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## Postponing design processes in unpredictable environments

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**Abstract** This work explores the effectiveness of design postponement in the concept development of large-scale engineering projects. Our empirical research shows limited use of postponement in semiconductor fabrication facility ('fab') projects despite evidence that the customer inevitably requests design criteria changes in the project's life. We simulate fab concept development as a 2-stage process—conceptualization followed by design. We find that postponing the start of design in relation to the completion of conceptualization reduces the average resources spent on design and the variability in the concept development duration but increases the average concept development duration. A sensitivity analysis on the postponement lag duration indicates, however, that some degree of postponement may allow reducing design rework without increasing the risk of overrunning the project completion date, in comparison to the risk with early commitment. Further, simulation indicates that the effectiveness of postponement decreases as designers' capability to reuse work increases.

**Keywords** Design · Postponement · Large-scale engineering design · Uncertainty · Project management · Design reuse · Change

### 1 Introduction

Project organizations involved in new product development—in computing, automotive, and other industries—have to cope with increasingly dynamic, uncertain, high-velocity and turbulent market environments. To accommodate these fast-moving markets, project organizations seek both to compress time-to-market and to accommodate the many design changes that arise during the project development cycle (e.g., Clark and Fujimoto 1991; Eisenhardt and Tabrizi 1995; Iansiti 1995; Ward et al. 1995; Thomke and Reinertsen 1998). Empirical research shows that effective project organizations overlap the two major phases of the product development process—concept development and implementation—and postpone finalizing design decisions as late as possible to accommodate change (Iansiti 1995). By postponing commitments on critical design features until as late as possible during implementation, project organizations can not only account for implementation issues in their design but also gain flexibility for reacting to unanticipated changes.

Our work resides within the domain of large-scale engineering projects, and more specifically, investigates the concept development process for semiconductor fabrication facilities or 'fabs.' Fabs are complex high-tech buildings that house semiconductor manufacturing tools used either to research and develop new chip technologies (R&D fabs) or to mass-produce chips (high-volume manufacturing fabs). This research explores phenomena in this domain similar to those observed in new product development projects. First, a need exists to compress the fab project time (i.e., the time between the start of concept development and the date when the fab can start being used to produce chips) to facilitate early introduction of new products and to preempt competitive products. Second, during the long lead-time associated with designing, building, and ramping up new fabs multiple exogenous events arise, creating a need to change design criteria. These events

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are difficult for fab designers to anticipate because they tend to relate to external changes in the chip manufacturing technology and in the forecasts of market demand for chips. Other design changes are generated inside the fab project environment when designers unearth incorrect assumptions about product characteristics caused by lack of timely communication among design specialists and by poor understanding of work interdependencies. In contrast with related work in engineering design that has focused on the ability of project organizations to accommodate internal changes (e.g., Smith and Eppinger 1997a, b; Yassine et al. 2003), our research focuses on the ability of project organizations to accommodate significant, unpredicted external changes.

Intriguingly, our empirical investigation found limited evidence in fab projects of decision postponement as reported in the product development literature. Hence, we employed our empirical findings about the decisions made in fab concept development and about the frequency of customer-requested changes in design criteria to build a model of the concept development process. We, jointly with practitioners, numerically calibrated the simulation model for the case of R&D fabs and used it to investigate the pros and cons of using postponement in fab design projects.

Our research frames the development phases somewhat differently than the product development research we cite. We focus on what the product development literature calls concept development, and examine two phases within concept development: conceptualization and design. Conceptualization corresponds to the designers' initial effort to develop a fab technical concept, using rules of thumb and historical data. Design corresponds to the development of the technical concept into more complete drawings and specifications, using sophisticated analytical tools. Specifically, we use computer simulation to investigate the impact of postponing the start of design in relation to the end of conceptualization (see Fig. 1a and b).

In this work, we seek to answer the following questions:

1. When should fab designers start to design in relation to the completion of conceptualization?
2. How is the performance of concept development (conceptualization plus design) affected by postponing the start of design in terms of lead-time, resources spent, and design process reliability?
3. Is the effectiveness of postponement (delaying the start of design relative to the end of conceptualization) affected by the ability of designers to learn and reuse work developed prior to any significant change, and if so, how?

This paper is organized as follows. We review related literature, and report our empirical findings on the concept development process of fabs. Then, we describe the simulation model and discuss the main modeling assumptions. Finally, we use numerical experiments to

investigate the pros and cons of postponement for managing concept development of fab projects; we also discuss the managerial insights as well as the limitations of the simulation exercise.

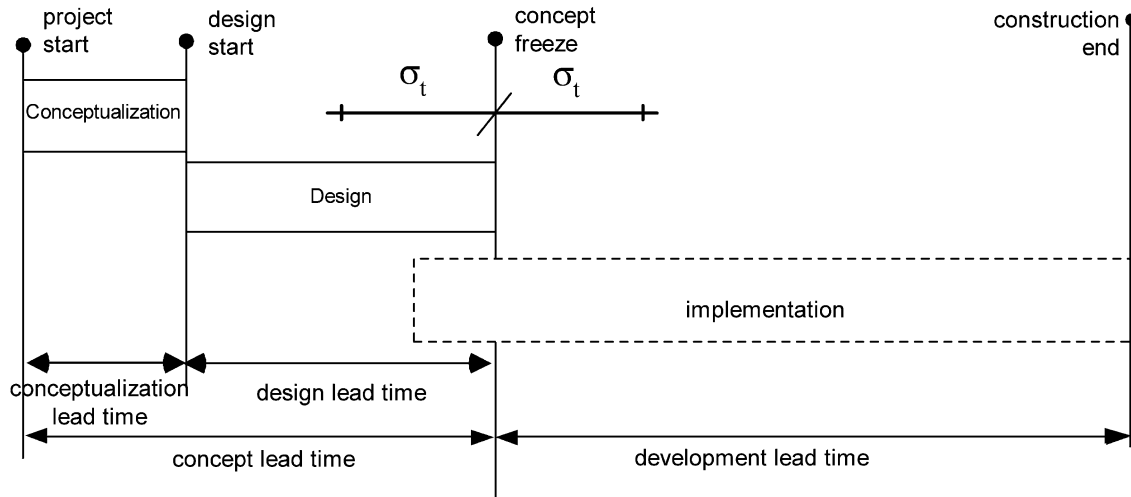
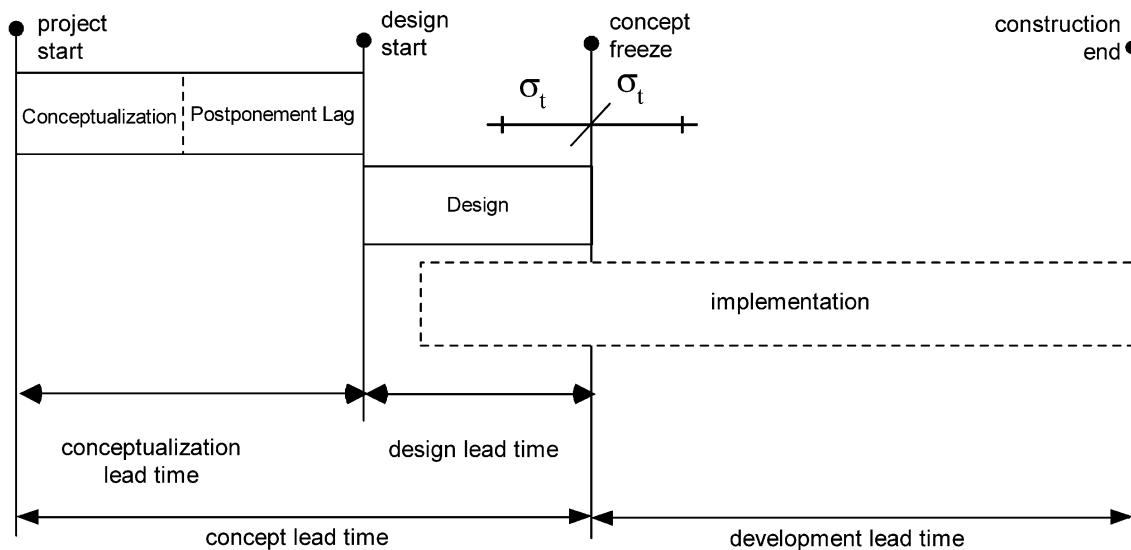
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## 2 Related work

To delay decision-making for supporting large-scale engineering projects in uncertain environments is not a new managerial concept. For the case of weapon systems development, Klein and Meckling (1957), for example, propose that designers postpone final commitments on critical design features until they gain more confidence in their estimates to allow efficient use of limited resources. Recently, van Hoeck (2001) reviewed the literature on postponement dating back to the 1960s to conclude that the recent growing interest in, and managerial application of postponement in domains as diverse as engineering design and operations/supply chain management, should be interpreted as a rediscovery of the concept. In the domain of engineering and construction projects, researchers have also long criticized the preference of project organizations to pursue early commitment strategies and to focus on single-point design solutions, which frequently result in missing promised project due dates and in performing extensive rework (e.g., Tommelein et al. 1991; Pietroforte 1997; Lottaz et al. 1999).

Related to our approach is research that has used analytical constructs to study the effectiveness of postponement for managing product development projects in unpredictable environments. Bhattacharya et al. (1998) claim that having a sharp product definition early on may not be desirable or even feasible for managing product development projects in high-velocity environments. Instead, they propose that firms delay commitments and gradually refine their product solutions, according to the levels of uncertainty they expect, their own risk profiles, the difficulty in making changes to the product solutions, and the value of new customer information. Along the same lines, Terwiesch and Loch (1999) use an analytical concurrent engineering model to demonstrate that uncertainty due to engineering changes and to interdependency between tasks may make concurrency less attractive. They suggest that managers trade off savings in project duration that result from overlapping activities against rework delays caused by changes of preliminary information.

Specific to the fab building environment, Wood (1997) uses an analytical model to analyze the effectiveness of modular tooling of fabs in accelerating the start of manufacturing and in meeting the manufacturer's need for flexibility. Modular tooling gives management the option to postpone decisions on tooling to as late as possible by tooling up the fab sparsely initially and then installing modules of tools as needed. Wood shows that postponement decreases risks associated with

**(a) Observed Model****(b) Proposed Model**

**Fig. 1** Two models of concept development for large-scale engineering projects (adapted from Iansiti 1995)

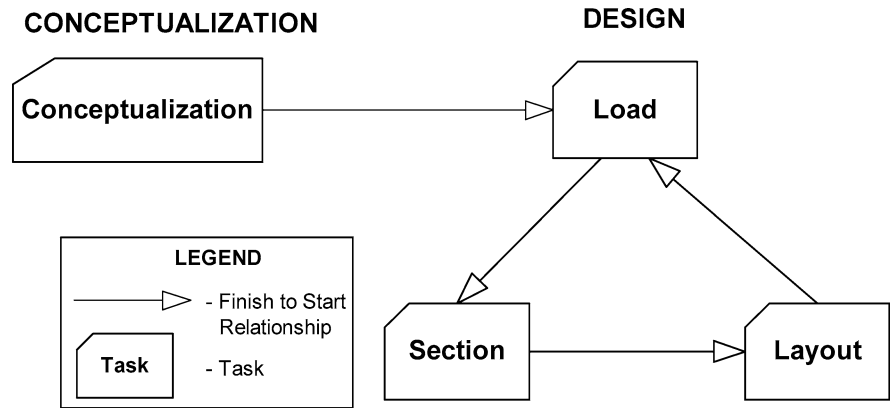
obsolescence of capital equipment and inventories since it allows for more accurate matching of fab capacity with demand and technology. This practice is only effective, however, if lead-times to add tooling capacity are short.

Other related work has developed modeling tools to support engineering design management in uncertain environments, such as work using the design structure matrix (e.g., Eppinger et al. 1994; Yassine et al. 2003). This research has primarily focused however on internal uncertainty caused by work dependencies between design specialties and between design and implementation. In contrast, our investigation uses discrete-event simulation to probe into the project performance impacts of significant changes caused by events exogenous to the design team.

### 3 Empirical research

We started to investigate the dynamics of fab projects by gathering empirical qualitative and quantitative data, primarily through three methods: interviews with practitioners, attendance at design and construction coordination meetings, and analysis of project records. This data gathering work was made possible through a close collaboration with Industrial Design Corporation (IDC), a leading design-construction firm specializing in high-tech facilities. Specifically, we used semi-structured questionnaires to interview senior people including lead designers of the mechanical, architecture, electrical, chemical, and structural specialties, construction-, design-, and project-managers, and customer representatives. We questioned practitioners about the critical decisions they make throughout conceptualization and design, the sequences and durations of tasks, and expected patterns, frequency, and implications of cus-

**Fig. 2** Concept development model



tomers-requested changes in design criteria. We interviewed 22 design-related people and 10 owner representatives. The interviews lasted approximately 1 to 2 h. We carried out follow-up interviews with all the interviewees.<sup>1</sup> In addition, we attended various construction and design coordination meetings for fab projects ongoing at that time as well as studied the records for several fab projects, including project proposals, meeting minutes, schedules, logs of design change orders, and project drawings and specifications.

To promote the validity and reliability of the empirical findings, we triangulated the data. Triangulation is ‘a vehicle for cross validation when two or more distinct methods are found to be congruent and yield comparable data’ (Jick 1979). van Hoeck (2001) suggests the adoption of triangulation for enhancing the richness of the findings on postponement research. From our empirical research, we developed two conceptual constructs: (1) a model of project concept development, and (2) a probabilistic model of the sequences of significant changes in the course of a fab project, as perceived by practitioners.

### 3.1 Construct 1: Concept development model

Figure 2 represents the concept development process for fab building systems (e.g., electrical, structural, mechanical, architectural, process, etc.) as a two-phase generic model: conceptualization followed by design. During conceptualization, designers use empirical rules, historical data, and customer requirements to set forth the design criteria and agree on the design definition for each building system. They estimate, for example, design loads, sizes of critical cross-sections, space requirements, and major equipment needs based on preliminary information about the expected area for the cleanroom or about the

expected number of wafer<sup>2</sup> starts per month. The conceptualization phase deliverable is a report that, for each building system, summarizes the main features of the design definition and may include order-of-magnitude estimates for the cost and schedule for construction.

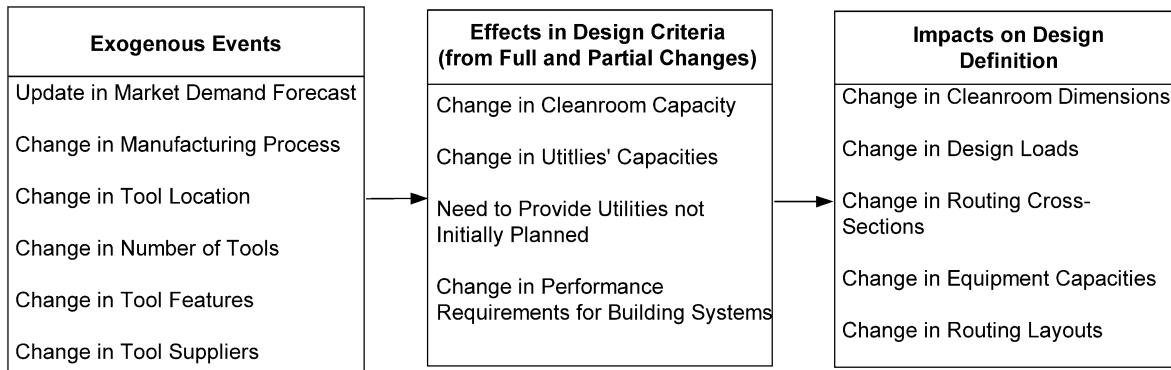
During design, designers use sophisticated computer-based tools to refine the design definition developed in conceptualization. Design is an iterative loop of three tasks: load-, section-, and layout-development. Load development is the process during which designers calculate the loads that the system should support. Section development is the process during which designers size the cross-sections of the main system given the design loads. Layout development is the process during which, based on the cross-section sizes, designers decide the routing of each utility system and the location of major pieces of equipment. During design, designers also size and procure equipment with long delivery times (for the sake of simplicity, we excluded this activity from the scope of the model). Typical design phase deliverables are sets of drawings and specifications for each building system, and more detailed estimates on cost and schedule for the construction phase. Conceptualization and design for each building system do not necessarily progress at the same pace. Instead, some work (such as foundation design) may go ahead of other work (such as architectural design) to allow construction work to start as early as possible.

### 3.2 Construct 2: External changes model

Diverse events exogenous to fab concept development projects, such as new or updated forecasts of market demand for future chips and modifications in chip manufacturing technology, affect the fab design criteria and the design definition. Figure 3 illustrates these cause and effect relationships. These updates or modifications

<sup>1</sup>Many professionals interviewed worked in several high-tech design or contracting firms or even at customer organizations prior to their job position at the time of the interview; therefore, the knowledge we gathered largely reflects current practices in the high-tech engineering and construction industry.

<sup>2</sup>Wafers are the basic units of production in a fab. They are discs of (usually) silicon, on which the semiconductors are etched. Wafers are then sliced into what we know as semiconductor chips.



**Fig. 3** Cause and effect relationships between exogenous events and fab design

create the need to change design *criteria* such as the capacities for the cleanroom and utilities. We observed that designers group external changes in fab design criteria into three categories: (1) Full changes, which cause designers to redo both conceptualization and design; (2) Partial changes, which affect work done during design but have less impact on the work done during conceptualization; and (3) Small changes, which have limited rework implications. Full and partial changes affect the fab design *definition* in terms of cleanroom dimensions, design loads, cross-sections of routings, equipment sizes, and layouts of the utility systems.

Regrettably, we found that (at IDC, at least) project managers seldom keep consistent logs of external design changes and of their impacts on concept development. A search in IDC's project database found consistent but limited data on design changes, logged on a monthly basis, for only one project, Fab X. Table 1 shows, for three specialties, the initial estimates of work-hours for conceptualization and design and detailing, as well as the number of additional hours spent in design changes. Note that significantly fewer hours are spent in conceptualization than in design and detailing, and workloads differ across design specialties.

**Table 1** Estimates of work hours for the design process and hours spent in external design changes (full, partial, and small) for the mechanical/hvac, electrical, and chemical specialties (Fab X)

	Mechanical/ HVAC	Electrical	Chemical
Conceptualization	290	340	660
Design and detailing*	11,955	10,710	14,626
Total conceptualization, design and detailing work hours	12,245	11,050	15,286
Design change work hours	1,723	3,215	4,993
Design change as a percent of total work hours	14%	29%	33%

\*An estimate of work-hours for design separate from detailing was not available; in detailing, designers develop the technical design concept into drawings and specifications for construction and precise bill of materials

Figure 4 shows how the design change work hours for the chemical specialty in Table 1 were spread monthly in the course of the project. Note the predominance in frequency of small changes, which cause less than 100 h of design rework per change. Full and partial changes occurred only sporadically: the third change in the first month of the project (caused by a modification of the design criteria for the industrial water system), the second change in the eighth month (caused by release of a new tool layout), and the second change in the eleventh month (caused by unanticipated need for a copper lab) all significantly affected the work developed by the chemical specialty. While the predominance of small external changes in the project's life suggests their project performance impacts merit further investigation, this work is limited to investigating the impacts of full and partial changes.

Jointly with senior designers, we developed a model of the set of possible and exclusive sequences of full and partial changes in a fab project's life (Fig. 5). The model reflects the following premises:

1. Full and partial changes happen independently.
2. Partial changes are more likely, and are likely to occur earlier than full changes.
3. The occurrence of the first change within a time interval after the project start conditions (i.e., affects the probability of) the occurrence of the second change of the same type after a time lag. In turn, the second change conditions the occurrence of a third change of that type, and so on. Senior designers interpret an early significant change in the design criteria as a signal that subsequent significant changes are somewhat likely to occur. In contrast, designers deem the scenario of a first, significant change late in concept development extremely unlikely.
4. The conditional probability of each subsequent significant change is lower than that of the immediately preceding change of the same type primarily because the more work that has been done, the more costly it will be for project organizations to execute another significant change, and thereby organizations will be increasingly reluctant to do so.
5. The time when a significant change occurs is more difficult to predict for significant changes that occur later in the process.

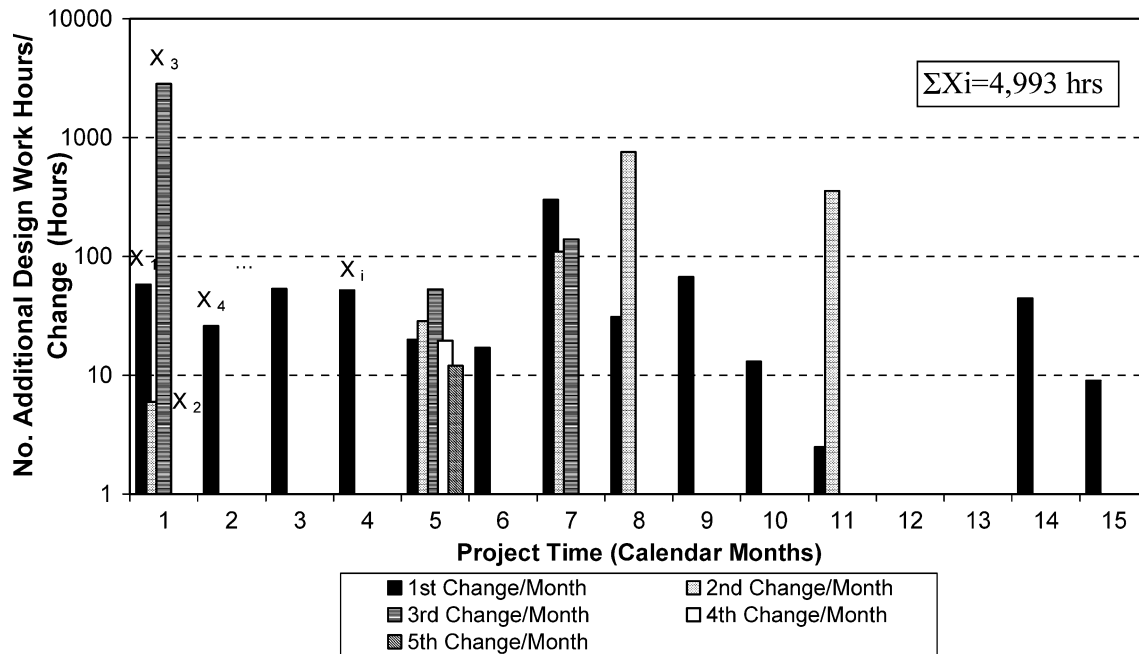


Fig. 4 Additional design work-hours per change for the chemical specialty over the duration of the project (Fab X)

## 4 Simulating concept development

### 4.1 Modeling conceptualization and design

Simple models have been used to develop insights into the pros and cons of various managerial propositions for product development projects in uncertain environments (Ha and Porteus 1995; Krishnan et al. 1997; Bhattacharya et al. 1998; Loch and Terwiesch 1998; Terwiesch and Loch 1999; Krishnan and Bhattacharya 2002). Simple models reduce the number of parameters that need to be estimated, and thereby provide a reasonable starting point to research. Modeling simplicity also facilitates understanding of how different factors interplay. Once the workings of a simple model are well understood, it can be developed further by adding factors initially left out but perhaps judged important by practitioners. As a result, insights from simple models can be useful to complement research with more complex models.

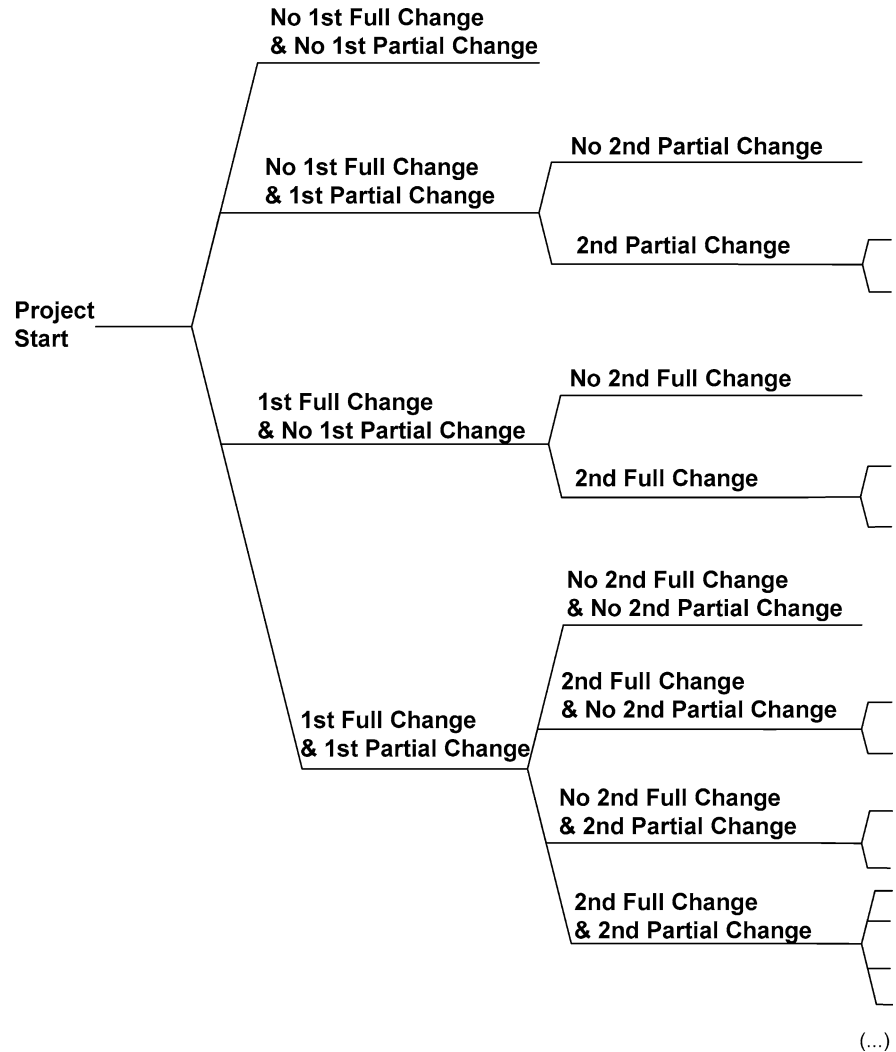
Regrettably, our empirical research found that the high-tech engineering and construction sector seldom produces reliable quantitative data on the concept development process. The scarcity of hard data as well as the need to ensure the simulation results were tractable determined our choice to simulate the fab concept development process with a simple event-graph model (Fig. 6). The interested reader can find detailed representations of this process in Gil (2001). The model integrates the concept development and uncertainty constructs described above, and was implemented in SIGMA, a discrete-event simulation environment based

on event scheduling (Schruben and Schruben 1999). Event-scheduling systems work by “identifying [a system’s] 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).

In the description that follows, words in all-caps denote geometric shapes in the figure, which represent events. Specifically, rectangles denote the beginning or end of design tasks, circles denote the start and end of simulation replications, and diamonds denote (full or partial) changes of design criteria. The arrows represent relationships between the events they connect. Associated with each arrow is a set of conditions. A solid arrow means that the event from which the arrow emanates schedules the event to which the arrow points after a time delay ( $\Delta t \geq 0$ ), if edge conditions are met. A dashed arrow means that the event from which the arrow emanates cancels the event to which the arrow points after a time delay ( $\Delta t \geq 0$ ), if the latter is scheduled to occur and the edge conditions are met.

Simulation starts with the START REPLICATE event, which schedules the START CONCEPTUALIZATION event. The START REPLICATE event may also schedule the first PARTIAL CHANGE and the first FULL CHANGE, with independent probabilities and stochastic delays. When a change event occurs, it schedules a subsequent change of the same type. START DESIGN LOAD may take place immediately after END CONCEPTUALIZATION or it may be postponed. (Whether to postpone is a choice made by the user, as discussed later). A FULL CHANGE unconditionally cancels all scheduled events related to conceptualization and design and schedules a new START CONCEPTUALIZATION event. Similarly, a PARTIAL CHANGE unconditionally cancels all scheduled

**Fig. 5** Partial model for the range of possible sequences of full and partial changes



events related to design and schedules a new **START DESIGN LOAD** event. Note that Fig. 6 only depicts two sequences of change events, but other sequences can be easily added to the model.

The model assumes that designers consider all design criteria changes (full or partial) that may occur before a set project horizon, whether or not design is completed by the time the change occurs. Changes occurring after that horizon, however, are ignored to simulate a design freeze at a specific deadline. This milestone is a decision variable that we purposely set far away from the **START CONCEPTUALIZATION** event in order to model a realistic situation that considers most significant changes. Once concept development is completed and the simulation time exceeds the set project horizon, the **END REPLICATE** event is scheduled. This event collects the values of the performance variables for the simulation run, cancels any changes that may still be scheduled to occur, resets all the simulation variables (except those that store data for purposes of statistical analysis), and schedules a **START REPLICATE** event for a new independent, identically distributed simulation run.

## 4.2 Modeling rework

When full or partial changes occur, designers return to tasks they have started and perhaps completed earlier and repeat them. The designers we interviewed suggested that some efficiencies typically exist as they repeat tasks; they believed that they could reduce the duration of a task by 50% or so the first time they repeated it, and that further reductions in the duration of any task would grow smaller and smaller as the task was repeated. However, no quantitative data was available to inform on the actual gains achieved by designers from reusing work. This led us to model two hypothetical algorithms to simulate designers' ability to reuse work (Fig. 7).

### 4.2.1 Algorithm 1: No design reuse

The first algorithm simulates an extreme situation in which designers do not reuse work. Whenever a full or partial change occurs, the expected duration for a task that needs to be repeated is equal to its initial duration. This scenario can be written as

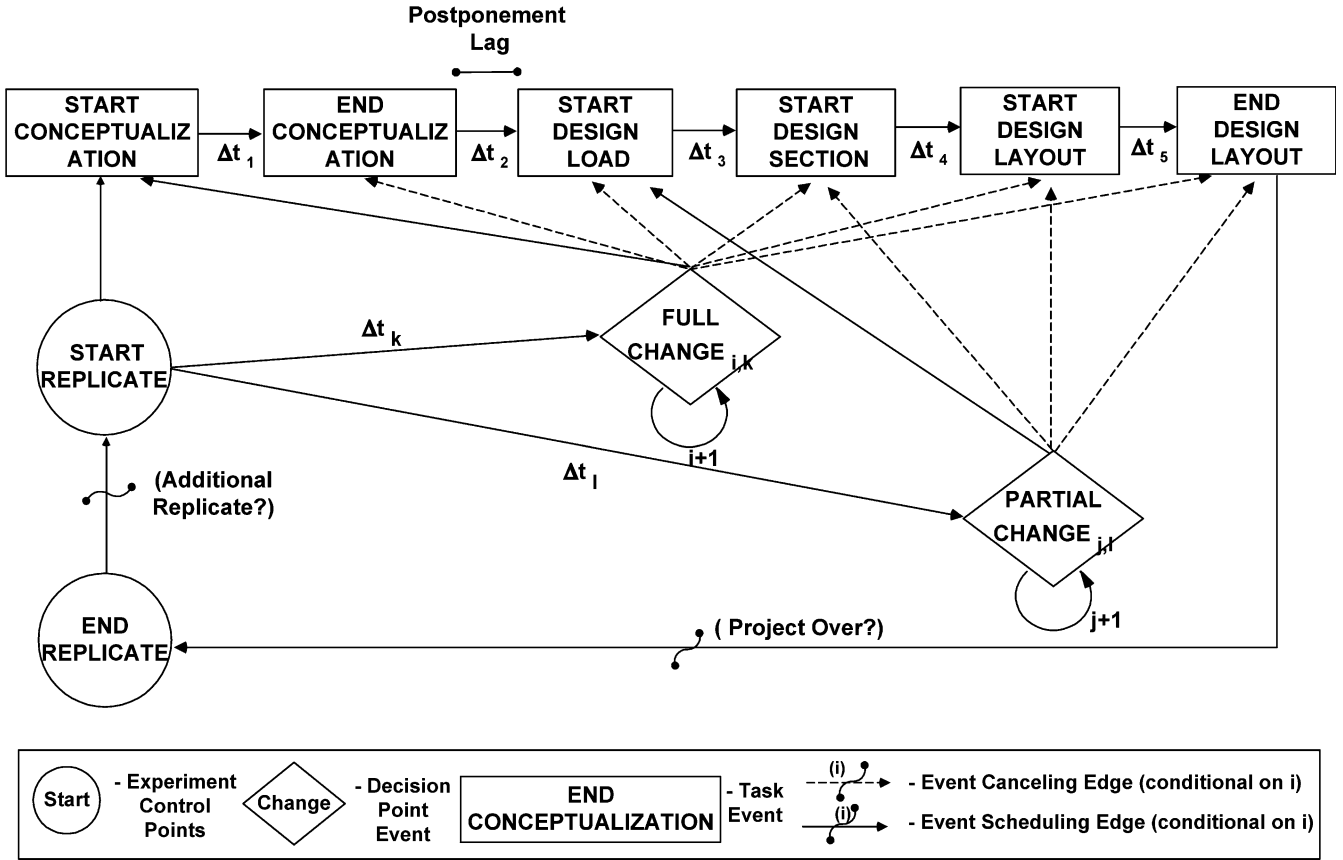


Fig. 6 Event-graph model for concept development

$$D_{i+1,n} = D_{i,n+1} = D_{i,n} = D_{1,0}, \forall i, n \quad (1)$$

where

$i, n$  Number of times ( $i=1, 2, 3, \dots$ ) designers have started to perform the task, given the number of times ( $n=0, 1, 2, 3, \dots$ ) designers already completely executed the task

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

#### 4.2.2 Algorithm 2: Limited design reuse

The second algorithm matches the designers' intuitions on their ability to reuse work. The duration of a task in a rework cycle is determined by prorating its duration in the preceding cycle:

1. If the task was concluded when the change occurred:

$$D_{i,n+1} = \frac{(n+1) \cdot D_{i,n}}{n+2}, \forall n, i \quad (2)$$

2. If the change interrupted the execution of the task:

$$D_{i+1,n} = D_{i,n} - T_{i,n} + \frac{i \cdot T_{i,n}}{i+1} = D_{i,n} - \frac{T_{i,n}}{i+1}, \forall n, i \quad (3)$$

where

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

This algorithm assumes that if a change occurs after completion of a task, the duration of this task decreases in the next iteration due to efficiency gains and learning. If a change interrupts a task, in the next iteration the work that is repeated benefits similarly but the work that remains will last what it was previously estimated to last. In addition, it assumes that these benefits decrease between successive iterations of complete and incomplete tasks. Figure 8 illustrates this algorithm for a sequence of complete task iterations. This algorithm mimics a learning curve, in which the three basic assumptions are: (1) the amount of time required to complete a given task will be less each time the task is undertaken; (2) this amount of time will decrease at a decreasing rate; and (3) the reduction in time will follow a predictable pattern (Chase et al. 1998, p. 446).

#### 4.3 Measuring concept development performance

We applied three metrics to assess the performance of the development process in our simulations: concept development duration, resources spent in design, and number of repetitions for each design task start event



Algorithm	Change Occurs After Task is Completed	Change Occurs While Task is Underway
No Design Reuse		
Limited Design Reuse		

$i, n$  - 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

Fig. 7 Graphical representation of the design reuse algorithms

(Table 2). Monitoring the concept development duration is critical for understanding the repercussions of postponing the start of design on this critical project dimension. Monitoring resources spent during design is equally critical because professionals skilled in designing

high-tech fabs are a scarce resource. The third metric—number of repetitions of the start of design tasks—provides a key measure of the rework that has to be done.

**5 Numerical applications**

5.1 Calibrating external changes

Jointly with practitioners, we developed a stochastic mathematical model that matched their perceptions of the possible random sequences of partial and full changes for the case of R&D fabs for leading-edge microprocessors and application specific integrated circuits (ASICs). We used re-scaled and shifted symmetric beta random variables  $[a + (b-a) \cdot \text{Beta}(\alpha_1 = 2, \alpha_2 = 2)]$  to express the variability around the time when a change occurs. We employed the beta distribution—a parameter input distribution—because the richness of shapes that it can take on with simple changes of its  $\alpha_1$  and  $\alpha_2$  parameters was needed to accurately align the mathematical modeling with practitioners’ perceptions. This flexibility is frequently exploited in simulation studies where a subjective approach to fit a distribution is

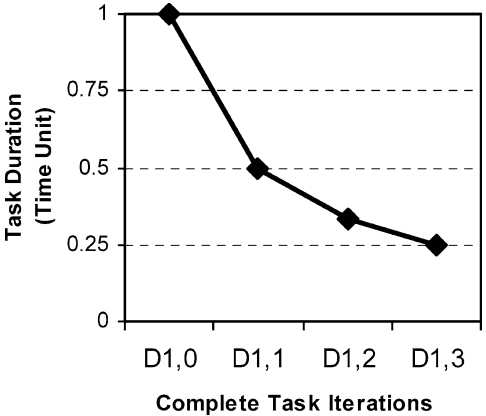


Fig. 8 Reduction in task duration due to efficiency gains for hypothetical sequence of complete task iterations

**Table 2** Description of performance variables

Performance variable	Description
Concept development duration (days)	Time elapsed between the occurrence of the first START CONCEPTUALIZATION event and the occurrence of the END DESIGN LAYOUT event for the last design iteration
Resources spent in design (workdays)	Workdays spent executing design tasks
Number of repetitions of each start design task event	Number of times each START DESIGN task event was repeated, regardless of whether the task was completed before being interrupted by design changes or not

needed because reliable hard data is not available (Law and Kelton 2000 p. 309).

A first set of interviews allowed us to quantify the parameters in the beta distributions (using Perry and Greig’s [1975] formulae for estimating the mean and variance of subjective distributions), as well as to estimate the parameters  $A$ ,  $B$ , and  $C$  in Table 3. Subsequently, jointly with practitioners, we analyzed the simulated histograms of changes (illustrated in Fig. 9) to ascertain that the modeling assumptions were consistent with their beliefs. The conditional probabilities and the temporal relationships between changes of the same type, within any stream of changes, can be stated as

$$P(\text{change}_1) = A \tag{4}$$

$$P(\text{change}_2|\text{change}_1) = \frac{A}{1 + B \cdot 1.0} \tag{5}$$

or in general:

$$P(\text{change}_i|\text{change}_{i-1}) = \frac{A}{1 + B \cdot (i - 1)}, i \geq 2 \tag{6}$$

$$P(\text{change}_i|\overline{\text{change}_{i-1}}) = 0, i \geq 2 \tag{7}$$

$$T_1 = C[1 + \text{Beta}_1(\alpha_1 = 2, \alpha_2 = 2)] \text{ (days)} \tag{8}$$

$$T_2 = T_1 + C[1 + \text{Beta}_2(\alpha_1 = 2, \alpha_2 = 2) \cdot (1 + B)] \text{ (days)} \tag{9}$$

or in general:

$$T_i = C \cdot \left[ i + \sum_{s=1}^i \{ \text{Beta}_s(\alpha_1 = 2, \alpha_2 = 2) * (1 + B \cdot (s - 1)) \} \right] \text{ (days), } i \geq 1 \tag{10}$$

where

**Table 3** Estimates of  $A, B$ , and  $C$  for R&D fab projects

Constant	Full change	Partial change
$A$	0.5	0.9
$B$	0.5	0.25
$C$	20	15

$P(i)$	Probability of change $i$ occurring
$P(i i-1)$	Probability of change $i$ conditional to occurrence of change $i-1$
$T_i$	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 $i$
$A$	Probability of a first change
$B$	Declining rate in likelihood and in time predictability for external changes (varied between 0 and 1)
$C$	Mean and standard deviation for time delay before occurrence of first change (days)

Note that the conditional probabilities of the second change and of the subsequent changes of a given type are smaller than the probability of the first change. Similarly, the model increases the time intervals between subsequent changes. Table 3 presents the designers’ estimates for the parameters  $A$ ,  $B$ , and  $C$  for the case of R&D fab projects. Specifically, designers assert that the first full change in any R&D fab project will occur between 20 to 40 days after the start of the project with a 50% probability and that the first partial change will occur between 15 to 30 days after project start with a 90% probability. The probability of subsequent changes—as well as the predictability of the moment when they will occur—decreases faster for full changes than for partial changes.

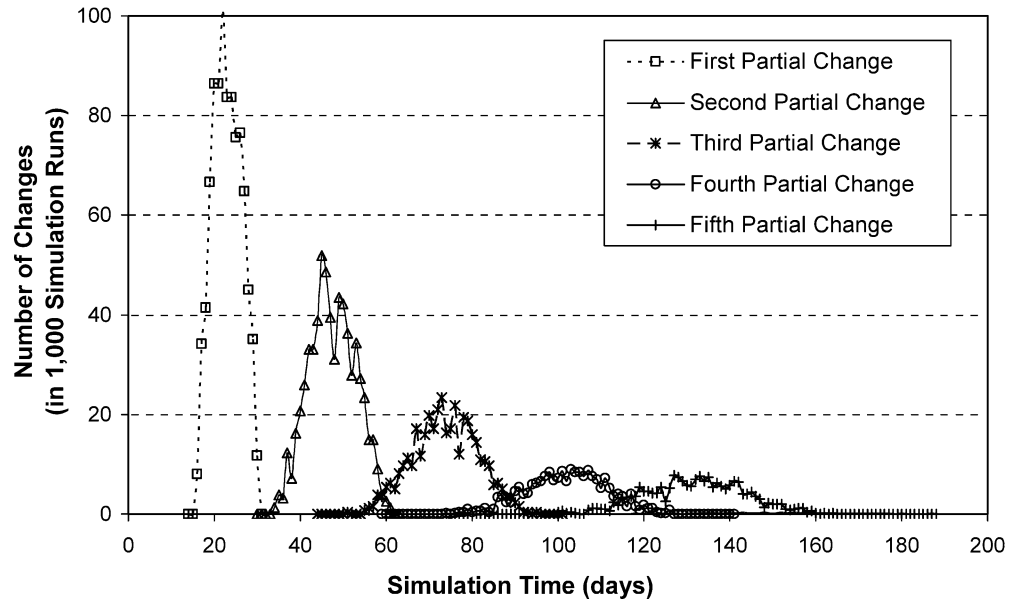
We employed Eqs. 4, 5, 6, 7, 8, 9, and 10 in the simulation model to generate the expected distribution of both full and partial changes over the duration of an R&D fab project (see Fig. 9). The distributions are as expected: the probability of occurrence of a change decreases over time, and the time lag between occurrences increases over time.

## 5.2 Computational assumptions

The numerical experiments reflect the following computational assumptions:

1. Each task has a deterministic duration. Given the sequential nature of the model, with simple finish-

**Fig. 9** Histograms of partial changes for 1,000 simulation runs



to-start relationships, stochastic task durations would not change the means of the performance variables resulting from a large number of experiments (a consequence of the *strong law of large numbers*), although the variability of the performance variables would increase somewhat.

2. As the focus of this work is on the project performance impacts of significant external changes, the design loop (including load, section, and layout) is done only once unless the design criteria change. We discuss a possible extension of the model to include internal design iteration in the model limitations section.
3. Resources—implicitly allocated by assuming specific task durations—are available to execute the tasks whether or not design is postponed. In practice, obtaining sufficient resources later on in a project may not be trivial, as we also discuss later in this paper.
4. We tested both algorithms (no design reuse and limited design reuse) to simulate design rework. Practitioners judge algorithm 2, limited design reuse, to be the most realistic representation as it is rare they do not reuse some work even after a significant change.

### 5.3 Sensitivity analysis on postponement lag

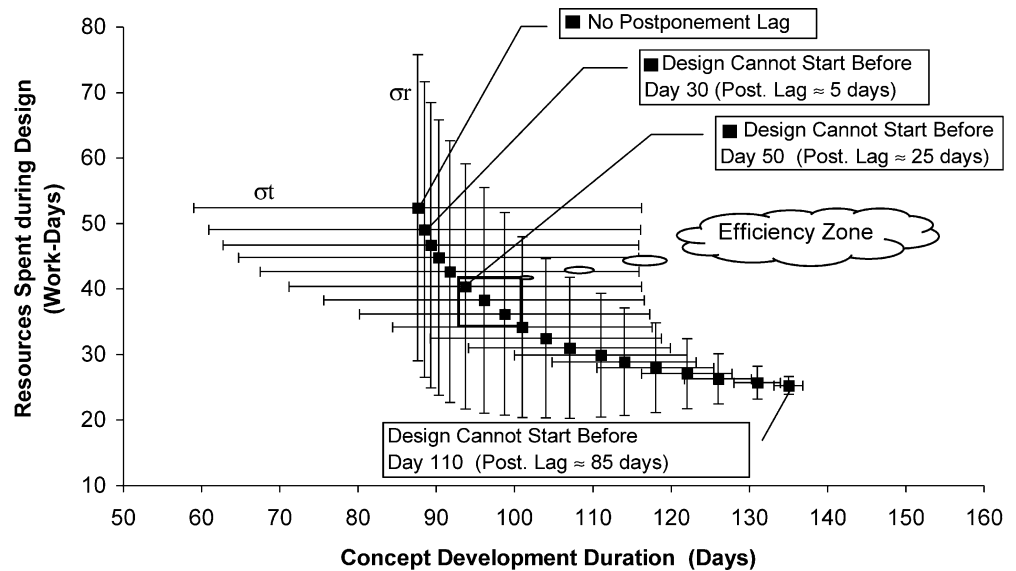
Because we empirically found limited evidence of the use of postponement—i.e., of delaying critical decisions until as late as possible in the concept development process—we constructed a simulation model to test the potential for their use. We evaluated several postponement strategies. To do so, we locked in the earliest day to START DESIGN LOAD at different points in the concept development process. One extreme scenario assumes that designers START DESIGN LOAD

immediately after END CONCEPTUALIZATION. This means that designers start design on day 25 (conceptualization lasts 25 days if no full changes interrupt it), or on whatever day conceptualization ends (if full changes occur in the mean time). The other extreme scenario assumes that designers postpone START DESIGN LOAD up to day 110 (corresponding to a lag of 85 days if conceptualization finishes on day 25). We hypothesized that the latter scenario would allow designers to maximize the probability of developing the design in a single pass. To develop a sense for how the various factors interacted, we tested several strategies in between, using increments of 5 days to vary START DESIGN LOAD from day 25 to day 110. For each scenario, we ran 1,000 simulations.

Figure 10 charts the relationship between the concept development duration and the number of resources spent during design as the postponement lag increases for the no-design-reuse scenario. The mean and standard deviation of each data point in the chart are calculated with their unbiased estimators applied to the results of 1,000 independent, identically distributed simulation runs. This assumes that the 1,000 observations for each of the two variables are approximately distributed as normal random variables. This is acceptable since the central limit theorem says, in effect, that if the number of observations is sufficiently large, the observations are approximately distributed as normal variables, regardless of the underlying distribution of the corresponding variables (Law and Kelton 2000, p. 248).

Figure 10 illustrates that as the postponement lag grows, the mean concept development duration increases, and the mean number of resources spent during design decreases. Further, the shape of the curve shows that as the postponement lag initially increases from a no-postponement strategy, the marginal reduction of the mean number of resources spent is very steep while the marginal increase of the mean concept development

**Fig. 10** Concept development duration versus resources spent during design, for alternative postponement strategies (1,000 runs for each data point)



duration is relatively small. As the postponement lag continues to increase, the marginal reduction of the mean number of resources spent is less significant while the marginal increase of the mean concept development duration tends to equal the corresponding marginal increase of the postponement lag. Figure 10 also shows decreasing variability in concept development duration as the postponement lag increases. Further, it shows that the one-standard deviation upper limit of the concept development duration ( $\mu_t + \sigma_t$ ) remains more-or-less steady for postponement lags up to approximately 25 to 35 days. Clearly, up to this lag, the marginal decrease in the variability of the concept development duration counterbalances the marginal increase of the mean concept development duration. As the postponement lag continues to increase beyond 25–35 days, the marginal increase of the mean concept development duration gets more significant and the marginal decrease in its variability no longer suffices to prevent the upper limit  $\mu_t + \sigma_t$  from also increasing.

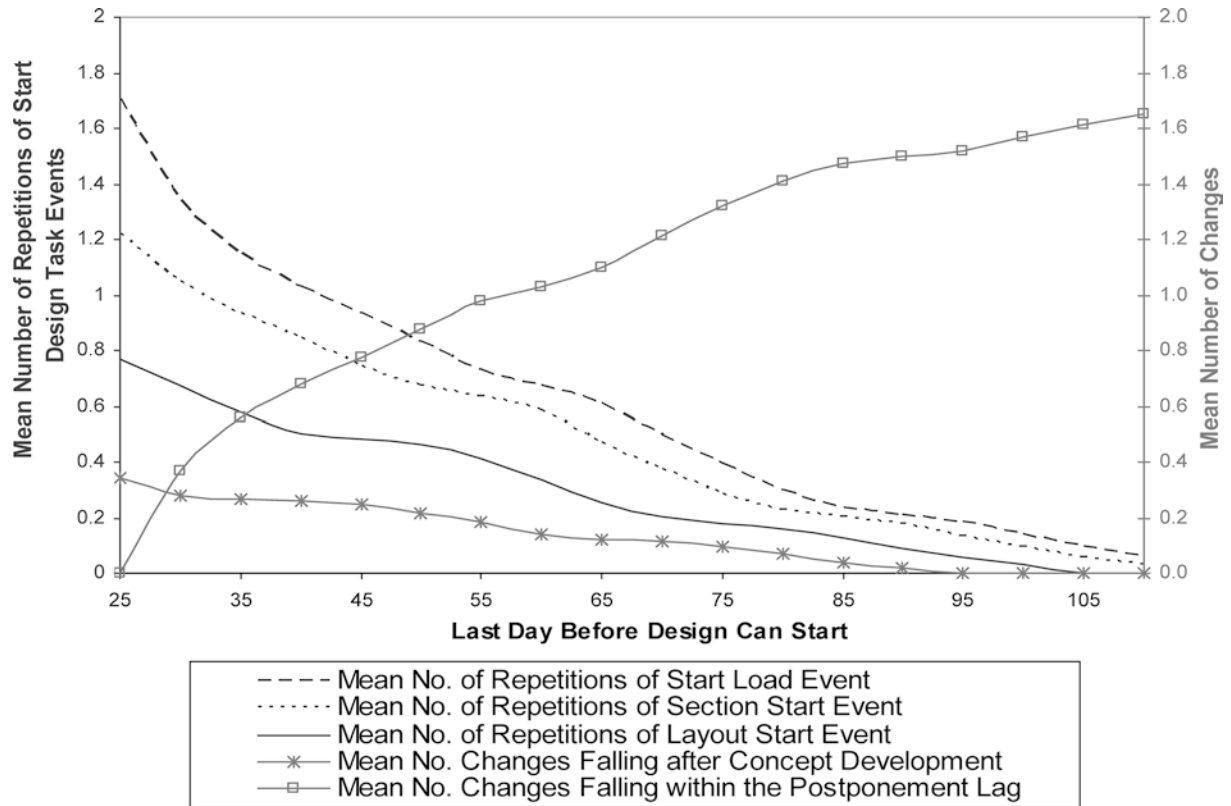
Postponement also decreases the mean and the variability of the number of resources spent because fewer changes fall during design, and thereby design tasks are repeated less. Figure 10 shows a square that encompasses a set of efficient postponement strategies that best simultaneously satisfy two conditions: (1) minimize the mean number of resources spent during design ( $\mu_r$ ) and their variability ( $\sigma_r$ ); and (2) do not increase the upper one-standard deviation limit of the concept development duration ( $\mu_t + \sigma_t$ ) beyond the value that  $\mu_t + \sigma_t$  assumes with a no-postponement strategy.

Figure 11 charts postponement lag versus (1) the mean number of repetitions for the start design task events, (2) the mean number of changes falling within the postponement lag, and (3) the mean number of changes falling after completion of concept development. Table 4 shows the corresponding standard deviations of these means for selected scenarios. Figure 11 shows that as the postponement lag increases, the mean

numbers of repetitions of the start design task events and of the changes falling after concept development decrease to nearly zero, whereas the mean number of changes falling within the postponement lag increases. The graph shows that the mean numbers of repetitions for any start design task event do not decrease steadily but rather oscillate slightly up and down along a decreasing trend line, ultimately reaching zero. These local phenomena indicate that an incremental increase in the postponement lag does not equally reduce the repetition of all the start design task events because of local interactions between the time-dependent means around which changes occur and the durations of the postponement lag and of the tasks. These phenomena would have been hard to anticipate without conducting a simulation, even for a process as simple as the one we present here. For more complex concept development processes, the effect of postponement will likely be even more difficult to gauge, since each specific postponement lag leads to unequal benefits for the various tasks. Given that the duration of design tasks and the timing of significant changes may differ for each design specialty, changes may force one specialty into doing more rework even though this rework does not reflect their own skills and abilities. One specialty 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.

#### 5.4 Sensitivity analysis on designers' ability to reuse work

Figure 12 provides a comparison of three scenarios. The baseline scenario is an extreme, unrealistic scenario that assumes fixed design criteria for all the 1,000 replications, thus eliminating external uncertainty and the occurrence of full or partial changes. It is shown as the



**Fig. 11** Variation of the mean numbers of repetitions of start design task events and of change occurrences for alternative postponement strategies (1,000 runs for each data point)

flat line across the bottom of the figure. The no-design-reuse curve developed in Fig. 10 is also shown; additionally, the mean limited-design-reuse scenario is shown along with a set of four curves that depict the variability around that mean curve. Figure 12 illustrates that the effects of postponement are more significant when there is no design reuse than when limited design reuse is assumed. This is intuitive: an increase in the length of the rework loop adds more work when design tasks have to be repeated, and thereby designers would be better off postponing design. Figure 12 also suggests that, when limited design reuse is assumed, the efficiency zone corresponds to somewhat shorter postponement lags. This is an expected result since, in this scenario, repetition of the tasks takes less time but the time-dependent means around which external changes occur remain the same.

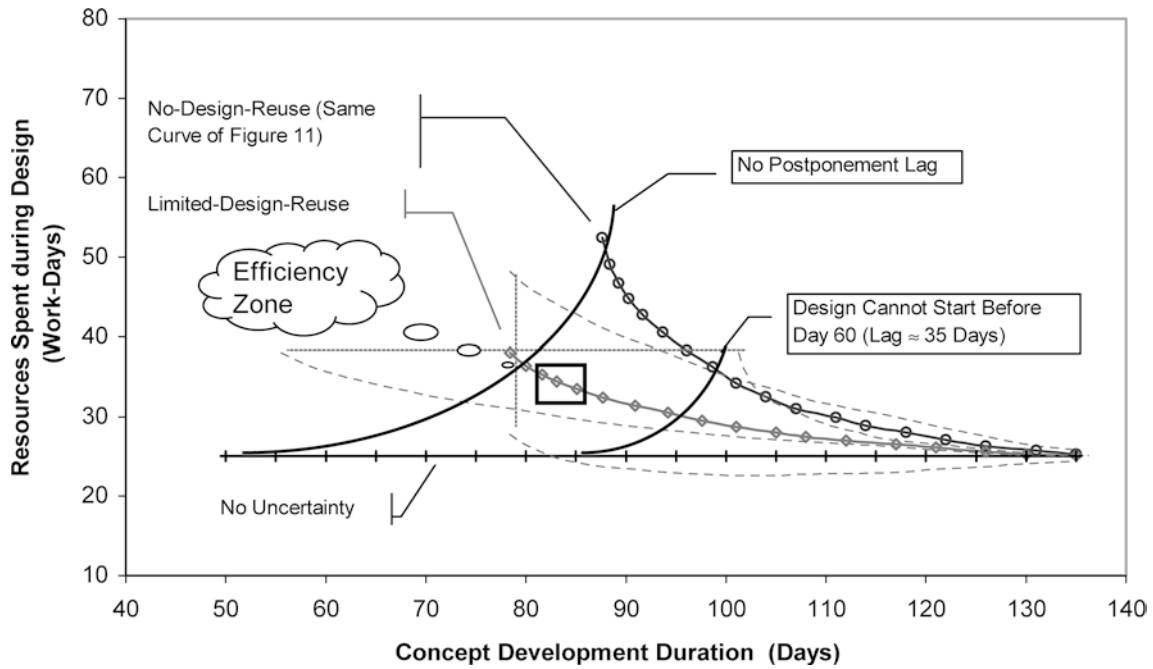
These results confirm what would be expected: design tools for enhancing designers' ability to reuse work—commonly used in software and chip design development (e.g., Jacome et al. 1999), but much less in construction—reduce the effect of external changes on the concept development process. These tools can help designers to cope better with changes and to estimate more accurately the duration of the concept development process in unpredictable environments.

## 6 Managerial insights and numerical sensitivity

The numerical simulation experiments analyze concept development performance as we vary two factors: the duration of the postponement lag and the ability of designers to reuse work. The results show that early commitment in uncertain environments, though efficient for compressing the mean duration of concept development (which may not be desirable if concept devel-

**Table 4** Postponement effects on performance variables (mean  $\pm$  one standard deviation)

Performance variable	No postponement	Design cannot start before day 45 [lag $\approx$ 20 days]	Design cannot start before day 90 [lag $\approx$ 65 days]
No. of repetitions of START DESIGN LOAD event	1.71 $\pm$ 1.21	0.93 $\pm$ 1.00	0.21 $\pm$ 0.43
No. of repetitions of START DESIGN SECTION event	1.22 $\pm$ 1.03	0.74 $\pm$ 0.90	0.18 $\pm$ 0.39
No. of repetitions of START DESIGN LAYOUT event	0.77 $\pm$ 0.98	0.48 $\pm$ 0.74	0.09 $\pm$ 0.29
No. of changes falling after concept development	0.34 $\pm$ 0.65	0.25 $\pm$ 0.52	0.02 $\pm$ 0.12
No. of changes falling within the postponement lag	0	0.78 $\pm$ 0.64	1.50 $\pm$ 0.97



**Fig. 12** Concept development duration versus resources spent during design for different rework algorithms and for alternative postponement strategies (1,000 runs for each data point)

opment is to overlap effectively with implementation), comes at a cost. First, it maximizes the average number of times that designers repeat the design tasks, and consequently maximizes the average resources spent during design. Second, early commitment makes it harder to predict the duration of the concept development process and the number of resources it will consume. In contrast, the results show that as design is gradually postponed—up to a certain efficiency zone—design iteration and resources spent in design can be reduced, while the risk that concept development may last longer than a preset milestone date ( $\mu_t + \sigma_t$ ) remains nearly the same. As the duration of the postponement lag increases beyond the efficiency zone, the mean concept development duration gradually increases proportionally to the increment in the postponement lag and the savings in the resources spent in design decrease.

We performed sensitivity analyses to examine the robustness of the simulation results with different numerical estimates for the task durations and for the change occurrences. For the sake of brevity, these results are not shown here but the simulation dynamics were as expected: initial increments in the postponement lag tend to correspond to marginal gains in process predictability and in savings in spent resources, while causing limited increases on the average concept development duration. Beyond a certain efficiency zone, increments on the postponement lag tend to increase equally the average concept development duration and to bring negligible savings in resources spent in design. Logically, according to the underlying numerical estimates, the curve in Fig. 10 shifts in the  $(x, y)$  space and the prominence of its concavity varies. For example, a

reduction in the frequency of changes reduces the effectiveness of postponement and vice versa. Also, the effectiveness of postponement increases if the levels of uncertainty remain the same, but the design loop lasts longer as would be the case if internal iteration had been modeled or if tasks had been assumed to last longer. Figure 12 illustrates these dynamics when we vary the assumption on designers' ability to reuse work. Readers interested in experimenting further with the model are encouraged to contact the first author to obtain the executable program.

## 7 Model limitations

Our simulation model was purposefully simple to ensure that results were tractable and to limit the number of estimated parameters given the limited amount of hard data that we found available. It is clear that the model does not encompass a broad range of issues important for engineering design.

First, difficulties in allocating resources—a factor not modeled in this research—can be a potential drawback in implementing postponement. Managers expressed concern that if they let team members get involved with another project during a postponement lag, they would have difficulty getting their teams back together later. We include no provision in our model to represent this possibility. Instead, our model in effect assumes sufficient capacity in the system to move resources as required. Note that under loading resources (i.e., adding a capacity buffer), an approach commonly used by Japanese manufacturing organizations, allows resources to accommodate variability in work demand and consequently increase workflow reliability throughout the process (Hopp and Spearman 1996, p. 157).

Second, the model only focuses on the design process itself, not on its output. It cannot differentiate, for example, the quality of a design solution that results from several iterations from the quality of a solution that is engineered with mature design criteria. The model also cannot reproduce the practice in the industry of over-engineering selected features in the design definition to shield it from external changes (as an alternative to designing a more flexible design process as explored here).

Third, this work only models the concept development process for one fab building system. It would be interesting to model the process for two or more systems, including critical information hand-offs between specialists. In doing so, simulation could generate insights on possible cascading effects in which a significant external change affecting one system increases the likelihood of significant changes affecting other systems. Such an expanded model could also investigate the implications for the design process of one system of postponing decision-making in the design of another system. Another interesting study would explore a situation in which postponement is applied only to a few selected design features in a building system, while allowing design of other features in that same system to start earlier.

Our numerical simulation experiments have other limitations. These experiments cannot guarantee that a specific postponement lag that performs best on average will perform best for a given real world project, even if the process model is precisely calibrated. Simulation results average a large number of realizations. In contrast, in the real world, decision-makers have to decide whether to postpone decisions without knowing for sure if external events will happen and cause significant design criteria changes, even if they anticipate these are likely to occur. Project organizations may nonetheless wish to consider our findings when deciding whether to postpone—and for how long—critical design decisions.

## 8 Concluding remarks

The main insight of this research on large-scale engineering design projects is that some decision-making postponement (when design criteria are uncertain in the early project stages due to external events) can help increase the predictability of concept development duration and reduce resources spent in design without increasing the risk that the project will overrun a completion date. This insight may help designers and customers in certain project environments to think about how long they can afford to postpone design decisions as a function of: (1) the last possible moment when concept development should be completed; (2) the risk they are willing to incur of overrunning that completion date; (3) the resources they can afford to spend; and (4) the extent to which they are able to reuse design work after any significant change in design criteria.

In the case of fab projects, these results matter because the completion date of the fab design phase is a

critical project milestone. Once a customer and a designer contractually agree on a completion date, the customer project manager very seldom allows the designer to slip that milestone, regardless of any late changes requested by the customer. As a result, designers frequently have to resort to working overtime and under intense pressure to meet contractual milestones if major external changes indeed occur. This damages the job reputation and may contribute to scarcity of skilled designers wanting to work in high-tech projects. Interestingly, the designers we interviewed expressed conviction that postponement would jeopardize their ability to meet project milestones even as they acknowledged that they repeated the same tasks several times because of customer-requested changes. This work shows, however, that in certain project environments, some degree of postponement may actually help designers to meet the customer requirements. Fab designers and customers may want to consider these findings before committing to when the fab design will be completed and, accordingly, to allocating the necessary resources.

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