# MODELING THE DESIGN-BUILD DEVELOPMENT PROCESS FOR A FACILITY COMPONENT

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## ABSTRACT

In unstable environments, characterized by frequent client-driven changes in design criteria and by huge pressure to compress project delivery times, practitioners must search for innovative ways to structure the design-build process. Involving specialty contractors from project inception onwards, helps to satisfy client needs. Based on empirical research in the semiconductor industry, this paper presents a product-process model that reflects the joint system of designing and building a facility component. The model expresses, in a parametric fashion, critical design, procurement, and construction decisions as the design-build process unfolds. A model implementation that uses discrete-event simulation contrasts the effects of early vs. late specialty-contractor involvement in design. Results show that early contractor involvement benefits the average project duration but increases the duration variability and may significantly increase the waste of construction resources if improperly implemented. Postponement of design decisions helps to reduce waste without penalizing the project duration much. Results also show that fabrication decisions should not be neglected in early design efforts when expediting a project.

## KEYWORDS

design-build development process, design postponement, specialty contractor knowledge, design criteria change, discrete-event simulation, early commitment, postponement

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## INTRODUCTION

The potential contributions specialty contractors can bring to the design-build process, especially when they get involved early in design, have long been recognized (e.g., Crichton 1966, Bennett and Ferry 1990, Tommelein and Ballard 1997, Gil et al. 2000). In current practice though, it remains all too often the case that specialty contractors get involved in design only after competitively bidding a set of drawings and specifications, when they have to develop and submit detailed shop drawings to the architect/engineer. As a result, specialty-contractor knowledge seldom gets leveraged in early design. It may not get leveraged later either, because contractors are expected to 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). Competitive bidding also is a time-consuming process. It separates the upstream design phase from the downstream execution phase, and thus delays the start of procurement, fabrication, and construction. Nonetheless, industry practices are changing and contractors increasingly participate in early design. New problems may then arise if design criteria are prone to changing while downstream work is already under way. Changes that occur later in the process logically cost more to accommodate than those that occur during design, because more resources have been mobilized. How to balance allowances for change and the cost of rework is the underlying research question.

## RELATED WORK

Research on compressing project completion times in unstable environments is presented in the literature on new product development and concurrent engineering (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, Terwiesh and Loch 1999). The work in this paper differs, however, from this literature in that the domain of our modeling effort is architecture, engineering, and construction (AEC). AEC projects are of a one-of-a-kind nature, whereas product development typically precedes mass production. In product development, designers and suppliers may afford to go through multiple design iterations, because design improvements will pay off handsomely later, every time a replicate is made. In contrast, design and construction rework is usually charged entirely against the project itself.

Our work assumes that specialty contractors in AEC projects are the equivalent of suppliers in product development. The question then is: How to best structure the design-build process and involve contractors early in unstable environments?

Our work relates to research in lean production systems design as applied to the AEC industry. Tsao et al. (2000) define work structuring as the effort to develop a project's process design while trying to align engineering design, supply chain, resource allocation, and assembly efforts. Some lean construction researchers depicted supply chains from a production perspective and questioned their structure at a conceptual level. For instance, Tommelein and Weissenberger (1999) mapped structural steel supply and erection, and Holzemer et al. (2000) mapped HVAC ductwork fabrication and site installation. Other researchers provided case studies that challenge the traditional ways for organizing projects in an effort to create more efficient production systems (e.g., Miles 1998, Tsao et al. 2000).

Our research methodology, like Tommelein's (1998) who modeled pipe-spool installation, uses computer simulation, but the model presented here is different in scope. We first present a high-level view of the process of designing and building an acid-exhaust system. We then simulate alternative work structures and assess which ones, under which circumstances best meet the client's needs. The product-process simulation does not model organizational units. Accordingly, our work is complementary in approach to computational models of organizations, such as the Virtual Design Team (VDT) (Jin and Levitt 1996)—a process-information model that mimics actors' tasks and behaviors—or Lin and Hui's (1997) work—a computational model that contrasts problem solving capabilities based on different organizational structures.

## PRODUCT-PROCESS MODEL

### Model Description

The model focuses on the design, parts fabrication, assembly, and installation of the acid-exhaust system, as Figure 1 illustrates. Table 1 describes the modeling symbols used. Design development is decomposed in two phases: conceptualization and concept development. During conceptualization, designers make a set of initial estimates on critical parameters based on historical data and rules of thumb. During concept development they refine their estimates with the help of analytical tools. Concept development is composed of three sequential tasks: load-, section-, and layout development.

As the design development process unfolds, designers meet every 5 days to validate their decisions. Once all design parameters for the building system have been validated, the execution phase starts. If the specialty contractor was not involved in concept development we assume that two sequential delays will occur. The first delay corresponds to the bidding period from the end of concept development until one contractor is 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 answers. After this period, the contractor decides on the length of the spools, procures long lead items (e.g., fiberglass coated ducts and specialty items like valves), and prepares shop drawings. The fabrication process starts once the architect/engineer approves the shop drawings, and spools and specialty items arrive at the fabrication shop. Then, assembled spools are shipped to the site by truck, and installed.

## SIMULATION RATIONALE

### Uncertainty

AEC practitioners' design and construction work on a fab typically takes place concurrently with other design teams' development of the chip technology and layout of the production tools that sit in the cleanroom. As a result, whenever significant changes occur with the list of tools or the tool layout (e.g., due to technological breakthroughs or shifts in market needs) these changes impact the fab design definition. Figure 2 illustrates simulated samples from the probability density curves that synthesize design leads' mental models regarding the frequency and time of occurrences of changes in the tool list and cleanroom dimensions. These uncertainty curves were implemented within the simulation environment on top of the product-process model for the design-build development process.

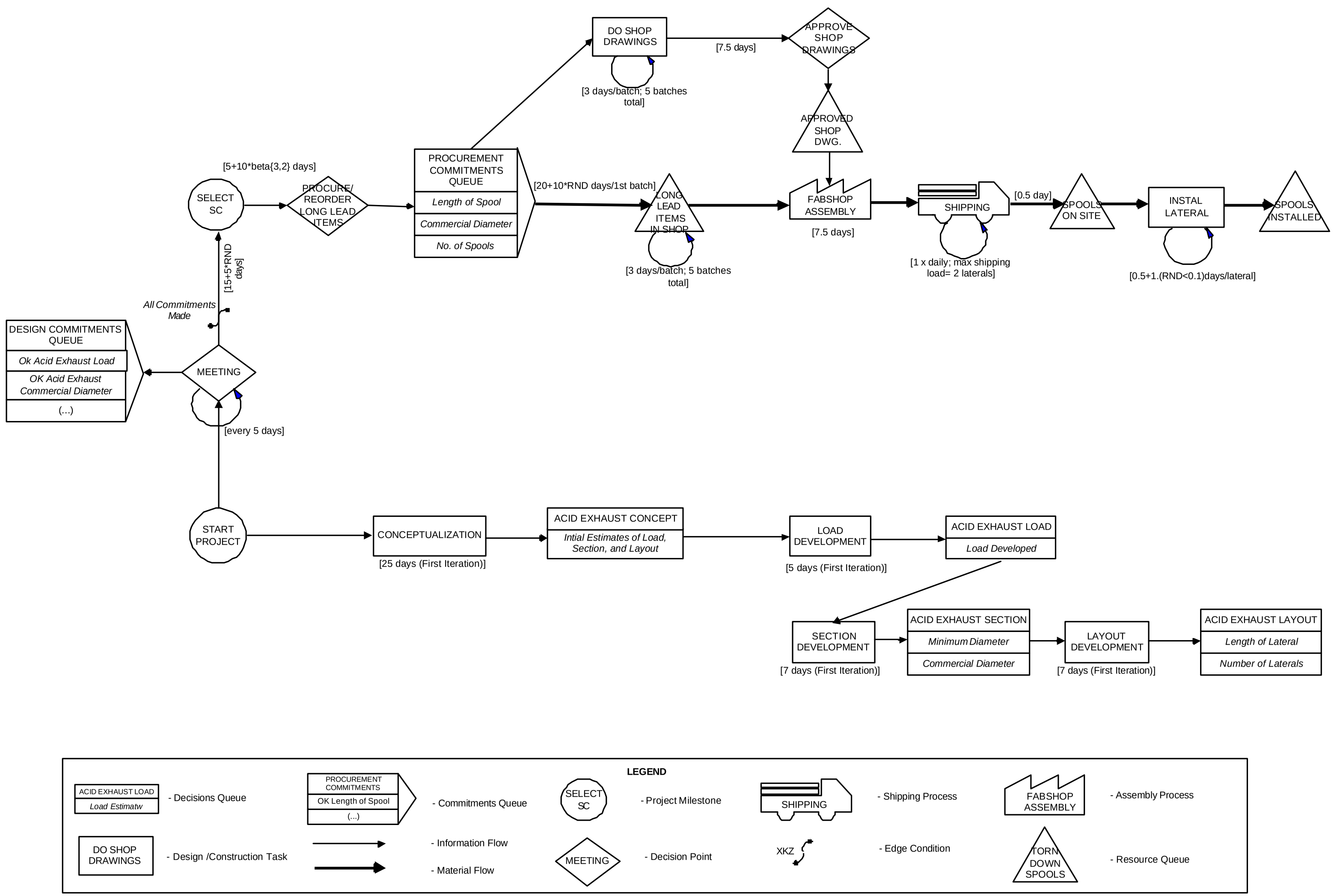


Figure 1: Product-Process Development Model for the Design-Build Process of an Acid-Exhaust System with Fixed Design Criteria

Table 1: Product-Process Development Representation Symbols

| SYMBOL | NAME | EXPLANATION |
|---|---|---|
| DO SHOP DRAWINGS | Design/ Construction Task | Expresses design or construction tasks. Tasks produce a set of design decisions and production choices or actions. A rectangle denotes a Task. Fabshop Assembly and Shipping are also instances of site tasks, although they have specific graphic symbols so as to enhance the legibility of the model. |
| ACID EXHAUST LAYOUT / *Length of Lateral* / *Number of Laterals* | Decisions Queue | Expresses the decisions that result from each design task. Examples of decisions are the determination of design loads, diameter of routing cross-sections, and length of routings. A closed rectangle denotes a DecisionsQueue. |
| MEETING | Decision Point | Expresses moments when the client, designers, or contractors make critical design, procurement, or construction decisions. A diamond denotes a DecisionPoint. |
|  | Information Flow | Indicates the push flow of information on design parameters from one task to the next. A solid arrow denotes an InformationFlow. |
|  | Material Flow | Indicates the push flow of materials from one task to the next. A wide, darker arrow denotes a MaterialFlow. |
| DESIGN COMMITMENTS QUEUE / *Ok Acid Exhaust Load* / *OK Acid Exhaust Commercial Diameter* / (...) | Commitments Queue | Expresses the decisions and choices resulting out of decision points. A closed rectangle with a right-pointing triangle denotes a Commitments Queue |
| Shop Dwg. Approved | Resource Queue | Expresses a queue of resources resulting from execution of a task and eventually waiting to be depleted by another task. An up-pointing triangle denotes a Resource Queue. |

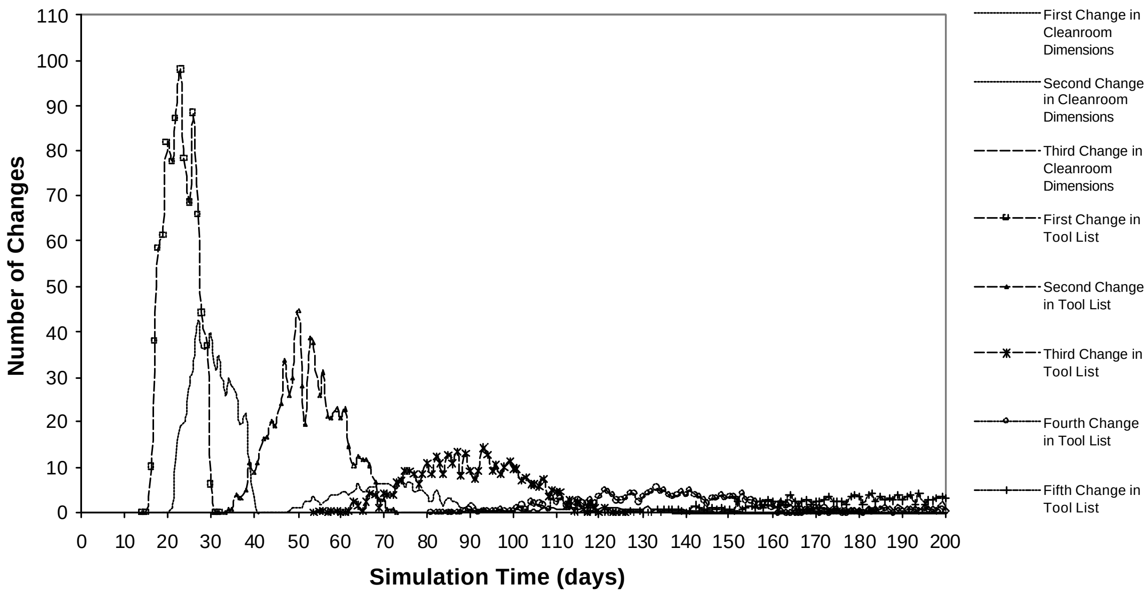


Figure 2: Histogram of Cleanroom Dimensions and Tool List Changes for 1000 Runs

**Further Simplifying Assumptions**

1. **Design Rework.** We assume that the duration of design tasks decreases between successive iterations of the same task. Gil et al. (2001) discuss the specifics of the algorithm that was implemented.

2. **Task Duration and Batch Size.** We used practitioners' estimates to quantify the duration of tasks, process delays, as well as the number of batches in which shop drawings are released and spools fabricated and assembled. For simplification, we used as input for the simulation work illustrated in this paper the deterministic averages of these estimates. Experimentation with the model using stochastic inputs led to similar results.

3. **Shop Drawing Approval.** We assumed that shop drawings always get approved. The extent to which relaxing this assumption would influence the development process merits further investigation. We also assumed that once a contractor is selected he would stay involved with the job despite any design changes that may occur afterwards.

4. **Execution Rework.** We assume that the cleanroom width and length increase 10% whenever a cleanroom dimensions change occurs. We also assume that a tool list change increases the acid-exhaust load needs by 10%. According to how close the choice of the spool commercial diameter is to the engineered minimum diameter, a change may or not invalidate the previous choice of the commercial diameter. We also assume that design criteria changes always force contractors to redo shop drawings whether or not the commercial spool diameter needs to increase to account for changes in the location and size of valves. Thus, f spools are already assembled when a change occurs and the spool diameter remains the same, contractors must still rework the previously assembled spools per the new shop drawings. In this case, we also assume that the spools assembled but not yet installed would be first installed and reworked afterwards. If a cleanroom dimensions change does not cause the spool diameter to increase but contractors had already procured the spools when the change occurred, contractors need to reorder more spools. If a change necessitates the use of larger spools, all exhaust spools that are already assembled and even installed must be torn down, the spools not yet assembled must be piled up aside, and larger spools must be ordered once contractors get the new developed concept. We assume that when the larger spools arrive to the site, the former spools have been in the mean time been torn down.

**Discrete Event Scheduling Simulation**

The model was implemented with the simulation engine SIGMA (Schruben and Schruben 2000). SIGMA is a discrete-event simulation environment based on the 'event graph' concept. Users can model a system in terms of event graphs 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, pp. 205). Process simulation evolves by executing the list of future events in a chronological order, and updating the list each time a new event gets processed.

**Simulation Scenarios**

We considered the following simulation scenarios:

I. **Competitively Bid Specialty Contractor.** Designers develop the design and once they commit on all the parameters, specialty contractors have to competitively bid that design. We associate a time delay with the bidding process of 3 to 4 weeks (15+rnd*5 days). Once one contractor gets involved he takes 5 to 15 days (5+10*beta{2,2}days) to get familiar with the design information, issue requests for information, and get answers from the architect/engineer. After that period, the contractor procures long lead items and details shop drawings. Each batch of shop drawings needs to be approved by the architect/engineer before the contractor can assemble the spools in the fabrication shop. The approval process takes on average 7.5 days.

II. **Specialty Contractor Involved Since Start of Concept Development.** The contractor is selected during conceptualization and participates in concept development (e.g., attending coordination meetings or co-locating his detailers in the architect/engineer's office). Once designers commit on all the design parameters, the contractor immediately procures long lead items and details shop drawings. We also assume approval of shop drawings is immediate.

III. **Postponement of Concept Development.** Designers do not start concept development until a predefined number of days (a lag) after completion of conceptualization. We vary the postponement lag from zero (in which case concept development starts on the day after conceptualization has ended) to 90 days, an extreme scenario! In between, we gradually increase the "no earlier than" constraint by 5-day intervals.

### Performance Variables

To contrast the alternative scenarios, we implemented the following performance variables:

Table 2: Description of Performance Variables

| Performance Variable | Description |
|---|---|
| Overall Project Duration (days) | Elapsed time from the start of conceptualization to the day when the last spool gets installed on site and no design changes occur afterwards. |
| Total Design Time (days) | Time designers spend on conceptualization plus concept development tasks. |
| Total Execution Time (days) | Elapsed time from the day the specialty contractor gets selected (or after design is fully developed and validated if the contractor is already involved) until the last of day of the construction process. |
| On-Site Rework Time (days) | Total time the on-site crew spends reworking assembled spools due to desig changes that did not alter the design decision regarding commercial diameters. |
| On-Site Wasted Time (days) | Total time on-site crew spends idle or tearing down installed spools due to design changes that required larger spools. |
| Torn Down Spool Length (feet) | Total length of spools that were already assembled (whether or not spools were installed) when a change occurred that required larger spools. |
| Unused Spool Length (feet) | Total length of spools that were already in the fab shop but not yet completely assembled when a change occurred that required larger spools. |

## ANALYSIS OF RESULTS

### Design-Build Process Development with Dynamic Design Criteria

Table 3 shows the results of the performance variables for the scenarios with fixed and dynamic design criteria. The mean and variance were calculated using the unbiased estimators for a sample of 1000 simulations (Law and Kelton 2000). Some results are, first, without competitive bidding, the project duration shortens approximately by the sum of the delays caused by bidding, but the wasted resources during construction increase significantly and the execution time increases slightly. Clearly, because early contractor involvement also allows the construction process to start earlier, more changes occur while the construction process is already underway. Second, when contractors get involved early, the sum of the average design time plus execution time is above the overall project duration. This reflects the overlap between design rework and non-value adding site tasks (rework, tearing down spools, or staying idle). In addition, when contractors get involved early, the reliability of process development decreases significantly as is shown by the increase in variability of the performance variables.

Table 3: Competitive Bidding vs. Early Contractor Involvement (mean ± standard deviation)
*(Scenario: no postponement and spools 10 feet long)*

| | Overall Project Duration (days) | Total Design Time (days) | Total Execution Time (days) | On Site Rework Time (days) | On Site Wasted Time (days) | Torn Down Spool Length (feet) | Unused Spool Length (feet) |
|---|---|---|---|---|---|---|---|
| SC Competitively Bid w/o Uncertainty | 125 ± 4 | 41 | 62 ± 4 | 0 | 0 | 0 | 0 |
| SC Involved Early w/o Uncertainty | 96 ± 3 | 41 | 51 ± 3 | 0 | 0 | 0 | 0 |
| SC Competitively Bid w/ Uncertainty | 162 ± 33 | 63 ± 13 | 79 ± 27 | 0 ± 2 | 4 ± 14 | 177 ± 847 | 141 ± 686 |
| SC Involved Early w/ Uncertainty | 137 ± 41 | 63 ± 13 | 81 ± 39 | 1 ± 4 | 15 ± 24 | 1180± 2211 | 298 ± 938 |
| SC Inv. Early w/ Conc. Dev. Start > day 60 | 151 ± 30 | 58 ± 12 | 68± 29 | 1 ± 3 | 6± 15 | 483± 1483 | 130± 630 |

*Total Final Spool Feet Installed in a Project (Number of Laterals * Length of Lateral) = 5170 ± 876 feet*

These results are not surprising given the probability density curves we assumed for the changes (Figure 2), which express that the frequency of changes decreases in the course of time. The results demonstrate, however, that if managers aim to structure the design-build process differently, they should adopt a systemic approach in order to assess less obvious consequences and find ways to minimize the undesirable ones. Driven by these findings, we next try to understand if postponed commitment strategies can help shield production from upstream changes while still compressing the project duration.

## Postponed Commitment Strategies at Design Development

We define postponed commitment as a managerial strategy that intentionally instructs designers to delay concept development instead of starting it with incomplete or unreliable information inputs and criteria. Postponed commitment strategies have been advocated and implemented for managing product development processes that unfold in unpredictable environments (e.g., Iansiti 1995, Ward et al. 1995, Bhattacharya et al. 1997, Thomke and Reinertsen 1998). Gil et al. (2001) studied the consequences of imposing a time lag between conceptualization and concept development. The results showed that postponing concept development consistently increased the average project duration but also increased its predictability. Gil et al. identified an efficiency zone (corresponding approximately to concept development not starting before day 55 to 70) within which the upper bound of the variability interval for the design duration stays steady while significant resource savings are achieved. Figures 3 and 4 illustrate how a similar postponement strategy influences the design-build development process, for scenarios with competitive bidding and early contractor involvement.

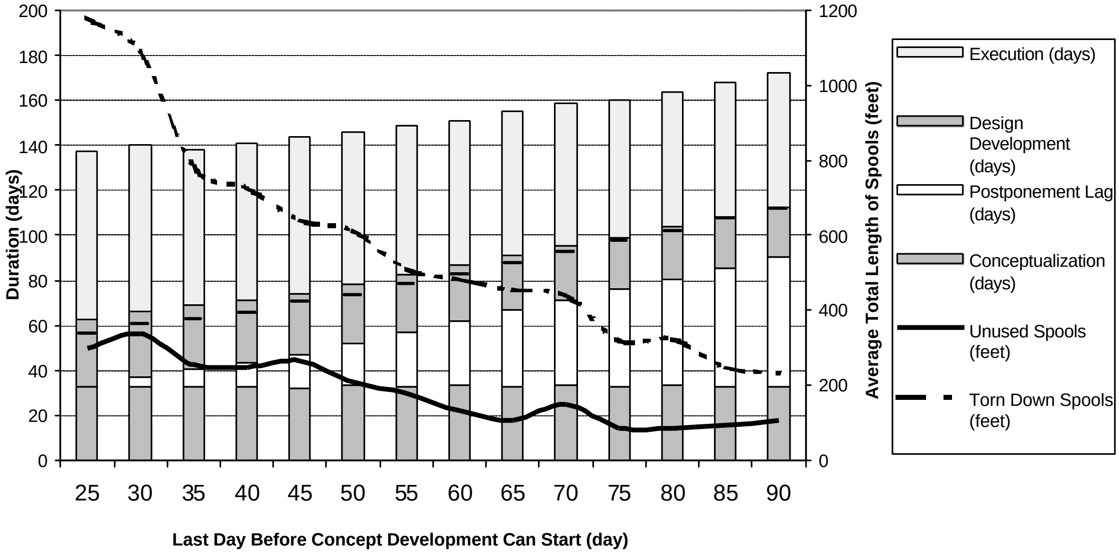


Figure 3: Average Effects of Postponement Strategies on Design-Build Development Process [Scenario: Specialty Contractor Involved since Concept Development]

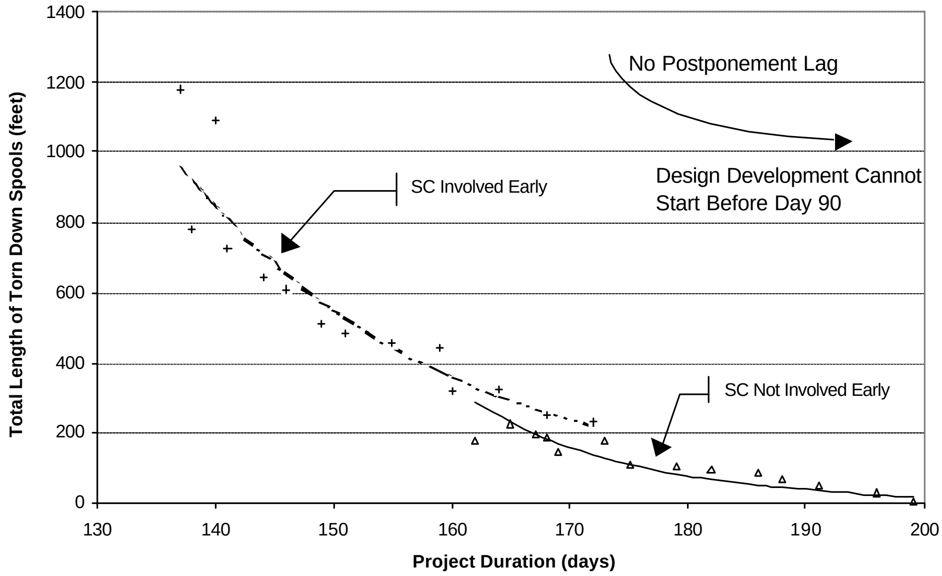


Figure 4: Average Effects of Postponement Strategies with and without Competitive Bidding

Results show that as the postponement lag increases up to its efficiency zone, an accentuated reduction of wasted construction resources is achieved at the expense of increasing the project duration by about 10%. Also noteworthy is that an increase in postponement lag leads to a disappearing overlap between design and execution rework. In addition, if we compare the early involved contractor scenario (with an efficient postponement lag) against the competitive bidding scenario (Table 3), we observe: 1) the value of torn down spools stays above that achieved in competitive bidding, 2) the value of unused spools is of the same order of magnitude, and 3) design, execution, and project duration remain shorter.

**Leveraging Specialty Contractors Knowledge in Design**

The simulated scenarios have shown that efforts to compress the project duration consistently come at the expense of wasting construction resources. However, these scenarios have assumed that construction methods would not change, whether or not contractors get involved early in the process. We now propose to relax this assumption. In a competitive bidding scenario, contractors are typically not familiar with the design and until late do not know for certain who the project participants will be. Chances then are that they will expect a confrontational project environment, unappreciative of the best construction sequences (e.g., Birrell 1985, Bennett and Ferry 1990, Hinze and Tracey 1994). Conversely, if contractors get the opportunity to contribute their process knowledge during early design, design solutions can be achieved that are more efficient to build (Gil et al. 2000).

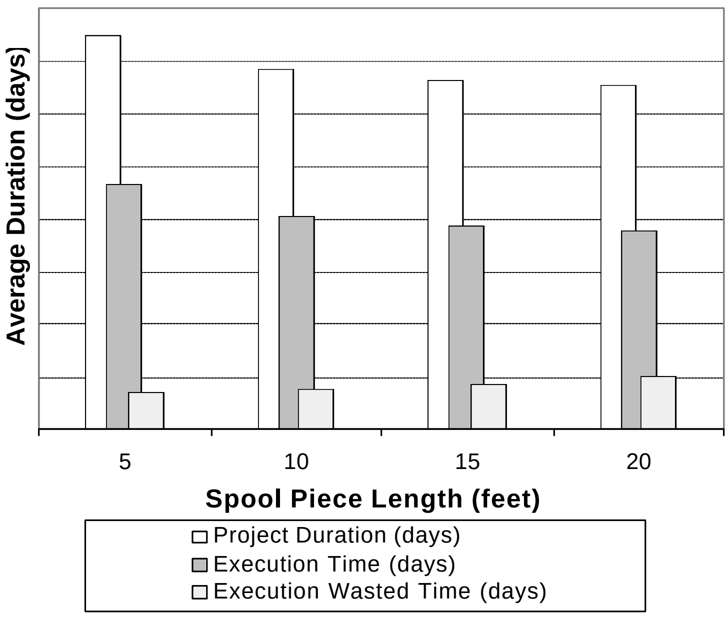


Figure 5: Average Influence of Spool Length on Design-Build Development Process

As a specific instance of how the project environment influences a contractor’s decision rationale, we learned during empirical research that a contractor’s decision on the spool piece length varies in function of their familiarity with the design and knowledge of other project participants. Thus, in a competitive bidding scenario, contractors often select the shortest spool pieces (around 8 to 10 feet long) because these are easiest to slide in the steel racks. In contrast, if contractors are involved earlier and have the opportunity to get to know the design and other project participants, they select longer spools. Longer spools minimize the number of required welds and can still be slid, if specific site access conditions exist. Because welding is the most crucial operation in acid-exhaust duct installation, the number of welds is more-or-less proportional to the duration needed to install the spool. Contractors roughly estimate that if the number of welds doubles, the time it takes to install the spools also doubles.

Within this framework, Figure 5 illustrates how the design-build process differed as we gradually increased the spool-piece length from 5 to 20 feet, assuming early contractor involvement. Results indicate that going from 5 to 20 feet decreases the execution time by approximately 20%, resulting in a 10% decrease in the overall project duration. Longer spools also increase, however, the relative percentage of time wasted by on-site crews: because spool installation progresses faster, crews are more idle in-between task iterations (Table 4). Longer spools do not influence the quantity of wasted resources during construction due to design iterations.

Table 4: Influence of Spool Length on Design-Build Process

| | Overall Project Duration (days) | Total Design Time (days) | Total Execution Time (days) | On Site Rework Time (days) | On site Wasted Time (days) | Torn Down Spool Length (feet) | Unused Spool Length (feet) |
|---|---|---|---|---|---|---|---|
| SC Involved Early w/o postponement +spool length 20 feet | 131 ± 39 | 63 ± 13 | 75 ± 37 | 1 ± 4 | 20 ± 25 | 1030± 2007 | 312± 962 |
| SC Involved Early w/ Concept Dev. Start > day 60 + spool length 20 feet | 149± 30 | 58 ± 12 | 66 ± 29 | 1 ± 3 | 12 ± 17 | 463 ± 1432 | 125 ± 567 |

*Total Final Spool Feet Installed in a Project (Number of Laterals * Length of Lateral) = 5170 ± 876 feet*

## DISCUSSION

A systemic analysis of alternative production designs 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 procurement and construction may start. Doing it in an unpredictable environment inevitably increases wasted construction resources.

Simulation results show, however, that alternative managerial strategies may result in worthy compromises. Postponement of concept development 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 a postponement strategy will vary with his willingness to accept risks, the expected stochastic nature of changes, and the criticality of the performance variables being traded off. Thus, if compressing the project duration is of utmost importance, then a no-postponement strategy will be best because it maximizes the chances of fast project delivery. However, if costs resulting from resources wasted during construction matter, then a postponement strategy is appropriate. In addition, empirical research indicates—and simulation modeling confirms it—that other opportunities to expedite process development exist for those organizations that successfully leverage specialty contractor knowledge in early design. The example implemented in this paper—using longer spool pieces so as to reduce the number of welds and consequently the time spool installation takes—illustrated this point.

In the competitive bidding scenario, we assumed that the contractor would start procurement before he had the shop drawings approved. In practice, contractors may be forced to do so 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. Specialty contractors may be willing to accept some risks, but not others. Selecting longer spools that could turn out to be physically impossible to slide into the steel racks is one such risk. When the contractor selects shorter spools, the end result is a less efficient construction process that delays the overall project duration. Multiple welds also increase the probability of future leakage and flow impurity problems, making it in the long term a lower quality solution from a performance standpoint. The extent to which client organizations are thoroughly informed of the consequences that alternative contractual agreements may have on production system design and product quality merits further investigation.

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