meet clients' needs. Such practices reflect management directions, which other segments of the AEC industry may follow in the future. Accordingly, the semiconductor industry provides a most interesting setting to do research in and to build theory on project and production management practices in the AEC industry.

III.2. EMPIRICAL RESEARCH METHOD

The empirical research I conducted consisted of approximately 85 interviews with people experienced in the design-build process of fabs (Table III.1). Throughout the empirical research, I worked closely with Industrial Design Corporation (IDC), which is headquartered in Portland, Oregon. IDC is a leading design-construction firm, with a wealth of expertise in high-tech facilities. Interviews started in November 1998 with a one-day visit to IDC headquarters, and lasted through August 2000. During this period, I interviewed IDC lead designers and managers involved in designing and building fabs, representatives of specialty contractors involved in design detailing and on-site execution of high-tech facilities, and representatives of manufacturers. The interviews lasted approximately one to two hours. Frequently, I carried out follow-up interviews with the interviewees. I did not use any written questionnaires. With the permission of those interviewed, I audio taped all interviews except for those that I did over the telephone.

Table III.1 - Number of Interviews with Practitioners in the Semiconductor Industry

Interview Group	No. Interviewees	No. Interviews
Design-Build Firm (IDC)	22	52
Piping Specialty Contractor (e.g., Kinetics, Harder)	7	8
Mechanical Specialty Contractor (e.g., Southland, Streimer)	9	10
Electrical Specialty Contractor (E-C-CO)	3	3
Owner' s Representative (e.g., Intel, James Lee & Associates/Hyundai, Currie&Brown)	10	12

The interviews with lead designers focused on the design process pertaining to the specialty of the interviewee. I questioned interviewees regarding the decisions they make in early design, the information they typically have on hand versus what they wished they had before making decisions, and the content of the information hand-offs between design specialties. Using this information and jointly with lead designers, I developed and validated a product-process model for the design development of high-tech facilities.

The interviews with representatives of specialty contracting firms helped to articulate their contribution to early design. The interviewees belonged to different organizational levels in the contracting firms, ranging from labor manager to vice-president. I limited the interviews to the mechanical, electrical, and piping (MEP) trade contractors. Mechanical contractors build the dry-mechanical systems, such as the heating, ventilation, and air conditioning system (HVAC) and exhaust systems, and the wet-mechanical systems, such as the chilled water and steam systems. Electrical contractors install the electrical systems and also, occasionally, the data communication systems. Piping contractors install the systems that transport other utilities to the tools and equipment in the fab, such as the specialty gases, ultra-pure water, and chemicals. Occasionally, these trades overlap in the tasks they can do.

The interviews with representatives of manufacturers aimed at better understanding their needs in terms of, for instance, product quality, speed of project execution, and flexibility for accommodating design changes. I also probed interviewees into innovative management practices that could add value to the design-build process of high-tech facilities.

Though I conducted a large number of one-on-one interviews in this empirical research, the questions and answers did not lend themselves to statistical analysis. Instead, I report in Chapter IV anecdotal evidence of the knowledge specialty contractors contribute to early design and of the ways to leverage such knowledge in practice.

In addition to the interviews, I examined the records of several fab projects during my residence periods at IDC headquarters. These documents consisted primarily of project proposals, meeting minutes, specifications of facility components, equipment lists, drawings, and in-house guidelines for orienting lead designers. I also visited three construction sites: Hyundai Semiconductor America in Eugene, Oregon, Lam Research Facility in Fremont, California, and Intel D1C, in Hillsboro, Oregon. At Intel D1C, I worked as assistant to the tool dock coordinator during an internship in the summer 2000.

Before I proceed with reporting the findings of the empirical research, I inform the reader that the numbers presented next result from the interviews I conducted with practitioners. They are estimates only aimed to give the reader an order of magnitude for the respective variables. The reader should bear in mind, however, that the accuracy of the numbers reflects the limited ability of the interviewees to disclose information.

III.3. DESIGN-BUILD DEVELOPMENT PROCESS

III.3.1. DESIGN DEVELOPMENT PROCESS

The design development process of a fab typically starts with a set of performance requirements and design criteria the client provides. According to the client's experience in building fabs and the project specifics, the definition of these requirements may vary significantly. Inexperienced clients—such as start-up companies or investment banks—may substantially rely on AEC firms' knowledge and hardly constrain designers' work, whereas established clients may impose stringent restrictions. Whenever the performance requirements are poorly defined but the client desires that the AEC firm starts to design the fab, designers must make educated guesses on the information they lack. Designers will base their assumptions on the knowledge gained during past experience and on the information they have at hand.

Simplistically stated, the performance requirements for a fab primarily consist of: (1) the type of technological process that the fab should accommodate (e.g., state-of-the-art DRAM chips, or chips for televisions), (2) the target capacity in terms of the average number of chips to produce every month, (3) the floor area of the cleanroom, and (4) the list of production tools to house inside.

With the help of rules of thumb and of historical data, designers convert these requirements into design criteria. Design criteria govern the decisions on design features (such as the diameter of critical cross-sections for utility routings) and on production choices (such as choices of major equipment pieces like transformers, boilers, and scrubbers). Practitioners typically summarize the design criteria into several groupings of information:

Cleanroom Layout - a plan that shows the cleanroom area, the configuration of the functional areas inside, and the location of the process tools in each functional area.

Facility Matrix - a spreadsheet that characterizes the required utility loads and the environmental conditions for each functional area.

Tool List Description - a spreadsheet that characterizes the operating requirements of the process tools in terms of utility loads, gravity loads, floor area needs, and space clearances driven by service needs.

As the design process unfolds, designers gradually release design packages to specialty contractors. Each package typically consists of drawings and specifications. Drawings graphically represent the components of the facility to be built. Specifications define, either by features, by brand name, or by performance requirements, the materials and the equipment that contractors must procure and install. Designers may first release a package for excavation and foundations, then a package for the structure and outside shell, and then several packages for the interior building systems. The initial construction operations, such as the excavation of foundations and the erection of the steel or concrete structure, may start as soon as two to three months after design was started.

The drawings and specifications in a package may not constitute the complete detailed design. Uncertainty in design criteria—for instance, uncertainty regarding the exact set of utilities one kind of tool will need—may prevent designers from developing a detailed design. Alternatively, designers may develop the design concept of a facility component and leave its detailing to the contractors if they trust qualified contractors will bid the work. Other times, designers may leave detailing to contractors because design fees are low, they run out of time, or they lack the capacity or knowledgeable people to do it. If designers do not detail the design, contractors will have to do it later. Designers will then approve the details before contractors are allowed to proceed with their work.

III.3.2. CONSTRUCTION DEVELOPMENT PROCESS

The construction development process of a new fab usually evolves in phases. Practitioners call the first phase 'base-build'. Base-build comprises an array of operations such as excavating, building foundations, erecting the steel or concrete structure, and installing the architectural shell and selected interiors.

The second phase is 'fit-up'. During fit-up, builders install the Chemical Utility Building (CUB), the bridge that connects the CUB with the fab, the main and lateral routings in the subfab, and finish the remaining architectural interiors. The fit-up phase involves a multitude of construction trades, such as sheet-metal workers, electricians, pipe fitters, and carpenters. During this phase, MEP trades install the utility routings and equipment while carpenters install the walls, floors, and ceiling of the cleanroom.

The third phase is 'tool-install'. During tool-install, the tool manufacturers (spread all over the world) ship at various times tools and process support equipment from their facilities to the fab construction site. Concurrent with this process, teams of designers specialized in tool installation prepare and gradually release the design packages that will guide the trades in the tool-install process on-site. Tool-install design generally involves five design specialties: structural, electrical, mechanical, chemical, and architecture. The designers and the contractors involved in tool-install are not necessarily those that were involved in the previous design and construction phases (base-build and fit-up). On a project with a cleanroom varying between 80,000 to 100,000 sq.ft., more than 1,000 workers may be present on-site daily during any one of these phases.

Tools arrive at the fab in trucks that get unloaded at the loading docks. Move-in crews then move the tools and the process support equipment to their final places in the cleanroom and subfab. Once each tool is in position, electricians, pipe fitters, and sheet metal workers place the branch routings that hook up the valves left on subfab routings (laterals) with the tie-in points at the tools and at the support equipment. Carpenters are also involved in this phase, in operations such as cutting floor tiles and wall partitions, so as to make each tool fit in a predetermined space.

Contractors may start the tool-install phase before the tools have arrived on site, in a process they term 'pre-facilitation'. Pre-facilitation consists of placing selected hook-up routings that go from the valves left on laterals to below the most convenient pop-outs of the cleanroom waffle slab (Figure AI.2). Tool-install designers typically determine which pop-outs should be used according to the place where they expect the tool to be located. After a tool is put in place, contractors can then open the pop-outs in the waffle slab and complete the hook-up operation for each utility. Once the tool is hooked up, MEP trades must check and balance the performance of all the utility systems to guarantee that all tools are performing according to specifications (e.g., in terms of steady flow of supply gases and absence of leakage). Then, carpenters must put back the floor tiles and wall partitions they had removed. At this point, if the tool performs as required (or in other words, if the tool 'qualifies'), the client considers the tool-install phase to be finished.

At present, clients are demanding that design-build organizations deliver fabs (including design, base-build, fit-up, and tool-install phases) in less than 18 months. Specifically, the Semiconductor Industry Association (2000 p.11) currently is looking for solutions to reduce the fab construction time (defined as the number of months from the first concrete pour to the time the first piece of production equipment is ready for qualification) to less than 11 months; and to reduce the time elapsed from the first concrete pour to the first full loop of wafers to less than 16 months. In order to meet these targets, the fit-up and tool-install phases are being divided in multiple modules, to be built successively. Each module, which can be one quadrant in the cleanroom, corresponds to a distinct set of tools that on their own may constitute a production line. The ramp-up process may last up to two years before the fab achieves full production. During this process, the client will progressively add more tools to the production lines, or even add new production lines, for increasing throughput up to the target rates.

III.3.3. FINANCIAL OVERVIEW

According to Professor Robert Leachman in the Industrial Engineering and Operations Research Department at University of California, Berkeley, approximately 150 to 180 fabs have been built to date in the world for accommodating the production processes that use 200 mm diameter wafers. (Wafers are thin circular pieces of a semiconductor on which integrated circuits or chips are formed.) Professor Leachman predicts that around 50 fabs will be built throughout the world to accommodate the present 300 mm technology. He also predicts that eventually a single digit number of fabs will be built to accommodate the next 450 mm technology (not expected to start before 2010). The primary reason for this decreasing trend is the escalating cost of semiconductor projects.

The total cost of a semiconductor project with an average cleanroom size between 80,000 to 100,000 sq.ft. is presently on the order of $1.2 to 1.4 billion. These are numbers quoted by practitioners and mentioned in press releases and in the specialized literature (e.g., Chasey and Merchant 2000). The cleanroom area of the largest fabs may reach

200,000 sq.ft, in which case the total project cost may exceed $2.0 billion. (The frequency of construction of these large projects has decreased significantly in recent years.) The total project cost includes the construction cost of the fab, plus the cost of tooling the fab (tools in and of themselves plus tool installation).

Practitioners typically evaluate the construction cost of a fab in terms of cost per cleanroom square foot, for which estimates vary from $2,000/sq.ft. to $4200/sq.ft. The cost of one foot of an installed routing system, such as Teflon coated stainless steel or fiberglass ductwork, can get up to $1,000. The construction cost roughly represents 10 to 15% of the overall project cost for the most recent fabs. The construction cost used to represent up to 60% of the total cost of the early fabs built in the 1970s but this percentage has been decreasing due to the escalating cost of tools. The Semiconductor Industry Association (2000 p.11) defines the fab construction costs as follows:

> "Factory construction cost includes all site work, design, construction, and construction management costs. This includes construction of the factory building shell, office space, factory cleanroom, support spaces, central utility pad or building, mechanical systems, ultrapure water systems, wastewater treatment systems, bulk gases and chemical systems, life-safety systems, control systems, and electrical systems. This excludes costs for land, production equipment, and gas/chemical distribution systems typically included in production equipment installation."

Regrettably, the semiconductor industry does not have a more precise standard to quantify and compare the construction cost of different facilities. This cost is directly influenced by criteria such as the cleanroom tool density, and by the way the cleanroom area is measured (regarding, for instance, whether or not ancillary areas are included). Most comparisons of costs of fabs owned by different manufacturing organizations are, therefore, rather inaccurate.

The cost of designing the hookups for tools, then installing, hooking up, and qualifying a set of tools ranges from 7 to 15 % of the tools' cost. This cost is of the same order of magnitude as the construction cost of the fab, so it is significant. Its significance is even higher if one considers that during a fab's lifecycle, the production tools in the cleanroom will be renovated several times. Technological cycles due to the decrease in size of the circuitry on the chip surface (the line width) may happen every year. During these cycles on average 15 to 20% of the tools may change.

Practitioners estimate the life cycle of a semiconductor facility to be roughly 15 to 20 years, but to be more precise, a facility can continue to operate as long as its cleanroom maintains the capability to accommodate lines of tools that produce chips with market demand. The dollar value of chip production in one operating day of a fab can be on the order of $2.5 million to $5 million, according to whether the chip technology is old or state-of-the-art. Shutting down a fab (or part of it) that it is in operation in order to install a new set of tools—even for one day—results in enormous operating losses for the manufacturer, assuming the delay causes loss of sales.

III.4. UNCERTAINTY IN THE DESIGN-BUILD DEVELOPMENT PROCESS

Three main sources of uncertainty affect the design-build development process of a fab. A first source of uncertainty is the fab's purpose—fabs can be distinguished as research and development (R&D) fabs, high-volume manufacturing (HVM) fabs (also known as production fabs), or foundries. A second source is the degree of technological innovation in the production tools that the fab will house. A third source is the nature of the chip product that will be produced inside the fab.

1. Fab's Purpose

In R&D fabs, the manufacturer has not fully developed the chip production processes at the time the decision is made to start designing a new fab. Instead, the manufacturer will develop the production processes inside the R&D fab by progressively installing pilot lines of tools. Consequently, these are the most complex fabs to design and build since the fab design criteria are likely to change frequently during the design-build and tool-install phases. In contrast, production fabs are built to house production tool lines that the manufacturer has already developed and tested in a R&D fab. After testing, manufacturers need to replicate the process to mass produce the new chip and to meet market demand. Production fabs are less complex to design and build than R&D fabs because design criteria change less.

Still, in order to gain time, major clients such as Intel may decide to start the design and construction of one or more production fabs while the construction of the R&D fab is still underway (Figure III.1). Such overlap also creates uncertainty on the design criteria of a production fab throughout its design-build process.

Unlike Intel, a giant in the chip industry, there are few manufacturers with the financial capability to build multiple fabs in a short period. Smaller manufacturers rely instead on the foundry model to meet their production needs. Foundries are fabs that produce products for other manufacturers who have the knowledge to develop technological processes but may not (want to) have the financial or technological capability to mass produce the products. When AEC practitioners design and build a foundry, the client does not know exactly what processes the fab will house once in operation. The design definition of foundries therefore needs to be flexible in order to accommodate an array of opportunities that may arise later.

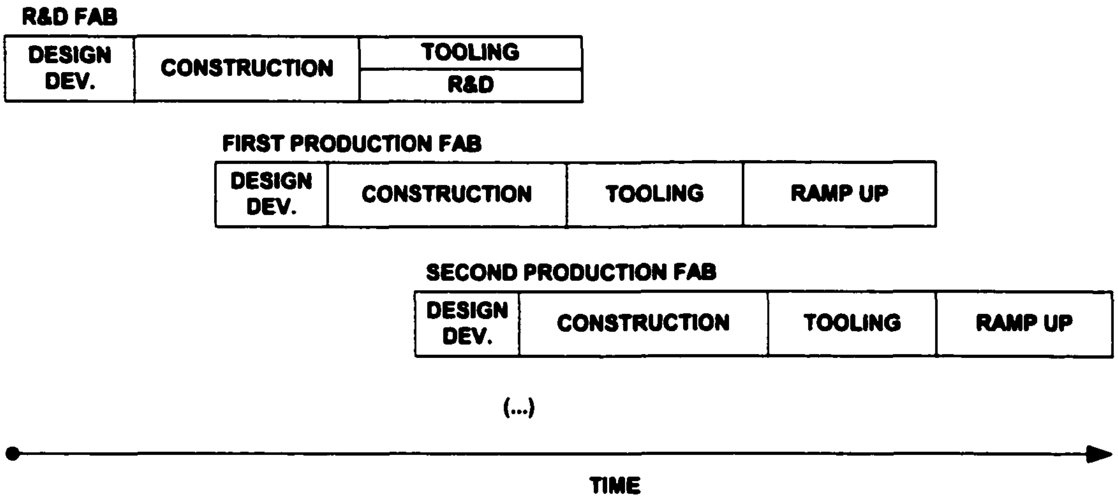


Figure III.1 - Cycles of Development of Semiconductor Fabrication Facilities (Garrett 2000)

Intel is but one firm that periodically builds a R&D fab and then replicates that fab's design definition to the greatest extent possible in production fabs. In order that chips reach the market on time, the design and building development process of a production fab must start once the chip production process is close to being fully developed in the R&D fab.

To support a replication process, Intel has instituted the "Copy Exactly Technology Transfer Method" ('copy exact'). This method was developed to minimize the time required to transfer technology without compromising product quality and yields (McDonald 1998). In terms of the fab design definition, the method recommends to "exactly copy everything about equipment and its installation down to diameters of piping and number of bends" (McDonald 1998). Because of the multitude of variables involved in fab design definition and of the complexity of the interdependencies between facility systems, manufacturers have a limited understanding of how a variation in the details of the fab design may influence the production yields. By instructing designers to copy the fab definition, manufacturers expect to increase their chances to replicate the yields already obtained at the fab being copied.

2. Degree of Technological Innovation

A second source of uncertainty is the degree of innovation in the tools' technology. Tool innovation typically is driven by two parameters: the technological breakthroughs in terms of wafer size, and the decrease of the circuitry width on the wafer surface. Whenever the chip manufacturing industry worldwide agrees to increase the size of wafers, the design features of many production tools significantly change, as do the tools' performance requirements.

At the time of this writing, a change from a diameter of 200 mm to 300 mm is underway, and there are plans for a change to 450mm around the year 2010. New tools may require different utilities with higher loads as wel! as more process support equipment, such as vacuum pumps, heat exchangers, or gas cabinets. These changes may affect the design criteria and fab design features in terms, for instance, of larger cross-sections of utility routings, higher equipment capacities, or greater floor space needs in the cleanroom and in the subfab. Changes in the circuitry width are much more frequent, and result in the so-called "tool conversion cycles". These cycles require fewer changes in the characteristics of the fab utility systems.

When leading-edge process tools are to be installed, AEC practitioners seldom will have all the information in hand on the upcoming changes in fab design criteria. Consequently, practitioners have to work in extreme conditions of uncertainty. Such fabs will logically be more complex to design and build than fabs that receive mature production technology.

3. Nature of the Chip Product

A third source of uncertainty in the design-build process is the nature of the product the client wants to produce. Thus, uncertainty is low in fabs whose purpose is to produce mature products, such as dynamic random access memories (DRAMs), or to produce less complex products such as chips for instrumentation and telecommunications. In contrast, uncertainty is high in fabs that house more complex technology, such as leading-edge microprocessors and application specific integrated circuits (ASICs).

III.5. PRODUCT FLEXIBILITY IN THE DESIGN-BUILD DEVELOPMENT PROCESS

Product flexibility, as AEC designers define it, is the ability of the fab design definition to accommodate technological changes during design, construction, and operation. Designers consider flexibility to be a major design criterion for fabs. Flexibility directly influences the way they make decisions and production choices. Designers may choose equipment at the high end of available alternatives because they may expect design loads to increase. Likewise, they may oversize cross-sections of utility routings or they may allocate empty space in the subfab so that the fab will be able to accommodate future increases in the flow requirements or utilities not initially forecasted. Such future needs are highly plausible, for instance, if the client later decides to swap the location of cleanroom functional areas. In addition, designers believe that by over-designing and by providing extra capacity, the fab will be more flexible in accommodating changes that result from tool conversion cycles and more able to endure a longer operating lifecycle.

However, the flexibility designers embed in the design features may not be exercised. Designers build flexibility in the design definition primarily based on their experience and ability to predict future needs. However, these educated guesses do not guarantee that design allowances will be needed at all or tat allowances will be able to accommodate the hard-to-predict changes the client may later request. A design specialty may have to reiterate its design process if design allowances for accommodating design changes turn out to be insufficient. Because the facility systems are largely intertwined, reiteration by one specialty is likely to affect other specialties.

Occasionally, changes occur after long lead items have been procured or when construction is already underway. The design-build team then may have to resort to less optimal alternatives for accommodating the changes. At the limit, parts of what was built may have to be torn down and rebuilt anew. Because the remaining facility components may constrain the space of new design solutions, it may be hard to find solutions that perform equally well. In any event, changes will be costly. They will delay the construction process and likely hurt the fab performance.

Design allowances may also lead to unwanted waste because designers base allowances primarily on experience and intuition—the risk that some will be excessive is real. Designers from one specialty may base their allowances on the information they receive from other specialties. It may not be explicit that the received information already included some allowances. Ultimately, designers run the risk of unknowingly developing an unnecessarily over-designed solution. If the client later expresses the need to lower the estimated construction costs (which frequently happens) designers may be challenged to cut out the allowances that clients suspect are embedded in the design definition and that clients do not want to pay for. New iterations and rework will then follow.

Product flexibility translates in practice into three different design strategies for fab design: decoupled, coupled, and semi-coupled. In a decoupled fab, designers try to keep the same design features of the facility systems across the various cleanroom functional areas (such as etching, diffusion, and lithography) regardless of the specific needs of each area. Instances of such design features are the span between subfab columns and the diameter of critical cross-sections of utility routings. Decoupled designs give the client the flexibility to swap the location of cleanroom functional areas without being constrained by the facility's characteristics. Design features in a decoupled fab are more conservative because they have to satisfy the most stringent criteria of all functional areas pooled together.

In contrast, in a coupled fab, designers assume that functional areas will not move throughout the design, construction, and operation phases. As a result, they can closely tie design features to each functional area. For instance, a functional area where tools for lithography will be located requires more stringent vibration criteria than others such as etching. This difference affects the thickness of the waffle slab, the spacing between subfab columns, and eventually the height of the subfab.

In-between these two extreme strategies, designers may opt for a semi-coupled fab. In this case, they assume that selected functional areas (those with more stringent design criteria) will not move, and they design accordingly. For the remaining areas, designers decide conservatively on the design features, logically excluding the stringent criteria associated with the areas they assumed fixed.

III.6. PROCESS FLEXIBILITY IN THE DESIGN-BUILD DEVELOPMENT PROCESS

Some clients synthesize in the motto "*faster, cheaper, and better quality*" the values that they wish AEC practitioners would pursue throughout the design-build development process of a fab. A client who decides to build a fab stipulates precise schedule milestones. He also imposes contractual penalties upon AEC practitioners in case they should fail to meet the milestones without acceptable justification. Such milestones are typically critical for ensuring the profitability of the project.

With *faster*, a client means that he wants AEC teams to deliver the project at the earliest time possible and be reliable in meeting project milestones.

With *cheaper*, a client means that he wants the project costs to not exceed the costs competitors worldwide are experiencing, according to the client's information. Yet, because the industry has failed to institutionalize any kind of standard that practitioners may use to accurately describe and compare project costs, discussion on costs across different projects unfortunately fails to be objective. In addition, a client also expects that project costs do not escalate beyond the initial estimates. This frequently is a reason for disagreement between clients and AEC practitioners. The industry in general struggles with how to solve this issue.

With *better quality*, a client means that he wants the fab design definition to meet reliably the stringent performance requirements in terms, for instance, of air cleanliness, vibration criteria, and steadiness of utility flows. Currently, the Semiconductor Industry Association (2000 p.11) looks for solutions that provide a facilities service reliability no lower than 99.9%. Facilities services include all utilities for which the facilities organization is responsible (such as power, water, fuel, house gases, and wastewater). Facilities service reliability is defined as:

$$\frac{\text{(total hrs/year of operation) - (total hrs/year of utility interruption) (outage or out of spec.)}}{\text{[(total hrs/year of operation)]}}$$

Despite imposing stringent requirements and criteria, clients normally are very cautious when letting design-build teams innovate in the product-design definition to meet the requirements they impose. Their primary reason is that any kind of innovation in a fab system comes with a perceived risk that the fab may not perform as expected. This perception primarily stems from the fact that the complexity of the fab definition makes it hard to absolutely prove that any innovation that gets implemented will not harm the performance of other fab systems.

Thus, if a new fab (e.g., a production fab) will house a process technology that is already installed in another fab and apparently performs well, the client may want the new fab to be a copy exact of the existing one (McDonald 1998). If a new fab (e.g., a R&D fab) will house leading-edge technology, the client may still limit the number of innovations for minimizing mal-functioning risks. Moreover, from a logistics perspective, copying the design of a fab makes it easier for the client to transfer people who operate and maintain an existing fab to the new one.

In addition to *faster, cheaper, and better quality*, clients find it crucial that designers and builders be flexible in accommodating changes without compromising the project goals. Clients acknowledge that over-designing the product definition, as designers often advocate, can be an effective strategy to shield the design definition from late changes. Clients also acknowledge that the up-front costs implicit in that practice are not significant in the face of the potential savings that may derive if changes indeed occur.

Yet, such product flexibility has an initial up-front cost. Clients today more frequently feel they cannot afford this up-front cost because shareholders demand that their fabs be not—nor appear to be—more expensive than those of competitors. Accordingly, clients have been demanding a more flexible design-build process rather than a more flexible fab definition. The search for such a flexible process (or 'process flexibility') sets the research direction that I follow in this dissertation.

IV. LEVERAGING SPECIALTY-CONTRACTOR KNOWLEDGE IN DESIGN-BUILD ORGANIZATIONS

IV.1. INTRODUCTION

Architecture, engineering, and construction (AEC) projects invoke complex processes for designing and building a product. These projects typically involve a client, a lead design firm and several design specialists, a general contractor, and an array of specialty contractor firms. Design firms typically are in charge of most of the design development process and they help to manage or supervise the management of the construction work. General contractors may execute some part of the construction work (e.g., cast concrete or erect steel). In turn, specialty contractors competitively bid to perform different parts of the remaining construction work. Their work is divided according to different specialties or trades, such as mechanical, electrical, and process piping.

How to effectively coordinate the work of specialty contractors in AEC projects has been an industry concern for long (Crichton 1966, Hinze and Tracey 1994). The work of specialty contractors has evolved from requiring artisanship to sophisticated assembly of components (Bennett and Ferry 1990). Specialty work, typically done on-site, has progressively extended to include off-site tasks, such as creating detailed fabrication and installation drawings, selecting vendors, procuring and expediting delivery of materials and equipment, building, starting-up, and maintaining building systems (Tommelein and Ballard 1997). Inefficiencies during construction result from lack of interaction between contractors and designers.

In contrast, other industries are increasingly involving suppliers in product development and manufacturing. Organizations with lean manufacturing practices have suppliers work closely together with their own personnel in order to streamline the production processes (e.g., Womack et al. 1990, Clark and Fujimoto 1991, Ward et al. 1995). They share information on their production systems with the following goals: to reduce inventories, to deliver parts just in time, to increase reliability of supply lead times, and to cut cost. To achieve these goals, manufacturers have adopted different practices. They move their people to work at suppliers' facilities and they welcome supplier employees in their own manufacturing plants. In addition, they have established incentives for suppliers to participate in early design: they have increased the size of orders and commit to longer-term contracts.

Given these observations, I set out to study supplier involvement in the AEC industry. Design and construction overlap in fast-track projects, but knowledge is transferred in one direction mainly. Design is broken up in pieces, conservative assumptions are made regarding succeeding pieces, and completed design pieces are then handed off to construction. In contrast, product developers and manufacturers have found means to enable two-directional knowledge transfer (Iansiti 1995, Figure I.1). Assuming that specialty contractors on AEC teams are one kind of supplier—the equivalent of suppliers in manufacturing—a key question therefore is: What knowledge can these suppliers bring to the table?

IV.2. AVAILABILITY OF SPECIALTY-CONTRACTOR KNOWLEDGE

Specialty-contractor knowledge can contribute to early design in multiple ways. Contributions fall in four categories.

IV.2.1. ABILITY TO DEVELOP CREATIVE SOLUTIONS

Specialty-contractor knowledge can bring to early design creative solutions, which designers may not necessarily be aware of. On one hand, specialty-contractor creativity derives from 'cross-fertilization': it results from the specialty contractor's involvement in projects owned by different clients and designed by different design firms. Such diversification and rotation of work exposes specialty contractors to alternative ways of solving design problems and keeps them up-to-date on technological innovations. On the other hand, specialty-contractor creativity also reflects the specialty contractor's own pursuit of technological innovations and their knowledge of constraints affecting the construction process (Slaughter 1993).

Admittedly, this is a double-edged sword. Specialty contractors who participate in early design may try to impose the solutions they prefer because these are easier to develop, procure materials for, and build, that is, they are more lucrative to the contractor. Nevertheless, designers face a similar condition when contractors do not get involved early. Should the design prove to be impossible to build, an added risk then is to have to redesign solutions.

IV.2.1.1. Example Creative Solution: Modularization of Plenum Body

In a recent semiconductor project, the original design of the air plenum body specified a steel structure to hang from the ceiling (the plenum is the space above the false ceiling of the cleanroom; the cleanroom houses the process tools). The structure was to be built on site. Once the mechanical contractor was selected based on his bid for the original design, the contractor developed and proposed jointly with the ceiling manufacturer an innovative system to build the plenum body. The system consisted of 560 modules to be fabricated in a shop and then assembled on site. These modules require pre-assembly of ventilation ductwork, light fixings, and ceiling grid. The client accepted the proposal and the plenum was built accordingly. This solution brought significant savings in labor hours, installation time and cost, and increased safety during installation. However, it led to redesigning the plenum body at a cost to the client and stripping off the electrical system that was already installed according to the original design. Savings in cost and time were largely associated with the efficiencies gained in the off-site shop fabrication of the modules and with their ease of installation. The performance quality of this solution is higher because of better conditions available in the shop to carry out work such as welding. The solution was patented and the client is presently exploring its applicability to future projects.

IV.2.1.2. Example Creative Solution: Use of Rolled Offsets

Offsets, rolled offsets, and 45-degree fittings (as opposed to 90-degree fittings) are ways for changing the direction of pipes and ductwork (Figure IV.1). They achieve shorter routings and can potentially lead to savings in terms of materials, labor, space, as well as savings in the number of welds, flanges, and fittings. They also improve performance by restricting flow less. Yet, these alternatives are seldom used in design development. Apparently, their use is less intuitive for design detailers because designers are too used to drawing and viewing orthogonal and two-dimensional graphical representations of building systems. Moreover, in absence of knowledge about the skills of the construction labor force, 90-degree elbows are used throughout design because they are easier to build.

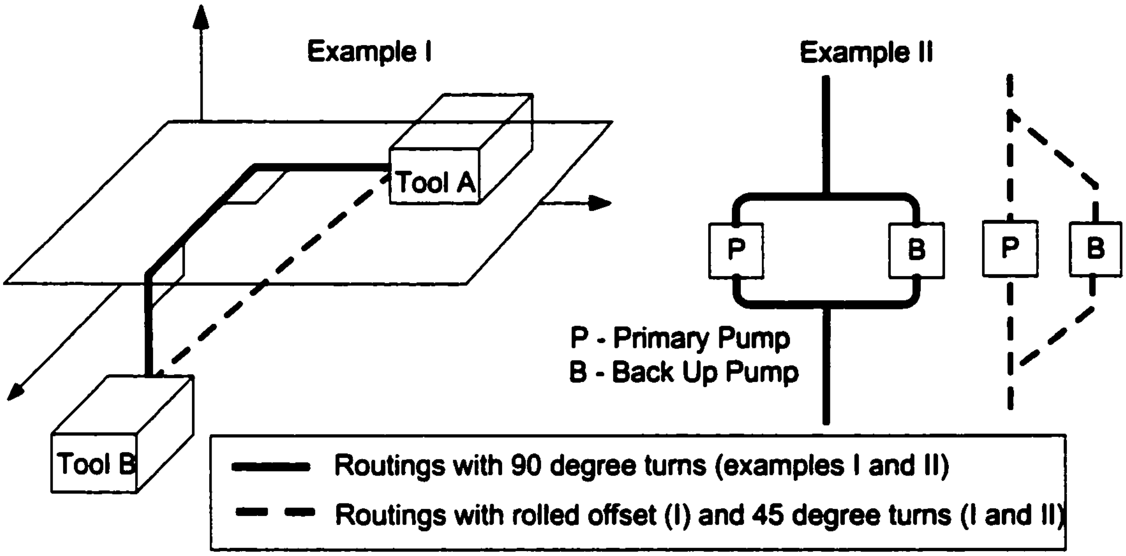


Figure IV.1 - Examples of Alternative Design Solutions

In contrast, sophisticated contractors create three-dimensional computer models to detail their work. Such models are easier to interpret than blueprints are. Their use by construction workers eases planning for the installation process on site and helps in identifying space constraints; it prevents errors during execution. Specialty contractors also know if they will have qualified labor on site and can thus choose to match labor skills with design solutions while detailing the design. Involving specialty contractors earlier in design would yield these benefits. Contractors could then also start looking for labor earlier, level their labor utilization over a longer look-ahead time frame, and be more certain regarding continuous employment of its best, hourly work force.

In addition, detailers working for specialty contractors have a better sense for using alternative routing solutions than design detailers do. In a subfab, the piping contractor got involved early in design and took advantage of alternative routings to a great extent. This yielded savings in terms of shorter routings, fewer labor hours, and less material. Kim et al. (1997) and Zabelle and Fischer (1999) have reported similar instances where the early and concurrent use of three-dimensional models by contractors and designers brought significant gains to the design-build process.

IV.2.2. KNOWLEDGE OF SPACE CONSIDERATIONS FOR CONSTRUCTION PROCESSES

Because specialty contractors build the design, they have developed a sense for space needs that would allow construction to proceed efficiently, if accounted for in early design. Instances of such knowledge concern access paths to bring in equipment and materials, and clearances around routings so people have space to work in and move around. Involvement of specialty contractors in early design can prevent designers from developing solutions that are inefficient or impossible to build.

IV.2.2.1. Example Space Consideration: Access versus Dimensions of Components to be Installed

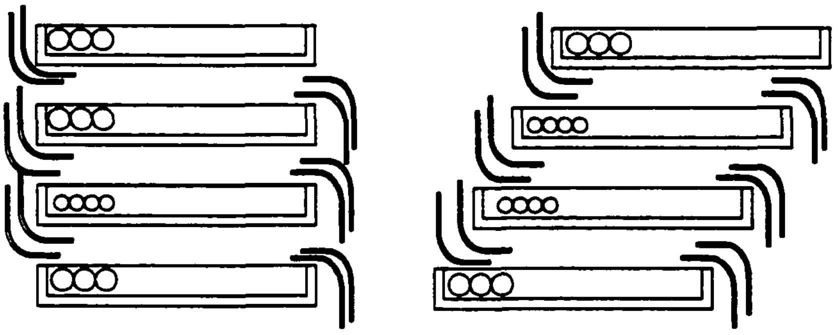
To install routing lines in the main and laterals of a semiconductor subfab, piping and mechanical contractors typically follow a sequence of steps. First, they have to decide on the length of spools to order, according to the space conditions they anticipate will exist on site when the spools arrive. Once the spools arrive, contractors have to bring them separately into the building. They slide the spools up into the steel racks where they put them in rows ready to weld. To weld the spools around, they need 2 to 3 feet (0.5 to 1 m) of empty space sideways. Finally, to hoist the routing line into its final position, they need vertical clearance between the area where they welded the spools and their final location. If routings are stacked, contractors can install those on top only after installing those at the bottom. Yet, because contractors do not get involved in the design, they cannot contribute to the creation of alternative configurations that would add flexibility to the construction process. Because they are uncertain about the space constraints that they will face when spools arrive, they order the shortest spools in anticipation of not being able to slide longer ones into place. Unfortunately, shorter spools augment the number of welds and may unnecessarily increase labor hours and time to install.

IV.2.2.2. Example Space Consideration: Access versus Work Method and Component Design

To weld stainless steel, fiberglass, and other materials on site, mechanical and piping contractors use equipment of significant dimensions, such as orbital welding machines. Contractors suggest, for instance, a minimum of 6 inches (15 cm) between adjacent lines to efficiently weld spools and valves. In addition, contractors need designers to consider access paths to reach work areas with welding tools. Lack of consideration for such requirements may result in subfab drawings that specify welding operations hard—if not impossible—to perform. When this is the case, contractors may propose to replace welded- for bolted connections. Yet, because some think bolted connections are more prone to leaking, such change orders may demand significant attention, effort, and co-operation from all parties involved.

IV.2.2.3. Example Space Consideration: Access versus Component Layout

Designers typically arrange cable trays in the laterals of subfabs by stacking them (Figure IV.2-I). They graphically represent such an arrangement with cross-sections at regular distances. Stacking can be inefficient during cable-tray installation, if the design does not leave enough space between trays for the contractor to enter and leave with cables. Having a contractor check for ease of installation during design could benefit the process later. Staggering cable trays could potentially facilitate such tasks, according to one electrical contractor, but this configuration requires more space in the laterals (Figure IV.2-II).



I. Stacked Cable Trays

II. Staggered Cable Trays

Figure IV.2 - Alternative Arrangements for Cable Trays

IV.2.3. KNOWLEDGE OF FABRICATION AND CONSTRUCTION CAPABILITIES

Capabilities of specialty contractors reflect the qualifications of the labor force available at the time of construction, and of the equipment and tools used off- and on site. For instance, mechanical contractors who know which laborers will fabricate ductwork in their shops and which machines those laborers will work on can detail their design for the most effective fabrication. Such knowledge can enable designers to better match early decisions and production choices with contractor capabilities without sacrificing design creativity or quality.

IV.2.3.1. Example Fabrication and Construction Capabilities: Work On-site versus Work in Shop

Welding stainless steel is a sophisticated operation. Welding on site takes longer than welding in the fabrication shop due to multiple reasons, such as safety concerns for people working on ladders or the time people spend bringing in specialized equipment and setting it up on site. These concerns also result in higher costs (especially insurance) for site work. Contractors estimate, for instance, that it takes approximately 2 hours to weld a 24" (60 cm) stainless steel pipe in the shop and 10 to 12 hours to perform the same welding task on site. When procurement and shop fabrication are coordinated with ongoing site work, materials handling costs may even be reduced.

IV.2.3.2. Example Fabrication and Construction Capabilities: Product Configuration and Postponed Commitment

A lateral is a set of routings including pipe and ductwork that branch off the main routing. From the valves on laterals, other pipes and ducts branch off to connect with the process tools up in the cleanroom and with the process support tools down on the subfab floor. The location of tools in the cleanroom determines the valve spacing on the laterals. Designers, however, typically decide on the diameter and spacing of valves during early design development, when the tool layout is still prone to many changes. They do so because the client needs the design specified for contractors to bid it. Involving contractors early in design would create understanding regarding which commitments on features could be postponed and thereby leave sets of design alternatives open (e.g., assuming different valve spaces or duct diameters) until the client would have a more definite layout. Such a set-based design practice has been successfully adopted in manufacturing where design is subject to similar unpredictable environments (e.g., Ward et al. 1995) and it has been explored in AEC computer-based applications (e.g., Lottaz et al. 1999).

Because contractors and designers would be sharing information during design, contractors would then be able to order materials and to execute the design more promptly once the client committed to a specific layout. Contractors would also know better what valves would be located in positions that are difficult to access and hook up to the process tools and support equipment. If given the opportunity, they could pre-assemble those valves in the shop before shipping spools to site. Besides, contractors could create points of connection using valves on Ts, so as to increase their accessibility once the pipe was installed, and thereby ease hook-up work.

IV.2.4. KNOWLEDGE OF SUPPLIER LEAD TIMES AND RELIABILITY

Specialty contractors can contribute in various ways to equipment and material selection in early design. Designers typically detail the equipment and material that contractors have to procure. They do so in part because they worry that contractors might opt for low quality or cheap alternatives, if specifications were less precise. Design specifications are, however, not necessarily customized to the specific project at hand. Moreover, by making product choices, designers make implicit process choices because chosen products have their respective lead times and installation requirements (Sadonio et al. 1998). Once contractors start procuring what is specified, they may discover that these items are not readily available. Alternatives that are acceptable from a delivery performance perspective may not exactly conform to what was specified. Specifications then end up creating unnecessary delays. Further investigation of 'or equal' specifications is appropriate in this regard (de la Garza and Oralkan 1995, Ganeshan et al. 1991, Bernold and Treseler 1991).

In contrast, specialty contractors have a strong sense of urgency when procuring long lead items because they install such equipment and materials on a regular basis. Specialty contractors also have ongoing relationships with distributors and suppliers and know their reliability regarding shipping dates and product quality. If specialty contractors and suppliers are involved earlier in design, they can inform designers of the lead times associated with different alternatives and make designers aware of the impact poor supplier selection may have on production. In addition, specialty contractors frequently maintain the systems they build for a warranty period. They can therefore help designers and clients differentiate between alternative equipment and system designs in terms of performance reliability and operations-and-maintenance needs. These issues as well as others pertaining to supply-chain management are becoming increasingly important in AEC product delivery.

IV.2.4.1. Example Supplier Lead Time and Reliability: Influence on Construction Sequences

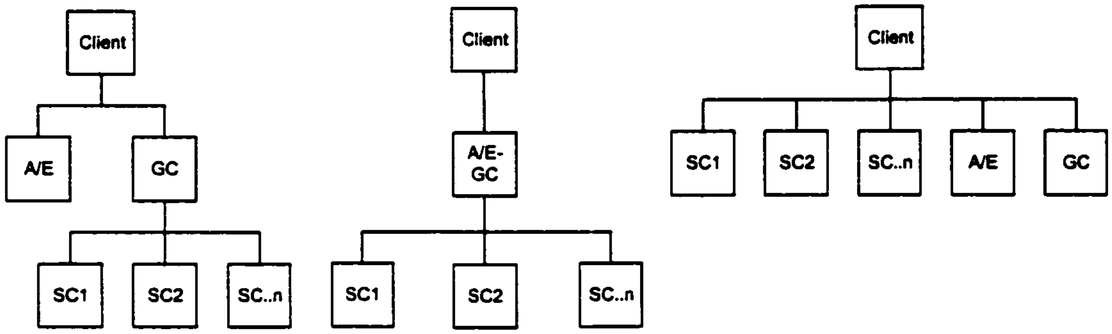
Knowledge of material lead times is essential for specialty contractors to develop and adhere to the most efficient construction sequences. In the case of the laterals in subfabs, experience recommends that contractors first install vertical lines, such as vacuum lines that hook up vacuum pumps to process tools, because of their length constraints. Installation should then proceed with drain lines and ductwork because they are part of large-diameter gravity systems that have to slope. Then, installation of process piping should follow. Finally, electrical cables should be installed as they offer flexibility to be routed around obstacles.

Material lead times affect in different ways the readiness of mechanical, electrical, and piping (MEP) trades to start work. Electrical contractors are not constrained by long lead items for a number of items, so this enables them to promptly start work once space is available. Other trades, such as process piping and mechanical, often have lead items of 4 to 6 weeks if not longer, depending on the kinds of spools and fittings needed and the suppliers involved. Accordingly, electrical contractors may start their work while other contractors are still waiting for orders to arrive. Electrical systems may then end up blocking the access paths that other contractors had relied on. When this happens, either electrical systems have to be ripped out and built anew later, or piping and mechanical contractors have to find alternative ways to execute their work, using, for instance, shorter spools. In any event, time delays and additional labor expenditures are likely to result.

IV.3. BEYOND AVAILABILITY OF SPECIALTY-CONTRACTOR KNOWLEDGE

IV.3.1. CONTRACTUAL AGREEMENTS

Many more examples exist of contributions of specialty-contractor knowledge to early design than those that have made it into practice. The examples in this dissertation characterize the nature of such contributions. Whether or not specialty contractors have the opportunity to participate in design, often is a contractual issue. Figure IV.3 illustrates three different contractual agreements: (I) design-bid-build, (II) design-build with A/E-GC, and (III) design-build with SC. Only the latter expressly accounts for specialty-contractor involvement in design. Furthermore, design firms may request specialty contractors to provide design-assist services or clients may get specific contractors involved in a project—and potentially in design—by nominating them.



I. Design-Bid-Build Contract II. Design-Build Contract with A/E-GC III. Design-Build Contract between Client and SCs

SC - Specialty Contractor
A/E - Architecture/Engineering Firm(s)
GC - General Contractor

Figure IV.3 - Alternative Contractual Agreements between Client, General Contractor, Architecture/Engineering Firm(s), and Specialty Contractors

IV.3.2. DESIGN-BID-BUILD AND DESIGN-BUILD BY ARCHITECT/ENGINEER-GENERAL CONTRACTOR (A/E-GC)

In design-bid-build and design-build projects, specialty contractors are typically left out from the initial contractual agreements between the client and the architect/engineer, and the client and the general contractor (Figure IV.3-I), or the client and the design-build consortium (Figure IV.3-II). Instead, the general contractor selects specialty contractors primarily through competitive bidding after obtaining a set of drawings and specifications defining the AEC product. By involving specialty contractors earlier, design-build organizations may be able to not only leverage specialty-contractor knowledge but also to jointly create new knowledge. Such involvement implies that selecting contractors by competitive bid based on more-or-less completed drawings and specifications should be abandoned in favor of earlier contractor selection. In doing so, design-build organizations and clients must address other issues, such as establishing communication, means and incentives, and liability, which I discuss later in this chapter.

IV.3.3. DESIGN-BUILD BY SPECIALTY CONTRACTOR

The client or design-builder may contract directly with one or with multiple specialty contractors to develop the design and execute the work (Figure IV.3-III). This practice is becoming increasingly common, particularly with mechanical, electrical, and piping trades, as their work gets to be more specialized (e.g., ENR 1997, Iskra et al. 2000). Alternative contractual agreements to competitive bidding, such as unit pricing or cost-plus contracts, enable clients to involve contractors earlier, while clients can still maintain a good sense of the expected cost of work. Still, design-build by specialty contractors leads to other issues in terms of project-based operations management. It raises questions as to who should take the project lead and how to coordinate the work during design and construction. Recent publications have started to tackle these issues and to present innovative tools to support new process designs. Examples are: (1) WorkPlan (Choo et al. 1999)—a database program to support production scheduling for specialty contracting work on projects, (2) the 'Parade Game' (Tommelein et al. 1999)—a game that illustrates the impact of work flow variability on the performance of construction trades, and (3) the '5 WHYs' (Tsao et al. 2000)—a quality management method for identifying root causes of problems.

IV.3.4. NOMINATED CONTRACTORS

A client may identify and name a specific specialty contractor early on in the project, a so-called 'nominated contractor,' who is to later engage in construction. When this is the case, the general contractor does not have the opportunity to choose any other contractor for that specialty. The client may nominate a contractor because they already have a good working relationship, because the architect/engineer suggested that this contractor has significant knowledge and can help design a specific technology, or because of any other reason. However, nominated contractors get involved in early design decisions only when the client or the design-build organization explicitly asks them to. Contractors get compensated for early efforts in that nomination guarantees that they will get the work and it lets them save on bidding costs. In practice, nominating contractors essentially boils down to establishing a contractual relationship that formalizes an early contractor selection (Higgin and Jessop 1965 p. 44, Bennett and Ferry 1990).

IV.3.5. DESIGN-ASSIST

Design-assist is an informal arrangement between the architect/engineer and the specialty contractor. Design-assist has become common in the United States in recent years, but a description of this practice is surprisingly absent in the research literature. The objective of design-assist is to give specialty contractors the opportunity to comment on early design, based on their knowledge regarding design, procurement, and construction processes, but this does not mean that they will get the job. Specialty contractors may agree to assist designers because it gives them the opportunity to know more about the design, the designers, and the expected builder team. Such knowledge helps them to assess better what the risks may be during the post-award submittal process and construction, so they may be able to bid the work more favorably.

Design-assist has, however, only limited effectiveness. Because the participating contractors are not contractually guaranteed that they will get the job, they may not give much assistance because competitors who later bid the work will see their solutions. For instance, an electrical contractor told me that he often takes a priced one-line design diagram to design-assist meetings. However, whether or not he reveals that information depends on his assessment of the chances of getting the project, and how interested he is in getting it, given what he learned during the meetings.

IV.4. COMMUNICATION SYSTEMS

Communication is important for specialty contractors to share knowledge in design-build organizations. Communication will enable specialty contractors to better understand designers' intent, especially when designers insist on building in a way different from what contractors think would be the best solution. Confrontation often arises because of lack of understanding of other disciplines' concerns and of other's rationale for making specific choices. For example, the valves welded on Ts on pipe, which allow for future access by contractors, is a lesser alternative to valves welded on the perimeter surface of the pipe, from a design perspective. Designers prefer the latter because the absence of the T avoids stagnation of fluids and thus potential contamination by impurities.

Better communication will also enable contractors to discuss alternatives with designers. For instance, designers frequently complain how difficult it is to draw and specify their intentions regarding space they want to leave empty for future needs. As a result, such space may end up being invaded during construction. If designers subsequently insist on it being left free, contractors will have to rework their installation.

Communication between specialty contractors and designers can also help to estimate more accurately the cost of design alternatives. In semiconductor projects, estimates at an early design phase frequently turn out later to have been too low. Design-build organizations and clients tend to let less realistic estimates proceed through design development—even if individuals may be skeptical—because costs and the likelihood of changes are not explicitly acknowledged. When contractors bid the project, especially under lump sum contracts, higher-than-expected costs may be revealed. Clients may then request value engineering. This frequently means changing the design to bring back costs within the initial budget. This causes rework and wastes time and resources. Greater accuracy in estimating would help design-build organizations and clients to better rationalize early design decisions and choices.

AEC practitioners use various communication mechanisms in the semiconductor industry. One mechanism is to promote meetings between specialty contractors and designers during early design before design-build teams commit to specific design features. Such was the case in a hook-up project during which specialty contractors, designers, and client representatives worked together in small groups for two consecutive days; the project team jointly agreed upon major design decisions and production choices (Miles 1998).

Another mechanism is to co-locate contractors' detailers in design offices side-by-side with detailers working for the design firm during the design detailing phase; or co-locate engineers and detailers working for design firms on site while construction progresses. I know of several specialty contractors who co-locate their detailers in a single trailer with other specialty-contractor detailers on site for easing and expediting the identification and resolution of interference problems.

A third mechanism is to promote meetings between selected suppliers and specialty contractors. Such was the case in a project, which consisted of hooking-up tools that were manufactured in Japan. The client arranged meetings in the United States between the tool manufacturers and the suppliers before the tools arrived, and provided language translators to intermediate the participants' discussion on potential interface issues.

But providing the means for people to meet does not guarantee communication will happen. This is my critique on partnering efforts that lack an underlying formalism to streamline communication and fail to recognize explicitly what needs to be communicated and when. For instance, communication failed to occur on one project because people who work for specialty contractors (such as labor managers) were brought to design coordination meetings without proper guidance. These meetings may involve 20 or 30 people, including designers and client representatives, and may be intimidating. It is then natural that someone who intends to share what he knows, opts to remain silent.

However, organizations have alternative means for guaranteeing that available knowledge is shared effectively. In one project, a client representative used to meet periodically with specialty-contractor foremen to get their feedback on the design that was being developed concurrently. With that feedback in hand, the client representative then went to coordination meetings with design leads and authoritatively relayed the suggestions made by the foremen.

Tremendous organizational impediments need to be overcome for communication to be open and effective. My work to date has therefore focused on identifying what kinds of knowledge might be communicated and when, before tackling organizational issues.

In addition to promoting organizational change, existing and emerging information technologies (IT) can also ease communication between AEC project participants. Today's web-based collaboration tools track design drawing submissions (e.g., as .pdf files in Portable Data Format) and changes (e.g., using digital, two-dimensional red-lining features), but many still support a throw-it-over-the-wall mentality. Shared 3-

dimensional CAD models and databases begin to be used but are far from common. A follow-on step is to share set-based models for concurrent design that are annotated with design intent and rationale. Early prototypes of such systems exist (e.g., Tommelein et al. 1991, Ward et al. 1995, Lottaz et al. 1999). The AEC community is facing a long—yet exciting—path forward in terms of developing practical IT applications for true collaboration!

IV.5. MEANS AND INCENTIVES TO PROMOTE SPECIALTY CONTRACTOR INVOLVEMENT IN DESIGN

Specialty contractors have little incentive to share knowledge and to improve the design, especially when harsh contractual agreements are spelled out (Pietroforte 1997). To involve specialty contractors in early design means to involve people with construction experience, such as labor managers and foremen, who typically are very busy and extremely valuable on site. Thus, although specialty contractors may have the flexibility to pull one or two of their most experienced people from an on-going job so they can spend a couple of days with designers, they need to be assured that this is worth doing.

Other industries offer examples of incentives to get the right supplier representatives involved in product development. Specifically, manufacturers have fostered long-term relationships with suppliers, spelled out contracts that state those intentions, and increased the size of orders by reducing the number and proximity of suppliers they work with (Womack et al. 1990, Dyer 1997). Manufacturers and suppliers jointly may engage in target costing (e.g., Cooper and Slagmulder 1997). Similarly, design-build organizations should try to foster long-term relationships with specialty contractors, rethink their contracts, and reduce their pool of contractors so that the latter will recognize that their effort in early design will pay off with more work in future.

Observations of current practices confirm that AEC organizations are moving in this direction. In one case, a semiconductor client decided to reduce its pool of MEP trade contractors—traditionally selected by competitive bidding—to a steady few (two or three) for each specialty. In another case, a client selected a mechanical contractor early on and, to ensure that the contractor and designer would communicate effectively, the client contractually agreed with the contractor that his detailers (pipe fitter and sheet metal workers by trade) would be located in the design firm's office for the duration of the design process. In a third case, a specialty contractor became involved in early design of tool-install work. Tool installation, performed mainly by MEP contractors, is a complex job because tool characteristics may change frequently throughout the design and installation processes. Therefore, clients typically select specialty contractors early on. Detailers working for contractors and designers may even form interdisciplinary teams to collect information from tool vendors and to decide together on the best routings for the tool-install utilities.

IV.6. LIABILITY

Traditionally, designers have contractually assumed liability for design. The division of professional liability in current practice is far from being a trivial problem. Specialty contractors often propose changes to the original design that designers have to approve, but when designers approve such changes, they typically add the clause that their approval does not bind them to any professional liability. Such a clause, however, may not be enforceable in practice.

If specialty contractors participate in early design and contribute their knowledge to design definition, all on the AEC team have to jointly agree on how they will share professional liability. With increased involvement in design, the specialty contractor's liability is likely to increase. In the aforementioned example of the plenum body, for instance, the contractor assumed liability for the modular design. Other evidence that contractors are ready to assume professional liability is the recent acquisitions of design firms by specialty contractor firms. Such acquisitions provide contractors engineering capabilities as well as the professional competence to assume design liability.

IV.7. CREATING EXPLICIT KNOWLEDGE IN AEC ORGANIZATIONS

Tacit knowledge consists of informal technical skills, intuitions, insights of individual employees, etc., and is commonly captured in the term "know-how". Tacit knowledge is only implicit and people cannot easily articulate it (Nonaka 1991, Bohn 1994). In contrast, explicit knowledge exists in some kind of representation (e.g., books, guidelines, and procedure manuals) that makes it more independent from individuals. Explicit knowledge is easier than tacit knowledge to share and communicate among people who work in the same organization. Socialization and interaction among individuals are means to share tacit knowledge and such sharing contributes to company culture. By sharing tacit knowledge, individuals may find it easier to articulate and convert it into explicit knowledge. In turn, once new explicit knowledge is shared among individuals, it helps to extend each individual's own tacit knowledge base into new knowledge. This is what Nonaka (1991) defined as the 'spiral of knowledge'.

AEC practitioners working for specialty contractors or design-build organizations do not get enough opportunities to interact with each other. Efforts that aim to increase the level of interaction between them, such as partnering, have proven to be successful to some extent. Lack of interaction explains why potential contributions of specialty-contractor knowledge have not made it into design practice but there are numerous other explanations, including blue- vs. white-collar barriers.

The reluctance to interact is also fuelled by the perception that adversarial relationships must exist—as they historically have—between designers and contractors. Adversarial relationships arise when parties blame each other, even when it is impossible to assign blame to one party exclusively. On one hand, specialty contractors noticing errors and omissions in bid documents may not inform the design firm thereof and bid according to the original design. Bidding on an alternate solution may put a contractor at a disadvantage against competitors or disqualify that contractor altogether. In turn, the designer may consider an error or omission to be inconsequential and not worth spending time on. For instance, a specialty contractor reported a case where he noticed some valves were missing. These valves were needed to prevent equipment in the system from getting filled with the fluid used in the de-passivation of the piping before start-up. He let the error go unreported until he got the project. Because explicit communication between professionals from the two parties did not exist, there was no guarantee that designers who missed the valves could be informed of their usefulness.

On the other hand, contractors are said to not point out problems as soon as they notice them because changes after contract award are potentially lucrative, but which kinds of problems should one be expected to identify during bidding versus is one likely come across during detailed work planning? Whether or not these perceptions are valid in any specific circumstance is hard to evaluate. Consequently, contradictory views are bound to last as long as communication between the parties remains poor. AEC practitioners must learn to create win-win situations through increased interaction and collaboration, rather than setting themselves up for the loose-loose situations that are so prevalent today.

Tsao et al. (2001), who also question the way boundaries are drawn for work to be divided among AEC participants, phrase the issues succinctly. "Trades do not necessarily complain about [design] problems [encountered during construction] because (1) contractually speaking, site problems may be considered theirs to resolve, (2) they may have more important problems to address such as developing bargaining tactics and determining which battles to fight, and (3) complaining might reflect poorly on their trade skill and pride ('tricks of the trade') so they believe workarounds are what they are supposed to do. Such workarounds are costly and time consuming. However, they are an accepted way to perform work. Workers do not question the design because their contracts have already been signed and work must proceed according to the original design."

A second example of how the lack of interaction impedes the process of building explicit knowledge in AEC organizations relates to 'fitting-bound' problems. Fitting-bound problems consist of insufficient height to install a certain number of fittings needed on a pipe so that it would perform the changes of direction as needed. Fitting-bound problems are an intrinsic subject in the education of pipe fitters. In subfabs, valves left on laterals for later hook up to process tools in the cleanroom should be left at 45 degrees instead of horizontally. If these valves are designed horizontally, most certainly one additional fitting will be needed to turn the direction of the pipe and chances increase that installers will later run into fitting-bound problems. At present, designers consider this to be common knowledge, but because this knowledge mostly remains informal, not all designers necessarily know it. Besides, those who know it may have learned it in the hardest way, by repeatedly specifying solutions that were difficult or impossible to build.

A third example illustrates how the lack of interaction between specialty contractors and designers may further delay the resolution of problems. In one project, two cable trays were designed one on top of the other, merging at one end into one cable tray. Installation of the cable trays had started. The contractor was aware that code officials might not approve the transition the way it was designed because, as such, it would probably lead to a density of cables above what regulation allows. The problem was apparently well known at that point among individuals involved in the project. But because individuals thought that resolving the problem would be time consuming and they were too short on time to develop an alternative, they kept postponing its resolution.

If AEC organizations do not make an effort to create explicit knowledge that results from individuals' interaction, new recruits or employees not directly involved in the process are unlikely to share knowledge; there will be no common basis for understanding. Also, if people who have tacit knowledge leave, the organization loses that knowledge. Accordingly, mistakes will be made over and over again. By keeping knowledge tacit, the AEC industry forces itself to remain an experience-based industry and thereby looses a tremendous opportunity for theory-based learning (Koskela 1992, Tommelein 1999). Learning that is supported by theory—as opposed to learning based exclusively on experience—enables firms to more quickly integrate new recruits and get them to perform at higher levels of skill and competency. This should be a key concern in today's construction industry, which is facing an increasingly aging work force. Quicker integration may also lead to even higher mobility for employees (mobility already is high in construction), which is a good way to disseminate best practices and thereby advance performance in the industry. Higher performance levels lead to higher returns but demand higher wages or salaries. This too will help to attract new people into the industry.

Automated rule-based systems have offered a way for AEC organizations to leverage tacit knowledge and make it explicit (e.g., Hendrickson et al. 1987, Kartam and Levitt 1990, Winstanley and Hoshi 1993, Dzeng 1995, Dzeng and Tommelein 1996, Fischer and Aalami 1996, Aalami 1998, Akinci and Fischer 2000). These systems formalize tacit rules on best construction sequences and relationships between physical components to automatically generate construction layouts and schedules, given a design. Despite their potential, such automated systems are not widely used in practice today.

As opposed to creating construction plans that suit a design, my work addresses a different question. Why not use knowledge that makes construction easier and adapt the design to suit it? Such adaptation process should be done thoughtfully to ensure that construction convenience does not compromise the creativity and product quality of the design solution. Taking this thinking even further and questioning who should join an AEC organization to be best positioned to take on what work, is called 'work structuring' in lean construction (Ballard 1999a, Howell and Ballard 1999, Tsao et al. 2000, 2001).

Other organizations preserve tacit knowledge of employees by formalizing it in design rules or at least creating opportunities so colleagues can share their knowledge. For instance, some Japanese companies promote socialization among people from different parts of their organization. They make designers follow the execution of their design so they get exposed to other perspectives that they would normally not see (Nonaka 1991). Similarly, Iansiti (1995) reports on the effort that organizations in the computer industry make for retaining, leveraging, and sharing the knowledge of experienced employees across the organization. The rotation of new recruits, from estimating and bidding to field engineering and project management, is common in larger construction firms but it tends not to bridge design-construction boundaries.

IV.8. CONCLUSIONS

Current practice reveals that AEC organizations have few if any formal mechanisms in place to leverage specialty-contractor knowledge. Empirical research and others' work has shown, however, that this knowledge is available and may contribute significantly to the effectiveness of design-build processes and to the quality of AEC products. I classified this knowledge in four categories and provided examples. Industry practices illustrate that specialty contractors are increasingly getting involved in projects earlier.

AEC practitioners must become more aware of the opportunities currently being lost and rethink some of their practices. The involvement of specialty contractors in early design makes it possible for experienced design and construction people to share and leverage their knowledge.

One challenge for AEC organizations is to implement means and incentives for individuals to make their knowledge explicit and to share what they know within their organization as well as with individuals working for other firms. Not only the individual organization that succeeds in doing this, but also the industry as a whole, will benefit from such knowledge creation and sharing. This may become a key selling point for the construction industry to attract new blood.

V. PRODUCT-PROCESS MODEL FOR THE DESIGN DEVELOPMENT OF HIGH-TECH FACILITIES

V.1. PURPOSE OF THE PRODUCT-PROCESS MODEL

This chapter describes the product-process model that provides the foundation for the computer simulation models presented in the two following chapters of this dissertation. This model synthesizes the knowledge of the design development process of semiconductor fabrication facilities (fabs) that I gained through interviews with senior designers, design engineers and architects, draftsmen, and managers at Industrial Design Corporation (IDC). The product-process model represents this process from a production perspective. By this, I mean that it represents the design process in terms of the tasks designers must execute, the design criteria that guide such tasks, the types of decisions and production choices that designers must make, and the exchanges of information between designers.

The product-process model does not explicitly represent the actors who perform the design tasks, although the definitions of the task durations implicitly presuppose a specific allocation of human resources. Accordingly, this work is complementary in its approach to computational models of organizations, such as the Virtual Design Team (VDT) (Jin and Levitt 1996) and Fast-Track VDT (FT-VDT) (Salazar-Kish 2001)—two process-information models that mimic actors' tasks and behaviors without providing much detail on the nature of the work itself; or the work of Lin and Hui (1997)—a computational model that contrasts problem solving capabilities of different organizational structures.

V.2. SCOPE OF THE PRODUCT-PROCESS MODEL

The product-process model represents the design development in three phases—conceptualization, concept development, and design detailing (Figures V.1.1 and V.1.2). The model focuses on the concept development phase for five fab systems: chemical or process support; structural; heating, ventilating, and air conditioning (HVAC) (designed by dry-mechanical engineers); electrical; and architectural. Dry-mechanical, electrical, and chemical specialists calculate the utility loads, then size and lay out the routings and equipment of their respective systems. Architectural and structural specialists design other building structures, such as the foundations, exterior and interior walls, columns, floors, and the roof.

Admittedly, the decisions other design specialists make (such as engineers specialized in plumbing, wet-mechanical, instrumentation and controls, fire safety, and telecom) will directly or indirectly affect the decisions shown in the model. Likewise, interactions with third parties (such as city authorities, consultants, fire marshals, and insurance underwriters) also influence design development. For simplicity's sake, the model does not represent these interactions.

Table V.1 explains each symbol in the product-process model. In addition, Appendix II characterizes each symbol for the five fab systems. The estimates of hours spent by designers in each concept development task presuppose that they have on hand all the information that they need to execute the tasks and that they work on a full-time basis. These estimates are for a fab with a cleanroom size of approximately 80,000 to 100,000 sq.ft.

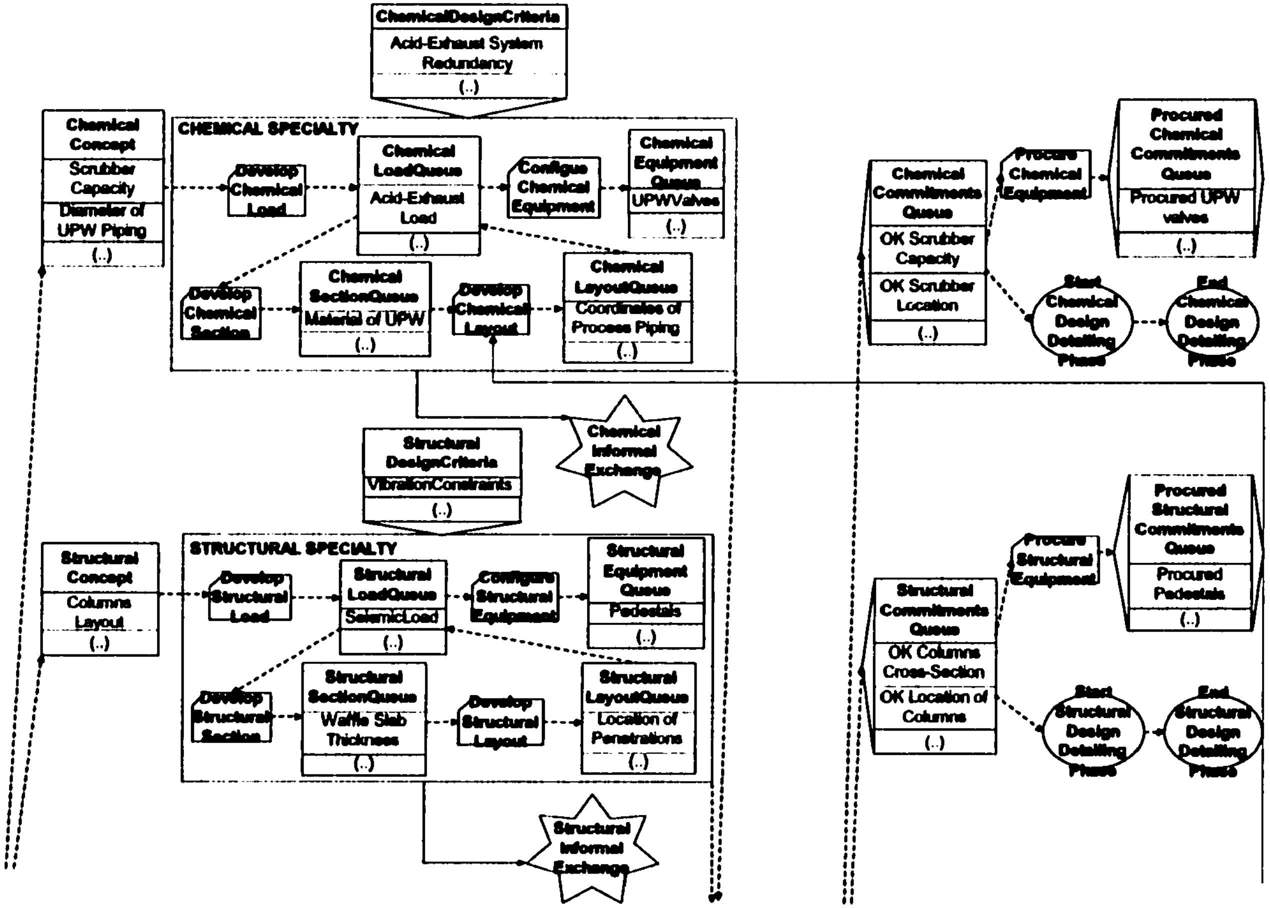


Figure V.1.1 - Product-Process Model for the Design Development of High-Tech Facilities (1 of 2)

(See Table V.1 for Meaning of Symbols)

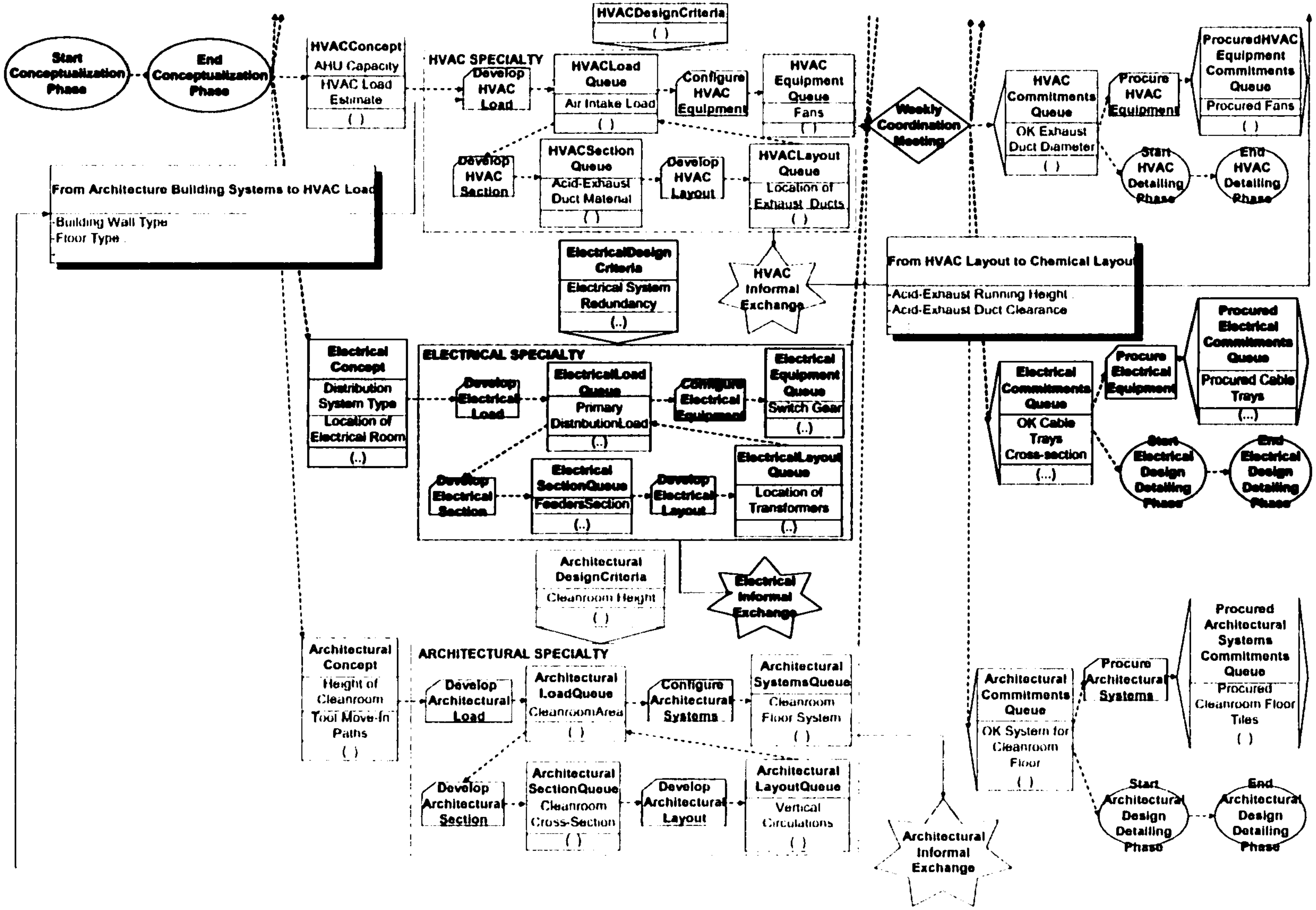
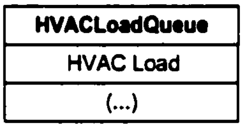
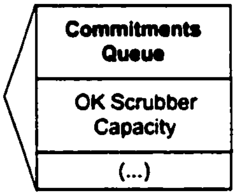
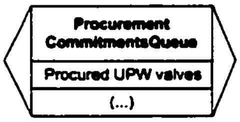
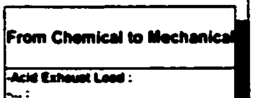
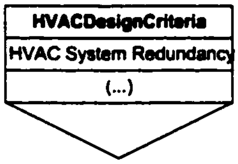
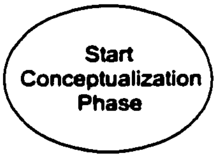


Figure V.1.2 - Product-Process Model for the Design Development of High-Tech Facilities (2 of 2)

Table V.1 - Symbols Used to Represent Design Development

SYMBOL	NAME	EXPLANATION
	Design/ Procurement Task	A rectangle with a cut-off corner represents a Design/ProcurementTask. Tasks produce a set of design decisions and production choices or actions.
	Decisions Queue	A subdivided rectangle denotes a DecisionsQueue. It represents the decisions that result from each DesignTask.
	Decision Point	A diamond denotes a DecisionPoint. It represents the moment at which designers make critical decisions, such as during a coordination meeting.
	Commitments Queue	A closed rectangle with a triangle at the left side denotes a CommitmentsQueue. It represents the commitments on design decisions and on production choices that result from a DecisionPoint.
	Procurement Commitments Queue	A closed rectangle with adjacent triangles at both sides denotes a ProcurementCommitmentsQueue. It represents the commitments that result from a ProcurementTask.
	Information Hand-off	A close shadowed rectangle denotes an InformationHand-off. It represents a subset of the design decisions that result from a DesignTask.

	Design Criteria	A closed rectangle with a triangle underneath denotes the DesignCriteria. It represents the criteria that guide the design decisions. These criteria can change along the design process.
	Distribution Point	A star denotes a DistributionPoint. It represents the informal distribution of InformationHand-offs by one design specialty to other specialties.
---------▶	Information PushFlow	A dashed arrow denotes an InformationPushFlow. It indicates the push flow of information from one DesignTask to the next.
————▶	Push/Pull Hand-off Flow	A solid arrow denotes a Push/PullHand-offFlow. It indicates the push or pull flow of InformationHand-offs between two tasks.
	Project Milestone	An ellipse denotes a Project Milestone. It represents important events, such as the start and end of the conceptualization phase.

During conceptualization, designers set forth the design criteria and one or more design concepts based on the client's performance requirements. Designers first review the alternatives they considered and the decisions they made in past projects, for the current client or others. They review historical data, such as CAD drawings, spreadsheets with utility loads, and analytical models. In light of the new design criteria, designers use empirical rules to decide to what extent they should replicate previous decisions in the new project. Empirical rules may take as input, for instance, the expected area for the cleanroom or the average number of wafer starts per month. The resulting fab concept (or alternative concepts) consists of initial estimates for the critical design features of each fab system, such as estimates on design loads, on sizes of critical cross-sections, on space requirements, and on major equipment needs. The conceptualization phase conducted by designers lasts on average four to six weeks.

During concept development, designers use sophisticated computer-based analytical tools to refine the fab concept for each functional area. Functional areas are the spaces inside the fab categorized by their programmed function, such as the cleanroom, the mechanical rooms, the electrical rooms, the process support areas, the HVAC shafts, the subfab, the circulation ways, the cafeteria, and the offices. In addition, designers may procure equipment pieces with long delivery lead times. This phase lasts, on average, two to three months.

During design detailing, designers further refine their prior decisions in order to produce the documentation that will guide on-site construction. Design detailing may be done by designers in the design firm (though not necessarily those who were previously involved), or by detailers working for the specialty contracting firms that will install the fab systems on site. Accordingly, the duration of this phase may vary significantly across different fab systems and across different projects.

I have not tested the validity of the product-process model with respect to its ability to represent the design development of other kinds of high-tech facilities or in other design-build organizations. Nevertheless, because the model focuses primarily on the decisions people make and less on the tasks they execute daily, I expect the model is adaptable.

V.3. ARCHITECTURE OF THE PRODUCT MODEL

Figure V.2 shows the product model architecture and its specific instantiation for the acid-exhaust system in a fab. The class diagram as shown uses the Unified Modeling Language (UML) (Booch et al. 1999). UML is a graphical notation system to model static and dynamic characteristics in an object-oriented environment. A class diagram presents a static view of a system that describes the properties of classes. Classes are sets of objects that have a common structure and behavior expressed in their attributes, operations, and relationships.

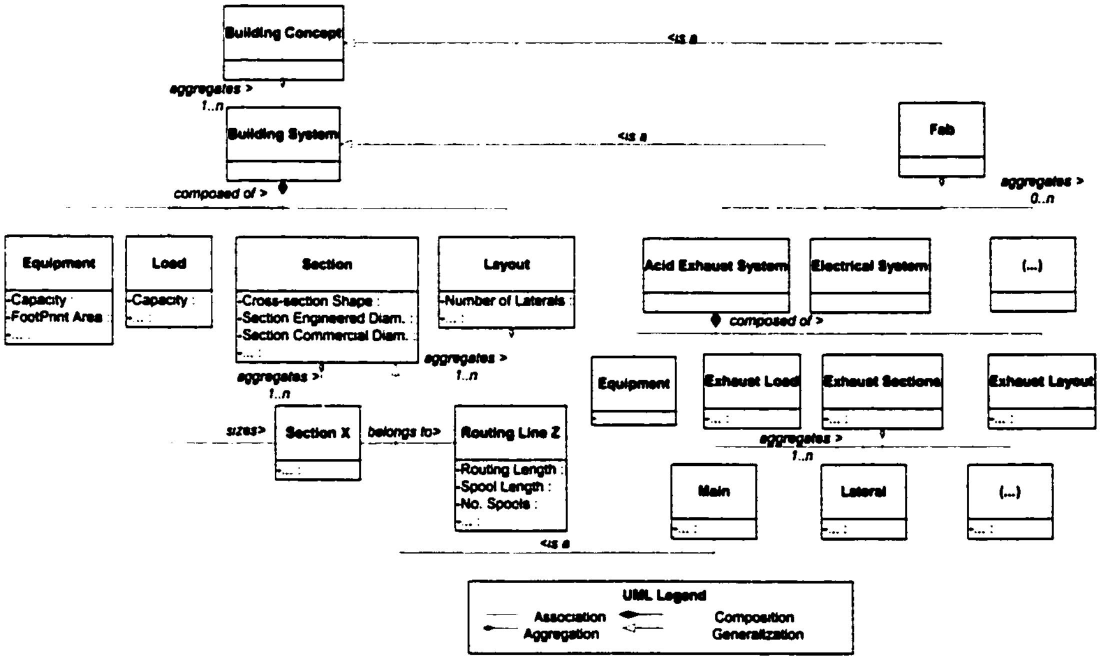


Figure V.2 - Generic Product Model Architecture and Instantiation of the Acid-Exhaust System

The types of relationships described in Booch et al. (1999) are:

- **Generalization**: objects of more specific classes inherit the structure and behavior of more general classes (is-a and can-be-a relationships).

- **Association**: a link describing a to-be-named relationship among a set of objects.
- **Aggregation**: a special form of association that specifies a part-whole relationship between the part and the aggregate (the whole) (part-of and has-part relationships), where destruction of the whole does not destroy the parts (e.g., the subfab system may or may not include the acid-exhaust system: the acid-exhaust system is part of the subfab system).
- **Composition**: a form of aggregation with mandatory ownership (e.g., a structural or functional relationship) and usually coincident lifetime of the parts relative to the whole. The parts are destroyed along with the whole: e.g., an acid-exhaust system will not function if its scrubber is defective: the scrubber is a part of the acid-exhaust system.

The product architecture defines a Building Concept (e.g., a high-tech facility) as an aggregate of Building Systems, including the electrical, structural, or the acid-exhaust systems. Each Building System is composed of four classes: Equipment, Load, Section, and Layout. The Load class characterizes the load that the system should serve in terms of intensity, frequency, and its static/dynamic nature. Instances of Load objects would be the gravity and dynamic seismic loads acting on the physical structure, or the load the acid-exhaust system has to exhaust. Load objects are used to size the Section and the Equipment objects.

The Section class characterizes the cross-sections of the system elements in terms of geometric configuration, dimensions, and materials. Instances of Section objects would be the critical cross-sections of beams, columns, and slabs, or the upstream and downstream cross-sections of selected utility routings, such as those of the main and lateral fab routings. Each Section object belongs to a Layout object. The Layout class characterizes the topology of the system elements in the three-dimensional space (e.g., extremes of a beam or a routing line). Instances of Layout objects would be the beams and slabs of the structural system, or the routing lines of the acid-exhaust system.

The Equipment class characterizes the major pieces of equipment of each system in terms of supplier, footprint area, supplier delivery time, and operating requirements. Instances of Equipment objects would be seismic isolator bearings, electrical transformers, scrubbers, pre-fabricated interior wall panels, or air-handling units.

V.4. CHOICE OF A SIMULATION PACKAGE TO IMPLEMENT THE PRODUCT-PROCESS MODEL

Many computer simulation packages are available. The main advantage of using a simulation package rather than using a general-purpose programming language, such as C or C++, is that simulation packages automatically provide most of the features to build a model of the kind envisioned in this research. Their use may therefore decrease the needed programming time significantly. Law and Kelton (2000) put simulation packages into two groups: general-purpose and application-oriented. They discuss the relative advantages of each group, in terms of, among other things, ease of use, modeling flexibility, and execution time. Another important categorization concerns the modeling paradigms that simulation packages use, which typically fall into one of the three approaches: (1) block languages or process interaction, (2) activity-scanning, and (3) event-scheduling systems.

Most commercially available simulation packages—such as EXTEND (Imagine That, Inc. 1997), ARENA (Systems Modeling Corporation 1999), or SIMPLE++

(Tecnomatix Technologies, Inc. 1998)—belong to the category of block languages. Block languages model systems from the perspective of transient entities or parts that enter and leave the system and that are occasionally seized by resident entities or by resources that stay in the system. These simulation packages provide multiple preprogrammed blocks of code, each of which has a specific functionality. Typically, these packages also provide animation modules that help to understand the behavior of the modeled systems.

However, block languages can have major disadvantages from a modeler's perspective. Because the precise functionality of blocks may not be clear, modelers using these simulation packages often run the risk that the systems they model do not behave as originally intended. The modeling flexibility of these packages is also constrained by the set of blocks and by the functionality each one provides. This feature may limit a package's ability to represent the behavior of more complex systems, even if some packages let users create new blocks. Moreover, because most of these packages serve commercial purposes, the free demos that potential users can order or download from the Internet frequently have limited capabilities or limited free trial time. Consequently, users can get a good grasp of the capabilities of a specific software package only if they commit significant time and financial resources in purchasing a copy of the system or in attending training sessions. These aforementioned features led me to not use a simulation package based on a block language for implementing the product-process model.

Activity-scanning systems—such as ALPHA/Sim (Moore and Brennan 1996) or STROBOSCOPE (Martinez 1996)—provide mathematical and graphical modeling techniques that focus on the operating cycles of resident entities (physical or abstract resources). ALPHA/Sim is based on Petri Nets, a conceptual and simple modeling technique originally developed by C.A. Petri (1962) in the early 1960s to characterize concurrent operations in computer systems. STROBOSCOPE, which was created more recently, provides several higher-level programming language constructs. STROBOSCOPE has been used mainly to model queuing problems in the AEC industry at large, including design and construction operations (e.g., Ioannou and Martinez 1996), and exchanges of information to support construction management (e.g., Tommelein 1998a).

These two activity-scanning systems do not contain explicit language constructs to model preemption. Preemption is an action taken to check another action beforehand. Preemption is required to model either the cancellation of a scheduled activity because of an event that occurs beforehand, or the interruption of an activity because of an event that occurs during its execution. Preemption is useful, for instance, to simulate (un)anticipated events such as disruptions caused by machine breakdowns (e.g., the expected mean time to failure is less than the planned activity completion time), and the release or draw of resources into an activity during the activity's execution (e.g., when it is discovered that some resources are lacking) (Gil and Tommelein 2001).

In the specific case of STROBOSCOPE, its developers carefully deliberated not to implement preemption. Preemption occurs in many systems beyond the most simple ones. Expressing the specifics of a case of preemption in a simulation language requires much more than merely interrupting an activity. It may require selecting one or a few instance(s) to interrupt among multiple instances of the same activity, or drawing one or a few resource(s) out of selected instances of multiple activities. Preemption may manifest itself differently for different instances of activities and resources. Numerous possibilities also exist regarding how to proceed with the simulation after preemption has occurred. Capturing useful cases of preemption in higher-language constructs is feasible. Nevertheless, given the inevitable complexity of those constructs if they were to capture any preemption subtlety at all, it is not obvious that learning to use them and then using them would make it any easier on the programmer than implementing the desired preemption mechanism using the already existing constructs. Consequently, users of today's STROBOSCOPE's version 1.5.3.0 must exert special effort in terms of code writing to implement preemptive behavior.

Event-scheduling systems model a system by "identifying its characteristic events and then writing a set of event routines that give a detailed description of the state changes taking place at the time of each event" (Law and Kelton 2000 p. 205). Event-scheduling systems have the ability to model both the process flows of transient entities as well as the operating cycles of resident entities (Schruben and Schruben 1999). Within the domain of this dissertation, transient entities can be the design decisions that flow between tasks, or the spools that are shipped from the fabrication shop to the construction site. Operating cycles of resident entities can be design tasks performed by designers or construction tasks performed by on-site crews.

SIGMA is a discrete-event simulation environment based on event-scheduling (Schruben and Schruben 1999). SIGMA was originally developed by Professor Lee Schruben who teaches in the Industrial Engineering and Operations Research Department at U.C. Berkeley. SIGMA provides fundamental, low-level programming language constructs on which higher-level constructs can be built. SIGMA can be used to model problems in any domain. It has been used in diverse applications, including queuing and scheduling problems, as well as in system dynamics problems such as the growth and decline of biological populations (e.g., Duenyas et al. 1994, Allore et al. 1998).

I chose SIGMA to implement excerpts of the previously-presented product-process model primarily because its graphical interface includes canceling edges, which makes it easy for users to build a model that can interrupt and cancel tasks along a simulation run. Thus, preemption is easily modeled. Ingalls et al. (1996) present an alternative way to model preemption using event graphs in SIGMA without using canceling arcs. Nevertheless, they acknowledge the convenience and functionality of the 'canceling edge' construct.

I used the following implementation procedures: (1) events correspond to the start- and end-points of each task (such as start and end of conceptualization) and to decision points (such as meetings); (2) global state variables store the value of the design features (e.g., the diameter of a duct cross-section) and of the production choices (e.g., the number and length of spools to procure); (3) state changes, programmed at each event, implement designers' rules of thumb; (4) scheduling edges model information and material flows between events; (5) Boolean statements, programmed at each edge, model time delays and edge conditions; and (6) canceling edges between events enable one event to cancel another event after a time delay if specific edge conditions are met.

In the next two chapters, I implement an excerpt of the product-process model that was described in this chapter with SIGMA. I use the resulting simulation models for sharpening theoretical understanding on the effectiveness of alternative ways to deliver projects in unpredictable environments. Specifically, in Chapter VI, I use a generic simulation model of design development for testing the effectiveness of postponed commitment to manage design processes. In Chapter VII, I characterize the generic simulation model for the case of the acid-exhaust system. I integrate this model with a product-process simulation model for the subsequent procurement, fabrication, assembly, and spool installation phases. I then use this systemic simulation model to study alternative systems to deliver projects. These systems differ based on when specialty contractors get involved in design and when construction starts relative to the completion of design.

VI. SIMULATION OF THE DESIGN DEVELOPMENT PROCESS IN UNPREDICTABLE ENVIRONMENTS

VI.1. INTRODUCTION

Empirical studies have shown that postponing design decisions can be effective for managing product development processes in unpredictable environments (e.g., Iansiti 1995). At Toyota automotive company, Ward et al. (1995) observed that decisions on design features are frequently postponed until the last possible moment so that designers can have more time to refine the design, understand clients' expectations, and ensure that the design is executable. In contrast, from what I observed during empirical research, AEC practitioners seldom use postponement strategies. Instead, they typically adopt early commitment strategies that frequently result in missing promised due dates and in performing extensive rework (Pietroforte 1997).

Here, I use computer simulation to study the effects of postponed commitment for managing design development of semiconductor fabrication facilities (fabs). The initial rationale was based on the belief that, given the frequency of changes in fab design criteria, designers would be better off delaying tasks to the last responsible moment. This is the moment that allows them to minimize design rework due to unanticipated design criteria changes while simultaneously they still meet the project delivery dates.

The purpose of this chapter is twofold. First, it describes a generic simulation model of design development processes. Second, it illustrates a methodology to explore the effects of postponing design tasks in unpredictable environments.

VI.2. RELATED RESEARCH

Many studies have theorized on the nature of design processes and developed tools to help manage these processes. The stage-gate system, for example, proposes a gate as an entrance to a design phase or stage (Cooper 1990). Managers can use the stage-gate system to manage progress on a product development effort as well as to evaluate the ongoing fit of each project with the company's overall product portfolio. The gates in-between stages are opportunities for senior management to give feedback to product development teams, to make resource allocation decisions, and to make "go/kill" decisions for the project (ibid. 1990).

With a different purpose, the Design Structure Matrix (DSM) parses the activities for product development into smaller tasks than those that would be specified in most stage-gate models (Gebala and Eppinger 1991, Smith and Eppinger 1997a). Managers can use the DSM to manage precedence relationships among project tasks, and then to organize personnel around completing those tasks. DSM provides partitioning and tearing algorithms for ordering tasks and thereby minimize the total duration of the process. DSM is, however, a static model since it assumes fixed design criteria throughout the design process.

Work in computational and mathematical organizational theory has also produced generic models that provide insight into the nature of design processes in uncertain environments (Carley 1995). Jin and Levitt (1996) describe the Virtual Design Team (VDT), a process-information simulation model that yields insight into the influence of the micro behavior of participants on the overall performance of the design process. Lin and Hui (1997) have conducted similar work to compare the performance of lean and mass organizational systems. In the field of system dynamics, Ford and Sterman (1998, 2000) have studied the effects on the design process of the propensity of actors to conceal changes and of task concurrency.

Empirical research on design development includes studies on concurrent engineering and product development practices in the automotive industry (e.g., Clark and Fujimoto 1991, Womack et al. 1990, Ward at al. 1995, Sobek II et al. 1999) and in unpredictable environments (e.g., Eisenhardt and Tabrizi 1995, Iansiti 1995, 1997, Thomke and Reinertsen 1998). These studies show gains in process efficiency and in product quality that result from different managerial strategies, such as the early and long-term involvement of suppliers in product development, postponement of decisions, and set-based concurrent engineering.

Recent analytical frameworks of design development are closer to the work presented here. Bhattacharya et al. (1998), for example, claim that having a sharp product definition early on may not be desirable or even feasible for product development in unpredictable environments. Instead, they propose that firms delay commitments and allow product definition along the development process, according to the level of uncertainty they expect, their own risk profile, and the value of customer information. Wood (1997) analyzes the effectiveness of scalable fab definitions for accelerating the start of manufacturing and for meeting the needs of manufacturers in flexibility—goals equivalent to those that direct the work that follows.

VI.3. PRODUCT-PROCESS SIMULATION OF DESIGN DEVELOPMENT

VI.3.1. PRODUCT-PROCESS MODEL

Figure VI.1 shows a generic product-process model for design development. Design development has two distinct phases: a conceptualization phase followed by a concept development phase.

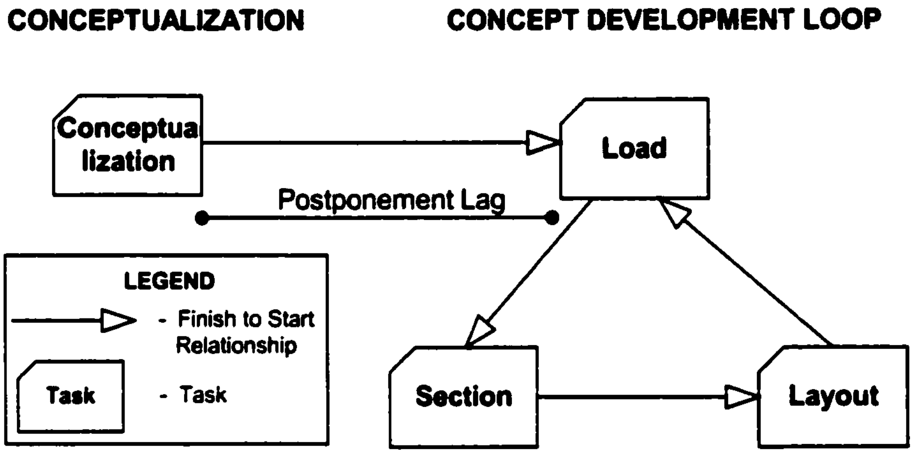


Figure VI.1 - Design Development Model

During conceptualization, designers primarily use rules of thumb and historical data to make a first pass at the design features. During concept development, designers may use sophisticated analytical tools to refine the decisions made at conceptualization, in light of updated design criteria. The model represents concept development as a loop of three tasks: load-, section-, and layout development. Load development is the process during which designers calculate the loads that the system should serve. During section development, designers size the cross-sections of the main system parts based on the loads previously determined. During layout development, designers decide the routing of the facility systems and the location of major pieces of equipment.

Designers may repeat the concept development tasks in their search for a satisfying solution. This may happen even when designers possess from the start all the information they need and they know that this information will not change (Simon 1969). For simplicity's sake, I assume that designers do each task only once to find a satisfying solution unless the design criteria change. Task iteration may also be caused by interdependencies between design specialties. Here, I focus on the impacts that client-driven changes cause into the design process and I disregard interdependencies between concurrent design processes. Thus, although I agree that iteration is part of the exploration process so common in the search for a good design solution, I question whether or not all iteration is equally valuable.

VI.3.2. DESIGN CRITERIA UNCERTAINTY

There are several sources of uncertainty in fab design criteria, such as the concurrency of the fab design effort with the chip product development, the unknown characteristics of the production tools, and the unpredictability of market demand. This uncertainty causes changes in design criteria. I focus my work on two of the most disruptive changes designers have to cope with: changes in the dimensions of the cleanroom and changes in the tools to be installed inside.

Changes in the cleanroom dimensions, although not frequent, can occur if the manufacturer needs to increase or decrease the fab capacity. Changes in tools, which are more frequent than cleanroom changes, may result from changes in the production technology or from changes in tool suppliers. Tool changes may directly affect the location of tools in the cleanroom, the number of tools of each kind, the technical characteristics of the tools, and the utility loads needed to serve the tools. Designers pointed out that when the cleanroom width and length increase by 10% or more, they have to rework the conceptualization and all the concept development tasks. Likewise, when tool changes increase the design load by 10% or more, designers have to redo all the concept development tasks. The impact of tool changes on conceptualization can be neglected because designers can more easily accommodate these changes throughout this phase. I assume that changes in cleanroom dimensions and in tools are stochastically independent from each other as well as from the ongoing design progress. Figure VI.2 shows an excerpt of the random tree that is the basis of the probability density curves that model changes in cleanroom dimensions and in tools.

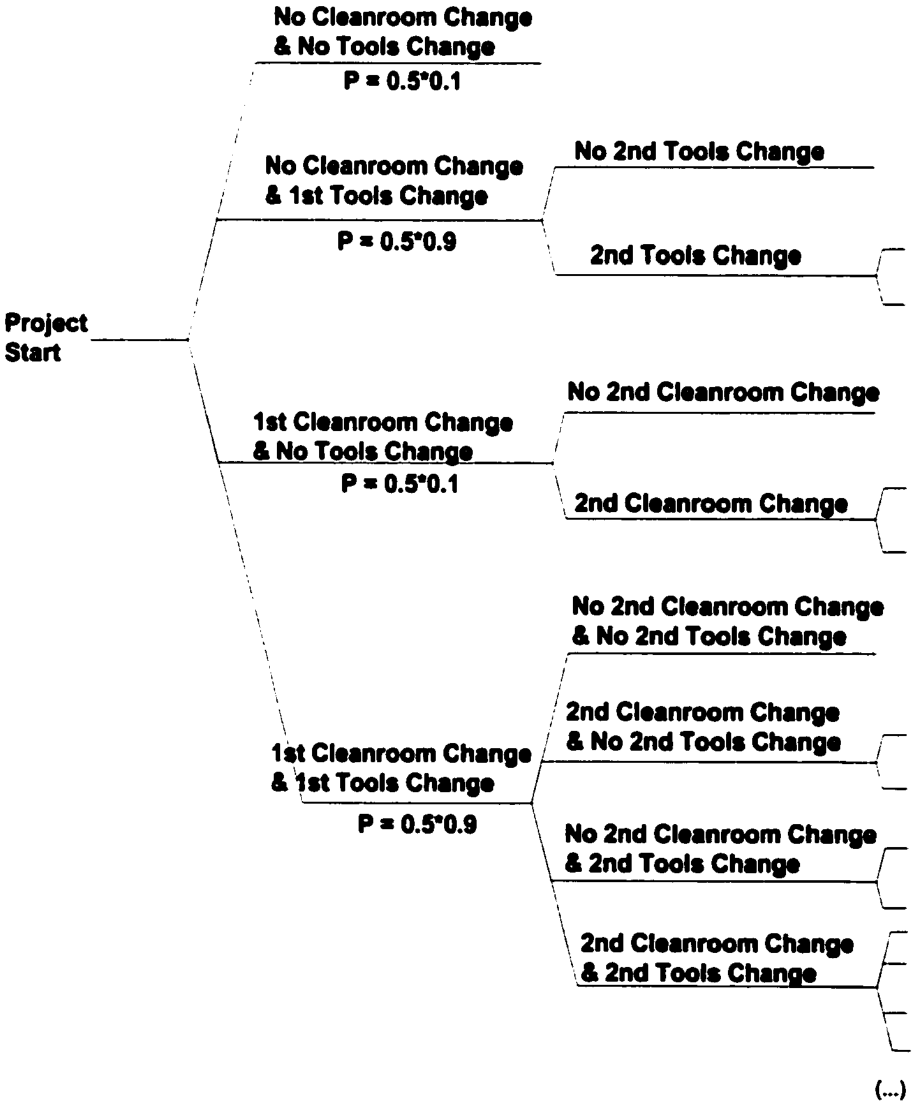


Figure VI.2 - Excerpt of Random Tree for Changes in Cleanroom Dimensions and in Tools

Figures VI.3 (a) and (b) represent the histograms of design changes that I developed jointly with lead designers for R&D fabs of complex process technologies, including leading-edge microprocessors and application specific integrated circuits (ASICs). I used re-scaled and shifted symmetric beta random variables [a+(b-a)*Beta ($\alpha_1=2,\alpha_2=2$)] to express the variability around the time when a change can occur.

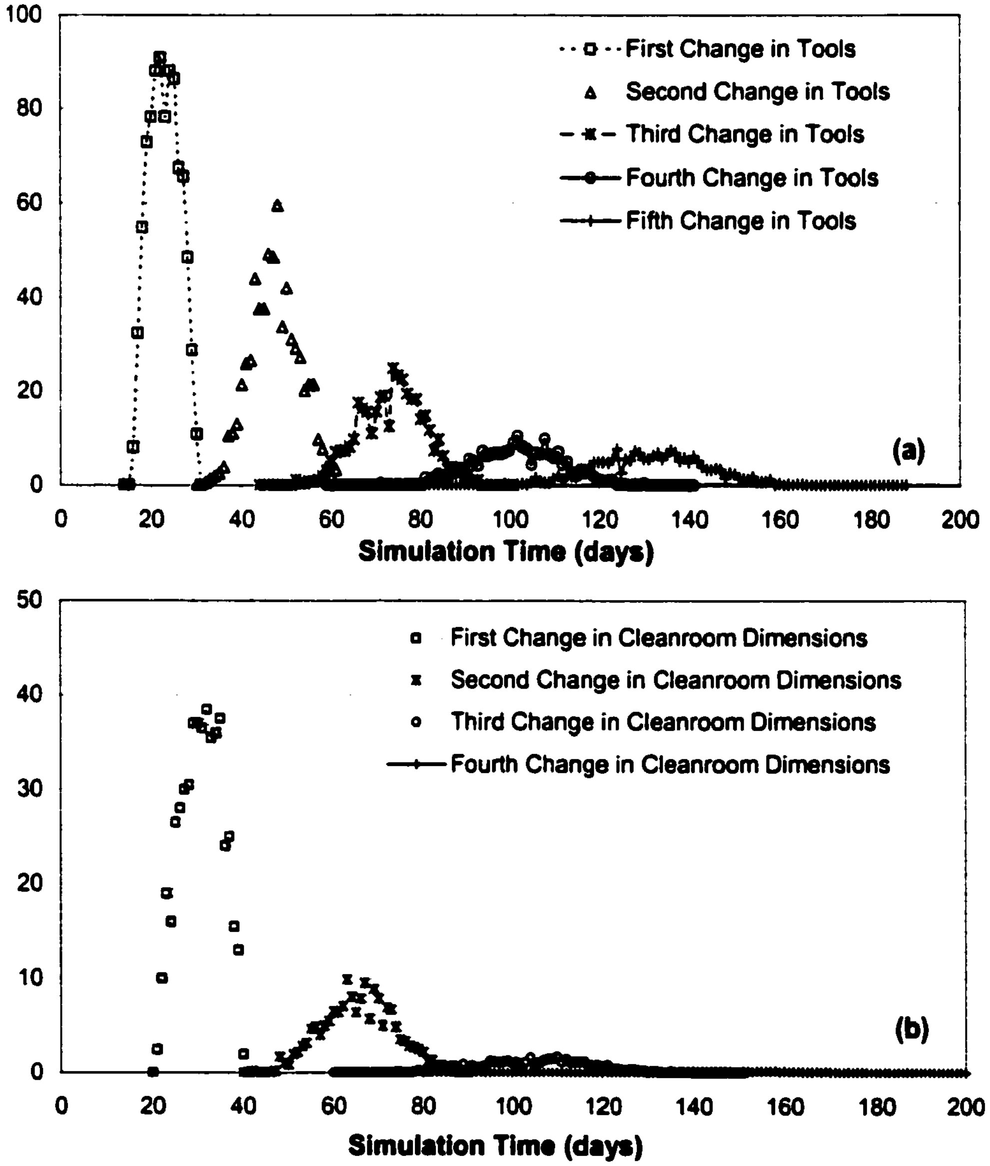


Figure VI.3 - Histograms for 1,000 Runs of Changes in: (a) Cleanroom Dimensions; (b) Production Tools

The probabilistic and temporal relationships between changes of the same kind, within any stream of changes, can be stated as

$$P(\text{change}_i) = A \qquad \text{(equation VI.1)}$$

$$P(\text{change}_2 \mid \text{change}_1) = \frac{A}{1 + B * 1.0} \qquad \text{(equation VI.2)}$$

or in general:

$$P(\text{change}_i \mid \text{change}_{i-1}) = \frac{A}{1 + B * (i - 1)}, \quad i \geq 2 \qquad \text{(equation VI.3)}$$

$$P(\text{change}_i \mid \overline{\text{change}_{i-1}}) = 0, \quad i \geq 2 \qquad \text{(equation VI.4)}$$

$$T_1 = C + C * \text{Beta}_1(\alpha_1 = 2, \alpha_2 = 2)\ (\text{days}) \qquad \text{(equation VI.5)}$$

$$T_2 = T_1 + C + C * \text{Beta}_2(\alpha_1 = 2, \alpha_2 = 2) * (1 + B)(\text{days}) \qquad \text{(equation VI.6)}$$

or in general:

$$T_i = C * \left[i + \sum_{s=1}^{i} \{\text{Beta}_s(\alpha_1 = 2, \alpha_2 = 2) * (1 + B * (s - 1))\} \right] (\text{days}), \quad i \geq 1 \qquad \text{(equation VI.7)}$$

where

P(i) = Probability of change i to occur

P(i|i-1) = Probability of change i to occur given the prior occurrence of change i-1

A, B, C = Constants

T_i = Time when change i occurs (days)

$\text{Beta}_i(\alpha_1=2, \alpha_2=2)$ = Symmetric beta random variable that is sampled for every value of i

The occurrence of a first change conditions the occurrence of a subsequent change of the same type. The probabilities of the subsequent changes decrease by dividing the probabilities of the first change by the terms of an increasing numeric sequence. In addition, the model increases the re-scaled intervals of the beta distributions between subsequent changes by multiplying them by the terms of the same numeric sequence. To clarify, the probability of occurrence of a stream of changes is

$$P(\text{change}_i \cap \text{change}_{i-1} \cap \ldots \cap \text{change}_1) = \prod_{s=1}^{i} \frac{A}{1 + B*(s-1)}, \; i \geq 1 \qquad \text{(equation VI.8)}$$

Table VI.1 presents the designers' estimates of the constants. These estimates reflect their perceptions of the frequency and time of occurrence of design criteria changes, for the case of R&D fab projects. I leave to the end of this chapter the discussion on the validity of the model inputs.

Table VI.1 - Estimates of A, B, and C, for the Design Development Process of R&D fabs

Constants	Cleanroom Dimensions Change	Tools Change
A	0.5	0.9
B	0.5	0.25
C (days)	20	15

The relations within a stream of cleanroom dimensions changes, illustrated in Figure IV.4, can be thus stated as

$$P(\text{change}_1) = 0.5 \qquad \text{(equation VI.9)}$$

$$P(\text{change}_2 \mid \text{change}_1) = \frac{0.5}{1.5} = 0.33 \qquad \text{(equation VI.10)}$$

$$P(\text{change}_3 \mid \text{change}_2) = \frac{0.5}{2.0} = 0.25 \qquad \text{(equation VI.11)}$$

or in general

$$P(\text{change}_i \mid \text{change}_{i-1}) = \frac{1}{1+i}, i \geq 2 \qquad \text{(equation VI.12)}$$

$$P(\text{change}_i \cap \text{change}_{i-1} \cap \ldots \cap \text{change}_1) = \prod_{s=1}^{i} \frac{1}{1+s}, i \geq 1 \qquad \text{(equation VI.13)}$$

$$T_i = 20 * \left[i + \sum_{s=1}^{i} \{\text{beta}_s(\alpha_1 = 2, \alpha_2 = 2) * \left(\frac{s+1}{2}\right)\} \right] (\text{days}), i \geq 1 \qquad \text{(equation VI.14)}$$

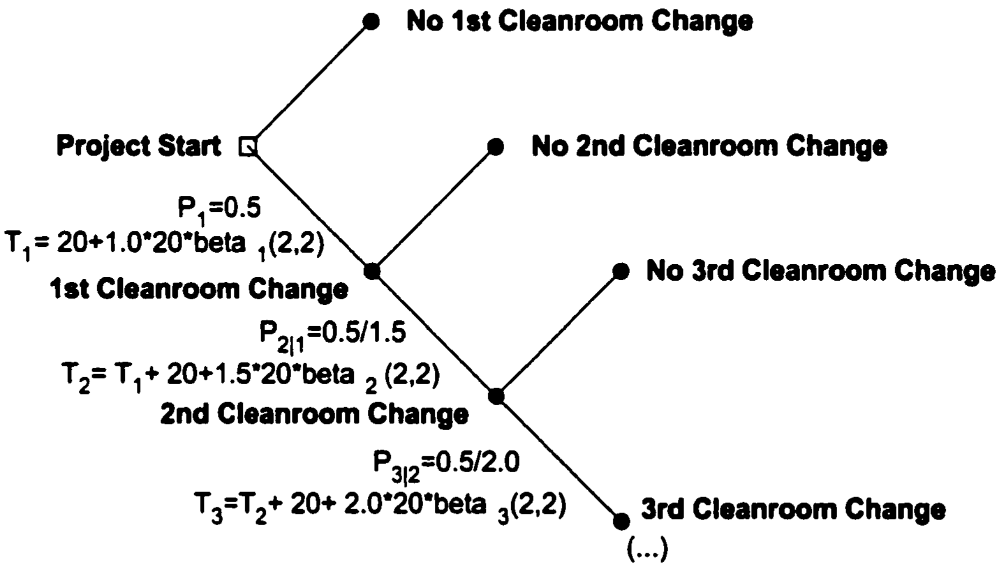


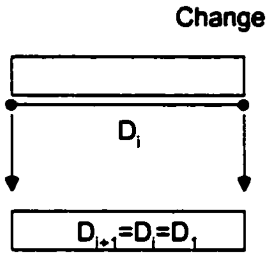
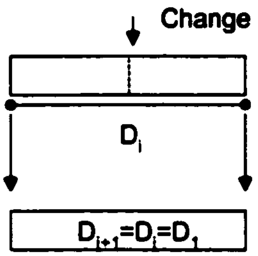
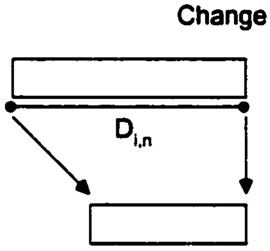
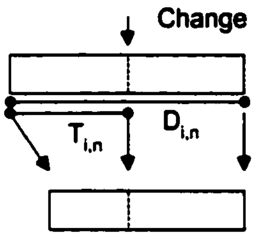
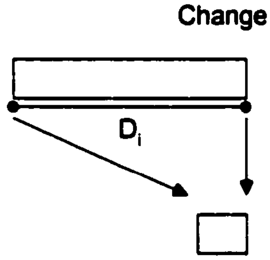
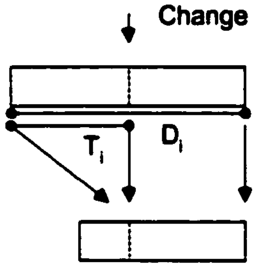
Figure VI.4 - Excerpt of Detailed Random Tree for Changes in Cleanroom Dimensions

VI.3.3. ON THE NATURE OF REWORK

I used three distinct, hypothetical rework algorithms, illustrated in Figure VI.5, for probing into the effects of postponing design tasks.

Algorithm 1: No learning

The first rework algorithm models a scenario in which, whenever a change occurs, the expected duration for a task that needs to be repeated is equal to its initial duration. In other words, the algorithm assumes that designers would not learn or gain process efficiencies when repeating a task. I assume that this scenario holds both for work interrupted by a change and for work that was already done when a change occurred.

Algorithm	Change Occurs After Task is Completed	Change Occurs While Task is Underway
No Learning	 $D_{i+1}=D_i=D_1$	 $D_{i+1}=D_i=D_1$
Limited Learning	 $D_{1,n+1}=D_{1,1}/(n+1)$	 $D_{i+1,n}=D_{i,n}-T_{i,n}/(n+1)$
Set-Based Design	 $D_{i+1}=c.D_1$	 $D_{i+1}=D_i-T_i+c.D_1$

i - iteration number

c - constant

i,n - number of times (i) designers have started to iterate the task, given a number of times (n) that they already completely executed the task

$D_{i,n}$ - expected duration of the task in iteration i, given that designers have already completely executed the task n times, if no design change interrupts its execution

$T_{i,n}$ - time designers spent working on iteration i before being interrupted by a change, given that they already completely executed the task n times

Figure VI.5 - Representation of Three Rework Algorithms

The no-learning scenario can be written as

$$D_{i+1} = D_i = D_1, \ \forall i \qquad \text{(equation VI.15)}$$

where

i = number of times designers start to perform the task ($i = 1,2,3,\ldots$)

D_1 = expected duration of a task at the first time designers execute it, if a design change does not interrupt its execution (days)

D_i = expected duration of a task at iteration i, if a change does not interrupt its execution (days)

Algorithm 2: Limited learning

The second rework algorithm models limited learning and efficiency gains between iterations. To determine the duration of a task in a rework cycle, its duration in the precedent cycle is prorated using the following equations:

1) if designers had concluded the task when the change occurred:

$$D_{1,n+1} = \frac{n * D_{1,n}}{n+1} = \frac{D_{1,1}}{n+1}, \quad \forall n \qquad \text{(equation VI.16)}$$

2) if the change interrupted the execution of the task:

$$D_{i+1,n} = D_{i,n} - T_{i,n} + \frac{n * T_{i,n}}{n+1} = D_{i,n} - \frac{T_{i,n}}{n+1}, \quad \forall n, \forall i \qquad \text{(equation VI.17)}$$

where

i, n = number of times ($i = 1,2,3,\ldots$) designers have started to perform the task, given a previous number of times ($n = 1,2,3,\ldots$) designers already completely executed the task

$D_{1,1}$ = expected duration of the task the first time designers execute it, if a design change does not interrupt its execution (days)

$D_{i,n}$ = expected duration of the task in iteration i, and given that designers have already completely executed the task n times, if no design change interrupts its execution (days)

$T_{i,n}$ = time designers spent working on iteration i, and given that they already completely executed the task n times, before a change interrupts its execution (days)

Algorithm 3: Set-based Design

The third rework algorithm represents a speculative scenario in which designers adopt a set-based design strategy. Set-based design is an alternative to point-based design. In point-based design, designers make early commitments to a single solution and progressively refine it as the design process evolves. By contrast, in set-based design, designers work with sets of solutions that they gradually narrow as information on design criteria and customer expectations sharpens (Sobek II et al. 1999).

The rework algorithm for modeling set-based design assumes that the initial set of design solutions exhausts all solutions that can satisfy any plausible change of design criteria. For limiting the amount of time to develop this initial set, I assume designers would prune it from solutions that they would consider unrealistic. Consequently, if a change of design criteria occurs after designers had already concluded a task, they only incur a time penalty to prune the incompatible solutions from the initial set. If a change interrupts a task, I assume that, in the next iteration, in addition to spending time pruning the set, designers still spend extra time to complete the work that was cut off by the change (Figures VI.5 and VI.6).

1) if designers have concluded the task when the change occurred:

$$D_{i+1} = c * D_1, \forall i \qquad \text{(equation VI.18)}$$

2) if the change interrupts the execution of the task:

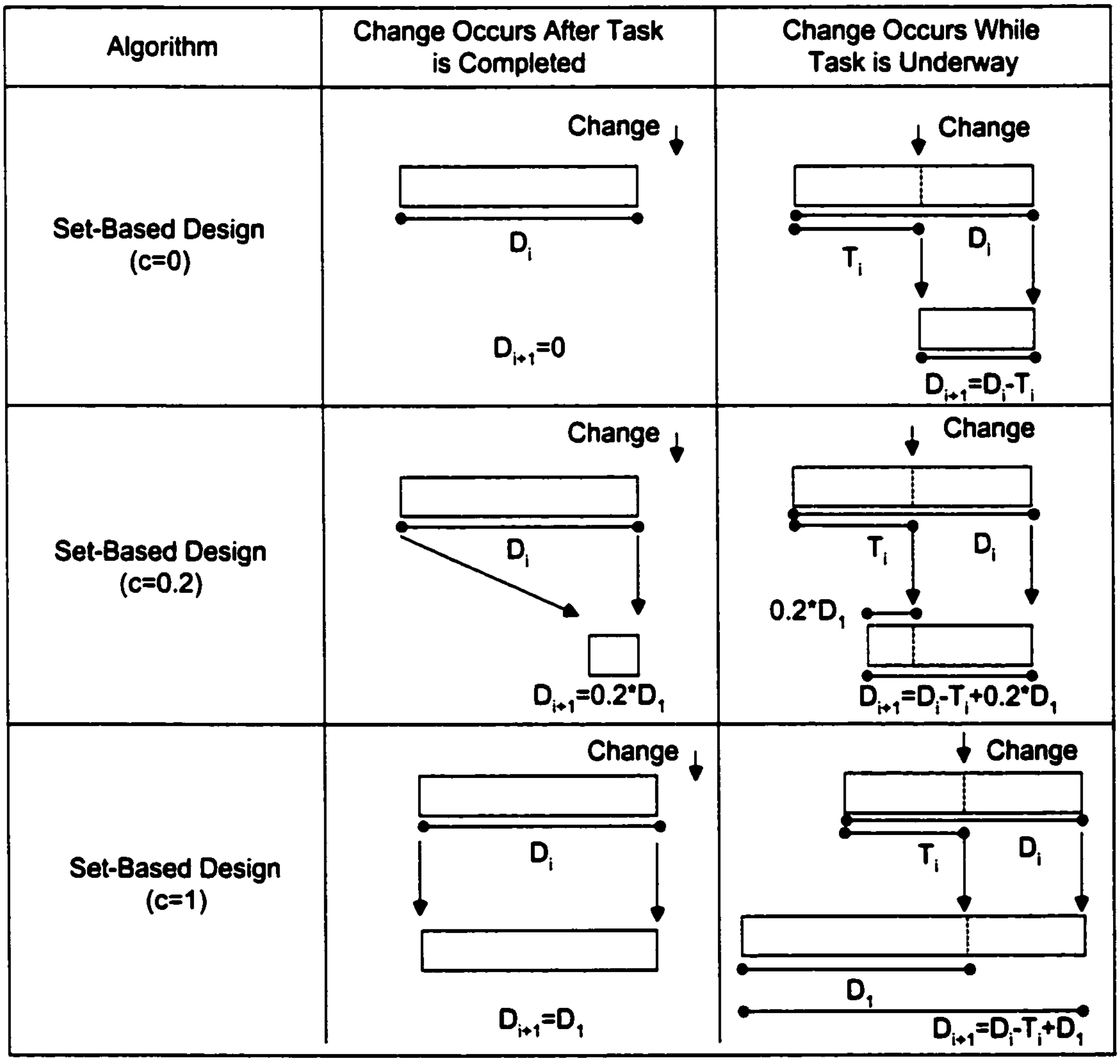
$$D_{i+1} = D_i - T_i + c * D_1. \forall i \qquad \text{(equation VI.19)}$$

where

i = number of times designers start to perform the task (i = 1,2,3,...)

D_1 = expected duration of the task the first time designers execute it, if a design change does not interrupt its execution.

D_i = expected duration of the task in iteration i, if a design change does not interrupt its execution



i - iteration number

c - constant

D_i - expected duration of the task in iteration i, if no design change interrupts its execution

T_i - time designers spent working on iteration i before a change interrupted the work

Figure VI.6 - Set-Based Design Algorithm for Different Values of c

To illustrate the set-based design scenario in the simulation runs, I used, admittedly without an empirical basis, a penalty for pruning the set of design solutions that corresponds to 20 percent of each task's initial duration (c=0.2). A value of c near zero means this effort is insignificant. When c equals one, the set-based design scenario performs more poorly than the no learning scenario (Figure VI.6).

VI.3.4. EVENT-GRAPH SIMULATION RATIONALE

I implemented the model in Figure VI.1 with SIGMA (Schruben and Schruben 1999). Figure VI.7 illustrates the corresponding event graph model. In the description that follows, words in all-caps denote geometric shapes in the figure, and they represent events. Specifically, rectangles with a cut-off corner denote the beginning or end of design tasks, circles denote the START and END of the design development process, and diamonds denote decision points—[coordination] MEETINGs and changes of design criteria (CLEANROOM CHANGE and TOOLS CHANGE). The arrows represent relationships between the events they connect. Associated with each arrow is a set of conditions. Solid arrows mean that the event from which the arrow emanates schedules the event to which the arrow points after a time delay ($\Delta t \geq 0$), provided that the edge conditions are met. Dashed arrows mean that the event from which the arrow emanates cancels the event to which the arrow points after a time delay ($\Delta t \geq 0$), provided that the latter is scheduled to occur and the edge conditions are met.

The design process simulation starts with the START event, which schedules the start of the CONCEPTUALIZATION task. This event also schedules, with some probability, the first TOOLS CHANGE and the first CLEANROOM CHANGE, each after independent stochastic delays. When a CHANGE event occurs, it may schedule a subsequent CHANGE of the same type. Once the process reaches END CONCEPTUALIZATION, the conceptualization phase finishes. START LOAD [development] may immediately take place or it may be postponed (whether or not to postpone is a choice made by the user, discussed in detail in section VI.5). The [coordination] MEETING event turns the decisions on the design features into commitments that can be annulled later if design criteria change. Each MEETING self-schedules the next MEETING, according to a preset lag between consecutive meetings (assumed to be 5 days in this work).

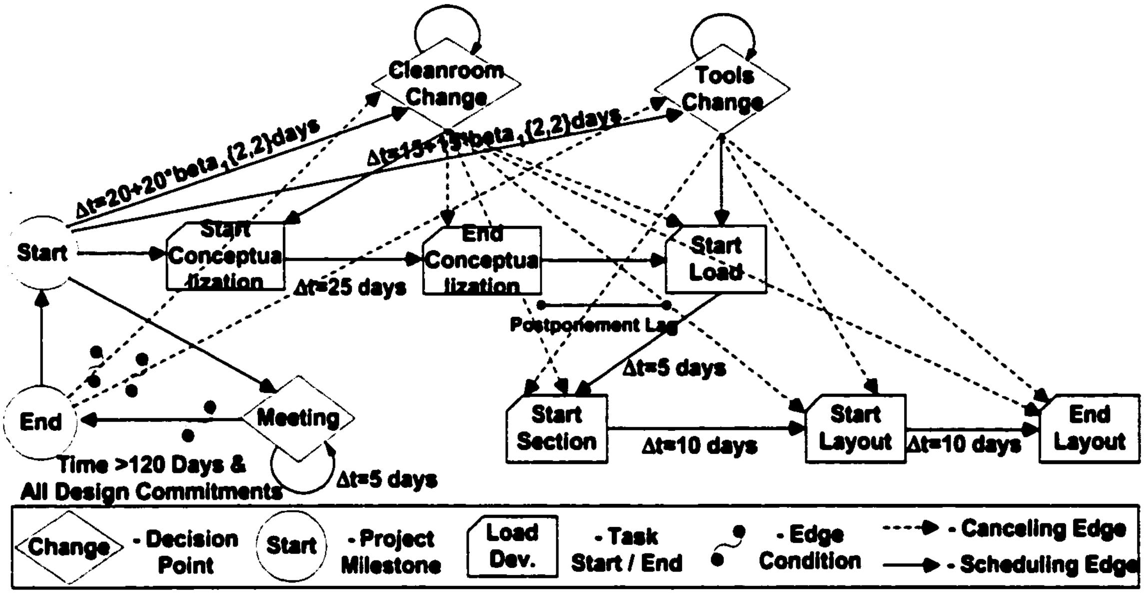


Figure VI.7 - Event-Graph Model for the Design Development Process

A CLEANROOM CHANGE unconditionally cancels all scheduled conceptualization and concept development task events and schedules a new START CONCEPTUALIZATION event. Similarly, a TOOLS CHANGE unconditionally cancels all scheduled concept development task events and schedules a new START LOAD [development] event. I assume that designers should consider all design criteria changes that occur before day 120, whether or not design is completed by the time the change occurs. (This milestone is a user decision variable that I purposely set far away from the project start in order to model a situation that considers most design criteria changes.) Designers should nevertheless consider changes that occur after day 120 if they have not yet completed concept development at the time the change occurs. However, the latter scenario will not occur for the particular set of inputs here, because time delays between successive changes become so large by then that the design process ends sooner rather than later.

Once concept development is completed and the simulation time exceeds 120 days, the MEETING schedules an END event. The END event collects the values of the performance variables for the simulation run, cancels any changes that are scheduled to occur after day 120, resets all the simulation variables (except those that store data for purposes of statistical analysis), and schedules a START event for a new independent simulation run.

Postponed commitment is modeled by locking in the earliest day to START LOAD [development] or in other words, the last possible day until when the conceptualization phase can be extended. The rationale for postponing is as follows. Given designers' common belief in the propensity of criteria to change throughout the development process, they would be better off postponing concept development, so that fewer changes would occur during this phase. By doing so, designers would minimize rework and they would be able to make decisions based on criteria that are more reliable.

CONCEPTUALIZATION lasts 25 days. If changes interrupt it, designers will have to repeat that effort. One extreme scenario assumes that designers START LOAD [development] immediately after the end of CONCEPTUALIZATION. This means that designers START LOAD [development] on day 25 if no cleanroom changes occurred, or on whatever day CONCEPTUALIZATION ends, if one or several changes occurred in the mean time. The other extreme scenario assumes that designers postpone START LOAD [development] up to day 110 (corresponding to a lag of 85 days if CONCEPTUALIZATION finished on day 25) to maximize the probability of developing the concept in a single pass. In between these two scenarios, I tested alternative strategies by gradually postponing START LOAD [development] in intervals of 5 days, from day 25 up to day 110.

For each scenario, 1,000 independent simulations were run. The sample means and variances of the performance variables were calculated with their unbiased estimators (Law and Kelton 2000). SIGMA automatically generates source code in C, which can be compiled into executable versions with Microsoft Visual C/C++ Version 6.0. 1,000 iterations of the compiled version took approximately 10 seconds on a Pentium 600-MHz computer running Windows 98.

VI.3.5. ASSUMPTIONS

For clarity's sake, the simulation model reflects the following assumptions:

1. Each task has a deterministic duration, despite the fact that it is easy to implement stochastic durations with a simulation engine such as SIGMA. Given the sequential nature of the model, with simple finish-to-start relationships, stochastic tasks do not produce changes in the mean of the performance variables (a consequence of the Central Limit Theorem). However, stochastic behavior increases the variability of the performance variables. By contrast, in slightly more complex models, such as those with partial handoffs between activities, stochastic tasks would influence the mean of the performance variables as well as the variability (e.g., Tommelein et al. 1999).

2. I used the limited learning algorithm (equations VI.16 and VI.17) to model the reworking of conceptualization due to changes in cleanroom dimensions. I used it in all scenarios to clearly show the effects of postponing concept development. By contrast, I used the three rework algorithms to model the reworking of concept development.
3. I assumed resources were available to execute the tasks whether or not concept development is postponed. In practice, obtaining sufficient resources may not be a trivial problem. This is discussed further at the end of this chapter.
4. If designers adopt set-based design, they work with sets of solutions instead of working with a single point solution. I assume that designers can execute tasks within the same timeframe as within that they used with single point design, despite the fact that multiple solutions have to be considered in set-based design. Actual research indicates that computational means are available to do that (e.g., Smithers 1989, Lottaz et al. 1999) and innovative organizations use them (e.g., Sabbagh 1996).

VI.3.6. PERFORMANCE VARIABLES

To evaluate the effects of postponed commitment on design development, I implemented the performance variables shown in Table VI.2:

Table VI.2 - Description of Performance Variables (Design Development Model)

PERFORMANCE VARIABLE	DESCRIPTION
Project Duration (Days)	Time elapsed between the occurrence of the first START CONCEPTUALIZATION event and the occurrence of the END LAYOUT [development] event, for the last design iteration.
Resources Spent during Concept Development (Work-Days)	Time spent executing concept development tasks, assuming that a unitary resource is allocated to each task.
Number of Design Iterations of Each Task	Total number of iterations for each design task, regardless of the state of progression of the task when it got interrupted by a change.

VI.4. ANALYSIS OF SIMULATION RESULTS

VI.4.1. DESIGN DEVELOPMENT PROCESS WITH FIXED DESIGN CRITERIA

Figure VI.8 (a) shows the results of the design process simulation for a baseline scenario without uncertainty. The horizontal axis charts the simulation time. The vertical axis charts the progression of design tasks. Each horizontal line in the chart represents the duration of the task described at its left. Each vertical line represents a transition from one task to the subsequent task. Multiple iterations were run, one after the other, and all results are shown in the chart. The shape of the curves reflects the deterministic duration of each task, 25 days for CONCEPTUALIZATION, and then 5, 10, and another 10 days respectively for LOAD, SECTION, and LAYOUT [development]. These are the average durations for design development tasks of an acid-exhaust system, according to anecdotal evidence provided by practitioners.

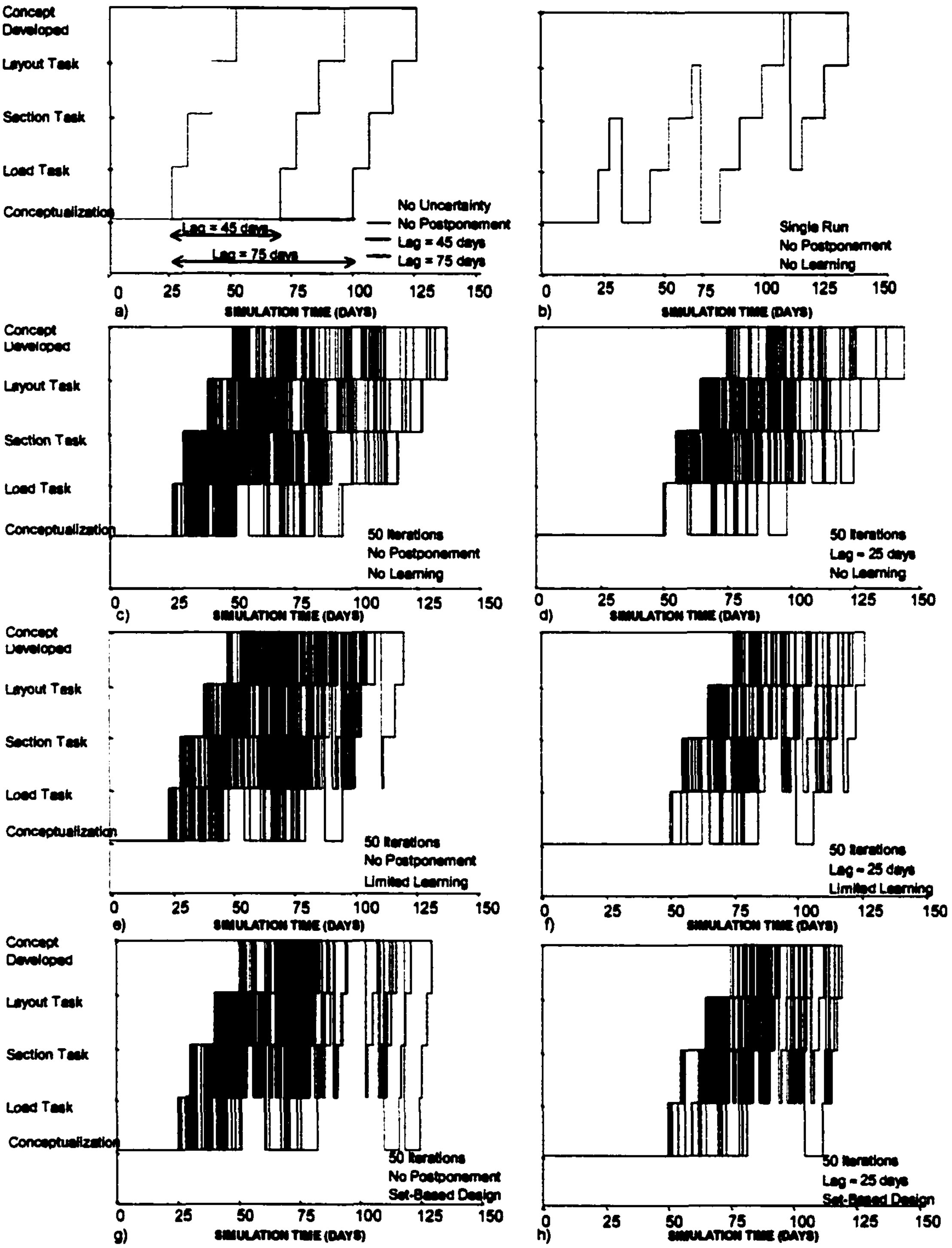


Figure VI.8 - Simulation Outputs of Design Task Progression versus Simulation Time: (a) No Uncertainty; (b) Single Run with Uncertainty; (c) and (d) 50 Runs with No Learning and Uncertainty (with and without postponement); (e) and (f) 50 Runs with Limited Learning and Uncertainty (with and without postponement); (g) and (h) 50 Runs with Set-based Design and Uncertainty (with and without postponement)

Figure VI.8 (a) illustrates 3 strategies executed one after the other: (1) no postponement, (2) concept development shall not start before day 70 (corresponding to a postponement lag of 45 days, given that conceptualization lasts 25 days), and (3) concept development shall not start before day 100 (corresponding to a postponement lag of 75 days). Each colored curve connects the points corresponding to the start and finish dates of conceptualization and of the three concept development tasks. If design criteria were fixed (not subjected to changes), the tasks would sequentially unfold and they would be executed only once. In that case, a postponement delay would equally delay the conclusion of concept development.

VI.4.2. DESIGN DEVELOPMENT PROCESS WITH DYNAMIC DESIGN CRITERIA

By implementing the probability density curves for design criteria changes depicted in Figure VI.3, the design development simulation exhibits stochastic behavior. Each simulation run tends to evolve differently according to the timing and frequency of changes.

Figure VI.8 (b) illustrates an instance of a single simulation run in a scenario with no learning between concept development iterations, and with no postponement. In this run, three changes occurred during the design process. First, a cleanroom dimensions change interrupted the section development task. Then, a second cleanroom dimensions change interrupted the layout development task. Finally, a tools change occurred after completion of concept development but before day 120. Figure VI.8 (c) illustrates the results of 50 simulation runs of (b)'s scenario. Figure VI.8 (d) illustrates the results of a scenario characterized by no learning between concept development iterations but with a postponement lag so that concept development would not start before day 50. Figure VI.8

(e) illustrates a scenario with the rework algorithm for limited learning and no postponement. Figure VI.8 (f) uses the same rework algorithm as scenario (e) but with a postponement lag so that concept development would not start before day 50. Figures VI.8 (g) and VI.8 (h) replicate the scenarios (e) and (f) respectively but with the rework algorithm for set-based design.

VI.5. POSTPONED COMMITMENT STRATEGIES

Postponed commitment has been advocated and implemented for managing product development processes in unpredictable environments (e.g., Iansiti 1995, Ward et al. 1995, Bhattacharya et al. 1998, Thomke and Reinertsen 1998). As Figures VI.9 (a) and (b) illustrate, the fundamental notion of postponement in product development means to extend concept development and to simultaneously start implementation early on, thus overlapping the two phases. By leaving some design features open throughout implementation, designers have more flexibility to accommodate late changes that may affect those features as well as to accommodate late input on the design decisions from manufacturing people. It is worth noting that the "traditional" and the "flexible" models show the same overall duration.

Here, the conceptualization of postponed commitment is somewhat different. Postponed commitment delays the start of concept development, thereby leaving more time for conceptualization (Figures VI.9 (c) and (d)). However, the conceptualization and concept development phases do not overlap because postponement is applied to the entire phases of concept development, fabrication, and construction. For example, postponement is applied to the entire phases of concept development, fabrication, and construction of the acid-exhaust system in the computer simulation model.

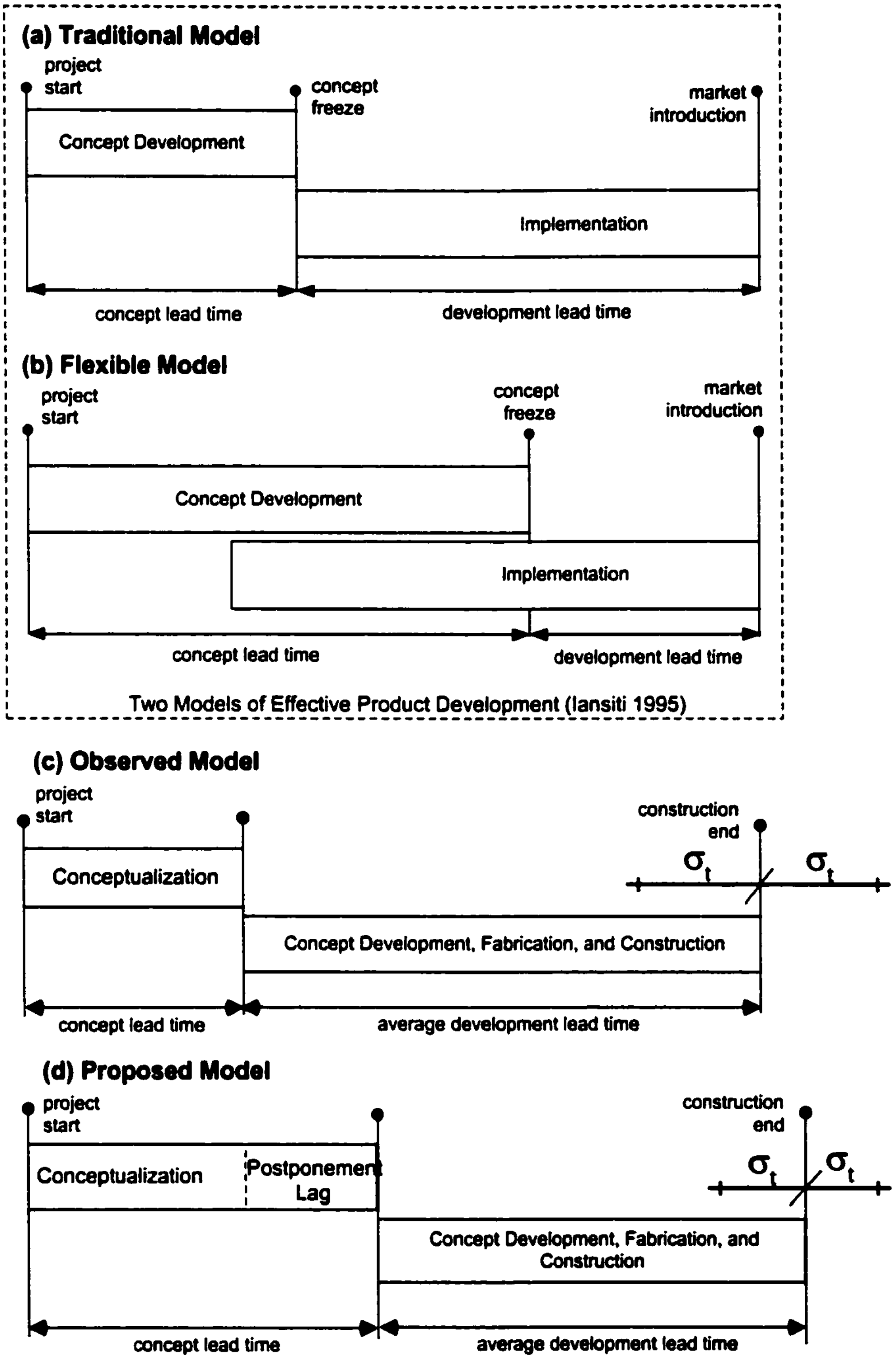


Figure VI.9 - Conceptual Comparison of Postponement Propositions

One conceptual alternative, not consider here, would be to start the fabrication and construction of selected parts of one fab system early on while postponing the fabrication and construction of other parts of that same system. Another alternative, which also falls out of the scope of this work, would be to model the development process of two or more fab building systems. By postponing the start of concept development of a selected few building systems, the concept development phase of those systems could hypothetically be overlapped with the construction and fabrication of the other systems that had not been postponed.

Regardless of their specific conceptualization, postponed commitment strategies are seldom used in the design development of fabs. The common argument design managers have against postponement is that it jeopardizes their ability to meet the project milestone dates. Managers are also concerned that they would have difficulties into assigning their teams back later to the initial project if they would let them get involved into another project because of the scarcity of skilled resources they typically face. In short, design managers believe that every possible day of work counts against meeting the deadline, so they act accordingly. Designers also acknowledge that they often repeat the same tasks several times because of changes in design criteria but they seem resigned to accepting iteration as an intrinsic feature of design development.

When I started this work, a reasonable hypothesis seemed to be that many of these iterations could be prevented without compromising the project deadlines if designers adopted postponement. This work sharpened my understanding on the validity of this hypothesis.

Figure VI.10 (a) charts the relationship between the mean project duration and the mean resources spent during concept development that results as the postponement lag increases. It depicts the scenario that uses the no-learning rework algorithm between concept development iterations. Each data point in the chart was calculated with the unbiased estimator applied to the results of 1,000 independent simulation runs. Figure VI.10 (a) illustrates that postponement consistently increases the mean project duration and decreases the mean resources spent during concept development. Specifically, as the postponement lag initially increases from a no-postponement strategy, the marginal reduction of the mean resources spent is very steep while the marginal increase of the mean project duration is hardly significant. Then, as the postponement lag keeps increasing, the marginal reduction of the mean resources spent is less significant while the marginal increase of the project duration tends to equal the corresponding marginal increase in the postponement lag.

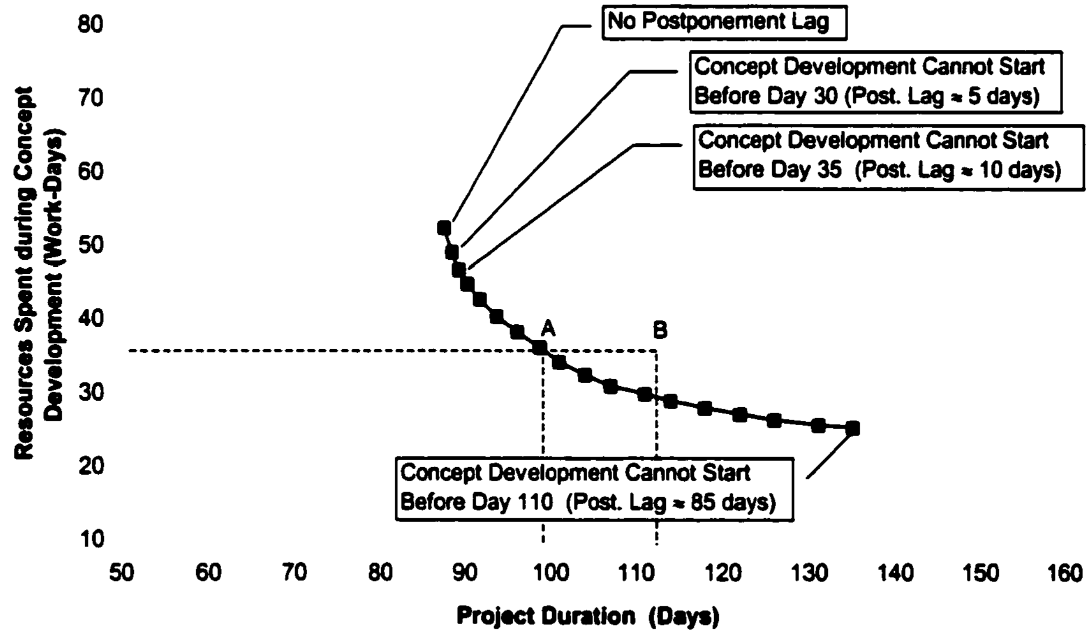


Figure 10 (a) - Mean Project Duration versus Mean Resources Spent during Concept Development, for Alternative Postponement Strategies (1,000 Runs for each Data Point)

An equivalent concept to that expressed by the curve in Figure 10 (a) is that expressed by production functions. De Neufville (1990 p. 7) defines a production function as the "locus of all the technically efficient combinations of resources." By technical efficient, de Neufville means that "each point on the production function represents the maximum product that can be obtained from any given set of resources" (ibid. p.6). Likewise, we can assume that: (1) the resources spent during concept development and the project duration are two resources needed for producing the design product in an unpredictable environment, and (2) the outcome product is the developed design concept. Hence, each point in the curve in Figure VI.10 (a) represents the maximum product that can be obtained (the developed concept) from any given set of these two resources (human resources and time). The curve bounds the feasible region of production. If one input is fixed, suppose the resources spent are fixed, and provided that the project is allowed to take more time (point B) than the correspondent time needed in the curve (point A), it is also possible to produce the design but it would be a less efficient use of the resources.

Figure 10 (b) adds the representation of the standard deviation of the mean project duration to Figure 10 (a). Figure 10 (b) shows that the one-standard deviation upper limit of the project duration ($\mu_t+\sigma_t$) remains more-or-less steady for postponement lags up to approximately 30 to 35 days. Clearly, up to a postponement lag of 30-35 days, the marginal decrease in the variability of the project duration (which corresponds to a decrease in the standard deviation) counterbalances the marginal increase of the mean project duration. As the postponement lag keeps increasing beyond 30-35 days, the marginal increase of the mean project duration gets more significant and the marginal decrease in its variability no longer suffices for preventing the upper limit $\mu_t+\sigma_t$ from also increasing.

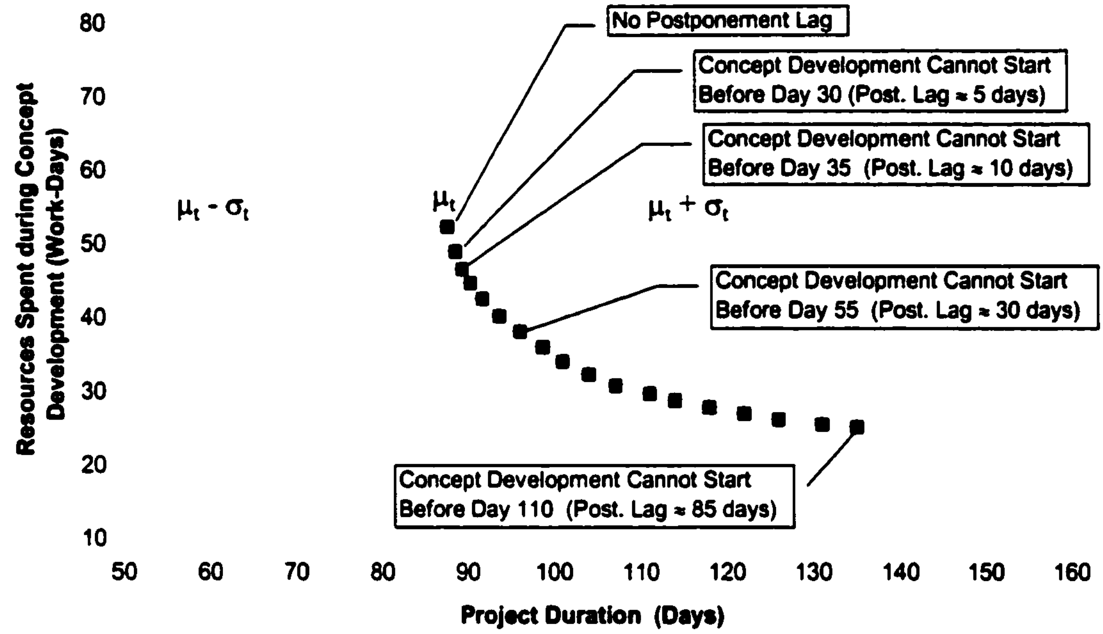


Figure 10 (b) - Mean and Standard Deviation of Project Duration versus Mean Resources Spent during Concept Development, for Alternative Postponement Strategies (1,000 Runs for each Data Point)

Figure 10 (c) adds the representation of the variability of the resources spent during concept development to Figure 10 (b). Postponement decreases the mean and the variability of resources spent because fewer changes fall during concept development so that the design tasks are repeated less. Figure VI.10 (c) shows two rays that define an "efficiency zone" for the design development process. This zone approximately defines the possible range of postponement strategies that best satisfy two conditions: (1) minimize the mean of resources spent during concept development (μ_r) and their variability (σ_r), and (2) do not increase the upper one-standard deviation limit of the total project duration ($\mu_t+\sigma_t$) beyond the value that $\mu_t+\sigma_t$ assumes with a no-postponement strategy. In Figure VI.10 (c), this efficiency zone corresponds to a set of postponement strategies with a lag of approximately 25 to 35 days.

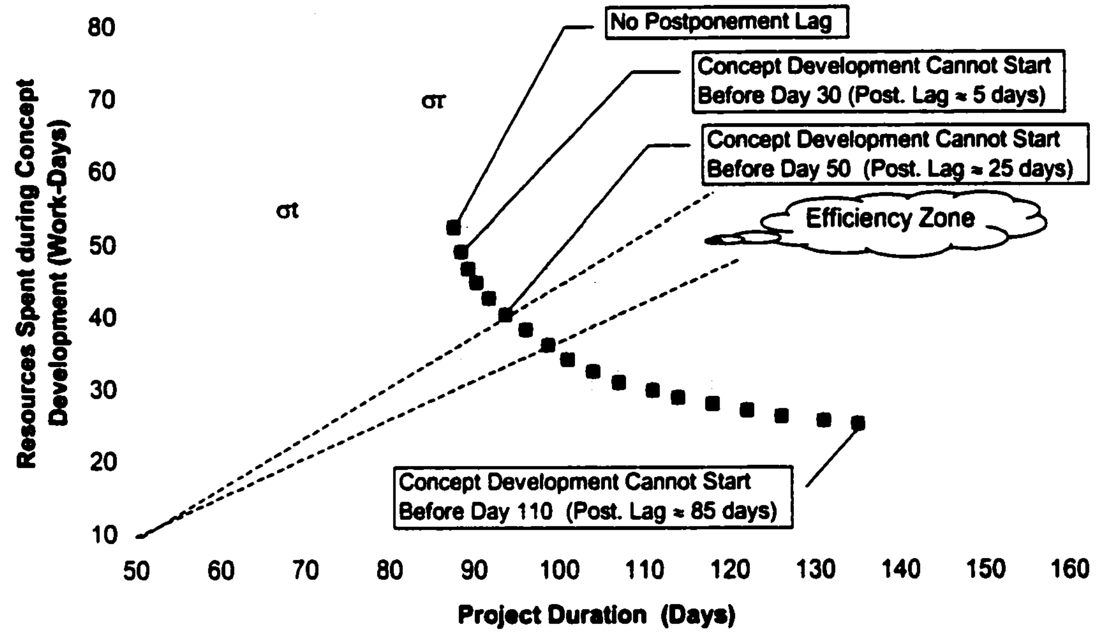


Figure VI.10 (c) - Project Duration versus Resources Spent during Concept Development, for Alternative Postponement Strategies (1,000 Runs for each Data Point)

Figure VI.11 shows three other curves in addition to the no-learning curve represented in Figures VI.10 (a, b, c): (1) a baseline scenario that presupposes fixed design criteria (no uncertainty), (2) a scenario that considers the rework algorithm for limited learning between concept development tasks, and (3) a scenario that considers the rework algorithm for set-based design between concept development tasks. Figure VI.11 illustrates that postponement is more effective for the scenario that assumes no learning between concept development iterations. This is a logical result given that if the length of the rework loop cycle increases, designers will be better off by postponing tasks.

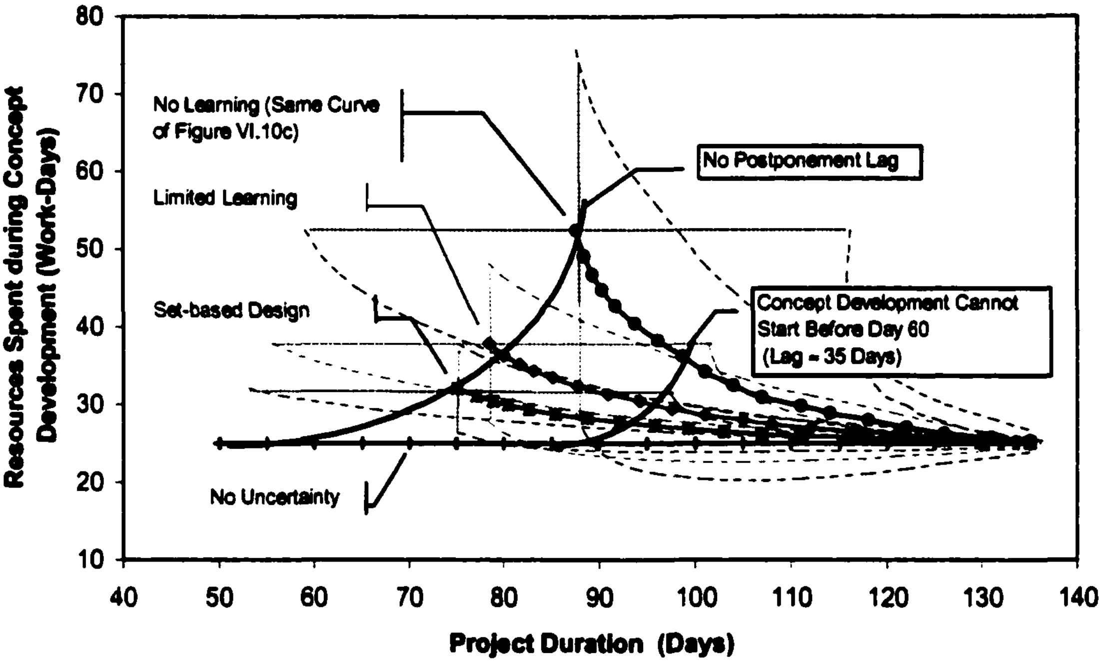


Figure VI.11 - Project Duration versus Resources Spent during Concept Development, for Different Rework Algorithms and for Alternative Postponement Strategies (1,000 Runs for each Data Point)

Figure VI.12 charts for the scenario with no-learning rework algorithm and for alternative postponement strategies: (1) the mean number of iterations per concept development task, (2) the mean number of changes falling within the postponement lag, and (3) the mean number of changes falling after completion of concept development. It shows that, as the postponement lag increases, the mean numbers of task iterations and of changes falling after concept development decrease almost down to zero, whereas the mean number of changes falling within the postponement lag increases.

Table VI.3 shows the corresponding standard deviations of these means for selected scenarios. The variability of the number of iterations per concept development task and of the number of changes falling after completion of concept development diminishes as the postponement lag increases. This behavior, similar to that expressed by the performance variables shown in Figures VII.10 and VII.11, reflects the increasingly more reliable development process that results as the postponement lag increases.

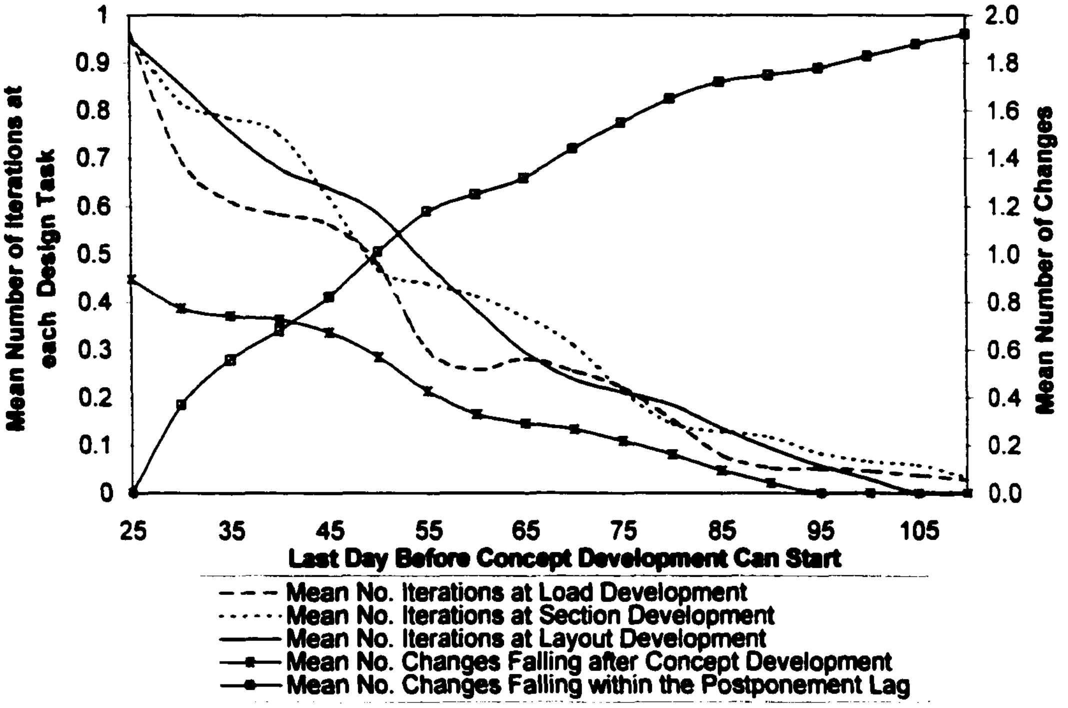


Figure VI.12 - Variation of the Mean Numbers of Task Iterations and of Change Occurrences, for Alternative Postponement Strategies (1,000 Runs for each Data Point)

Table VI.3 - Postponement Effects on Performance Variables (mean ± standard deviation)

Performance Variable	No Postponement	Concept Development Cannot Start Before Day 45	Concept Development Cannot Start Before Day 90
No. of Iterations at Load Development	0.96 ± 1.02	0.56 ± 0.79	0.05 ± 0.22
No. of Iterations at Section Development	0.96 ± 0.97	0.62 ± 0.85	0.12 ± 0.33
No. of Iterations at Layout Development	0.95 ± 1.00	0.64 ± 0.81	0.09 ± 0.29
No. Changes Falling After Concept Development	0.45 ± 0.70	0.34 ±0.60	0.02 ± 0.14
No. Changes Falling within the Postponement Lag	0	0.82 ±0.68	1.75 ± 1.20

Logically, the variability of the number of changes falling within the postponement lag increases when the postponement lag increases because of the increase in this variable's significance.

VI.6. DISCUSSION

Figure VI.10 shows that the mean numbers of task iterations do not decrease steadily but rather fluctuate up- and downward to zero along their respective trend lines as the postponement lag increases. Because design criteria changes occur at time-dependent means in the model, different postponement lags have different effects in the concept development process. This fluctuation would have been hard to anticipate without conducting a simulation, even for a simple design process as the one I presented here. For more complex design processes, the effect of postponement will be even more difficult to gauge, since each specific lag appears to lead to unequal benefits for the various tasks.

Given the design process structure and the actual circumstances (including the duration of tasks and the frequency of changes), one discipline may be forced into doing a lot of rework, even though this rework does not reflect their own skills and capabilities. One discipline may also benefit less from postponement than another, and therefore may be less eager to buy into this strategy. Design managers must be made aware of such phenomena so that they will reward team performance and not exclusively individual work.

There are other potential drawbacks to the implementation of postponement. First, given the scarcity of skilled designers, it is likely that few design managers would free up their team members for fear of not getting them back when they would next be needed. This is a fair concern. Regrettably, the AEC industry still seldom underloads the volume of work it expects human resources to undertake; instead, the industry typically loads their time to fully use up their work capacity. Underloading resources would allow designers to accommodate variability in work demand and consequently it would increase workflow reliability throughout the production process (Ballard 1999b).

Second, it may be justifiable for a client to let designers commit early on regardless of the resulting added costs in terms of resources spent and loss of process reliability. Suppose that a client has to decide on a duration for the postponement lag based on the curve in Figure VI.10, and that he values highly a reliable development process. That client may want designers to efficiently postpone concept development. In doing so, the resources spent in concept development can be significantly reduced and the risk that the project duration may last longer than a preset milestone date ($\mu_t+\sigma_t$) will be the same risk that the client would face would he decided to let designers commit early on. By contrast, if the client decides in terms of means or if he values highly the upside risk of shortening the project duration, he may want designers to commit early on. The outcome of the decision thus varies according to the risk the client is willing to incur.

Finally, note that the aforementioned analysis exclusively focuses on the process development perspective. The model cannot differentiate the product quality of a design solution that results out of several iterations vis-à-vis the quality of a solution that is developed with mature design criteria. My belief is that, in all likelihood, the latter may perform better. This issue certainly deserves attention in future research.

VI.7. MODEL VALIDATION

Law and Kelton (2000 pp. 264-265) define validation in the context of simulation as "the process of determining whether a simulation model is an accurate representation of the system [being studied], *for the particular objectives of the study*". They also state that a simulation model can provide only "an approximation to the actual system", that "there is no such thing as absolute model validity", and that the model's validity should be established "for a particular set of purposes" (ibid. p. 265). Along the same lines, Sterman (2000 p. 846) states that "no model can ever be verified or validated [in the sense of establishing truth, because] all models are wrong (...) models are limited, simplified representations of the real world". Alternatively, he advocates that modelers focus on "the important questions", namely "Is the model useful? Do its shortcomings matter? (...) Useful for what purpose? Matter to whom?" (Ibid. p. 851).

I used assumptions on the modeling rationale and on its inputs that I developed jointly with practitioners, based on anecdotal evidence. I did not test the validity, or in other words the close resemblance, of the mathematical relations nor of the input estimates with empirical data. Instead, I used the assumptions on the simulation rationale as the basis for developing a computer-based framework that simulates design processes in unpredictable environments. The assumptions on the inputs served to illustrate the usefulness of this framework for yielding insight into the effectiveness of alternative project delivery systems.

Furthermore, I tested the credibility and reasonableness of the simulation model by contrasting its results with practitioners' perceptions on real-world projects—what Law and Kelton (2000 p. 281) call "face validity". I also tested the simulation's usefulness for supporting learning on design management in unpredictable environments. For these purposes, I presented the model and its results to lead designers at IDC several times, I conducted one-on-one structured walk-throughs with lead designers, and I discussed the model's results with subject-matter experts working for a client organization and for specialty contractors. The conceptual agreement of the simulation rationale and of the results with practitioners' perceptions on real-world projects gave me confidence in the model's validity and usefulness.

Nonetheless, the ability of the simulation model to generate outputs that closely resemble the data of real-world projects—what Law and Kelton (2000 p. 279) call "results validation"—has not been assessed. Further research should look for establishing to what extent the model outputs resemble empirical project data, if empirical data is used for modeling inputs. In doing so, such research should also be assessing the ability of the model to predict system behavior—an issue further discussed in the last chapter of this dissertation.

VI.8. CONCLUSIONS

Clients commonly synthesize their critical project needs with the motto "faster, cheaper, and better quality." They are concerned that fab designs be delivered on the milestone dates that they strategically set, that fabs meet the criteria for performance reliability, and that fab projects stay on budget. Furthermore, clients want freedom to change the fab design criteria throughout the development process, yet simultaneously, they want designers to assure them that the projects will still meet the milestone dates and will stay on budget. Certainly, clients do not want designers to use changes for justifying delays or cost overruns.

On their side, AEC designers seldom use postponement or set-based design and they may be skeptical of these strategies' potential benefits when confronted with their use in other unpredictable environments. Instead, AEC designers commit early on to single-point design solutions. If design criteria later change, they have no other alternative than to proceed with design iterations.

Simulation results show that early commitment, though efficient for compressing the mean project duration, comes at a cost. First, it maximizes the mean number of task iterations that designers have to perform; and, consequently, it maximizes the resources spent during concept development. Second, early commitment makes design development less reliable, making it harder to predict the duration of each project and the resources it will consume. In contrast, simulation results show that judicious postponement decreases design iteration and resources spent, without affecting project duration within a one-standard deviation interval.

Simulation results also show that if designers adopt set-based design, postponement hardly yields any benefits because changes can be easily accommodated. This result is consistent with the speculative assumption I made when modeling set-based design—I assumed that designers would be able to anticipate all possible directions that design criteria could take. Accordingly, the need to rework design would be minimal if design criteria changes occurred later. If these assumptions hold in practice (a research question that needs further investigation), set-based design can help designers compress the project duration while the resources spent do not need to increase. Yet, AEC organizations that opt to implement set-based design must incur a certain cost up front, namely, the cost of learning how to develop set-based designs, investing in computational systems, and training people to use them.

In a recent project, the client had not yet chosen the tool vendor among three possible vendors but wanted a finished tool-install design by the time he made a choice. To satisfy the client needs, designers developed three distinct designs, a procedure close to set-based design. Set-based design, however, rather than having designers triplicate the work, would guide designers to work within a range of solutions to narrow by the time the client made a choice. Recent web ventures in the AEC industry, which allow clients to customize the configuration of residential apartments late in the design process, also show awareness of the opportunities afforded by set-based design (e.g., VirAps 2001). Evidence thus suggests that the quality transformation of AEC organizations—the goal behind this research (Tommelein 1998b)—is underway.

VII. SIMULATION OF THE DESIGN-BUILD DEVELOPMENT PROCESS FOR A FACILITY SYSTEM IN UNPREDICTABLE ENVIRONMENTS

VII.1. INTRODUCTION

Researchers have long recognized that specialty contractors can contribute to the design-build development process, especially if they participate early in design (e.g., Crichton 1966, Bennett and Ferry 1990, Tommelein and Ballard 1997, Gil et al. 2000). In current practice, though, it is all too often the case that specialty contractors get to participate only when design has been substantially completed. They develop and submit detailed shop drawings to the architect/engineer, after competitively bidding a set of drawings and specifications. Consequently, specialty-contractor knowledge seldom is leveraged into early design. It may not be leveraged later in design either, because contractors are expected to submit a bid and build the design according to the bid documents. Opportunities for improving the construction process thereby get lost and a confrontational climate often arises between designers and contractors (Pietroforte 1997).

Involving specialty contractors through competitive bidding has other drawbacks. First, competitive bidding is a time-consuming process that delays tasks such as procurement of long lead items, and fabrication and installation of parts, because the specialty contractor needs to be selected before these tasks can be executed. Second, once the contractor is selected and before he can effectively start executing the design, he must spend time to get acquainted with the design, write requests for information, provide submittals, propose alternative solutions, and wait for the client's answers and approvals.

Luckily, industry practices are changing and increasingly contractors are participating in early design.

In a project environment in which design criteria are expected to change throughout the design and construction phases, the early involvement of specialty contractors should be distinguished from an early start of the fabrication and construction work. Design changes that occur during the design phase but prior to fabrication and construction cost less to implement than those that occur when any of the latter processes is underway because more resources have then been mobilized. In these circumstances, project managers have to balance changes of design criteria and their willingness to tolerate those changes with the consequent cost of rework. This balancing act is far from trivial and the research presented in this chapter further elaborates on it.

VII.2. RELATED RESEARCH

The literature on new product development and concurrent engineering presents extensive research on compressing project delivery times in unpredictable environments (e.g., Womack et al. 1990, Iansiti 1995, Eisenhardt and Tabrizi 1995, Bhattacharya et al. 1998, Thomke and Reinertsen 1998, Sobek II et al. 1998, Terwiesch and Loch 1999). Several empirical studies report that postponing the date on which the design concept is frozen and involving suppliers from early design onwards are both critical strategies for compressing project duration and for accommodating late design changes (e.g., Iansiti 1995, Thomke and Reinertsen 1998).

Other empirical studies show, however, that the overlap of the design phase with the implementation phase, and early supplier involvement do not necessarily lead to shorter development times for products whose technologies and markets are extremely unpredictable. Instead, success may be contingent on the organization's ability to resolve upstream uncertainty (Terwiesch and Loch 1999) or on its ability to implement an experiential approach, based on multiple iterations, real-time interaction, flexibility, and improvisation (Eisenhardt and Tabrizi 1995).

Drawing from analytical constructs, Krishnan et al. (1997) argue that there are limits to concurrency between design and implementation when preliminary product information is prone to change. They propose a framework to help practitioners determine how to exchange information and how to overlap development steps, based on the properties of the information. Along the same line, Terwiesch and Loch (1999) use a concurrent engineering model to demonstrate that uncertainty due to engineering changes and to interdependency between tasks may make concurrency less attractive. Managers should trade off the savings in project duration that result from overlapping activities against rework delays caused by changes of preliminary information.

My work differs from the aforementioned research in that its domain is architecture, engineering, and construction (AEC). AEC projects are one-of-a-kind, whereas product development typically precedes a mass production process. In most product development processes, designers and suppliers can go through multiple design- and prototyping iterations because improvements will pay off handsomely later, every time a replicate is made. (An exception to this argument may be the airplane industry, in which each airplane is replicated relatively few times). In contrast, design and construction rework is usually charged entirely against the project itself.

I assume that specialty contractors in AEC projects are the equivalent of suppliers in product development. The questions then are: How to best structure the project delivery system and how to involve contractors early on in unpredictable environments? My work relates to research in lean production systems design as applied to the AEC industry, what has been termed 'lean construction'. To find effective ways to structure the work, and consequently the project delivery system, is one objective in lean construction (Lean Construction Institute 2001).

The research method that follows uses computer simulation, like Tommelein (1998a) used to model pipe-spool installation, but its scope is different. I first present a high-level view of the process of designing and building an acid-exhaust system, which is part of a fab. I then simulate alternative project delivery systems, and assess which ones, under which circumstances, best meet the client's needs. These systems differ based on when specialty contractors get involved in design and when construction starts relative to the completion of design.

VII.3. PRODUCT-PROCESS SIMULATION OF DESIGN-BUILD DEVELOPMENT

The systemic simulation model in this chapter focuses on the design, parts fabrication, assembly, and installation of the acid-exhaust system in a semiconductor fabrication facility. I chose to model one fab utility system because the design-build processes of the corresponding mechanical, electrical, and piping systems largely determine the project duration. Due to their technological complexity, these systems are also critical for the fab's performance and they are the most expensive to design and build. These systems are also the most vulnerable to changes in the cleanroom dimensions and in the tools because they directly serve the tools in the cleanroom.

The design-build process of one utility system is largely representative of the process for the other 40 to 80 utility systems that may be installed in the subfab. Such representativeness is useful in extrapolating the analysis of the simulation results to other utility systems, and, accordingly, in estimating the impact of alternative delivery systems as a whole. Specifically, I chose the acid-exhaust system given the depth of information on the design-build process that appeared to be available at the onset of this research and that I was able to collect.

VII.3.1. PROCESS DEVELOPMENT MODEL

The design development model for the acid-exhaust system is composed of two phases: conceptualization and concept development (Figure VII.1). In the description that follows, words in all-caps denote geometric shapes in the figure, and they represent events. During CONCEPTUALIZATION, designers estimate critical features based on historical data and rules of thumb. During concept development, they typically use analytical tools to refine their estimates in light of updated design criteria. The model expresses concept development as a loop of three tasks: LOAD-, SECTION-, and LAYOUT DEVELOPMENT. LOAD DEVELOPMENT represents the designers' attempt to calculate the loads that the fab system will serve based on the design criteria. SECTION DEVELOPMENT represents the designers' attempt to size the sections of the main elements based on the loads previously determined. LAYOUT DEVELOPMENT represents the designers' attempt to route each system and to locate major equipment in the three-dimensional space.

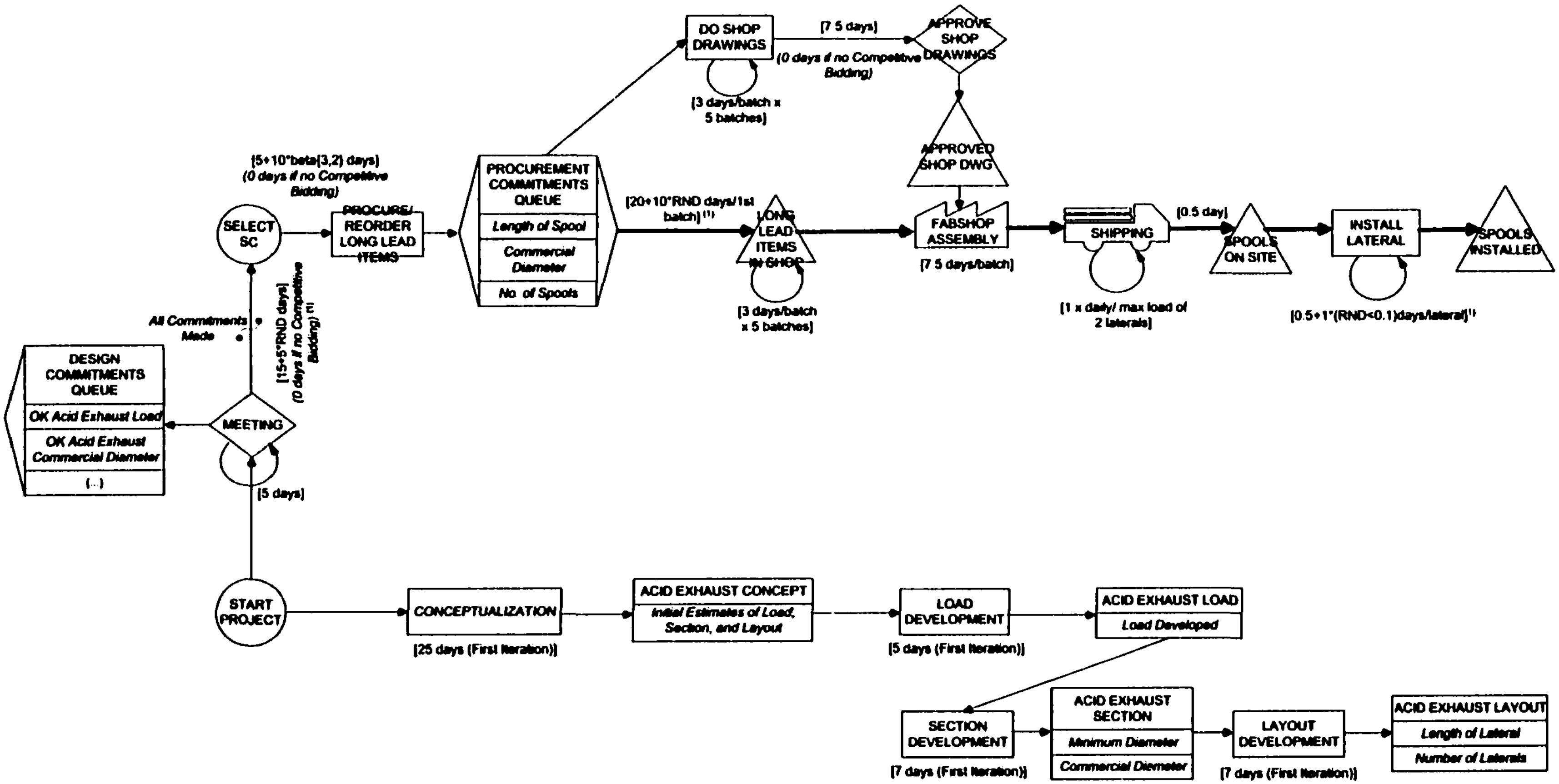


Figure VII.1 - Product-Process Model for the Design-Build Development Process of an Acid-Exhaust System with Fixed Design Criteria (See Tables V.1 and VII.1 for Meaning of Symbols)

(1) RND designates a random number selected from a uniform distribution of numbers strictly greater than 0 and less than 1

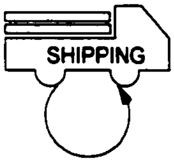
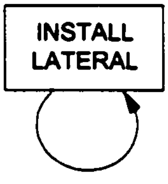
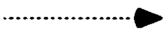
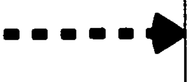
Design processes are typically iterative in the search for a satisfying solution (Simon 1969). Designers may repeat the same tasks several times until they find a solution that satisfies them, if they can afford to spend the time. For simplicity's sake, I assume the design process to be sequential unless design criteria change.

Throughout the design development process, designers hold periodic coordination MEETING[s] to validate their decisions and to make commitments. The execution phase starts once all the design features that are modeled have been committed to. This phase encompasses the period from SELECT[ion of] S[pecialty] C[ontractor] until the end of the on-site INSTALL LATERAL operation. Table VII.1 describes the symbols used to represent this phase.

If the specialty contractor was not involved in concept development, the model assumes that two sequential delays occur. The first delay corresponds to the bidding period from the day on which all design features are finally committed until the day on which one contractor among all bidders has been selected. The second delay corresponds to a follow-up period during which the selected contractor sends requests for information to the architect/engineer and waits for clarifications. After this latter delay, the contractor decides on the length and number of spools, PROCURE[s] long lead items (e.g., fiberglass coated ducts and specialty items like valves), and DO[es] SHOP DRAWINGS. The FABSHOP ASSEMBLY of the parts starts once 2 conditions are met: first, the architect/engineer APPROVE[s the] SHOP DRAWINGS, and, second, the spools and specialty items arrive at the fabrication shop. Then, the assembled spools are SHIP[ped] to the construction site by truck, and INSTAL[led]. Spool installation proceeds one routing line (typically called a lateral) at a time.

Table VII.1 - Symbols Used to Represent the Execution Phase of the Acid-Exhaust System

SYMBOL	NAME	EXPLANATION
	Procurement Commitments Queue	A rectangle with triangles at both sides denotes a ProcurementCommitmentsQueue. It represents the procurement commitments with long lead items (e.g., spools and valves). Here, I assume that these items arrive in 5 separate batches. The first batch of items takes between 20 to 30 days to arrive to the shop and the subsequent batches arrive in 3-days intervals after the first batch.
	Material Flow	A solid, bold arrow denotes a Material Flow. It indicates the flow of materials, such as spools, from one task to the next task.
	Resource Queue	An upward triangle denotes a ResourceQueue. Resources result from the execution of a task or of a decision point and they can be depleted by executing a subsequent task. For example, ApprovedShopDrawings that result out of the ApproveShopDrawings decision are needed to execute the FabShopAssembly. Likewise, SpoolsOnSite result from the ShippingProcess and they are needed to execute the InstallLateral task; this latter task originates SpoolsInstalled.
	Assembly Process	A symbol of a factory building denotes the AssemblyProcess of the valves and Ts on spools, which takes place inside the shop. Here, this process lasts 7 ½ days, for each of the five batches of spools.

	Shipping Process	A symbol of a loaded truck with a circular arrow underneath denotes a ShippingProcess. A full load corresponds to the number of assembled spools needed for installing 2 laterals. Trucks leave the shop fully loaded unless the number of assembled spools waiting in the shop is less than the number of spools required to install 2 laterals, in which case the truck load corresponds to the number of spools remaining in the shop. A loaded truck leaves the shop every day as long as there are spools to ship. Loaded trucks take ½ day to arrive to the job site.
	Install Lateral Task	A closed rectangle with a circular arrow underneath denotes the InstallLateralTask. The installation of one lateral lasts ½ day at 90% of the times and it lasts 1½ days at 10% of the times.
	Edge Condition	A curly line with dots at both ends denotes an Edge Condition. It indicates that the edge crossed by it only gets executed if the edge condition is met.
	Canceling Edge	A dashed arrow denotes a CancelingEdge. It indicates that the event from which the arrow emanates will cancel the event to which the arrow points, provided that a specific edge condition is met.
	Transformation Edge	A dashed, bold arrow denotes a transformation edge. It indicates that a resource type will be transformed into another resource type, if the edge condition is met.

VII.3.2. PRODUCT MODEL

I integrated the following product-design features with the process representation: acid-exhaust load; minimum engineered and commercial diameter of the upstream cross-section of the acid-exhaust laterals; number and length of laterals; and number and length of spools needed to assemble the laterals. Table VII.2 shows the designers' rules of thumb to estimate these design features during conceptualization, which were implemented in the simulation model.

Table VII.2 - Rules of Thumb to Estimate Product-Design Features for the Acid-Exhaust System

LOAD	Acid-exhaust load in the cleanroom	L	3.0 to 3.5 cfm/sq.ft
SECTION	Minimum engineered diameter for the upstream cross-section of the acid-exhaust lateral	D	$\sqrt{\frac{L*1*4*w}{V}}$
	Commercial diameter for the upstream cross-section of the acid-exhaust lateral (inch)	D_c	If D<16 then............ $D_c=16$ If 16≤D<20 then....... $D_c=20$ If 20≤D<24 then....... $D_c=24$ and so on in 4 inch (10 cm) increments
LAYOUT	Length of lateral line	l	$\frac{Width\_of\_the\_Cleanroom}{2}$
	Number of acid-exhaust laterals in the subfab	n	$\frac{2*Length\_of\_the\_Cleanroom}{w}$
PROCUREMENT	Number of spools	n_S	$\frac{Length\_of\_Lateral\_Line}{Length\_of\_Spool}*n$

w – width of subfab bays measured from one column to the next (feet)

V – maximum flow velocity in the lateral routing (fpm)

The inputs to these rules of thumb are the width and length of the fab cleanroom, and the initial estimate of the acid-exhaust load in the cleanroom. I assumed that other inputs that result from historical data, namely the maximum flow velocity and the width of the subfab bays, stay fixed throughout the design and construction processes. Commercial diameters for acid-exhaust duct start at 16 inch and increase in intervals of 4 inch up to more than 56 inch. The length of spools, typically a decision left to the contractor, was also assumed to be fixed. Moreover, I assumed that the estimates of the design features made by designers at conceptualization stay valid at concept development unless design criteria change.

VII.3.3. DESIGN CRITERIA UNCERTAINTY

The design and construction of a fab typically takes place concurrently with the development of the chip technology and of the tool layout. Consequently, changes in the tools or in the tool layout (e.g., caused by technological breakthroughs or by shifts in market needs) may impact the fab design definition. In the previous chapter, Figure VI.3 illustrated simulated samples from the probability density curves that synthesize lead designers' mental models regarding the frequency and time of occurrences of changes in cleanroom dimensions and in tools. The simulation here implements these uncertainty curves on top of the systemic model for the design-build development process.

In addition, the simulation assumes that the client has set day 200 as the last possible day he would consider and allow a design criteria change; this is, 10 months after the project started (one month in the simulation comprises 20 working days). An exception to this rule could happen only if a change occurred after day 200 and the acid-exhaust system were not yet totally installed on that day. However, this latter scenario is highly unfeasible for the particular set of inputs here because time delays between successive changes become so large by then that, sooner rather than later, the design and building processes end.

VII.3.4. EVENT-GRAPH SIMULATION RATIONALE

As I did with the generic design model described in Chapter VI, I implemented the systemic model illustrated in Figure VII.1 with SIGMA. Figure VII.2 illustrates the corresponding discrete-event simulation model, which uses canceling relationships between events (graphically represented by a dashed arrow) to model client-driven changes. A TOOLS CHANGE unconditionally cancels any scheduled SECTION- or LAYOUT DEVELOPMENT tasks and specific execution tasks (like SELECT SC and DO SHOP DRAWINGS), and it schedules a new iteration for LOAD DEVELOPMENT. Likewise, a CLEANROOM DIMENSIONS CHANGE unconditionally cancels any scheduled design tasks as well as specific execution tasks, and it schedules a new CONCEPTUALIZATION task.

If a commercial diameter for the acid-exhaust spools has been chosen before the occurrence of a change, the latter may or not invalidate the previous choice according to how close the chosen diameter was to the engineered minimum diameter. I assume that designers, before repeating the concept development tasks, correctly anticipate if a change necessitates a larger spool. Thus, a change immediately executes canceling edges (such as those pointing to SHIPPING or INSTALL LATERAL tasks) if the new acid-exhaust load resulting from the change will necessitate larger spools.

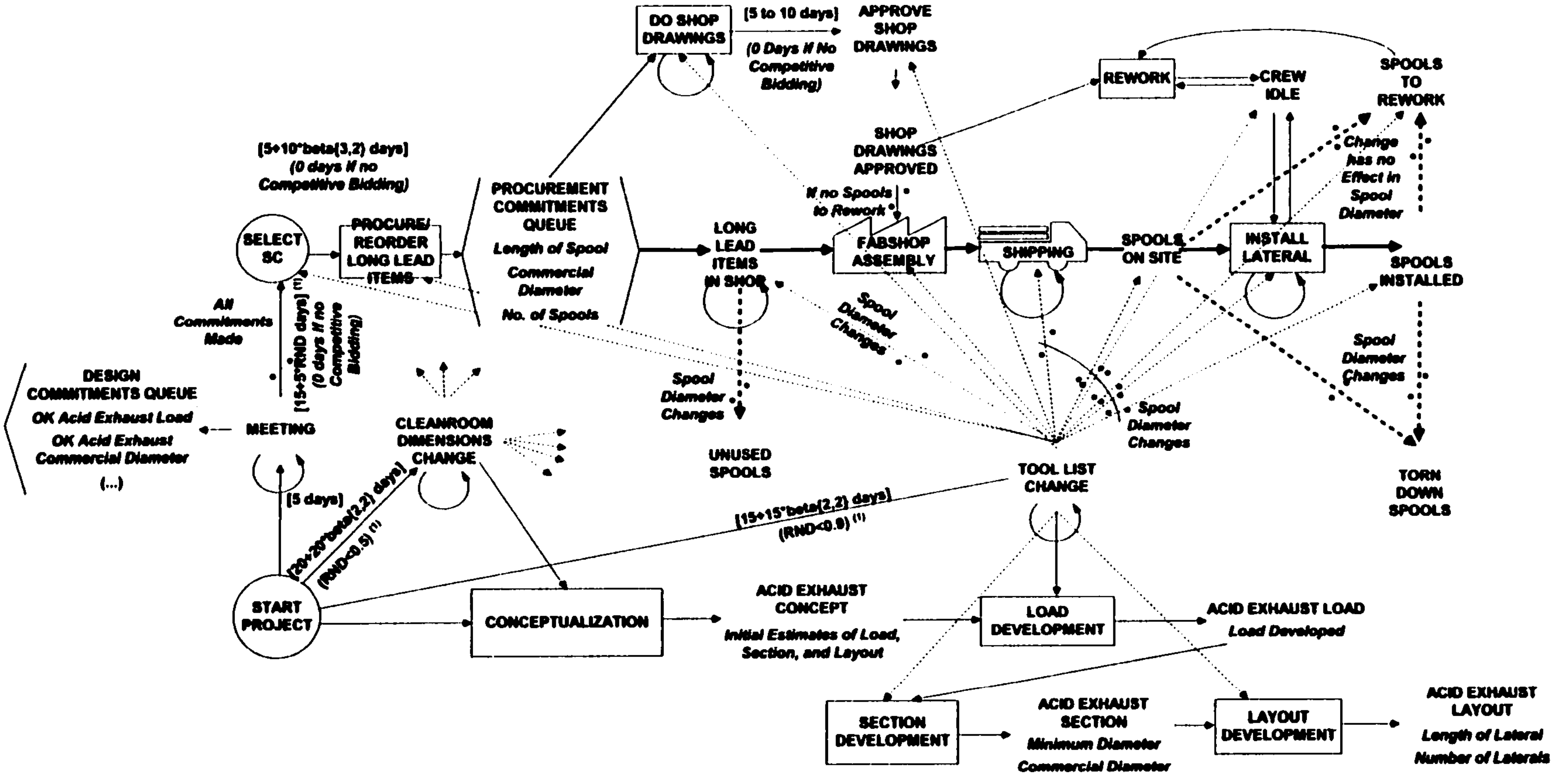


Figure VII.2 - Product-Process Model for the Design-Build Development Process of an Acid-Exhaust System with Dynamic Design Criteria (See Tables V.1 and VII.1 for Meaning of Symbols)

(1) RND designates a random number selected from a uniform distribution of numbers strictly greater than 0 and less than 1

If any spools and valves have already been ASSEMBLE[d] when a change occurs and the spool commercial diameter remains the same, the simulation assumes contractors must still REWORK the previously assembled spools per the new APPROVED SHOP DRAWINGS. In this case, the simulation also assumes that spools assembled but not yet installed will first be SHIP[ped], then INSTALL[ed], and REWORK[ed] afterwards.

If a CLEANROOM DIMENSIONS CHANGE does not affect the spool diameter but the contractor had already PROCURE[ed] the spools, the contractor needs to REORDER more spools to make up for the fact that the fab will have more laterals and these will be longer (I am assuming a change in cleanroom dimensions means a 10% increase). If a change necessitates larger spools, the spools that are already assembled must be TORN DOWN, the spools not yet assembled must be put aside (UNUSED SPOOLS), and larger spools must be PROCURE[d] once contractors have received the newly developed concept. I assume that when the larger spools arrive at the site, the smaller spools have in the meantime been TORN DOWN so that workspace is available to install the new ones.

VII.3.5. ASSUMPTIONS

For clarity's sake, the simulation model reflects the following assumptions:

1. Task Duration and Batch Size. I used practitioners' estimates to quantify the duration of tasks, process delays, and the size of batches in which shop drawings are released and spools fabricated and assembled. The inputs used here were the deterministic averages of these estimates.
2. Design Rework. Different rework algorithms can be implemented for representing the degree of learning between successive iterations of the same tasks. Here, I assume that the duration of conceptualization as well as the duration of the tasks in concept

development decrease between successive iterations, according to the algorithm for modeling limited learning discussed in Chapter VI.

3. Shop Drawings Approval. I assume that shop drawings always are approved. I also assume that once a contractor is selected, he stays involved with the job despite any design changes that may occur. In addition, I assume that perfect synchronization exists between the sequence in which shop drawings are done and approved—a total of 5 batches—and the 5 batches in which long lead items arrive at the fabrication shop. The influence of these assumptions in the development process merits further investigation but this is not part of this dissertation.

VII.3.6. SIMULATION SCENARIOS

I considered the following simulation scenarios:

1. **Competitively Bid Specialty Contractor**. Designers develop the design and once they commit on all the design features, specialty contractors competitively bid that design. The bidding process takes 3 to 4 weeks (15+Rnd*5 days). Once a contractor is selected and gets involved, he takes 5 to 15 days (5+10*Beta{3,2}days) to collect the design information, issue requests for information, and get answers from the architect/engineer. After that period, the contractor starts to procure long lead items and to detail the shop drawings. Each batch of shop drawings needs to be approved by the architect/engineer and the corresponding materials need to be delivered to the fabrication shop before spool assembly of that batch can start. This approval process takes 5 to 10 days.
2. **Specialty Contractors Involved Since Start of Concept Development and No Postponement.** The specialty contractor is selected during the conceptualization

phase and participates in concept development (e.g., attending coordination meetings or co-locating his detailers in the architect/engineer's office). Once designers commit to all the design features, the specialty contractor immediately starts to procure long lead items and to detail the shop drawings. No time is wasted in bidding neither in collecting information, and approval of shop drawings is immediate.

3. **Postponement of Concept Development.** Designers do not start concept development until a predefined number of days (a lag) passes after completion of conceptualization. This postponement lag varies from 0 (in which case concept development starts on the day conceptualization ends, which is day 25 if no cleanroom change interrupted conceptualization) to 90 days, an extreme scenario! From one scenario to the other, I increased the postponement lag by 5 days. Postponement of concept development can be applied in combination with any of the two aforementioned scenarios.
4. **Shortening of Long Lead Delivery Times.** Lead times for special coated spools and valves would be shortened from the typical 4 to 6 weeks (20+Rnd*10 days) to 1 to 2 weeks (5+Rnd*5 days). This scenario can also be applied in combination with any of the aforementioned scenarios.

VII.3.7. PERFORMANCE VARIABLES

To contrast these scenarios, I implemented the performance variables shown in Table VII.3:

Table VII.3 - Description of Performance Variables (Design-Build Development Model)

PERFORMANCE VARIABLE	DESCRIPTION
Overall Project Duration (days)	Elapsed time from the day conceptualization starts to the day on which the last spool is installed or reworked on site, and no more (eligible) changes occur.
Total Design Time (days)	Time designers spend at conceptualization plus at concept development tasks.
Total Execution Time (days)	Elapsed time from the day the specialty contractor gets selected (or from the day on which all design features get committed if the contractor is involved early on) until the day on which the last spool gets installed or reworked on site, and no more (eligible) changes occur.
On-Site Rework Time (days)	Total time the on-site crew spends reworking assembled spools due to changes that did not alter the choice of the spool commercial diameter.
On-Site Wasted Time (days)	Total time the on-site crew spends idle or tearing down installed spools due to changes that required larger spools.
Total Length of Torn Down Spools (feet)	Total cumulative length of spools that were already assembled when a change occurred that necessitated larger spools, whether or not the assembled spools were installed.
Total Length of Unused Spools (feet)	Total cumulative length of spools that were already in the fab shop but not completely assembled when a change occurred that necessitated larger spools.

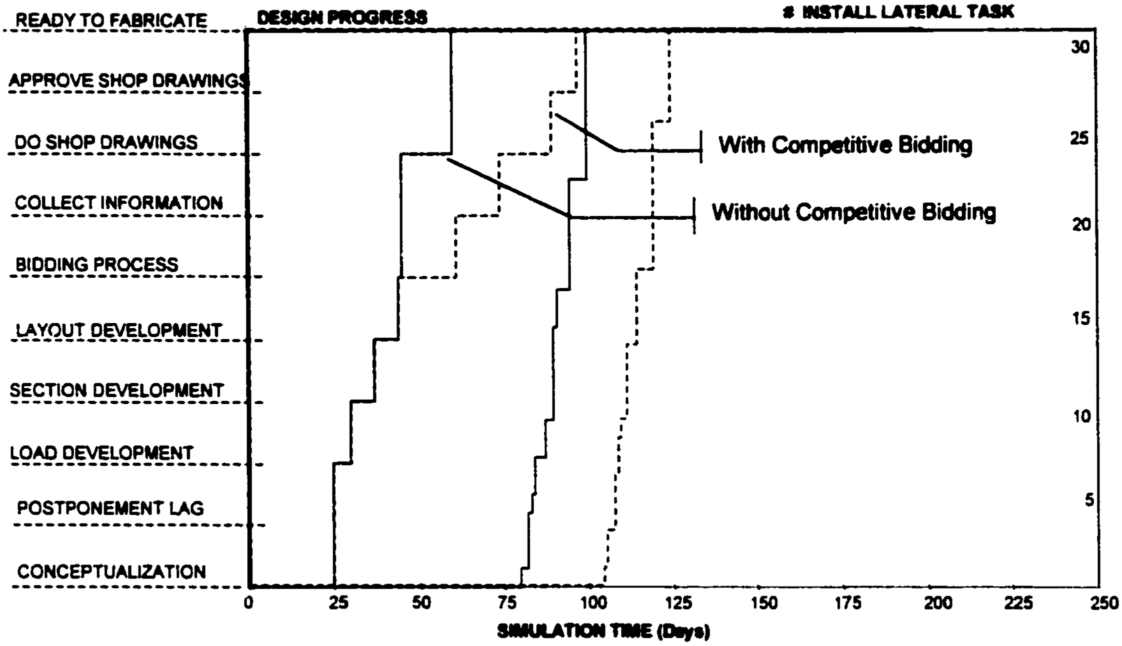
VII.4. ANALYSIS OF SIMULATION RESULTS

VII.4.1. DESIGN-BUILD DEVELOPMENT PROCESS WITH FIXED DESIGN CRITERIA

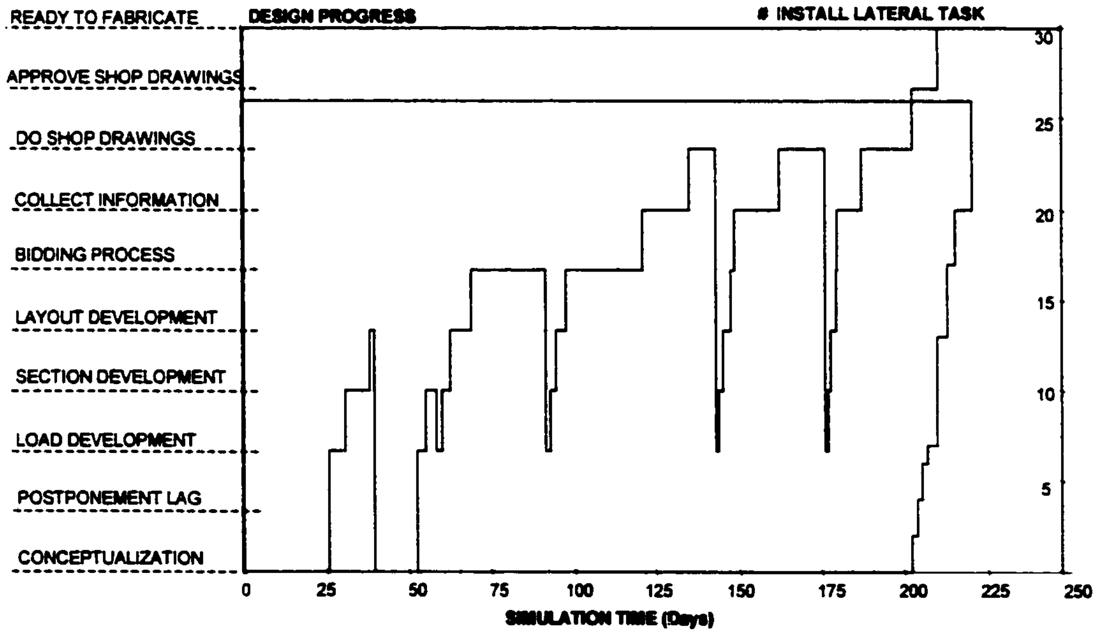
Figure VII.3 (a) illustrates the simulation results for two single runs with fixed design criteria. In one, the specialty contractor competitively bids the design. In the other, he is involved early on during design. The blue lines denote design development and the red lines denote the number of times the lateral installation task gets executed. The length of the horizontal lines expresses the duration of the design and construction tasks. Assuming design criteria were fixed, early contractor involvement compresses the overall project duration because it avoids the delays caused by contractor selection and by shop drawing approval. Lines A and B in Table VII.4 show the results for these two baseline scenarios.

VII.4.2. DESIGN-BUILD DEVELOPMENT PROCESS WITH DYNAMIC DESIGN CRITERIA

Figure VII.3 (b) illustrates an instance of a single run for a scenario with competitive bidding during which multiple changes occurred. Figures VII.3 (c) and VII.3 (d) illustrate separately the progress of the design and of the lateral installation processes for five stochastic runs, with competitive bidding. Figures VII.3 (e) and VII.3 (f) illustrate 30 runs respectively with and without competitive bidding (I purposely chose a small number of runs to enhance the legibility of the figures). Line C in Table VII.4 shows the results for the scenario with competitive bidding and uncertainty, and line D shows the results for the scenario without competitive bidding and uncertainty. I calculated the means and variances using the unbiased estimators for a sample of 1,000 simulations (Law and Kelton 2000).

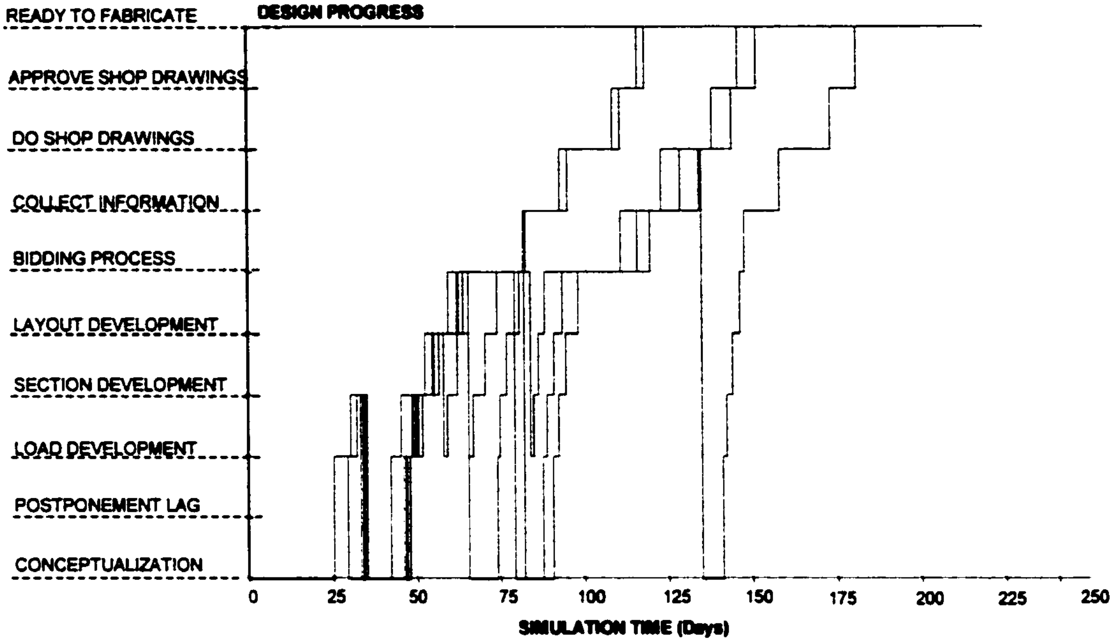


(a) Two Single Runs with and without Competitive Bidding, both with Fixed Design Criteria

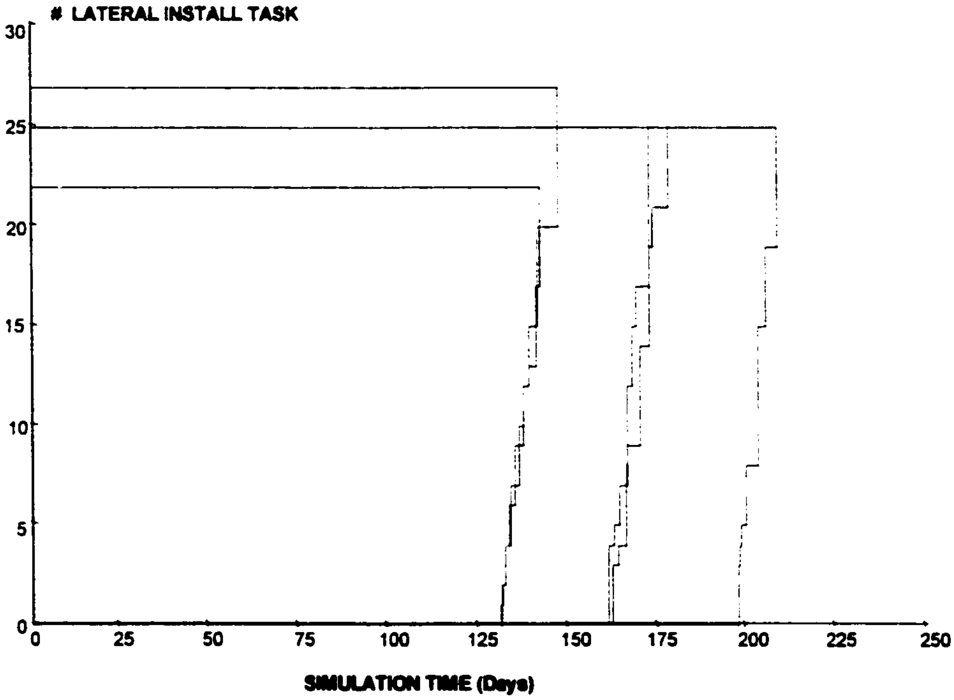


(b) Single Run with Competitive Bidding and with Uncertainty

Figure VII.3 - Simulation Outputs of Simulation Time versus Design Task Progression and Lateral Installation (1 of 3)

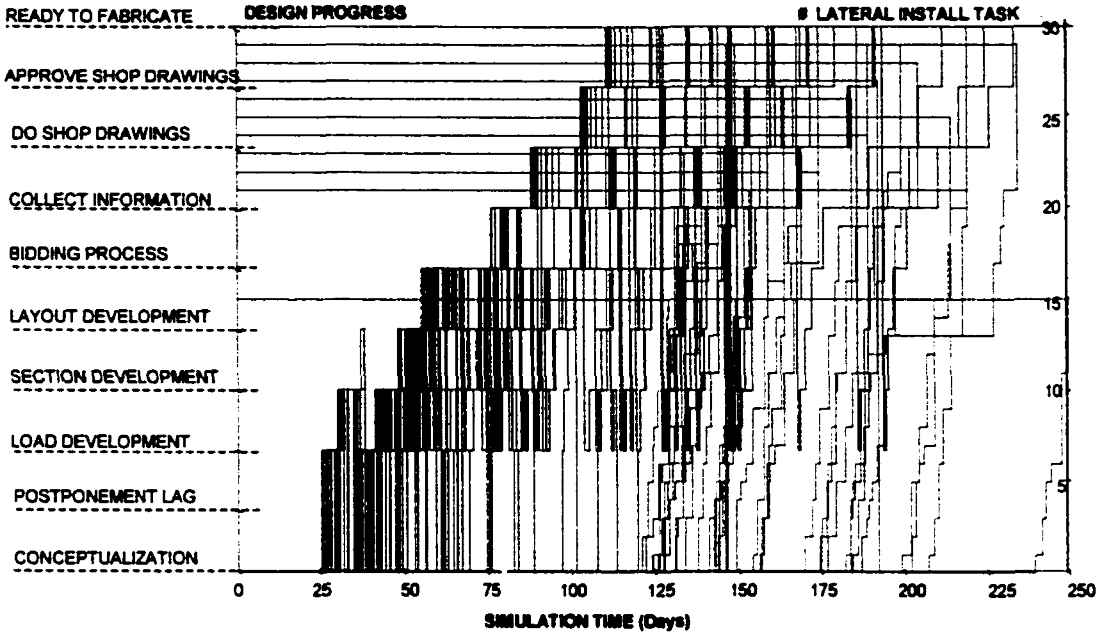


(c) 5 Runs with Uncertainty and Competitive Bidding (only Design Progress)

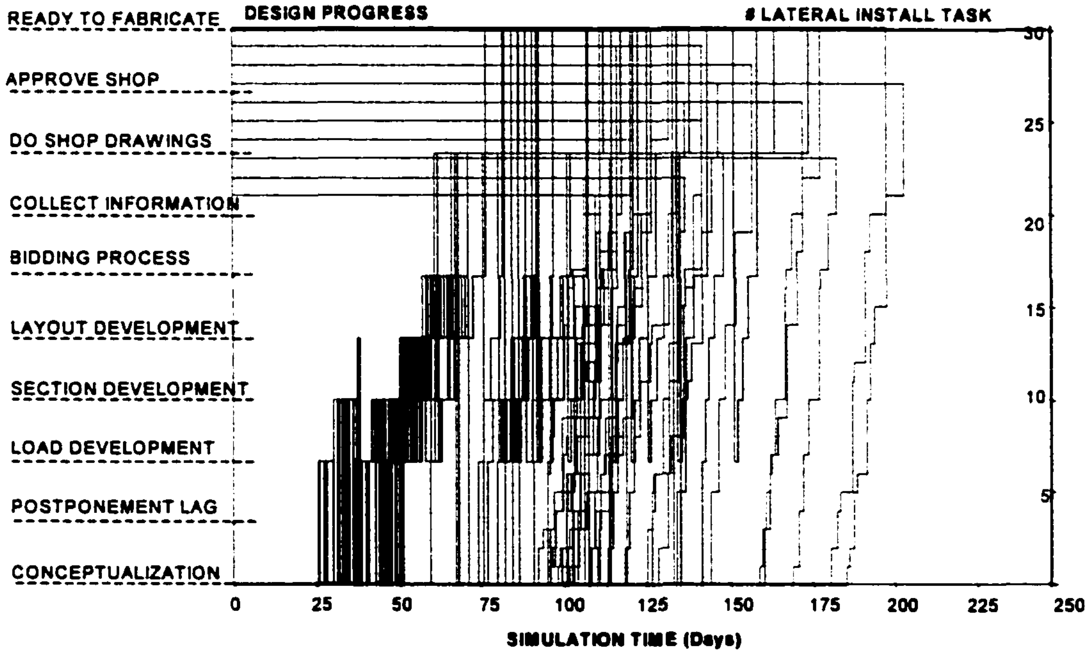


(d) 5 Runs with Uncertainty and Competitive Bidding (only Construction Progress)

Figure VII.3 - Simulation Outputs of Simulation Time versus Design Task Progression and Lateral Installation (2 of 3)



(e) 30 Runs with Uncertainty and Competitive Bidding



(f) 30 Simulation Runs with Uncertainty and no Bidding

Figure VII.3 - Simulation Outputs of Simulation Time versus Design Task Progression and Lateral Installation (3 of 3)

If, in conditions of design criteria uncertainty, the specialty contractor is involved early on in design (scenario D) as opposed to being competitively bid (scenario C) the results show: (1) the overall project duration shortens approximately by the sum of the delays caused by bidding, (2) the resources wasted during construction increase significantly, (3) the total execution time increases slightly, and (4) the variability of the overall project duration increases.

Table VII.4 - Competitive Bidding versus Early Contractor Involvement, for a Scenario with Long Lead Times and Spools 10 Feet Long (mean ± standard deviation)

Scenario	Overall Project Duration (Days)	Total Design Time (Days)	Total Execution Time (Days)	On-Site Rework Time (Days)	On-Site Wasted Time (Days)	Total Length of Torn Down Spools (Feet)	Total Length of Unused Spools (Feet)
(A) SC Competitively Bid without Uncertainty and without Postponement	125 ± 4	41	62 ± 4	0	0	0	0
(B) SC Early Involved without Uncertainty and without Postponement	96 ± 3	41	51 ± 3	0	0	0	0
(C) SC Competitively Bid with Uncertainty and without Postponement	162 ± 33	63 ± 13	79 ± 27	0 ± 2	4 ± 14	177 ± 847	141 ± 686
(D) SC Early Involved with Uncertainty and without Postponement	137 ± 41	63 ± 13	81 ± 39	1 ± 4	15 ± 24	1180 ± 2211	298 ± 938
(E) SC Early Involved with Uncertainty and with Concept Development Start > Day 60	151 ± 30	58 ± 12	68± 29	1 ± 3	6± 15	483 ± 1483	130 ± 630

Total Spool Feet Installed (No. Laterals * Length of Lateral) = 5170 ±876 Feet

These results are not totally surprising given that the likelihood of the occurrence of changes decreases in the course of time. Clearly, because early contractor involvement allows the fabrication and construction processes to start earlier, more changes occur while these processes are underway. However, an implicit assumption is made that early contractor involvement means to start fabrication and construction early on, which is not necessary. This assumption is relaxed in the next section, by showing how postponement of concept development can shield production from upstream design criteria changes when specialty contractors participate in early design. In addition, it is worth noting that work methods did not change between the previous simulation scenarios. Simulation therefore ignored other product and process benefits that derive from contractor involvement in early design, as Chapter IV makes clear. This latter assumption is relaxed in section VII.4.5.

VII.4.3. POSTPONED COMMITMENT STRATEGIES

Postponed commitment delays concept development by imposing a no-earlier-than constraint to its start date. The simulation results presented in Chapter VI showed that postponing concept development consistently augmented the mean project duration but decreased its variability. Moreover, in section VI.5, I identified an efficiency zone corresponding approximately to concept development not starting before day 50 to 60. In this zone, the simulation results show that the upper limit of the variability interval for the project duration stays steady while significant resource savings are achieved. Figures VII.4 and VII.5 illustrate how similar postponement strategies influence the design-build development process for the scenario in which the specialty contractor is involved early on in design.

Figures VII.4 and VII.5 show that, as the postponement lag increases up to its efficiency zone and for a scenario in which specialty contractors participate in early design, the wasted construction resources reduce significantly but the mean overall project duration increases only by about 10%. A comparison between the scenario in which the contractor is involved early on (with an efficient postponement lag so that concept development cannot start before day 60, line E in Table VII.4) and the competitive bidding scenario (line C in Table VII.4) shows that: 1) the mean and standard deviation of the total length of torn down spools in scenario E are significantly above the results achieved in scenario C, 2) the mean and standard deviation of the total length of unused spools, of on-site wasted time, and of on-site rework time are of the same order of magnitude, and 3) the means of the total design time, of the total execution time, and of the overall project duration are shorter in scenario E and the respective standard deviations are of the same magnitude.

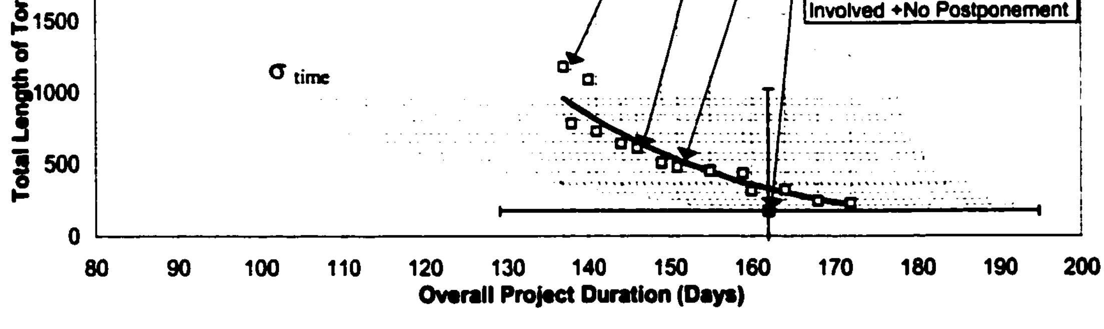


Figure VII.4 - Overall Project Duration versus Total Length of Torn Down Spools, for Alternative Postponement Strategies (1,000 Runs for each Data Point)

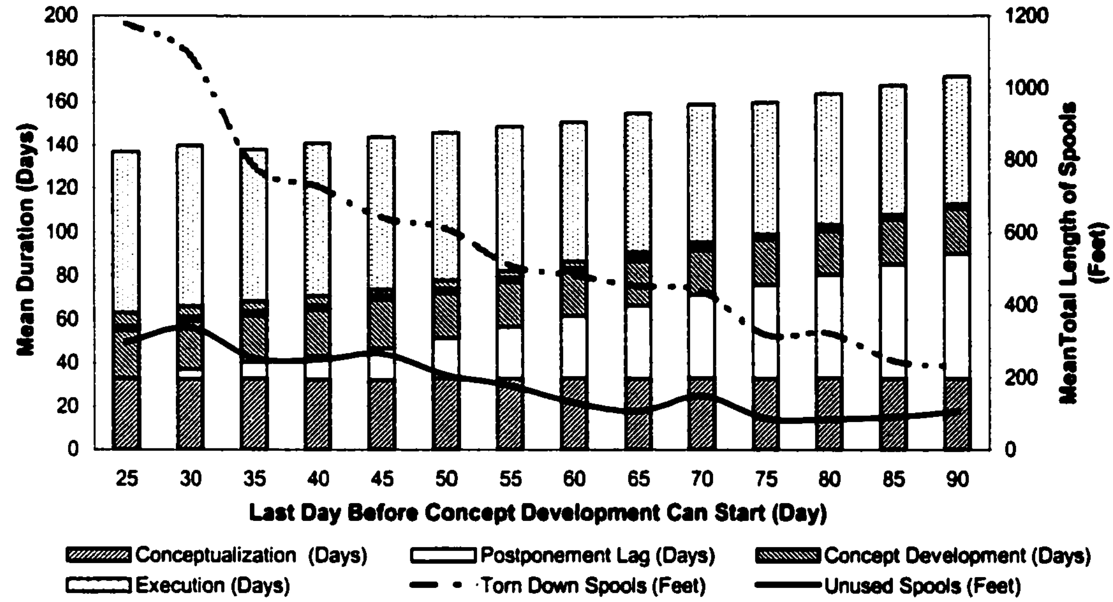


Figure VII.5 - Duration of Design and Building Processes versus Waste Generated During Construction, for Alternative Postponement Strategies (1,000 Runs for each Data Point) [Scenario: Specialty Contractor Involved since Concept Development]

These results confirm, from a design-build system perspective, the lesson learned in Chapter V on the trade-off faced by managers when postponing concept development in unpredictable environments: effective postponement decreases the waste caused by unanticipated changes of design criteria and thereby increases the reliability of the process; however, it slightly increases the mean of the overall project duration relatively to the expected mean if postponement would not be applied.

VII.4.4. SHORTENING LONG DELIVERY LEAD TIMES

Several studies have reported noticeable reductions in production cycle times as lean practices are adopted across manufacturing industries (e.g., Towill 1996, Womack and Jones 1996, Adler et al. 1996, Dyer 1997). Apparently, though, according to AEC practitioners, the reduction of delivery lead times has yet to happen within most manufacturing industries that serve construction. In this work, delivery lead times are defined by the moment at which the specialty contractor places a purchase order until the moment the order arrives at the fabrication shop. In the model, long delivery lead times vary from 4 to 6 weeks, though some orders in the real world may take significantly longer. Next, I speculate on what the consequences might be for the design-build process if delivery lead times could be shortened to 1 or 2 weeks.

Figure VII.6 and Table VII.5 illustrate the trade-off that project managers might face if suppliers were able to compress delivery lead times. Short lead times consistently reduce the mean of the overall project duration but they increase wasted construction resources, especially when specialty contractors participate in early design.

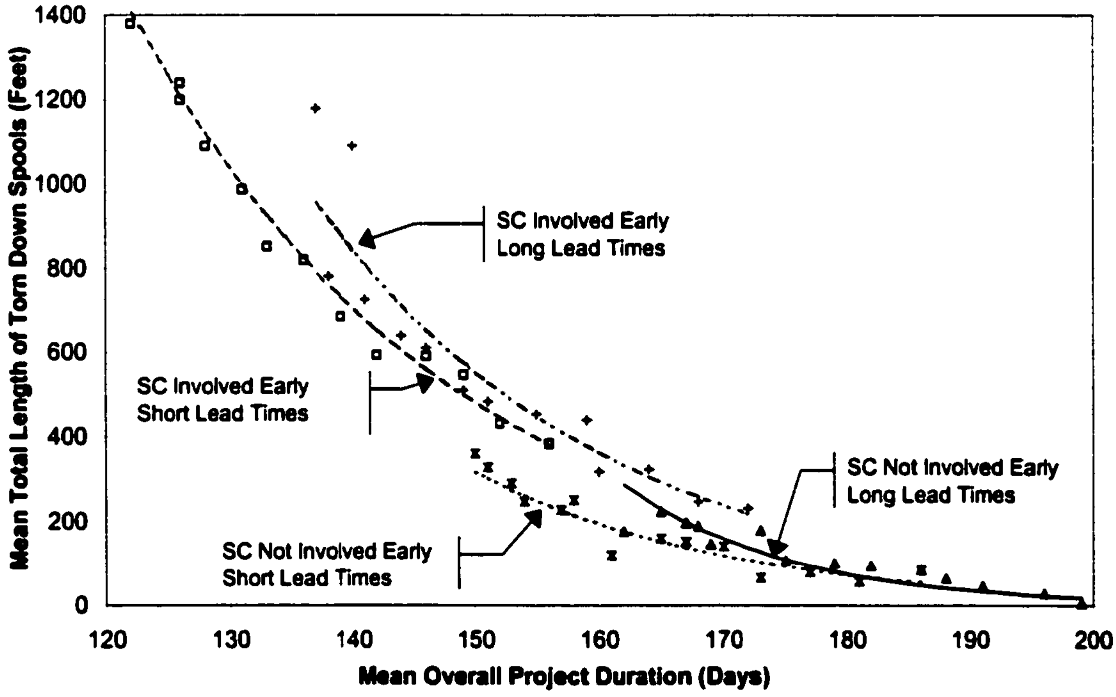


Figure VII.6 – Mean Overall Project Duration versus Mean Total Length of Torn Down Spools, from a No Postponement Scenario to a Scenario in which Design Development Cannot Start Before Day 90 [with and without Competitive Bidding, and with Short and Long Delivery Lead Times, Spools 10 Feet Long] (1,000 Runs for each Data Point)

Table VII.5 - Competitive Bidding versus Early Contractor Involvement, for a Scenario with Short Lead Times and Spools 10 Feet Long (mean ± standard deviation)

Scenario	Overall Project Duration (Days)	Total Design Time (Days)	Total Execution Time (Days)	On-Site Rework Time (Days)	On-Site Wasted Time (Days)	Total Length of Torn Down Spools (Feet)	Total Length of Unused Spools (Feet)
(F) SC Competitively Bid with Uncertainty and without Postponement	150 ± 37	63 ± 13	67 ± 31	1 ± 3	6 ± 16	360 ± 1192	293 ± 988
(G) SC Early Involved with Uncertainty and without Postponement	122 ± 40	63 ± 13	66 ± 38	3 ± 6	14 ± 21	1380 ± 2392	506 ± 1304
(H) SC Early Involved with Uncertainty and with Concept Development Start> Day 60	136 ± 32	58 ± 12	54 ± 30	2 ± 5	8 ± 15	820 ± 1903	331 ± 917

*Total Spool Feet Installed (No. Laterals * Length of Lateral) = 5170 ±876 Feet*

Delaying concept development, with short lead times, decreases waste of construction resources but increases the mean of the overall project duration, whether or not the specialty contractor is involved early on in concept development (Figure VII.6). In addition, for a certain reduction in delivery lead time, the savings in the overall project duration and the increase of wasted resources if the specialty contractor is involved early on are higher than if the specialty contractor is not involved early on. This result stems from the fact that, if the contractor is involved early on, fabrication starts once materials are available and shop drawings are ready because the model assumes that approval of shop drawings is immediate in these circumstances. Conversely, in a competitive bidding scenario, it can happen that the spools arrive at the fabrication shop but their assembly stays on hold until the architect/engineer approves the shop drawings, canceling out some benefit of short lead times.

VII.4.5. LEVERAGING SPECIALTY-CONTRACTOR KNOWLEDGE IN CONCEPT DEVELOPMENT

The simulated scenarios showed that efforts to compress the overall project duration consistently increase wasted construction resources. These scenarios implicitly assumed that construction methods would not change, whether or not the contractor participates in early design. The next scenario relaxes this assumption. In a competitive bidding scenario, contractors typically do not have much time to become familiar with the design and they do not necessarily know whom the project participants will be until late in the process. Chances are that they expect a confrontational project environment, which in turn may not be favorable for participants to follow the best construction sequences (e.g., Birrell 1985, Bennett and Ferry 1990, Hinze and Tracey 1994). Conversely, if contractors can contribute their process knowledge during early design, there is a greater chance of finding design solutions that are more efficient to build (Gil et al. 2000).

During this research, I learned that a contractor's decision on the spool piece length varies in relation to his familiarity with the design and to his knowledge of other project participants. In a competitive bidding scenario, contractors often select the shortest spool pieces (around 8 to 10 feet long) because these are easier to slide into steel racks. In contrast, contractors involved early in the process have the opportunity to get to know the design definition and other project participants, so they are comfortable in selecting longer spools. Longer spools minimize the number of required welds and they can still be slid, if specific on-site conditions exist. Because welding is the most crucial operation in acid-exhaust spool installation, the number of welds is more or less proportional to the time needed to install the spools. Contractors roughly estimate that if the number of welds doubles, the time it takes to install the spools also doubles.

Figure VII.7 illustrates how the design-build process changes as the length of spools increases from 5 to 20 feet, assuming early contractor involvement. Results indicate that going from 5 to 20 feet decreases the execution time, resulting in approximately a 10% decrease in the overall project duration. However, longer spools also increase the relative percentage of time wasted by on-site crews. Because spool installation progresses faster, crews are more idle in-between task iterations (Table VII.6). Longer spools do not significantly influence the quantity of material resources wasted during construction.

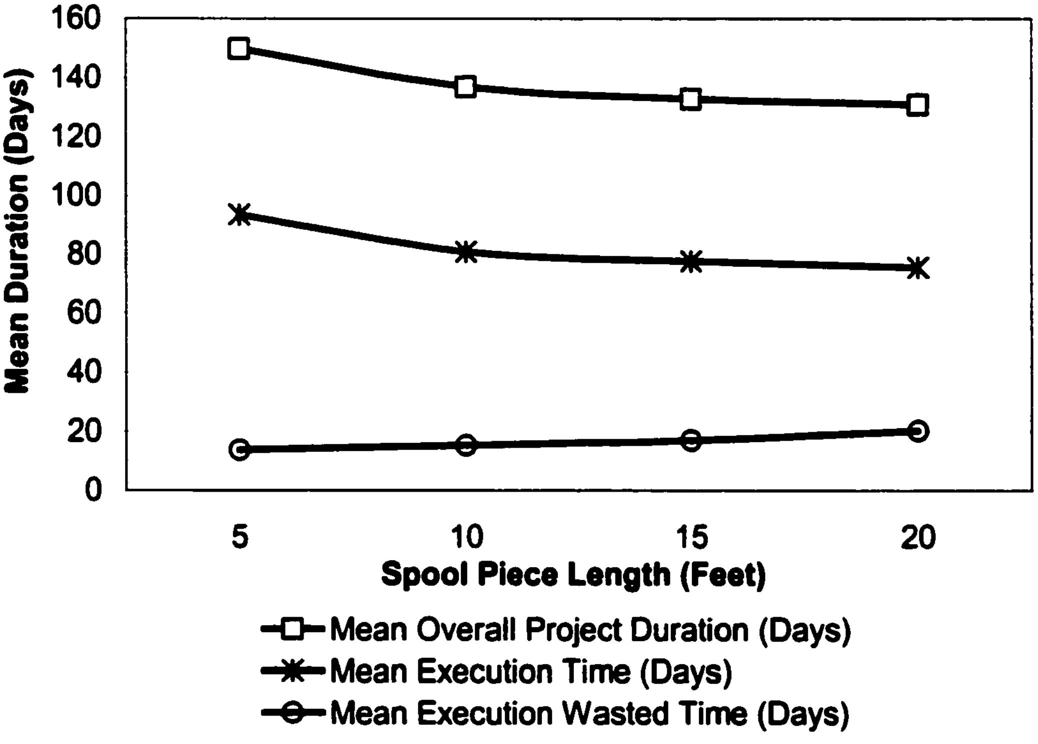


Figure VII.7 –Influence of Spool Length on the Design-Build Development Process (1,000 Runs for each Data Point) [Scenario: Specialty Contractor Involved Early On, No Postponement, Long Lead Items]

Table VII.6 - Influence of Spool Length on the Design-Build Development Process (mean ± standard deviation) [Scenario: Spools 20 Feet Long; with Uncertainty]

Scenario	Overall Project Duration (Days)	Total Design Time (Days)	Total Execution Time (Days)	On Site Rework Time (Days)	On site Wasted Time (Days)	Total Length of Torn Down Spools (Feet)	Total Length of Unused Spools (Feet)
(I) SC Early Involved without Postponement + Long Lead Times	131 ± 39	63 ± 13	75 ± 37	1 ± 4	20 ± 25	1030 ± 2007	312 ± 962
(J) SC Early Involved with Concept Dev. Start > Day 60 + Long Lead Times	149± 30	58 ± 12	66 ± 29	1 ± 3	12 ± 17	463 ± 1432	125 ± 567
(K) SC Early Involved with Concept Dev. Start > Day 60 + Short Lead Times	133 ± 31	58 ± 12	50 ± 31	2 ± 5	14 ± 17	777 ± 1780	244 ± 787

*Total Spool Feet Installed (No. Laterals * Length of Lateral) = 5170 ±876 Feet*

In the competitive bidding scenario, the model assumes that the contractor would start procurement before he had shop drawings approved. In practice, contractors may need to do this regardless, in order to meet the project milestones they contractually agreed upon to get the job. By doing so, the contractor bears the risk that if the design definition changes and the procured materials are rendered inadequate, the client may not provide financial compensation because the designer had not yet approved the drawings. Some specialty contractors may be willing to accept such risks, and others may not. Selecting longer spools, which may later prove to be too long for the steel racks, is one such risk. When the contractor selects shorter spools, the result is a less efficient construction process that delays the overall project duration. Multiple welds also increase the probability of future leakage and of flow impurity problems, making this scenario a lower quality solution from a performance standpoint in the long term.

VII.5. ECONOMIC ANALYSIS OF POSTPONED COMMITMENT STRATEGIES

The next analysis provides a simplified economic assessment of the trade-off between reducing construction waste and increasing the overall project duration as a result of alternative postponement strategies. The mean results of the simulation model support this analysis.

The lost opportunity cost reflects the production value that the manufacturer would forgo if a delay in the fab design-build process delayed the start of the manufacturing process, assuming this delay would cause an unrecoverable loss of sales. Practitioners estimated the opportunity cost associated with a R&D fab from $2.5 million up to $5.0 million per day. For simplicity's sake, I assume that this value stays constant regardless of the number of days that the project would be delayed. I traced the lost opportunity cost curve, first, by assuming that this cost is zero at the no postponement scenario, in which the mean of the overall project duration is the shortest possible. Then, as the postponement lag increases in 5-days intervals, the mean of the overall project duration increases somewhat and the lost opportunity cost consequently increases as well (Figure VII.8). This cost does not increase linearly because the mean of the project duration does not increase linearly as concept development is postponed in 5-days intervals.

In order to assess the cost associated with construction waste caused by any design criteria change that might occur while the spool fabrication and construction phases are underway, I used the following assumptions. First, changes of design criteria produce construction waste with the same order of magnitude for other fab utility systems as they produce waste for the acid-exhaust system. The analysis quantifies this waste in terms of total feet of unused spools and of torn down spools. The number of utility systems routed in a lateral typically varies from 40 to 80. Examples of these systems are the electrical cabling, exhaust and process ductwork, process piping systems, specialty gases, fire-sprinklers, etc. These systems are not constructed simultaneously, nevertheless the analysis assumes that a number of systems are affected simultaneously by any design criteria change.

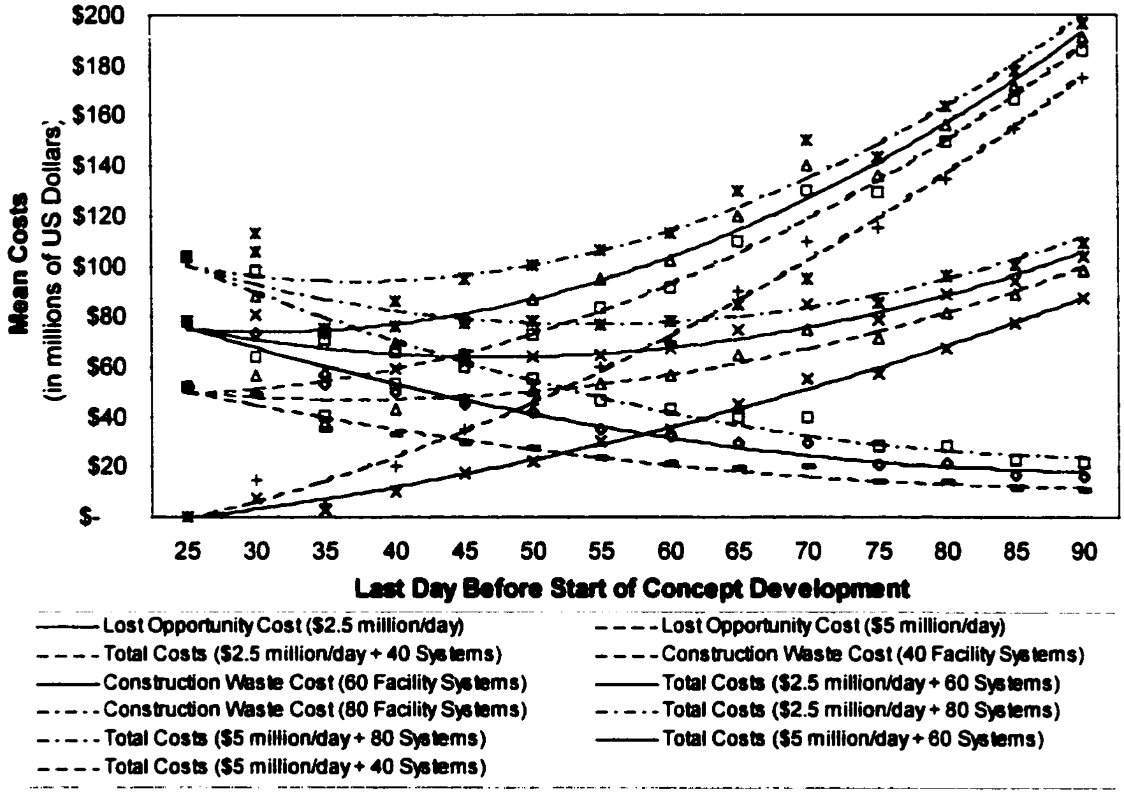


Figure VII.8 - Economic Analysis of the Trade-off between Minimizing Construction Waste and Extending the Project Duration, for Alternative Postponement Strategies [Scenario: Specialty Contractor Involved Early On, Long Lead Items, 10 Feet Long Spools]

Second, the analysis uses a cost of $600/foot for the materials needed for any utility system, not including installation. This includes the cost of one foot of ductwork or pipe—regardless of the material (e.g., straight stainless steel, Teflon coated stainless steel, and fiberglass)—plus an allowance for the cost of specialty items, such as taps, dampers, or valves. The analysis assumes a labor cost of $400 per foot for installation.

Each trade-off cost curve adds the lost opportunity cost to the construction waste cost that result as the postponement lag increases. Specifically, the trade-off cost curves in Figure VII.8 combine the lower and upper estimates of the lost opportunity cost with the construction waste cost that results as the acid-exhaust waste is extrapolated for 40, 60, and 80 fab utility systems. The results show that if I assume that the lost opportunity cost is at the high end, postponement is not economically attractive. However, if I assume that the lost opportunity cost is at the low end, then the trade-off cost curves show that an efficient postponement lag is beneficial, especially if I assume a high value for the construction waste. These results confirm the intuitions expressed by project managers when they state that the benefits associated with postponement may not make up for the rise in the lost opportunity cost in the case of R&D facilities.

Altogether, the results illustrate the usefulness of the simulation to sharpen the theoretical understanding of the effectiveness of alternative project delivery systems, to reason out the criteria with which to compare them, and to assess the economic value of each alternative in accordance. However, simulation cannot provide an optimal system for delivering a R&D fab project because each system's benefits are relative to the criteria that decision-makers consider and the assumptions they make. Subject-matter experts must decide which criteria and assumptions should guide decision-making, and act accordingly.

VII.6. MODEL VALIDATION

I conceptually validated the simulation model and its results and tested the usefulness of the simulation environment by following the method described in section VI.7. The rationale in the simulation model for the execution phase was developed and validated jointly with mechanical, electrical, and piping contractors, through interviews. The level of abstraction of the model makes it well suited to simulate the design detailing, procurement, and construction processes of a myriad of utility systems in a fab (e.g., electrical, piping, or ductwork systems). The numeric assumptions—in terms of size of batches, duration of tasks, lost opportunity costs, and construction waste costs—are based on practitioners' estimates; these estimates were not validated with empirical data.

The simulation of the design-build process does not aim to reproduce exactly the process of real-world projects. Instead, I aimed at developing a computer-based framework that enables users to compare alternative project delivery systems in unpredictable environments and to learn by using it. The assumptions on the numeric values—developed with practitioners' input—merely illustrate the usefulness of simulation to compare alternative management strategies and to make economic assessments. The agreement of the simulation rationale and of its results with practitioners' perceptions on the way real-world projects evolve gave me confidence in the validity and in the usefulness of the simulation.

VII.7. CONCLUSIONS

A systemic analysis of alternative project delivery systems reflects that "there is no such thing as a *free lunch*". Given the one-of-a-kind nature of AEC products, faster design-build development implies making commitments early, so that procurement and construction may start as soon as possible. If this takes place in an environment in which design criteria are extremely dynamic, wasted construction resources inevitably increase.

Simulation results show, however, that alternative managerial strategies may result in worthy compromises. The postponement of concept development (or the extension of the conceptualization phase, as it can be alternatively put), so as to let design criteria 'settle down' before design commitments are made, stands out as an efficient strategy. The extent to which a client should adopt postponement will vary with several factors, namely: (1) the client's willingness to accept risks, (2) the relative importance he assigns to each of the performance variables being traded off, (3) the expected stochastic nature of changes, and (4) the value of the lost opportunity and rework costs.

Thus, if increasing the chances of compressing the overall project duration is of the utmost importance, then no postponement will be the best strategy because it maximizes those chances. However, if the costs associated with resources wasted during construction matter, then postponement may be more appropriate. In addition, empirical research indicates—and simulation modeling confirms—that other opportunities to expedite process development exist for organizations that can successfully leverage specialty-contractor knowledge in early design. The example used here—using longer spools so as to reduce the number of welds and consequently to reduce the time spool installation takes—illustrates this point. The extent to which client organizations are informed of the consequences that alternative contractual agreements may have on production system design and on the product quality merits further investigation.

VIII. CONTRIBUTIONS TO KNOWLEDGE AND FUTURE RESEARCH DIRECTIONS

VIII.1. CONTRIBUTIONS TO KNOWLEDGE

This dissertation contributes to knowledge in the field of construction engineering and management in several ways. First, it provides a description of industry practices and a product-process representation of the design development process of high-tech facilities. Second, it characterizes the contributions of specialty-contractor knowledge to the early design phase. Third, it provides an innovative application of computer simulation for modeling complex projects. Finally, it compares the effectiveness of alternative project delivery systems in unpredictable environments. A detailed explanation of these contributions follows.

1. Design Development Process of High-Tech Facilities

This dissertation provides a description of industry practices related to the delivery process of high-tech facilities, in particular, semiconductor fabrication facilities (fabs). Specifically, this description identifies sources of uncertainty throughout their design-build process, describes which attributes of the development process are most valued by the client, and clarifies the conceptual difference between product and process flexibility. In addition, this dissertation delivers an innovative product-process model for the design development of high-tech facilities. This model provides a foundation for developing tools to support design development. Although I only validated its applicability to represent the design development of fabs, given its level of abstraction, I expect the model will be equally well suited to represent the design development of other kinds of AEC products.

2. Contributions of Specialty-Contractor Knowledge to Early Design

This dissertation refines the understanding of the value of involving specialty contractors in early design, a principle of lean construction theory. Specifically, it categorizes the contributions of specialty-contractor knowledge to the concept development phase, it illustrates each category with multiple examples drawn from current practices, and it puts these contributions in the context of knowledge creation theory. To the best of my knowledge, this work is the first to characterize these contributions so distinctly.

3. Innovative Application of Computer Simulation

This dissertation contributes in two ways to the knowledge in modeling AEC processes: first, by showing a creative use of preemption capabilities in simulation engines for explicitly modeling uncertainty; and, second, by integrating (in a single simulation model) product design decisions with the development process, from design inception until the end of construction. These contributions advance the knowledge of simulating the complexity of real-world projects.

4. Comparison of Alternative Project Delivery Systems

This dissertation illustrates the usefulness of simulation for sharpening theoretical understanding on the effectiveness of alternative project delivery systems in unpredictable environments. In particular, it makes explicit a trade-off that practitioners must consider in these circumstances: postponing design commitments so as to increase the reliability of the development process and to minimize rework, versus making early commitments so as to increase the likelihood of finishing the project early at the expense of increasing expected rework.

Admittedly, the simulation model represents one abstraction that synthesizes interviewees' mental models of the design-build process of a fab, or one *microworld*, using Papert's term (Papert 1980). "Mental models are deeply ingrained assumptions, generalizations, or even pictures or images that influence how people understand the world and take action" (Senge 1990 p.8). However, computer simulation allows users—students, managers, and novices alike—to customize the inputs so that the model can better match their own mental models. Accordingly, simulation can help users learn by conceptualizing alternative project delivery systems, experimenting in a risk-free environment, and reflecting on project goals, priorities, and performance trade-offs.

The ultimate purpose of the model is to cause decision-makers to change their project delivery practices, if the model reveals alternative systems that better meet the clients' needs. The model does not statistically forecast the duration of real-world projects in unpredictable environments, nor was it validated for that purpose. Still, several researchers and professionals, to whom I presented this research, would like to see the simulation work developed further in this direction, an issue I discuss later in this chapter.

VIII.2. FUTURE RESEARCH DIRECTIONS

Diverse research directions can give continuity to the work initiated in this dissertation. I grouped these in the next three sections.

VIII.2.1. SHORT-TERM REFINEMENTS OF THE SIMULATION MODEL

Several refinements of the simulation model, which would require a limited effort, are possible. For one, I modeled only the design-build development process for one facility system. The simulation model can be expanded, however, to encompass the development processes of other facility systems and their dependencies, as shown in the conceptual product-process model in Figure V.1. This expansion would improve the ability of simulation to yield insight into the implications of design changes to the process and into the appropriateness of alternative management strategies to cope with this unpredictability.

Second, the simulation model assumes a point-based design strategy by assigning a specific value to each decision designers make. Therefore, whenever design criteria change, designers are likely to redo their tasks. The simulation model also assumes that designers would always opt for the smallest commercial diameter of ductwork above the engineered minimum diameter. In practice, however, designers occasionally over-design product features for accommodating anticipated changes. This practice can lead designers to choose, for instance, a larger commercial diameter for a ductwork other than the smallest diameter that satisfies design requirements; or to choose a piece of equipment with more capacity than the one required by design criteria. Further investigation into how to computationally implement the capabilities for contrasting alternative design strategies is warranted.

Third, the graphical user interface (GUI) and the delivery of simulation outputs should be more user-friendly. Currently, the executable versions of the computer models in this work automatically run successive batches of simulations for various scenarios, if users specify the respective inputs in a batch file. However, the analysis of results is time-consuming: users must collect the statistics resulting from each scenario, paste them into a spreadsheet, and plot the graphics. Ideally, users ought to have the ability to customize the model inputs with the help of window menus. These menus would let users, for example, vary the duration of tasks according to different resource allocations and technologies, implement various probability density curves for design changes, shift client deadlines to accept changes, or experiment with alternative management strategies such as postponed commitment. Likewise, the graphics that illustrate the trade-offs among performance variables should be automatically produced at the end of a set of simulation runs.

VIII.2.2. LONG-TERM REFINEMENTS OF THE SIMULATION MODEL

This research has not tested the ability of simulation to produce results that are statistically similar to data from real projects. Instead, it has used simplified inputs because the primary purpose of the simulation was to sharpen theoretical understanding on the effectiveness of alternative project delivery systems. Future research can test the ability of the model to reproduce the development process of real-world projects.

For that purpose, the simulation inputs in terms of resource allocation and frequency of changes in design criteria should be based on real data. This data may be found in records of billable hours, project schedules, change order documentation, etc. The simulation results should then be tested against the results from those same projects. In doing so, the research would test the accuracy of the assumptions in the simulation rationale and the ability of the simulation model to predict the outcome of real-world projects. If the results prove to be as good as I expect they will be, the simulation model and its results will have gained extra credibility.

Furthermore, abstractly, the model showed the effectiveness of postponing design commitments and of involving specialty contractors in early design. However, as a client representative pointed out, clients would need more tangible information to implement innovative strategies, namely: (1) which specific design decisions can they postpone and which ones they cannot for each facility system? (2) which are the corresponding financial implications of these decisions (3) which deliverables correspond to each design decision (such as process and instrumentation drawings, specifications, and arrangement drawings)? and (4) which contributions can specialty-contractor knowledge bring to each decision? To integrate the actual process representation with the deliverables used by designers merits further research. Such work could ultimately result in a tool for helping project managers in real time decision-making.

VIII.2.3. RESEARCH ON DESIGN-BUILD DEVELOPMENT PROCESSES OF HIGH-TECH FACILITIES

This dissertation shows that if project managers expect a predictable environment ahead, where design criteria are expected to stay fixed, early commitment may be beneficial—from a process perspective—because it will help to compress the project duration. This work has not probed, however, into the implications of early commitment on the product quality, a research question by itself. If project managers expect an unpredictable environment ahead, they face two alternatives.

On one hand, they may implement a set-based design strategy. Set-based design would allow designers to work with broader sets of design solutions that they would narrow to converge on a final solution, as project information became more certain (Lottaz et al. 1999). Set-based design demands, however, the computational means and a trained work force. Both demand time and commitment from any AEC organization. More research is needed on tools to support the use of set-based design in AEC practice.

On the other hand, project managers may opt for postponed commitment. The model identifies an efficiency period, following the conceptualization phase, after which designers should start concept development. If they do so, they can achieve significant resource savings without increasing the downside risk that the project will last longer than what it would last if they would commit early on. Still, more research needs to be done to understand better in which ways changes of design criteria affect concept development decisions for each facility system. Such understanding will inform at which point concept development—or parts of concept development—should start for each system, and to what extent concept development of some systems can start while concept development of other systems is postponed.

Moreover, an implicit assumption in this work is that the client would let the project duration vary if changes of design criteria occurred. Indeed, schedule failure is a common problem in managing concurrent development projects (Ford and Sterman 2000). In the reality of the semiconductor industry, however, this assumption may not hold. As a client representative made clear to us, often the client cannot tolerate an extension of the project beyond the deadline that was initially planned despite the occurrence of any changes of design criteria. The reason is that a time extension could compromise other strategic business goals, such as the planned date for the chip to reach the market, and ultimately compromise the profitability of the overall project.

In these circumstances, when changes of design criteria occur, AEC organizations have to find alternative ways to cope with resulting rework. For example: organizations can add more resources to the project; designers can work extra hours or work during weekends; the client can alter the scope of the work; or the design team can modify the level of detail in design. Clearly, my work does not consider any of these alternatives nor does it assess the performance trade-offs associated with choosing one instead of another. Adding a constraint to the design-build development model that would bar a possible extension of the project duration in an unpredictable environment provides another interesting avenue for research.

VIII.3. FINAL CONSIDERATIONS

If specialty-contractors participate in early design, they can contribute a wealth of knowledge in product and process design—empirical research has clarified this principle of lean construction theory. In addition, simulation modeling lends support to the benefits of involving specialty-contractors early on regardless of the degree of predictability of the project environment. Organizations should nonetheless distinguish early involvement of specialty contractors in design from early commitment on procurement, fabrication, and construction decisions. These are answers to the research questions at the onset of this research.

Many other questions can be posed along these lines:

- To what extent can the product definition of fabs be broken down in modules? Modularization would let, hypothetically, practitioners build a part of a fab (for example a fab quadrant), and accordingly make design commitments for that part. The ramp-up process could then be sped up for the production lines in that part, while decisions on other design features could be postponed. Some conceptual work exists on the benefits resulting from fab modularization (Wood 1997) and I actually observed some ad hoc practices that followed this principle, but more research needs to be done on how to implement it effectively.

- The balance between product flexibility versus process flexibility needs to be better understood. Is the up-front cost that results from over designing some product features unaffordable to clients, or does over-design clearly pay off during the facility life cycle? If so, which are those features that should be over designed?
- How does rework of design, of construction, and of tool install affects: (1) the operating performance of a fab, (2) the fab's ability to allow fast replacement of tools once in operation, and ultimately (3) the chip production yields that can be attained?
- Which facility systems are more appropriate to standardize and how can this effort be coordinated among industry players? Standardization of the facility components and of their interfaces is crucial. More standards would let project managers sped up the design and installation of selected components while the design and fabrication of other components could be delayed because practitioners could reliably anticipate the constraints imposed by the components not yet available.
- What kinds of contracts should AEC organizations write for supporting new project delivery systems?

These are not trivial questions and I do not have answers to them. I expect answers will not be simple, but rather they will emerge as complex balances of multiple factors and assumptions. In all likelihood, other questions will arise in the quest to answer these questions. Exciting research opportunities lie therefore ahead for those that choose to carry on research in the framework of lean construction theory.

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APPENDIX I

TECHNICAL SYNOPSIS OF SEMICONDUCTOR FABRICATION FACILITIES

AI.1 INTRODUCTION

Semiconductor facilities (fabs) can be broken down into three main areas: (1) the cleanroom, (2) the subfab, and (3) the air chamber. Figure AI.1 schematically illustrates a cross-section of a fab and Figure AI.2 illustrates a cut-away arrangement of a production tool set.

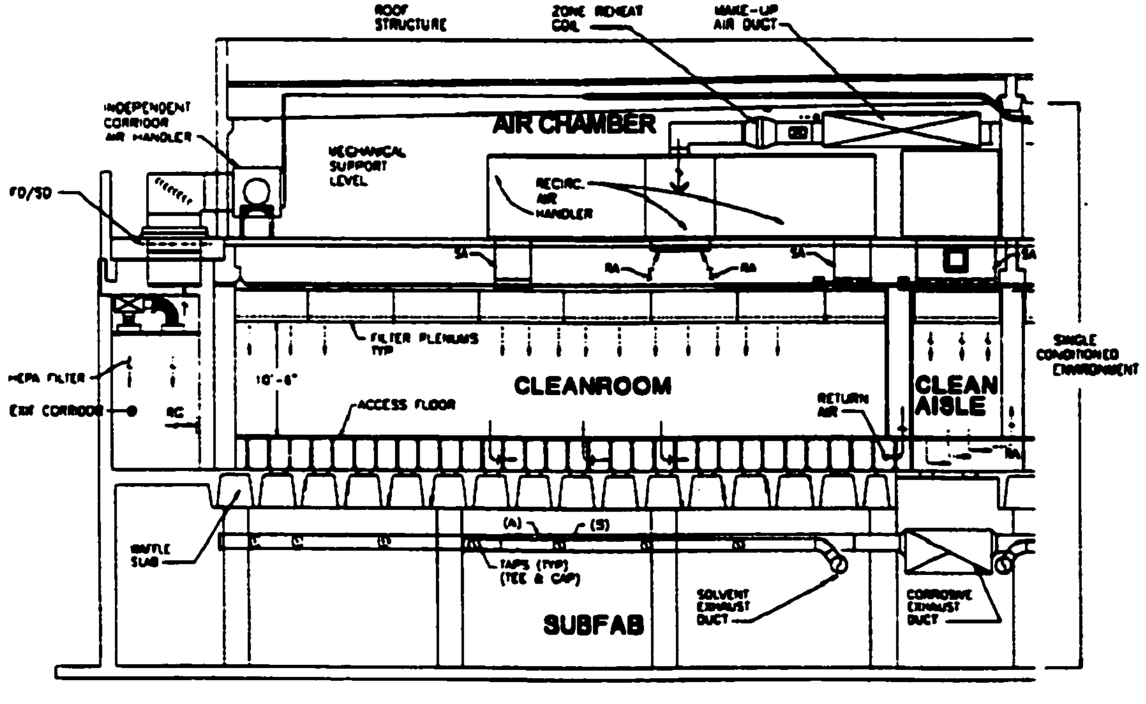

Figure AI.1 - Cross-Section of Fab with Three Levels and Modular Air Handling (Reprinted from Accorn 1997, p.195)

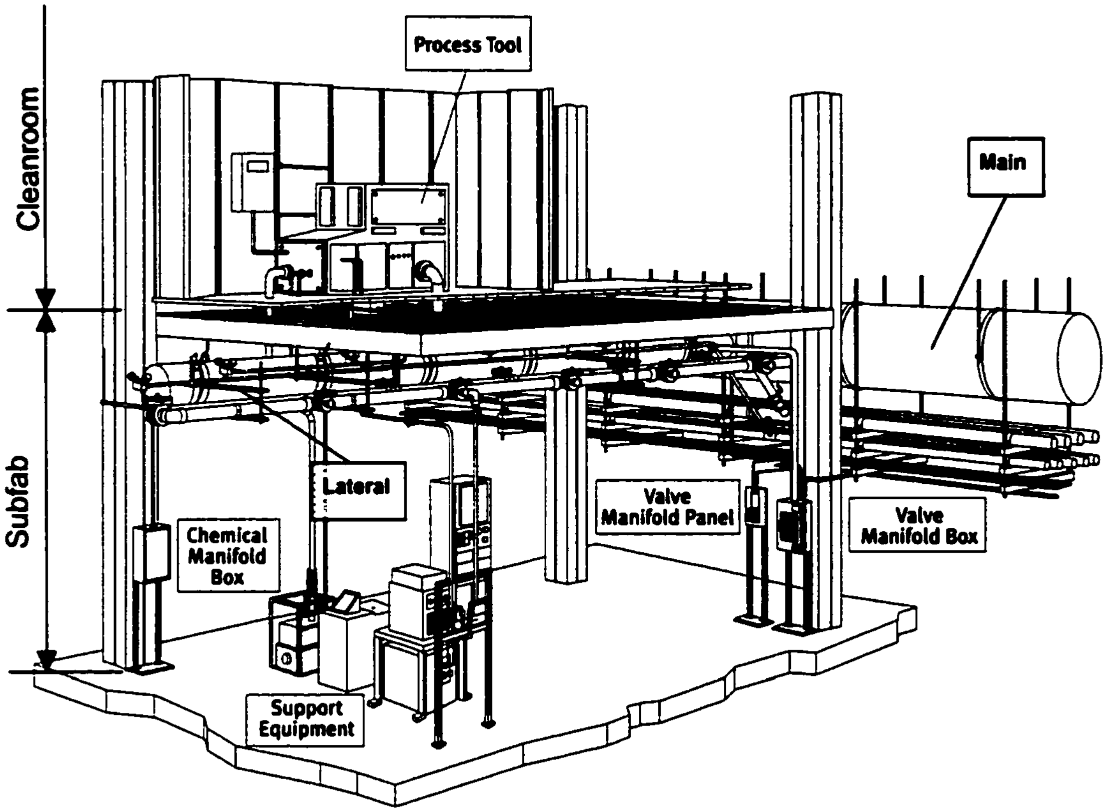

Figure AI.2 - Cut-Away Arrangement of a Production Tool Set (from *Terms and Terminology* poster by microKinetics, Inc. ©. Reprinted by permission of microKinetics, Inc.)

The cleanroom is the space inside the semiconductor facility where the production tools are located, such as etchers, steppers, tracks, ashers, and planars. The subfab is the space under the cleanroom that houses: (1) utility routings such as process piping, exhaust ductwork, and power distribution cables, (2) equipment to support the facility systems, such as transformers, chillers, pumps, and boilers, and (3) equipment to support the production tools, such as vacuum pumps, gas cabinets, temperature and humidity controls, air filters, and heat exchangers. The air chamber is the space above the cleanroom that houses most of the heating, ventilating, and air conditioning (HVAC) equipment (e.g., air handling units and fan units) and HVAC ductwork routings.

AI.2 CLEANROOM

The technology associated with the production processes that occur inside the cleanroom largely determines the performance requirements that the facility has to meet. The performance requirements are synthesized in two main pieces of information that guide AEC practitioners throughout the design process: (1) the tool list and (2) the tool layout. The tool list is typically a spreadsheet document that lists the production tools the manufacturer expects to install in the cleanroom and their respective utility needs, such as electrical power, specialty gases, ultra pure water, and acid-exhaust requirements. The tool layout defines the spatial arrangement of the production tools in the cleanroom. These documents frequently change throughout the design-build development process due to changes in production technology or in the characteristics of the tools.

Tools are typically grouped in functional areas inside the cleanroom. In each functional area, generally one kind of tool predominates, such as etchers, chemical-mechanical polishers, steppers, or photolithographers. Each area may require specific environmental conditions regarding air quality, pressurization, temperature and humidity, light intensity and color, floor stiffness, or process utilities.

The interior architecture of the cleanroom space may follow different philosophies. The main options are a bay-and-chase layout, a ballroom layout, or a hybrid between the two. Simply put, the bay-and-chase layout consists of a series of parallel corridors—bays and chases—that cross a central corridor. The central corridor runs perpendicular to the bays and chases, and it runs lengthwise down the middle of the cleanroom. The body of the production tools and, occasionally, some process support equipment sit in the chases.

The front of each tool faces a bay so that operators can interface with the tool and hand the wafers in and out. Bays require more stringent air cleanliness conditions than chases.

In contrast, the ballroom layout has no interior partitions, relying instead on the ability of each tool to maintain a clean mini-environment around itself. The arrangement of tools in a ballroom layout, in terms of functional areas and within each functional area, is similar to that in a bay-and-chase layout despite the absence of partition walls.

The typical spacing between production tools in the cleanroom is 30 to 40 inches. Production tools may be connected by means of an Automatic Material Handling System (AMHS). The AMHS transports wafers in boxes (called Front Opening Unified Pods or FOUPS); alternatively, operators can manually carry the FOUPS between tools. The AMHS system is called intra-functional if it just transports wafers within one functional area and inter-functional if it circulates among different functional areas. The AMHS requires enormous topographical precision during both its and the tools' installation for exactly aligning the fronts of the tools with the AMHS overhead tracks.

Irrespectively of the cleanroom's interior architecture, most process tools hook up (beneath the raised cleanroom floor) to a set of routings that carry utilities such as electricity, process vacuum, ultra pure water, acid exhaust, and specialty gases. The list of utilities varies for each tool. Smaller tools may connect to only 4 or 5 utilities while more complex tools may connect to more than 30 utilities. Tools of the same kind do not necessarily hook up to the same set of process support utilities. Some utilities—such as process vacuum and specialty gases—are provided by routings that branch off from process support equipment located at the chases or at the subfab. Other utilities—such as acids and volatile organic compounds (VOC)—are provided by routings that branch off from valves on the lateral routings in the subfab.

Ideally, the process support equipment in the subfab should be vertically aligned as much as possible with the corresponding tool in the cleanroom for minimizing the length of routings and minimizing the consequent pressure drops. However, this goal is getting harder to achieve because the number of support equipment pieces that must connect with a production tool has been increasing and also because tools are getting more densely packed in the cleanroom.

AI.3 SUBFAB

Subfabs can have different configurations. They can be composed of one floor, two floors, or one floor and a trench. Some subfabs provide a clean air environment and others do not. The subfab area can extend underneath the whole cleanroom area, or just part way. The subfab design features may or may not vary across the different functional areas in a subfab, depending on the design philosophy followed. Chapter III presents a discussion of coupled, decoupled, and semi-decoupled subfabs.

The utility routings in the subfab are typically arranged in alignments called the main and laterals. The main and each lateral consist of a set of routings such as pipes, electrical cables, and ductwork. The main runs lengthwise under the central corridor of the cleanroom. The laterals branch at right angles off the main in regular intervals and they run along the width of the subfab. Practitioners estimate that mains may include more than 100 utility routing systems. A lateral may include 40 to 50 systems but this number can easily reach more than 80 systems if routings of specialty gases (which have a very narrow cross-section) are included. Typically, fabs have two kinds of laterals—(1) the process lateral and (2) the exhaust lateral—that branch alternately off the main. The process lateral primarily runs the process support routings whereas the exhaust lateral primarily runs all sorts of exhaust routings. Ideally, laterals should be vertically aligned as much as possible with the rows of tools up in the cleanroom for minimizing the lengths of the routing branches that connect the valves on the laterals with the tools.

AI.4 AIR CHAMBER

The air chamber above the cleanroom can be either a fan deck or a full floor. The primary purpose of the air chamber is to allow space to run the HVAC routings and to locate the equipment, such as air handling units. The HVAC system should keep a laminar airflow in the cleanroom (this is an "airflow in parallel flow lines with uniform velocity and minimum eddies" (ASHRAE 1987 32.1)). Typically, the clean air stream flows vertically through the suspended ceiling of the cleanroom (made of several High Efficiency Particulate Air (HEPA) filter panels) down through the cleanroom raised floor. The air re-circulation system then collects the dirty air, purifies it, and re-circulates the air again, or exhausts it to the exterior. The cleanroom classification indicates the degree of air cleanliness required for the cleanroom, in terms of maximum limits of particle count for a specific size, and in terms of the size of the largest particle. For example, ASHRAE (1991 p. 16.1) specifies the criteria for classifying a Class 1 cleanroom as follows: "particle count not to exceed 1 particle per cubic foot of a size 0.5 μm and larger, with no particle exceeding 5.0 μm." A challenge that faces practitioners involved with design and construction of clean spaces is the fact that equipment currently available for controlling the air cleanness is not sensitive enough to precisely measure particles at the high cleanliness levels required today.

AI.5 SOURCES OF INFORMATION

To my knowledge, more sources of technical information are available on the design and construction of clean spaces in general than on design and construction of fabs. Far from pretending to be comprehensive, I list next some credible and useful sources for information on clean spaces: (1) the Chapter 16 of ASHRAE's HVAC applications (ASHRAE 1991), (2) the Chapter 32 of ASHRAE's Handbook HVAC Systems and Applications (ASHRAE 1987), and (3) some papers of the Construction Congress V - Managing Engineered Construction in Expanding Global Markets—namely Clifford (1997), Acorn (1997), and Pitts (1997).

The magazine Fabtech (http://www.fabtech.org) regularly publishes articles on various problems and technical solutions faced by AEC practitioners working in the semiconductor industry. Also, the International Technology Roadmap for Semiconductors (http://public.itrs.net/) and the Intel Technology Journal are credible sources for assessing the technological needs and challenges that AEC practitioners face ahead in this field.

APPENDIX II

CHARACTERIZATION OF THE PRODUCT-PROCESS DESIGN MODEL FOR FIVE FACILITY SYSTEMS

AII.1 INTRODUCTION

This appendix characterizes the nodes in the product-process model illustrated in Figure V.1 for the five design specialties: (1) chemical, (2) structural, (3) HVAC, (4) electrical, and (5) architectural. It provides information regarding: (1) decisions that designers make while executing each task; (2) design criteria that they use to make those decisions; (3) information exchanges that ideally must precede or succeed the execution of a task, (4) resources that each task requires, and (5) durations of the concept development tasks in terms of time actually spent on a specific project with a cleanroom size around 80,000 to 100,000 sq.ft. The node types are shown in brackets.

The depth of the information and the number of examples provided vary among the different design specialties in function of the opportunities presented to me during empirical research. Although far from being comprehensive, this information helps to clarify—clearly within the limits of a doctoral dissertation—the complexity of the design development process of semiconductor facilities. In particular, I expect it to be useful for others who initiate research in this domain.

AII.2 CHEMICAL SYSTEM

Chemical engineers design the process support systems that serve the production tools in the cleanroom. These systems comprise gases (e.g., N_2, O_2, H_2, Ar), specialty gases (around 20, such as nitrogen trifluoride (NF_3) or silicon tetrachloride (Cl_4Si), chemicals (somewhere between 10 to 30), ultra pure water (UPW), wastewater, compressed air, house vacuum (for building cleaning purposes), and process vacuum (for supporting production processes). Some process support utilities such as heated and chilled water, steam, compressed air, house vacuum, and process vacuum may fall in the scope of the chemical or the wet-mechanical specialties. Process exhaust systems typically fall in the scope of the dry-mechanical specialty.

The design of the chemical systems evolves in intense conditions of uncertainty because the decisions that need to be made require specific information on production tools and on the tool layout. The list of tools characterizes the tools the client expects to install in the cleanroom and their respective utility requirements. The tool layout defines the location of each tool in the cleanroom. The list of tools frequently changes as the fab design progresses (the tool layout also changes although less frequently) because of internal occurrences, such as technological changes during the chip product development, or external occurrences such as changes of market-demand forecasts. As a result, during concept development, chemical engineers usually have to size and lay out pipe routings and equipment based on educated guesses.

I collected most information on the chemical design process through interviews with lead designer McRae (Mac) Willmert, designer Jeannine Cheney, draftsman Romuald Polkowski, and subfab coordinators Dick Trunfio and Charlie Priest. Mac Willmert provided the estimates of the average man-hours that engineers spent per task.

ChemicalConcept [Conceptualization]

ChemicalConcept represents the initial estimates for the major features of the chemical system. Instances of these features are the loads and the equipment needs, the size and the geometry of critical cross-sections of piping routings, and the schematic routing layouts (commonly referred to as "one-line diagrams"). These decisions are formalized typically in spreadsheets and in Piping and Instrumentation Drawings (P&IDs).

ChemicalDesignCriteria [Conceptualization]

ChemicalDesignCriteria represents the design criteria that guide concept development of the chemical systems. Empirical rules primarily govern the allocation of space for the routing systems in the subfab. One main criterion rules that the subfab space should be allocated according to the following priorities: first, the most expensive pipe routings, such as vacuum forelines (the lines that connect vacuum pumps in the subfab with production tools in the cleanroom), for minimizing their length; second, larger routings such as exhaust ductwork and gravity routings (e.g., drains); finally, more flexible routings such as electrical distribution systems. Other criteria for spatially allocating routings of some specialty gases and chemicals reflect design thresholds on pipe lengths. Corrosion criteria frequently guide the choice of the materials.

DevelopChemicalLoad [Design Task]

DevelopChemicalLoad refines the decisions on the chemical loads, such as on the acid-exhaust and process vacuum loads. Once chemical engineers complete this task they hand over the information of the Volatile Organic Compound (VOC) exhaust load to dry-mechanical engineers so that the latter can size the process exhaust routings. DevelopChemicalLoad involves, on average, 1 lead engineer for 3 to 5 days.

ChemicalLoadQueue [Decisions Queue]

ChemicalLoadQueue represents the decisions resulting from DevelopChemicalLoad.

DevelopChemicalSection [Design Task]

DevelopChemicalSection refines the decisions on the critical cross-sections of process support pipes in terms of diameter, space clearances, thickness, insulation, and materials. The choice of the materials varies according to the function of the pipe. For example, process vacuum routings are preferentially in copper, specialty gases in stainless steel or copper, process chilled water in PolyVinyl Chloride (PVC), and ultra-pure water in PolyVinyliDene Fluoride (PVDF). DevelopChemicalSection involves, on average, 3 to 4 engineers for 2 weeks.

ChemicalSectionQueue [Decisions Queue]

ChemicalSectionQueue represents the decisions resulting from DevelopChemicalSection.

DevelopChemicalLayout [Design Task]

DevelopChemicalLayout refines the decisions on the chemical systems layout in terms of the location of pipe routings and equipment in the three-dimensional space. Typically, chemical engineers also coordinate the space that each facility system should occupy in the subfab. DevelopChemicalLayout involves, on average, 5 to 6 engineers for 2 weeks.

ChemicalLayoutQueue [Decisions Queue]

ChemicalLayout represents the decisions resulting from DevelopChemicalLayout.

ConfigureChemicalEquipment [Design Task]

ConfigureChemicalEquipment refines the configuration of the chemical equipment, such as scrubbers, wastewater treatment plants, ultra-pure water (UPW) tanks, air compressors, and specialty equipment such as valves. Once engineers complete this task they hand over information as follows: (1) electrical power needs to the electrical specialty, (2) heat loads to the HVAC specialty, (3) volumetric characteristics and location of equipment to the architectural specialty, and (4) operating weight and vibration control requirements to the structural specialty. ConfigureChemicalEquipment involves 3 engineers from 2 ½ days to 2 weeks, with 1 week as the average.

ChemicalEquipmentQueue [Decisions Queue]

ChemicalEquipmentQueue represents the decisions resulting from ConfigureChemicalEquipment. Many equipment pieces (such as UPW systems, the waste water treatment plant, the gas and chemical pipes, pumps, and heat exchangers) have long delivery lead times. Engineers typically make early commitments on the configuration decisions of such major equipment pieces so that they can start procurement early on.

AII.3 STRUCTURAL SYSTEM

Structural engineers develop the system that provides the physical support for allowing the other facility systems to withstand static and dynamic forces, such as gravity, tool vibration, and seismic or wind dynamic forces. I collected most information on the structural design process through multiple interviews with structural lead designer Bob Stimpson.

StructuralConcept [Conceptualization]

StructuralConcept represents the initial estimates for the major features of the structural system. Examples of these features are: the choices of materials for the fab structure (e.g. steel, cast-in-place concrete, or pre-cast concrete), the spans between columns in the subfab, the span of the roof trusses, the pop-out dimensions in the cleanroom waffle slab, and the thickness of the waffle slab. Often, a fab is composed of a cast-in-place concrete structure under the cleanroom waffle slab and a steel structure above the waffle slab. According to Bob Stimpson, steel structures generally make the fab structure less expensive to build in the U.S.A., but steel pieces usually have longer delivery lead times than pre-cast pieces. Whenever the design team opts for a steel structure, for expediting the delivery of the steel pieces, steel mills should ideally be involved in the project from its inception. Typical spacing between subfab columns varies from 16' to 20' on center in the X and Y directions. The thickness of the waffle slabs typically varies from 3 ½' to 4'. There are, however, other fab configurations with values as low as 12' on center between subfab columns and a cleanroom waffle slab 2 ½' deep.

StructuralDesignCriteria [Conceptualization]

StructuralDesignCriteria represents the design criteria for concept development of the structural system. Vibration criteria are critical in the structural considerations. These criteria are primarily a function of the type of tools to locate in the cleanroom and of the way the client expects production technology to evolve. Vibration criteria drive decisions such as the thickness of the cleanroom waffle slab, the spans between subfab columns, and the height of subfab floors. Empirical rules guide other structural decisions such as the location of shear walls and of bracing systems. Engineers normally prefer to create reinforcing systems against dynamic loads in the exterior walls for minimizing the obstructions to routings inside the fab.

DevelopStructuralLoad [Design Task]

DevelopStructuralLoad represents the refinement of the structural loads. Structural engineers must collect information from numerous other specialties before doing this task. For example, engineers need to get the tools' operating weight and the tool density in the cleanroom from industrial engineers, and the location and operating weight of equipment and suspended routings from the electrical, chemical, and wet-mechanical specialties. If engineers opt for a decoupled design, they typically are conservative in estimating the design loads. This strategy allows them to keep critical design features (such as the thickness of the cleanroom waffle slab and the spans between the subfab columns) fixed across all functional areas of the fab. A conservative load for the cleanroom waffle slab varies between 300 to 400 pounds/sq.ft., based on a scenario in which the cleanroom is densely packed with the heaviest production tools. In contrast, in a coupled design, the structural loads will vary by functional area and, consequently, the design features vary too. In a semi-coupled design, structural engineers rely on the fact that the location of the most demanding functional areas in the cleanroom is fixed. Accordingly, they customize the design loads for those areas. For the remaining areas, they estimate a conservative load because they assume that floor use can vary. DevelopStructuralLoad involves, on average, 2 senior engineers for 1 week.

StructuralLoadQueue [Decisions Queue]

StructuralLoadQueue represents the decisions resulting from DevelopStructuralLoad.

DevelopStructuralSection [Design Task]

Develop Structural Section refines the cross-sections of major structural elements. The corresponding design decisions relate to the geometry, dimensions, and materials of the cross-sections of subfab columns, cleanroom waffle slab, roof trusses, and beams. DevelopStructuralSection involves, on average, 2 engineers for 1 to 2 weeks.

StructuralSectionQueue [Decisions Queue]

StructuralSectionQueue represents the decisions resulting from DevelopStructuralSection.

DevelopStructuralLayout [Design Task]

DevelopStructuralLayout refines the location of the structural elements such as subfab columns, shear walls, bracing elements, horizontal members, and penetrations. To execute this task, structural engineers need the layout plans from architects, and they need the location of equipment and routing layouts from the mechanical, chemical, and electrical specialties. In the case of steel structures, once structural engineers conclude the layout development, they typically issue a fabrication order to the mill based on the cross-sections and centerline lengths for the main pieces. DevelopStructuralLayout involves, on average, 2 senior engineers for 1 to 2 weeks.

StructuralLayoutQueue [Decisions Queue]

StructuralLayoutQueue represents the decisions resulting from DevelopStructuralLayout.

ConfigureStructuralEquipment [Design Task]

ConfigureStructuralEquipment refines the structural equipment configuration, such as the configuration of seismic isolator bearings and of customized anchor bolts.

StructuralEquipmentQueue [Decisions Queue]

StructuralEquipmentQueue represents the equipment configurations and product choices resulting from ConfigureStructuralEquipment.

AII.4 HVAC SYSTEM

The heating, ventilating, and air conditioning (HVAC) system can be broken down in several subsystems, such as the makeup air, re-circulation, and general exhaust systems. It belongs to the category of dry-mechanical systems. Dry-mechanical systems, a subset of the mechanical systems, in addition to HVAC also include diverse exhaust systems, such as general, acid, and volatile organic compound (VOC) exhaust. Wet-mechanical systems supply, for example, chilled water, boiling water, and steam. Some utility systems that directly supply the production process, such as process chilled water and ultra-pure water, may either fall under the scope of mechanical or chemical specialties. I collected most information on the HVAC design process through interviews with mechanical lead designers Dennis Grant and Robert (Bob) Miles. Dennis Grant provided the estimates of the man-hours that engineers spent per task.

HVACConcept [Conceptualization]

HVACConcept represents the initial estimates for the major features of the HVAC system. Examples of these features are the loads and equipment needs, size and geometry of the critical cross-sections of ductwork routings, the air characteristics of the tool microenvironments, and the schematic routing layouts. This information is synthesized in "one-line diagrams". During conceptualization, HVAC engineers frequently use empirical rules to estimate these features. For instance, to estimate the make-up air load, engineers may input the cleanroom area in a rule of thumb.

HVACDesignCriteria [Conceptualization]

HVACDesignCriteria represents the criteria that guide concept development for the HVAC system. Examples of these criteria are the functional area requirements in terms of temperature, humidity, acoustics, pressurization, airflow direction, and air quality. Other criteria are the flexibility necessary to accommodate a future need to increase the HVAC load and the redundancy level that the HVAC system should exhibit.

DevelopHVACLoad [Design Task]

DevelopHVACLoad refines the HVAC design loads such as make-up air and general exhaust loads. Before doing this task, engineers ideally like to have the following information on hand:

- From Architecture: area and height of functional spaces, occupancy requirements (e.g., number of users and types of use), fenestration percentages on exterior walls, and configuration of building systems such as roof, ceiling, and walls.
- From Chemical: heat and general exhaust loads generated by process support equipment.
- From Electrical: heat loads generated by equipment and by lighting systems.
- From the Client: heat and exhaust loads generated by production process tools and the air quality needs.

DevelopHVACLoad involves 1 senior engineer from 3 to 7 days, with an average of 5 days, and 1 engineer from 1 to 5 days, with an average of 2.5 days.

HVACLoadQueue [Decisions Queue]

HVACLoadQueue represents the decisions on the HVAC loads resulting from DevelopHVACLoad.

DevelopHVACSection [Design Task]

DevelopHVACSection refines the design features for the critical cross-sections in the HVAC system routings, such as the upstream, transition, and downstream sections of the ductwork main, the intersections of the laterals with the main; and upstream, transition, and downstream sections of chases, intakes, and exhaust stacks. At the end of this task, engineers should hand over, for example, the information on the linear weight of the cross-sections to structural specialists. DevelopHVACSection involves 1 senior engineer from 3 to 10 days, with an average of 7 days, and 1 engineer from 5 to 10 days, with an average of 7 days.

HVACSectionQueue [Decisions Queue]

HVACSectionQueue represents the decisions resulting from DevelopHVACSection. These decisions relate to characteristics of the duct cross-sections (e.g., geometry, dimensions, and materials), space clearances around cross-sections, the location of valves on the cross-sections, and the choices of isolation materials.

DevelopHVACLayout [Design Task]

DevelopHVACLayout refines the location in the three-dimensional space of HVAC equipment, ductwork routings, exhaust stacks, and chases. Engineers often call the large equipment pieces "monuments" because they seldom change their location after initial commitments have been made. The decisions made during this task must be coordinated with the decisions resulting from other layout tasks, namely with: (1) the decisions on the subfab and on the cleanroom heights in DevelopArchitecturalLayout, (2) the depth of the structural members in DevelopStructuralLayout, and (3) the location of the power distribution routings and of the respective clearances in DevelopElectricalLayout. Once HVAC engineers complete this task they must hand over information subsets to the other specialties; for example, they hand over the location of HVAC equipment to the electrical and wet-mechanical specialties so that these specialties will know the tie-in point locations. DevelopHVACLayout typically involves 1 senior engineer from 3 to 10 days, with an average of 7 days, and 2 engineers from 5 to 10 days, with an average of 7 days.

HVACLayoutQueue [Decisions Queue]

HVACLayoutQueue represents the decisions resulting from DevelopHVACLayout.

ConfigureHVACEquipment [Design Task]

ConfigureHVACEquipment refines the configuration of the HVAC equipment (such as air handling units (AHUs), filters, and fans) with the help, for instance, of psychrometric analytical models. HVAC engineers need diverse information to execute this task such as the client's preferences on the equipment configurations and on suppliers, and the vendors' information on available products, delivery times, prices, and warranties. Once HVAC engineers conclude this task, they must hand over information subsets to other specialties: (1) the wet utility loads, the pressures at points of connection, and the equipment pressure drops to wet-mechanical engineers; (2) the power needs to electrical engineers; (3) the operating weight of equipment, vibration criteria, and equipment footprint areas to structural engineers; and (4) equipment footprint areas, heights, and respective service clearances to architects. ConfigureHVACEquipment typically involves 1 senior engineer from 5 to 10 days, with an average of 7, and 1 engineer from 2 to 4 days, with an average of 3 days.

HVACEquipmentQueue [Decisions Queue]

HVACEquipmentQueue represents the decisions on the HVAC equipment configuration resulting from ConfigureHVACEquipment. These decisions are related to the internal arrangement of AHUs (e.g., draw-through or blow-through air handling, vertical or horizontal stacking of components), and power needs (e.g., voltage, capacities, emergency power). Although manufacturers offer perhaps more than 100 AHU configurations, Dennis Grant guesses that the high-tech industry may use only 30 of them. Likewise, he guesses that perhaps only 5 configurations of fan units may be used in practice. This fact reflects the limited ability of engineers to deal with the variety of product alternatives presently available. It also raises questions regarding the usefulness of some of these alternatives, and if all of them can be indeed useful, it suggests that computational tools, different from the existing ones, need to be developed to support the decision-making process.

AII.5 ELECTRICAL SYSTEM

Electrical engineers develop the design of the power distribution systems that serve the production tools, process support equipment, lighting, and the facility power needs in general. I collected most information on the electrical design process through multiple interviews with electrical lead designer Hadi Azari.

ElectricalConcept [Conceptualization]

ElectricalConcept represents the initial estimates for the major features of the electrical system. A major decision relates to the kinds of electrical systems that engineers should consider, including primary, secondary, emergency, miscellaneous, and uninterrupted power systems (UPS). The primary system connects the high voltage tie-in point provided by the local utility company to the substations in the fab. The secondary system connects the substations to the panel boards inside the fab; it typically does not include the branch circuits. The designation of the remaining systems is self-explanatory. Examples of critical design features are the characteristics of the loads for each system (e.g., voltage, capacity, number of hook-ups), the power distribution type (e.g., loop scheme, radial distribution, or bifurcated distribution), the routing system type (e.g., cable tray, bus duct, rigid conduit), and equipment characteristics (e.g., number, capacity, location).

Engineers typically use rules of thumb and historical data to estimate the electrical features. From experience, for instance, Hadi Azari points out that, for a 80,000 sq.ft. cleanroom, the lighting load is usually under 1 VA/sq.ft. in the cleanroom, the production process load varies between 300 and 400KVA/sq.ft., and miscellaneous loads do not usually exceed 4 VA /sq.ft.

Engineers must also decide if the electrical system will be coupled, semi-coupled, or decoupled from the specifics of the tool layout in the cleanroom. This decision directly influences, for instance, the number of transformers to procure. Typically, the electrical concept is depicted in one-line diagrams that show the equipment location and their characteristics, the system topology, and the characteristics of the routing cross-sections. ElectricalConcept involves, on average, 240 hours of work for a senior engineer, 240 hours of work for a midlevel engineer, 240 hours of work for a junior engineer, and 120 hours of work for a draftsman.

ElectricalDesignCriteria [Conceptualization]

ElectricalDesignCriteria represents the criteria that guide concept development of the electrical system. Some design criteria are driven by the operating characteristics of the production tools and support equipment. For example, some production tools only need normal power while other tools need a backup system with a generator; certain tools require a UPS to keep them in operation for at least 5 minutes after an accidental power shutdown. Equipment redundancy and load diversity are also critical to design the electrical system. Other criteria are empirical in nature. Space management rules recommend that substations be located close to the equipment rooms in the fab for minimizing the conduit length and minimizing the power losses between the electrical transformers and other equipment. Another space rule recommends that engineers avoid crossing electrical cables under piping routings because doing so creates a hazardous condition should a pipe leak. Finally, other criteria may express a personal preference. For instance, Hadi Azari prefers to route the main conduits underground because he finds that it eases the construction process and it increases the flexibility of the system to accommodate changes later.

DevelopElectricalLoad [Design Task]

DevelopElectricalLoad refines the electrical load estimates per functional area. To execute this task, electrical engineers need the operating modes of the production tools from the client, the power needs of the support equipment from the mechanical and chemical specialties, and the lighting conditions in the functional areas from the architectural specialty. DevelopElectricalLoad involves, on average, 1 to 2 senior engineers for 1 to 2 days.

ElectricalLoadQueue [Decisions Queue]

ElectricalLoad represents the decisions resulting from DevelopElectricalLoad.

DevelopElectricalSection [Design Task]

DevelopElectricalSection refines the critical cross-sections of the power distribution systems (e.g., the cross-section of the cables that hook up the substations with the electrical panels) in terms of the material, geometry, insulation, and support system. Electrical engineers typically must commit early on the diameter of the ground conduit because its definition needs to be included in the excavation design package. Apparently, the bus duct system is one of the cheapest distribution systems but it is not very flexible in case it needs to be moved after installation. In contrast, a conduit system is flexible but also more expensive. Once the electrical cross-sections are developed, engineers must hand over information on the linear weight to the structural specialty and on the dimensions of cross-sections and space clearances to the other design specialties. DevelopElectricalSection involves, on average, 240 hours of work for a senior engineer, 200 hours of work for a midlevel engineer, and 100 hours of work for a drafter.

ElectricalSectionQueue [Decisions Queue]

ElectricalSectionQueue represents the decisions resulting from DevelopElectricalSection.

DevelopElectricalLayout [Design Task]

DevelopElectricalLayout refines the location of the electrical equipment (e.g., substations, transformers, and panels) and the layout of the power distribution routings (e.g., underground and overhead cables). Inside the electrical transformer, the electrical power drops from high voltages to 208/120V. One design option consists of putting a few large transformers in the electrical rooms; another option consists of spreading various small transformers across the subfab floor. In Hadi Azari's opinion, the second option requires less space because it allows to transport high voltage power for longer distances. Higher voltage cables have proportionally smaller cross-sections.

To develop the electrical layout, engineers need to know the location of the other specialties' equipment and the location of the structural columns so that they can decide where the underground grid ties to the columns. Typically, electrical engineers have some degree of flexibility to route the power distribution systems because these systems bend more easily around obstacles than ductwork or piping routings do. However, such flexibility is seldom valid for the larger cross-sections or after the cables are installed. DevelopElectricalLayout involves, on average, 160 hours of work for a senior engineer, 160 hours of work for a midlevel engineer, and 80 hours of work for a drafter.

ElectricalLayoutQueue [Decisions Queue]

ElectricalLayoutQueue represents the decisions on the design features that result from DevelopElectricalLayout. These decisions relate to the location of the power equipment, and of the electrical main and laterals. ElectricalLayoutQueue typically does not include the lighting layout or the layout of the routings between the panels and the production tools because these design features are most often developed later, in the detailing phase.

ConfigureElectricalEquipment [Design Task]

ConfigureElectricalEquipment represents the refinement of the configuration of major equipment such as transformers and distribution panel boards. The client's preferences typically have a strong influence in these decisions.

ElectricalEquipmentQueue [Decisions Queue]

ElectricalEquipmentQueue represents the design features of the equipment configurations that result from ConfigureElectricalEquipment. Transformers, for instance, exist in the following capacities: 5, 10, 15, 30, 45, 75, 125, 225, 300, and 500 KVA. A commonly picked transformer for fabs is the 300 KVA.

AII.6 ARCHITECTURAL SYSTEM

Architects design the exterior building shell, the interior spaces of the fab except for the subfab space, and they configure specific architectural systems, such as the walls, roof, and floors. The conceptualization effort is partly a creative process, during which architects may redesign the architectural concept two or more times, or they may develop several concepts concurrently. I collected most information on the architectural design process through multiple interviews with senior architects Harry Dinihanian and Robert Kirkendall. Harry Dinihanian provided the estimates of man-hours that architects spent on average per task.

ArchitecturalConcept [Conceptualization]

The ArchitecturalConcept represents the initial estimates for the design features of the architectural system. Frequently, when a new project starts, the client prefers that the design of one of his existing fabs be reused to the greatest extent possible. The architectural concept should define the topology of the functional spaces, the circulation paths for people and for the tools, and the choices on the specific architectural systems. The architectural decisions are formalized in the facility layout plans and cross-sections. The layout defines the cleanroom's net and gross areas, and its interior configuration (e.g., ballroom or bay-and-chase arrangement, the location and width of the circulation areas and partition walls). The cross-sections of the fab define the cleanroom floor-to-floor and clear height, and the height above the cleanroom ceiling. The configuration of the architectural systems characterizes, for example, the diverse materials that make up the exterior and interior floors and that make up the wall building systems.

ArchitecturalDesignCriteria [Conceptualization]

ArchitecturalDesignCriteria represents the criteria that guide the concept development of the architectural system. Most criteria have an empirical basis, such as those that guide the definition of the fab topology. For instance, the process support and exhaust areas outside the cleanroom should stay adjacent to the groups of tools they serve inside the cleanroom for minimizing the length of utility routings. Similarly, half of the Chemical

Utility Building (CUB) area that faces the fab building should be divided in two parts: one part serves the process support equipment and the other part serves the wet-mechanical equipment. The remaining half of the CUB area should serve the electrical equipment. In the space above the cleanroom ceiling, the power distribution should run immediately above the ceiling for easing the installation of the lighting system. HVAC ductwork should then run above the power distribution system. The flexibility to accommodate future technological changes influences the percentage of space to leave empty inside the fab. Other design criteria result from emergency safety rules, which determine, for instance, the minimum width of the circulation aisles, the fire resistance properties of the architectural elements, and the maximum distances between the workstations and the fire exits.

DevelopArchitecturalLoad [Design Task]

DevelopArchitecturalLoad refines the architectural loads in terms of people, computers, and equipment occupancies for each functional area. After architects conclude this task, they should hand over diverse information (e.g., light colors, power requirements, and air cleanliness) to other design specialists.

ArchitecturalLoadQueue [Decisions Queue]

ArchitecturalLoadQueue represents the decisions that result from DevelopArchitecturalLoad.

DevelopArchitecturalSection [Design Task]

DevelopArchitecturalSection refines the longitudinal and transversal cross-sections and elevations of the fab. The design of elevations is typically the most creative task for architects throughout the design process of high-tech facilities. Architects must account for diverse information hand-offs from other specialties before executing this task. Examples of such hand-offs are the cleanroom clear height, the depth of the horizontal structural members, the locations of the HVAC exhaust stacks, air intakes, and ductwork, and the area requirements for the chemical and mechanical routings under the cleanroom's raised floor. DevelopArchitecturalSection involves, on average, 1 architect for 20 days or 2 architects for 12 days.

ArchitecturalSectionQueue [Decisions Queue]

ArchitecturalSectionQueue refines the decisions that result from DevelopArchitecturalSection. These decisions pertain to the floor-to-floor height of each functional space; the cleanroom heights under the raised floor, above its ceiling, and its clean height; the height of the subfab; the thickness of exterior and interior walls; and the fenestration of exterior walls.

DevelopArchitecturalLayout [Design Task]

DevelopArchitecturalLayout refines the fab layout in terms of functional areas and topology. To perform this task, architects need to know, for instance, the location of each set of tools in the cleanroom (e.g., photolithography, etching, diffusion, implant), the location of the HVAC chases and exhaust stacks, and the layout of the ductwork and piping systems. Architects must also coordinate with other design specialists: the layout of the move-in paths for major equipment, the location of heavy equipment, and the location and dimensions of floor and wall penetrations. DevelopArchitecturalLayout may involve on average 1 senior architect for 10 days, 2 senior architects for 5 days, or 1 senior architect and 2 junior architects for 5 days.

ArchitecturalLayoutQueue [Decisions Queue]

ArchitecturalLayoutQueue represents the layout decisions resulting from DevelopArchitecturalLayout.

ConfigureArchitecturalSystems [Design Task]

ConfigureArchitecturalSystems refines the decisions on the configuration of the architectural systems, such as the exterior building walls, the roof, and the cleanroom systems (e.g., raised floor, ceiling, and walls). Architects need information from other specialties to configure each system. To define the connection between the exterior wall and the cleanroom floor, architects need to understand: (1) the structural connection between the cleanroom waffle slab and the perimeter beam, and (2) the distance from the structural columns to the edge of the building. To define the cleanroom ceiling, architects need to know the direction of the airflow, the exact dimensions of the cleanroom, and the characteristics of the lighting system. ConfigureArchitecturalSystems involves, on average, 2 architects, 1 of them senior, for 2 weeks.

ArchitecturalSystemsQueue [Decisions Queue]

ArchitecturalSystemsQueue represents the decisions that result from ConfigureArchitecturalSystems. Harry Dinihanian grouped the critical architectural system configurations as follows:

- Roof: skin cross-section, equipment curb cross-section, and edge condition.
- Exterior Building Skin: cross-section of wall, and intersection of wall with floor.
- Cleanroom: cross-sections of perimeter walls, firewalls, floor, ceiling, and intersection between wall and floor.
- Building Interiors: sections of expansion joints and fire rate walls.

- Chemical Resistant Coatings: intersection of wall to column, curb condition, cross-section of control joints, intersection of column to floor, and cross-section of termination point.
- Attachments: sections of canopies, balconies, etc.

In addition to the nodes described above, Figure V.1 depicts the procurement task for each design specialty. These tasks are not characterized in detail here. This Appendix also does not provide information on the construction tasks that are modeled and explained in Chapter VII. This is so because the interview process primarily focused on the concept development phase and less on procurement, design detailing, and construction. Only for the acid-exhaust design-build process, did I collect limited information on procurement, design detailing, and construction activities. This information is provided in Chapter VI.