External Change in Large Engineering Design Projects: The Role of the Client

Nuno Gil, Iris D. Tommelein, and Lee W. Schruben

***Abstract*—A problem facing the management of large engineering design projects is: Why do clients often adopt an early commitment strategy on design decision-making when they want to speed up project delivery, yet allow late changes to the project definition to accommodate the resolution of (un)foreseen external uncertainties? Empirical findings illustrate this problem and underpin a 2-stage model of the concept development process, in which conceptualization is followed by design, and stochastic pre-emption simulates asymmetric changes. Simulation experiments demonstrate that when clients make commitments early on in conditions of high uncertainty, they increase the likelihood (upside risk) of speeding up delivery if external events do not materialize; however, if these events do materialize, they increase the likelihood (downside risk) of causing design rework and losing process predictability—especially when the ability to reuse design work after a change is limited. We show that moderate design postponement is appropriate if clients relinquish some of the upside risk of finishing the design sooner. Moderate design postponement does not increase the downside risk of overrunning the delivery completion date in relation to the risk clients incur when they commit earlier because it reduces expected variability in design. These insights highlight the client's role in foreseeing external uncertainties and judiciously instructing changes to design teams. They also demonstrate the applicability of postponement to large engineering design projects where external uncertainty emerges as a fundamental contingency.**

***Index Terms*—Large-scale engineering design, postponement, project management, semiconductor, simulation, uncertainty.**

I. INTRODUCTION

EXAMPLES of large engineering projects are capital and transportation infrastructures, complex information technology systems, and military/aerospace systems procured by business or governmental organizations. A problem in managing such projects is how design teams can best accommodate unplanned client-requested changes in the project definition without failing to meet the original schedule and resource budgets for concept development. Concept development here means a project process in which an upfront conceptualization stage is followed by a design stage. In conceptualization, the client's project brief gets translated into a technical concept expressed through models, drawings, and specifications. The technical concept is then refined and developed with the help of computer-based tools in design. Timelines associated with large engineering design projects are long so the environment inevitably will change in the course of delivery. It is, thus, reasonable to expect that the client—who procures and governs the coalition of project design suppliers (the client may or not be the owner)—may wish to change the project definition over time. Clients are also likely to urge the design team to speed up delivery because of opportunity costs. These two premises underpin our core research question: Why do clients of large engineering projects opt for an early commitment strategy on design decision-making?

The articulation of this problem is not new. Genus' [23] study of the Channel Tunnel project describes administrators' decision to commit early to the design and manufacture of specialized rolling stock when, paradoxically, it was possible that late safety-related, costly, and time-consuming changes might be needed. Indeed, changes manifested themselves, and resulted in a $90 million cost increase and 9-mo delay. In large software projects, scholars note that practitioners repeatedly fail to accept that the project definition is likely to remain incomplete and ambiguous until late in the development cycle, thereby ignoring an important disruptive factor [31], [54]. Similar articulations of the problem are found in empirical studies on projects in the aerospace, defense, and petrol sectors (e.g., [41], [42], and [57]). Loch and Terwiesch [37] phrase it as the dilemma between "rush and be wrong" or "wait and be late." Project management literature recommends that project teams spend more time at the front-end examining options, testing scenarios, involving local/user communities, and understanding the political/economical environment [10], [26], [42]. Applications of sequential decision models, similar to the real options approach, show that the greater the uncertainties at the onset of a large engineering project, the greater value of investment into gaining information on uncertainties as well as deferring decision-making until uncertainties get resolved [15]. Paradoxically, scholars recognize that project teams traditionally rush the front-end to start working on permit applications and fund raising activities (e.g., [42]).

To shed light on this problem, we differentiate internal from external project changes and focus on the latter. Internal

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changes are caused by uncertainties intrinsic to engineering processes, including iterative design loops and work interdependencies [61]. External changes are requested by the client as a result of (un)foreseen events. They are exogenous to the engineering design process and typically are not planned for upfront due to project's size or urgency, inadequate communication, or lack of contingencies [46], [62]. External changes are frequent as clients push projects into the field prematurely and are unable to relate change requests with schedule and cost implications. This inability is in part attributable to the lack of experienced personnel and institutional memory that results from downsizing of in-house design capabilities [16], [24], [38]. Scholars call them 'emerging properties' [27], "strategic surprises" [19], "goal changes" [16], "outside risks" [31], or "initiated changes" [17].

Two major insights emerge from our study. Assuming that the probability of external changes decreases over the duration of concept development (an assumption that is rationalized later in this paper), first, we show that early commitment minimizes the expected average delivery duration but maximizes the expected variability as well as the expected time spent on design rework. Hence, early commitment may be sensible when the client is willing to increase the likelihood (upside risk) of compressing delivery at the expense of increasing the likelihood (downside risks) of overrunning its schedule and budget as well as of design reworking. Second, we show that moderate postponement of the design stage reduces design rework and increases process predictability without increasing the likelihood of overrunning the completion date for concept development in relation to the equivalent likelihood were commitments made earlier. The postponement strategy, long-proven successful in managing new product development and R&D projects (e.g., [8] and [66]), transfers to large engineering design projects where external uncertainties are an important contingency.

The next section relates our work with literature in project management and product design. Section III summarizes the research methods. Section IV describes how we abstracted the empirical findings into conceptual constructs. Section V presents and analyses the simulation results and Section VI discusses research limitations. Finally, we discuss implications to practice and theory in project management.

II. Related Work

Theory development in project management is still in its infancy [46], [59]. Drawing from classical contingency theory [3], [34], [67], project managers are encouraged to classify each project at the planning phase along two dimensions—technological uncertainty and project complexity/size—before making strategic decisions [59]. Scholars have articulated three project management strategies: instructionism (prespecification of action), trial-and-error learning (capacity to replan), and selectionism (pursuit of multiple solutions [37], [46], [62]. Learning and selectionism fit better when future events cannot be anticipated and their effects are difficult to evaluate because too many variables interact. Otherwise, instructionism (which includes activity networks and decision trees) can be adopted. More research is needed, however, about how contingent factors, such as urgency and history, influence how to best combine these strategies [46].

Theory applied to the management of new product development projects is more mature. In this domain, sources of uncertainty are both internal (e.g., lack of interteam communication, inadequate understanding of work interdependencies, and late discovery of design errors) and external (e.g., incorrect assumptions about market conditions, customer needs, and available technology) [32]. Effective product development teams postpone design decisions until uncertainties get resolved (e.g., [8], [29], [64], and [66]). Similar conclusions have been reached for effective R&D project teams (e.g, [28]).

In contrast, we know little about the use of design postponement to manage large engineering design projects. Such projects exhibit a high degree of complexity and uncertainty due to urgency, lack of information, unpredictable changes introduced by clients, users, and regulators, a large quantity of engineered-to-order components and subsystems, and a high degree of technological novelty [27], [48]. They also experience a high degree of ambiguity, or as Clegg *et al.* [9] point out: "governmentality projects premised on stakeholder conceptions are particularly susceptible to discrepancies between ambition and outcome."

The escalation literature uses organizational behavior theory to explain what went wrong on large projects and which actions compounded losses. It recommends that administrators make more explicit the economic costs of persistent changes, and decouple the project from its constituencies [53]. Other studies are more prescriptive. Some formulate lists of "critical success factors" to guide strategic and tactical project decisions [47] and develop techniques such as risk management and scenario-planning to help identify and quantify the likelihoods of possible but uncertain events and to develop contingent actions to counter impacts [10], [11]. Others develop techniques to measure and manage the level of project scope definition [51] and formulate contractual arrangements between the client and contractors to shape the behavior of the parties and contribute to project success [14].

Prescriptive techniques without a strategic framework do not suffice, however, to help large project teams cope with uncertainties. Scholars accept the inevitability of unplanned external changes and recommend that projects be developed in self-standing modules so that parts remain viable while the whole may change [42]. Others encourage project organizations to develop capabilities to reduce external uncertainty. Pitsis *et al.* [48], for example, show the value of frequent meetings involving project managers and clients' administrators which allow for discussing how to accomplish a project's future when "planning is almost impossible" [48]. Likewise, rapid preprototyping techniques allow for minimizing conflicts and growth in unplanned functionalities when end-users are involved early in large software projects [13]. Our study adds to this stream of work with insights on the value of postponement to manage the delivery of large engineering design projects.

III. Research Methods

Our research approach involved two steps. First, we carried out in-depth field research on projects to conceptualize and design semiconductor fabrication facilities ("fabs") to better understand the problem. Fab projects are medium high-tech systems, i.e., projects that involve a limited amount of new/untested technology but multiple development cycles until separate units are integrated into one working piece [58].[1] A fab project budget (including design, construction, and tooling) can reach up to $3 USD billion (2002 prices). At the time of this research, the industry was seeking solutions to deliver fabs in less than 16 mo (time elapsed from groundbreaking start to first full loop of wafers out) [56]. Despite clients' urgency to complete fab projects, they typically requested multiple changes in design requirements over the duration of concept development to accommodate unplanned modifications in chip technology, in regulation, and in the market demand for chips.

Our empirical findings illustrate the problem. In one high-volume manufacturing fab project, for example, the client rushed conceptualization to move quickly into design because it wanted to reach the market before competitors, yet research and development on the chip technology was still on-going: four major external changes—including two end-user requested changes, a building expansion, and a release of a new tool layout—caused 10 000 design rework hours. In a second example, the client's forecast for chip demand changed significantly in mid-course of project execution. The fab design solution was reworked to increase capacity by 30%. This was done by converting an adjacent infrastructure into fab space. In a final example, a fab was first designed to process 200-mm wafer technology.[2] The design solution was reworked a few times because the client later decided to use 300–mm wafer technology, which requires higher input loads and disproportionally more space for locating equipment.

Second, we abstracted our findings into a simulation model that integrates empirically-developed constructs of the project concept development process and uncertainty. Our "middle-range" model fits between high-range system dynamic models [63] and micro-operational simulations of project teams (e.g., Levitt *et al.*'s [35] Virtual Design Team). It simulates alternative processes for gaining insight into which strategies best suit particular goals and into what the corresponding tradeoffs are, similar to other organizational engineering models [5]. These models are based on and encode real-world organizational data and must be realistic to be relevant, yet the modeling purpose has priority over closeness to reality [4]. Technically, the model resembles a Graphical Evaluation and Review Technique (GERT)-simulation of an activity network with feedback loops [50].

Third, we compare the tradeoffs between the observed early commitment strategy and hypothetical postponement strategies in conditions of asymmetric external uncertainties, by measuring the concept development duration and the resources spent in design. We perform sensitivity analyses on the length of the postponement lag, on the duration of the tasks, and on the design reuse capabilities. The simulation results show that an analysis of mean values and variances yields understanding of system performance that would be hard to unveil through an analysis restricted to mean values alone.

IV. FIELD RESEARCH AND CONSTRUCTS

We carried out field-research in collaboration with a leading engineering firm specializing in high-tech facilities and, independently, with a large semiconductor manufacturer. The first author conducted field research over a 30-mo period, including three one-week industrial stays and two summer internships, one at the engineering firm's main office and the other at a fab project site. During the internships, he worked as project assistant to design and project managers who acted as 'key informants.' Simultaneously, he pursued contacts with client representatives. Empirical data was triangulated by method to cross validate the findings [30]. The first author conducted 52 semistructured interviews, each approximately 1 h to 2 h long, with 22 lead designers and design/construction/project managers and 10 client representatives.[3] He used an interview protocol to ask practitioners about the critical design decisions, the patterns of client-requested changes, and the impacts of these changes. Interviewees were selected by using intensity sampling, i.e., sampling of a selection of experts and authorities about a particular experience [43, p. 228]. All interviews were tape recorded, except a few made over the phone, and the recordings were transcribed. For several ongoing projects, the first author attended project meetings, collated clippings from professional publications and press releases, and examined archival data, including proposals, meeting minutes, electronic schedules, and one digital log of client-requested design changes. He ethnographically gathered further data during the internships [68]: he observed project participants in their work routines, shadowed lead designers and managers, had spontaneous conversations, and cultivated relationships with workers.

A. Problem Illustration

Field research helped to illustrate the research problem. Client representatives of fab projects state the criticality of committing early in concept development to accelerate funding request and planning approval processes: "We cannot wait [to start design] until we have full funding because then it will be too late. We need a Capital Project Approval [CPA] as soon as possible which allows for finding funding, procuring long-lead items, starting mobilization and preliminary design" (Facilities Director 2000). They also acknowledge the risks involved in premature design decision-making: "We have to take risks all the time at the speed we are going" (Director Technology Development 2000). Designers corroborate these observations: "Everything is going so fast that the decisions are made and we just live by it... more meetings with the client means more changes and not [being] able to make it faster" (Chemical Design Lead 2001).

Client representatives recognize that the project definition is prone to changes: "We have an appetite for change... we can

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[1] Other projects in this category include the development and installation of a military information system, and the upgrade and improvement of an aircraft [58].

[2] Wafers are discs of (usually) silicon, on which the semiconductors are etched; wafers are then sliced into chips. The 300 mm diameter wafer doubles the silicon surface area per wafer relative to 200 mm wafers. A transition from 300 mm to 450 mm wafers is foreseen around 2015–2020.

[3] Most interviewees had worked for other engineering firms and/or clients prior to being interviewed. This largely makes empirical findings representative of current practices in the sector, rather than representing only the interviewees' current employer.

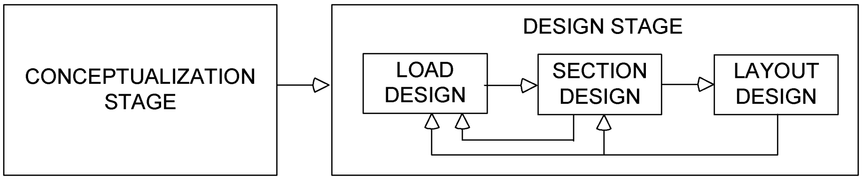

Fig. 1. Conceptual representation of the project concept development process.

tolerate some degree of change and we expect it" (Facilities Director 2001). Clients attribute changes to events outside of their control, such as to variability in technology: "it is difficult to control our equipment suppliers; tool parameters will always remain unpredictable, you cannot control that variability… our tool layouts can change up to the last minute" (Program Manager 2000). Changes are perceived to be inevitable by designers: "our clients wants us to design for what they know and modify it later" (Mechanical Lead Designer 2000), or as put by another lead: "every time we start a new fab it seems a major change always comes after the steel package is out for bid" (Structural Design Lead 2000). The multiple design rework cycles leave designers often frustrated and resigned: "I do not want to alienate the client; at some point I decide the client is right—although I've done more fabs than the client, my opinion does not count" (Chemical Lead Designer 2001).

B. Project Concept Development Construct[4]

During field research, we applied cross-case comparative analysis [39] to represent the project concept development process. This was an iterative effort involving three tasks: first, we conducted interviews and studied archival documents to collect data on the concept development tasks and decisions; second, we collated the information into conceptual categories interconnected graphically in a process map; and third, we tested the robustness and the generalizability of the process map by instantiating it separately with data for five major specialties in fab design.

We represent the concept development process as a two-stage model: conceptualization and design (Fig. 1). In conceptualization, the design team uses empirical rules and historical data to translate the client requirements' brief into a technical concept that includes models, drawings, and specifications, as well as order-of-magnitude estimates for the project cost and duration. Design encompasses three main tasks: load, section, and layout design. First, designers calculate the loads that the fab systems should support. They then use these loads and computer models to size the critical systems' cross sections. Finally, they use the cross section sizes to route the utility systems and to locate major pieces of equipment. Even when design criteria are stable, these three design tasks form work loops that designers iterate multiple times in their search for a satisfying solution within the timeframe agreed upon with the client [60].

C. External Changes Construct

Jointly with senior designers, we modeled possible sequences of major external changes over the duration of concept development for a fab, and numerically characterized the model's probabilities for the case of technology development (TD) fabs for leading-edge microprocessors and application specific integrated circuits (ASICS). A major external change means that the client deems its implementation so fundamental that the decision to request the change is independent from the degree of progress accomplished in concept development. These unplanned changes occur sporadically. The Asian financial crisis of 1997, for example, slowed down international demand for chips, decimated the semiconductor industry plans for rolling on the 300-mm wafer fabs in 1998, and caused major changes in on-going design projects regardless of how far ahead they were. In late 1999, manufacturers foresaw a recovery and announced the reactivation of their 300-mm wafer fab projects. Project designs were again reshaped when another downturn left chipmakers with too much capacity in 2001. The following two educated assumptions underpin our conceptual construct.

1) There are two types of major external changes: 1) Full changes, which cause the design team to repeat both the conceptualization and design stages; 2) Partial changes, which affect work done during the design stage but have less impact on the conceptualization work.
2) The occurrence of a first change of a particular type allows for a second change of the same type with lower probability. In turn, the occurrence of a second change allows for a third change of that type with even lower probability, and so on. Lead designers interpret an early change as a signal that more changes are likely to follow. In contrast, they deem unlikely a very late first, full or partial, change.

To model the variability around the time when changes occur, we use re-scaled and shifted beta distributions $[\mathrm{a} + (\mathrm{b} - \mathrm{a}) * \mathrm{Beta}(\alpha_1, \alpha_2)]$. We employed the beta distribution—a parameter input distribution—because the richness of shapes that it can take was needed to align the mathematical modelling with practitioners' beliefs. This flexibility is frequently exploited in simulation studies where a subjective approach to fit a distribution is needed because hard data is absent [33, p. 309]. A set of interviews allowed us to quantify the parameters in the beta distributions (using Perry and Greig's [45] formulae for estimating the mean and variance of subjective distributions), as well as to estimate the parametric relationships between changes of the same type parameters. A geometric decay rate suitably matched the decay between the probabilities of successive changes of the same type; and a geometric increase rate matched the increase in the time lag variability between changes of the same type.

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[4] Readers interested in the cross-case display for five design specialties (chemical, mechanical, architectural, structural, and electrical) can consult the technical appendix, which can be obtained upon request from the first author or downloaded from http://www.personal.mbs.ac.uk/ngil/.

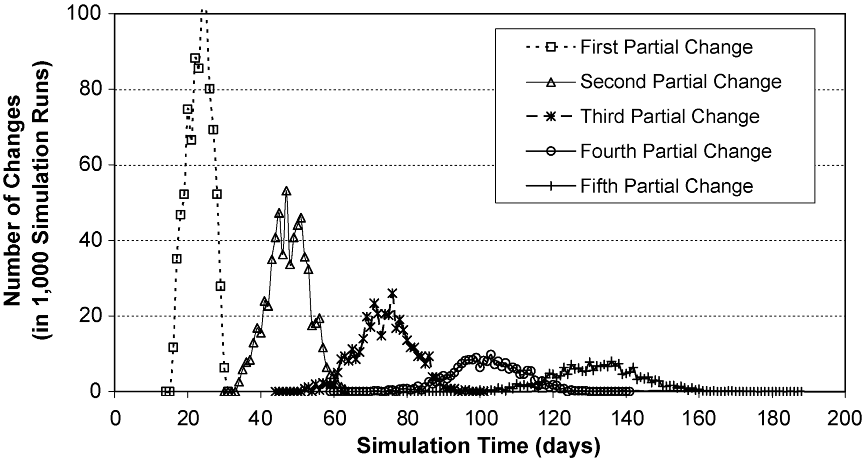

Fig. 2. Simulated histograms of partial changes in a TD fab project's life.

TABLE I
INSTANCES OF PARAMETERS USED FOR MODELS OF TD FABS

	Definition	Full Change (t=1)	Partial Change (t=2)
$P_{1,t}$	Probability of a first change of type t	0.5	0.9
r_t	Rate parameter for decaying probability of a change [varied between 0 and 1]	0.5	0.25
d_t	Rate parameter for increasing time variability between successive changes [varied between 0 and 1]	0.5	0.25
μ_t, σ_t	means and standard deviations for time delays before occurrence of first change [days]	20	15

Jointly with practitioners, we subsequently analyzed the simulated histograms of design changes, illustrated in Fig. 2, to ascertain that the rationale and assumptions were consistent with their beliefs.

Let $\mathrm{P}_{1,\mathrm{t}}$ denote the probably of a first design change of type t. The conditional probabilities of successive changes of the same type were modeled as geometrically decaying with a rate $\mathrm{r_t}$

$$\begin{aligned}\mathrm{P}(_{\mathrm{i,t}}|_{\mathrm{i-1,t}}) &= P\{i\text{th change of type } t|(i-1)\text{thchange of type } t\}\\ &= \frac{\mathrm{P}_{1,\mathrm{t}}}{1+\mathrm{r_t}.(\mathrm{i}-1)}, \qquad \mathrm{i}\geq 2\end{aligned}$$

The times of the successive change occurrences were modelled as a sum of increasing Beta distributions with the time of the first change of type t being at $\mathrm{T}_{1,\mathrm{t}} = \mu_{\mathrm{t}} + \sigma_{\mathrm{t}}.\beta_1(\alpha_{\mathrm{t}1}, \alpha_{\mathrm{t}2})$ and the times of subsequent changes being

$$\begin{aligned}\mathrm{T}(_{\mathrm{i+1,t}}) = \mathrm{i}.\mu_{\mathrm{t}} + \sigma_t \sum_{s=1}^{i} \beta_s(\alpha_{t1}, \alpha_{t2})\\ *(1 + d_t(s-1)), \qquad \mathrm{i}\geq 1 \quad [\text{days}].\end{aligned}$$

Fig. 2 shows an example of the probability of partial changes. Clients are circumspect to instruct major changes to the design team because they are conscious that changes deteriorate delivery performance; as the concept development unfolds, more demand is increasingly put on decision-makers to write down the reasons for the change ("white papers") before administrators decide whether to instruct the change, which explains the geometric decay rate in the conditional probabilities of successive changes. The clients' circumspection also gets reflected in the proportional increase in the time lag variability between changes, as well as in the use of similar parameters for the rates $\mathrm{r_t}$ and $\mathrm{d_t}$ (Table I).

V. SIMULATION EXPERIMENTS[5]

Event-scheduling models simulate a system 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" [33, p. 205]. Event-scheduling simulation captures both the flows of transient entities as well as the operating cycles of resident entities [55]. Table II shows how the low-level simulation constructs served the modelling purposes.

The event-graph model in Fig. 3 represents the project concept development process. Different shapes represent classes of events: circles express experiment control points, rectangles express the start and end of tasks, and diamonds express the major external changes. Directed edges represent relationships between the events they connect. Associated with edges may be a set of Boolean expressions. A solid edge means that the event from which the edge emanates schedules the event to which the edge points, after a time delay $(\Delta\mathrm{t} \geq 0)$, if the edge conditions

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[5] A model running version, a version in commented C source code, and a model translation to English can be obtained from the first author upon request or downloaded from http://www.personal.mbs.ac.uk/ngil/.

TABLE II
PURPOSES OF THE SIMULATION CONSTRUCTS

Simulation Construct	Purpose
Events	Express the start- and end-points of tasks and external changes
Event Scheduling Edges	Model information flows that schedule events
Event Cancelling Edges	Model information flows that pre-empt events
Boolean Expressions	Model the contingencies that affect relationships between events

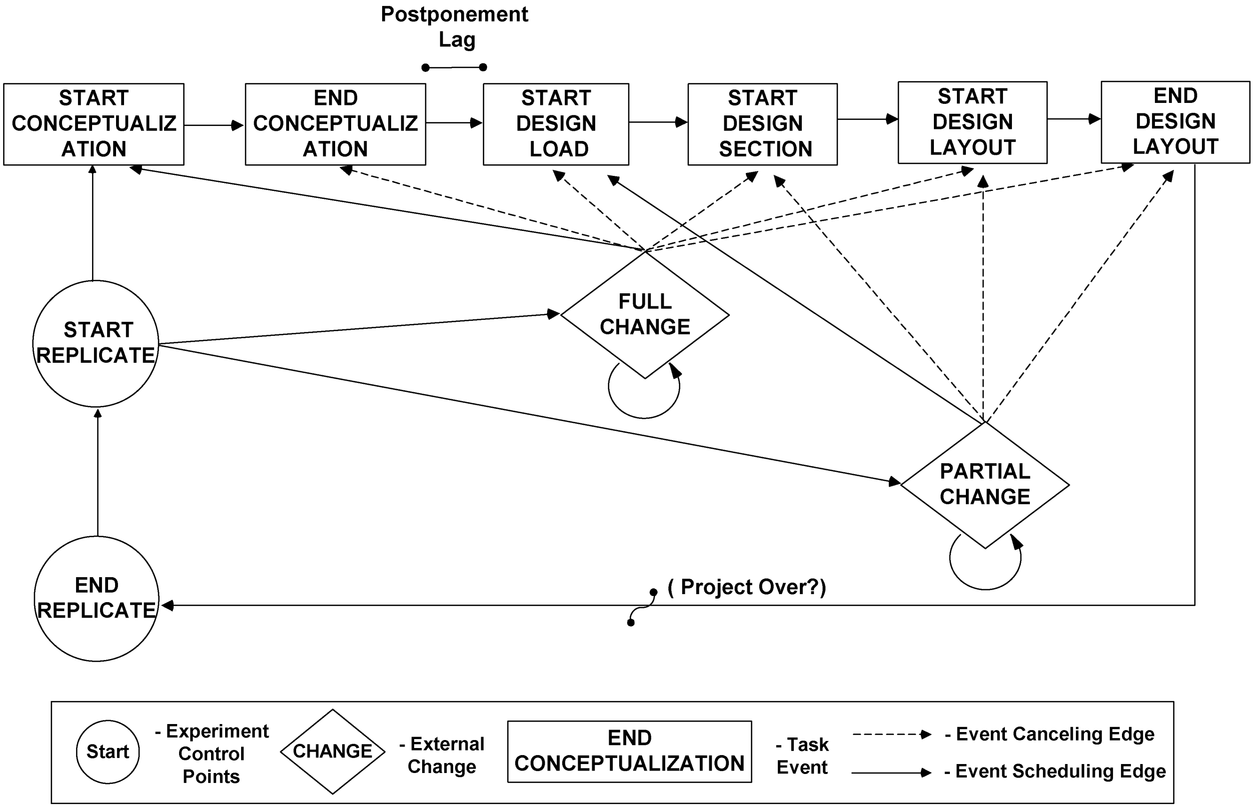

Fig. 3. Event graph model for the project concept development process.

are met. A dashed edge means that the origin event cancels the destination event, after a time delay $(\Delta t \geq 0)$, if the latter is scheduled and the edge conditions are met. A convenient feature of an event graph model is that the system dynamics can usually be described completely using a single sentence for each edge in the graph. Using italics to denote events, the logic for the event graph model in Fig. 3 is as follows:

The simulation experiment starts with the *start replicate* event, which schedules the *start conceptualization* event which, in turn, schedules a subsequent event after an appropriate time delay unless interrupted by a change. The *start replicate* event also schedules, with some probability, the first *full change* and the first *partial change* events, each after a stochastic delay. When a change event occurs, it may stochastically schedule a subsequent change event of the same type. The *start design load* event may take place immediately after the *end conceptualization* event or a strategic decision may be made to postpone it. 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 events related to design and schedules a new *start design load* event. Once concept development is completed and the simulation time exceeds a specified milestone, the *end replicate* event is scheduled and a new replication starts if called for in the experiment.

The model assumes that design teams consider all changes that occur before a specified milestone, whether the design stage is completed at the time the change occurs or not. Changes occurring after that milestone, however, are ignored. This milestone is a decision variable that we purposely set far into the future to model a realistic situation that considers most major external changes. The reader is requested to see the Appendix for a discussion of the major computational assumptions.

A. *Making Design Postponement Strategies Operational*

To implement a design postponement strategy is a users' choice in the simulation, and means simply to postpone the start of the design stage. To make postponement operational, we lock in the earliest day to *start design load* at different points. We hypothesized that, by postponing the *start design load* event, we would maximize the probability of the design team developing design in a single pass and reduce the concept development duration. To develop a sense for how the various factors interact, we perform sensitivity analyses: 2) on the duration of the postponement lag; 2) on the duration of the conceptualization and design stages; 3) on the design team's capability to reuse design work after a major external change.

B. Performance Metrics

We apply three performance metrics to understand the effects of postponing design:

1) *Concept Development Duration:* 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.
2) *Resources Spent in Design:* Workdays spent executing design tasks.
3) *Number of Repetitions of Task Events:* Number of times each design task event is repeated.

The values of the first two metrics matter because, first, a client's major concern is to compress the project concept development duration, and second, skilled designers are a scarce resource. The third metric provides a key measure of the rework that designers have to do.

C. Simulation Results

Fig. 4(a) illustrates 3 strategies for an extreme scenario without external uncertainty: 1) no postponement; 2) design is postponed moderately; 3) design is postponed to extremely late. The shape of the curves reflects the assumed mean durations of the tasks, which we discuss in Appendix. Later, we perform sensitivity analysis on the numerical estimates. If there were no changes, the tasks would progress sequentially and each one would be executed once. In this case, a postponement lag would equally delay the completion of concept development.

Fig. 4(b) illustrates a single simulation run in a scenario with uncertainty. Three changes occur: the first interrupts section design and the second interrupts layout design—these are full changes because in both cases conceptualization restarts; the third change occurs when concept development is done—this is a partial change because the process restarts from design load. Fig. 4(c) illustrates the results of 50 simulation runs based on Fig. 4(b)'s scenario, and Fig. 4(d) illustrates the results of a scenario similar to Fig. 4(b) but with a moderate postponement lag. Fig. 4(e) and (f) replicates the scenarios in Fig. 4(c) and (d), but for a situation with reuse of design work.

D. Sensitivity Analysis on the Postponement Lag

Fig. 5 charts the relationship between concept development duration and number of resources spent in design as the postponement lag increases, assuming the design team does not reuse design work. The no-postponement scenario assumes that the design team *starts design load* immediately after *end*[ing] *conceptualization*. This means that it *starts design load* on whatever day *conceptualization* ends. The other extreme scenario assumes that the design team postpones *start design load* to extremely late (day 110). This corresponds to postponing design for approximately 85 days after *end*[ing] *conceptualization*. We tested several postponement lags in-between the extremes using 5-days increments.

The mean and standard deviation of each data point in the chart were calculated with their unbiased estimators using the results of 1000 independent, identically distributed simulation runs, which assumes these observations are approximately distributed as normal random variables. This assumption reflects the central limit theorem which 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 [33, p. 248].

Fig. 5 illustrates that, as the postponement lag increases from a no-postponement to moderate postponement, the marginal reduction in the average resources spent is large while the marginal increase in the average concept development duration is small. As the postponement lag increases beyond a moderate lag, the marginal reduction in the average resources spent is less significant while the marginal increase in the average concept development duration tends to equal the marginal increase in the postponement lag.

Fig. 5 also shows that the variability in concept development duration decreases as the postponement lag grows. Thus, the one-standard deviation upper limit of the concept development duration $(\mu_{\mathrm{t}} + \sigma_{\mathrm{t}})$ remains more-or-less steady for moderate postponement lags (up to 30 to 40 days in the numerical conditions as shown). Up to a moderate 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 increases further, the marginal increase in the mean concept development duration gets more significant and the marginal decrease in its variability no longer prevents the increase of the upper limit $(\mu_{\mathrm{t}} + \sigma_{\mathrm{t}})$.

Furthermore, Fig. 5 shows the variability in resources spent during design. Postponement decreases the average and the variability of resources spent in design because design tasks require less repetition. The square area in the middle of the figure includes a set of "efficient" postponement strategies that best satisfy two conditions simultaneously: 1) minimize the average resources spent during design (μ_{r}) and their variability (σ_{r}); 2) do not increase the upper one-standard deviation limit of the concept development duration $(\mu_{\mathrm{t}} + \sigma_{\mathrm{t}})$ beyond the value that $\mu_{\mathrm{t}} + \sigma_{\mathrm{t}}$ assumes with no postponement.

For the same numerical assumptions, Fig. 6 shows the variation in the probability of restarting design X times, measured by the distribution frequency of start design load events in each experiment. When early commitment is employed (value 0 on the ordinal axis), the probability of executing design once (no restarts) is approximately equal to the probability of restarting the design one, two, three, or more times; that is, early commitment has about a 20% chance of being appropriate. This agrees with empirical evidence describing the difficulties encountered by large design teams to meet planned durations and budgets when they adopt an early commitment strategy (e.g., [42]). In contrast, when moderate design postponement is employed (≈35 days on the ordinal axis), the project has a 50% chance of not requiring design restarts, and an almost 0% probability of exceeding two design restarts.

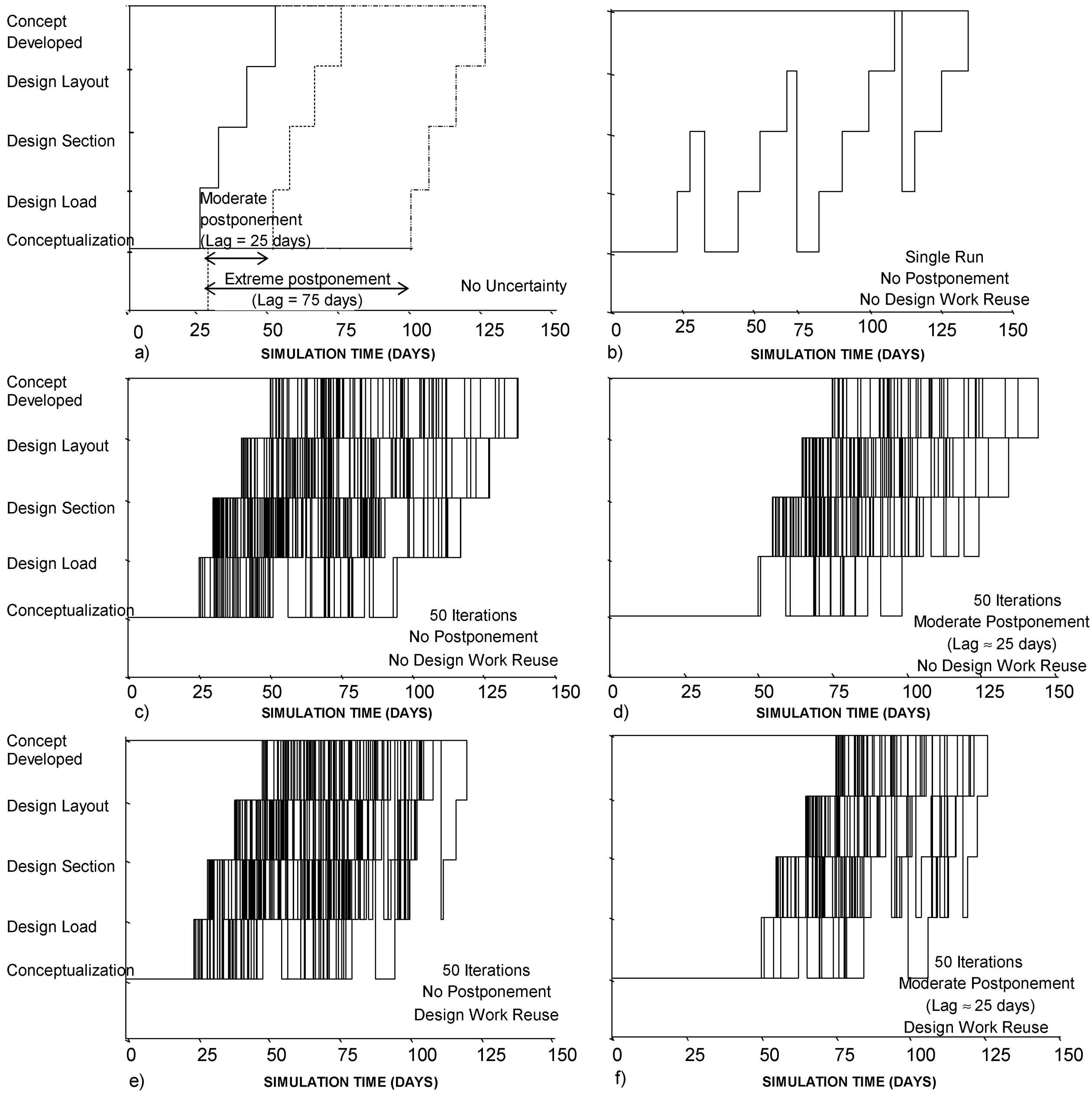

Fig. 4. Simulation outputs of progression in concept development versus simulation time: (a) three runs without uncertainty; (b) one run with uncertainty and no work reuse; (c) and (d) 50 runs with uncertainty and no work reuse (without and with postponement); (e) and (f) 50 runs with uncertainty and work reuse (without and with postponement).

E. Sensitivity Analysis on Task Durations

Fig. 7 illustrates the results of simulation experiments with different numerical assumptions for the task durations. Assuming the stochastic pattern of the changes remains unchanged, a shorter duration for conceptualization results in more changes falling during design unless design is postponed, thereby corresponding to a much steeper curve and a longer "efficient" lag [Fig. 7(a)]. In contrast, more time spent on conceptualization shields design from changes in a way similar to what postponement accomplishes, resulting in a less steep curve and a shorter 'efficient' postponement lag. This latter situation may, however, not be viable because clients often rush conceptualization as they need to use its output for securing funding, obtaining regulatory approvals, and procuring specialized equipment, processes that involve lengthy negotiations [42].

A variation of the design duration does not shift the "efficient" lag since the number of changes falling in each postponement lag remains the same; this variation also does not change the number of design restarts if we assume the same duration for the conceptualization (Fig. 8). However, a variation in design duration alters the impact that postponement has on system performance. When the design cycle is longer, more resources can be spared by postponing design. Further, the number of average changes falling after concept development decreases to zero with longer design tasks, reflecting the characteristics of the mathematical pattern of changes which assumes stochastic

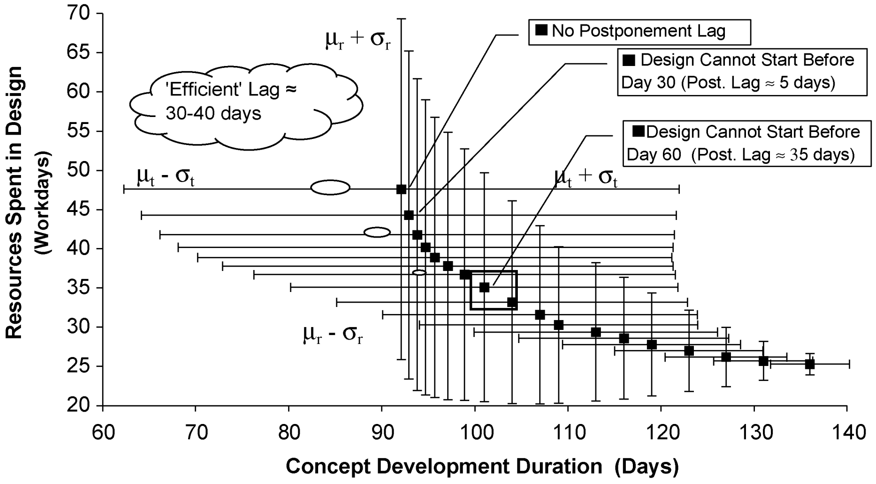

Fig. 5. Concept development duration versus resources spent in design for alternative postponement lags (1000 runs for each data point) (no reuse of design work).

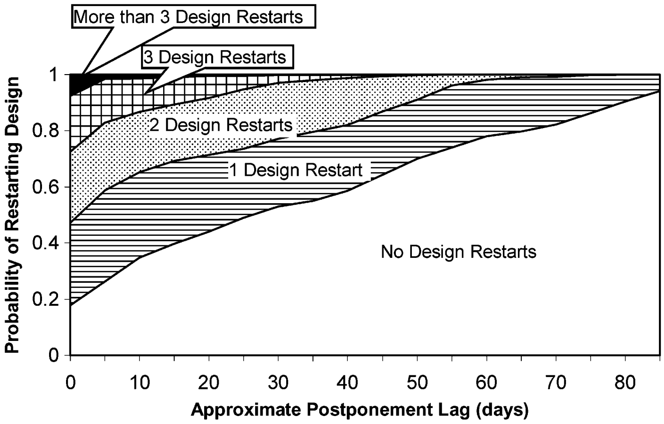

Fig. 6. Probability of restarting design X times for alternative postponement lags.

changes, independent from concept development work, occurring around time-dependent means with decreasing probability.

F. Sensitivity Analysis on the Capability to Reuse Work

Fig. 9 compares two scenarios: the extreme no-work-reuse scenario (illustrated in Fig. 5) with a work-reuse scenario, using the computational assumption described in Appendix. The graph illustrates that postponement is more effective when there is no ability to reuse design work. This is easy to understand: when the length of the rework loop increases (the rework cycle is the longest if there is no work reuse), design teams are better off postponing design. Fig. 9 also shows that the "efficient" lag shortens if work reuse is assumed. With a shorter rework cycle, the savings in process variability that are achieved as the postponement lag increases quickly fail to counterbalance the increase in the expected average of the concept development duration. In the unrealistic extreme, postponement would be useless if design practices were so robust that even major changes would cause negligible rework. Hence, the more clients underestimate the length of design rework cycles in conditions of external uncertainty, the higher will be the risks associated with early commitment.

VI. LIMITATIONS AND OUTLOOK

Our simulation experiments were kept simple on purpose so we could trace the results, as well as make sure the number of estimated parameters related to the data available. Discussions and workshops we held with our interviewees confirmed that the results agree with their views of the world. These discussions also highlighted a few limitations of this study that suggest directions for future research.

First, the model represents the concept development process without showing that many development processes, one for each design specialty, unfold at the same time but not at the same pace. This limitation precludes the model from generating insights on cascading effects when the impacts of an external change ripple through multiple design specialties [17]. It also remains indeterminate how postponing the design for one specialty impacts the work of other specialties.

Second, the model represents engineering design work without expressing dependencies with implementation work, such as off-site manufacturing and on-site construction. Large engineering projects exhibit however increasing degrees of overlap between the two phases as clients strive to compress the projects (e.g., [20]). We observed, for example, the start of excavation works on-site about two weeks after the start of the design in some fab projects. Likewise, design and coding

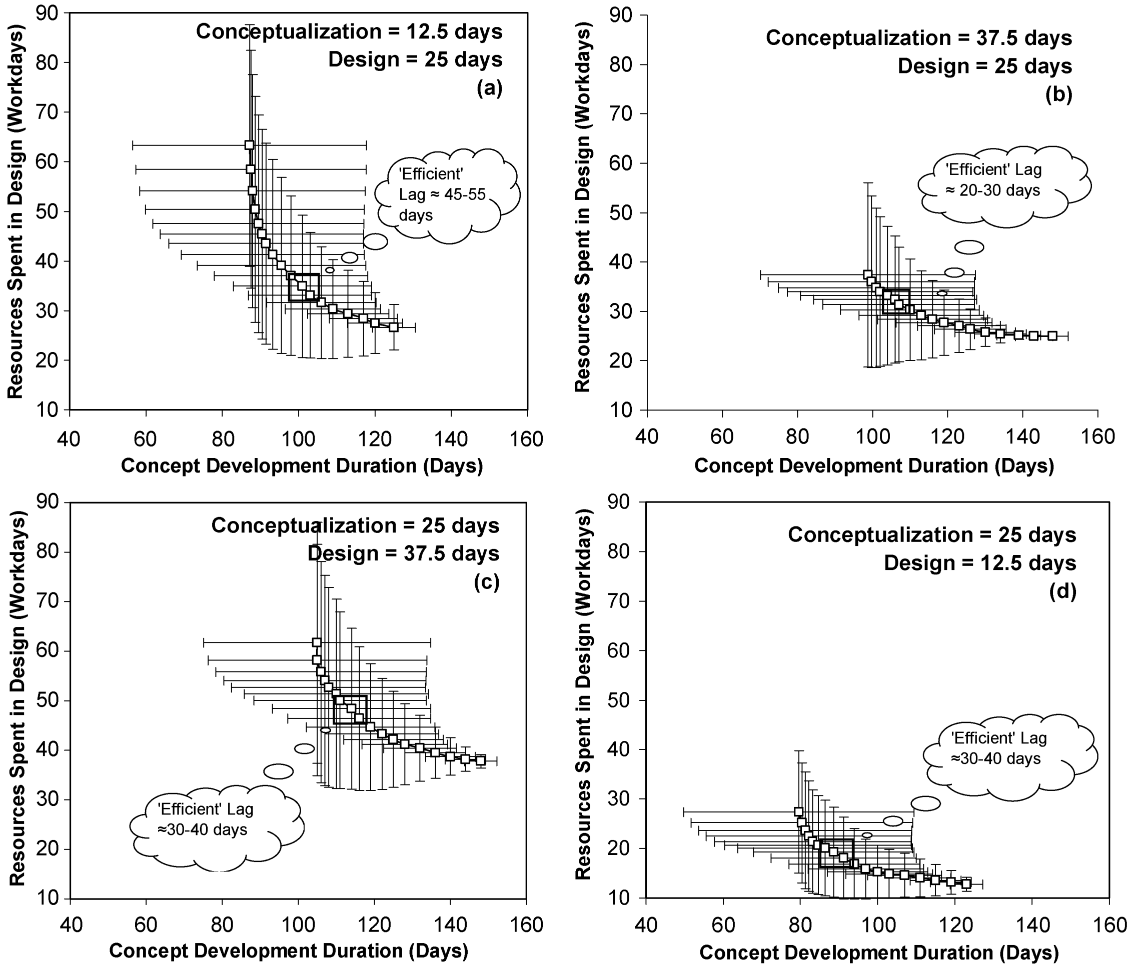

Fig. 7. Concept development duration versus resources spent in design for different numerical assumptions on the postponement lag and task durations (1000 runs per data point).

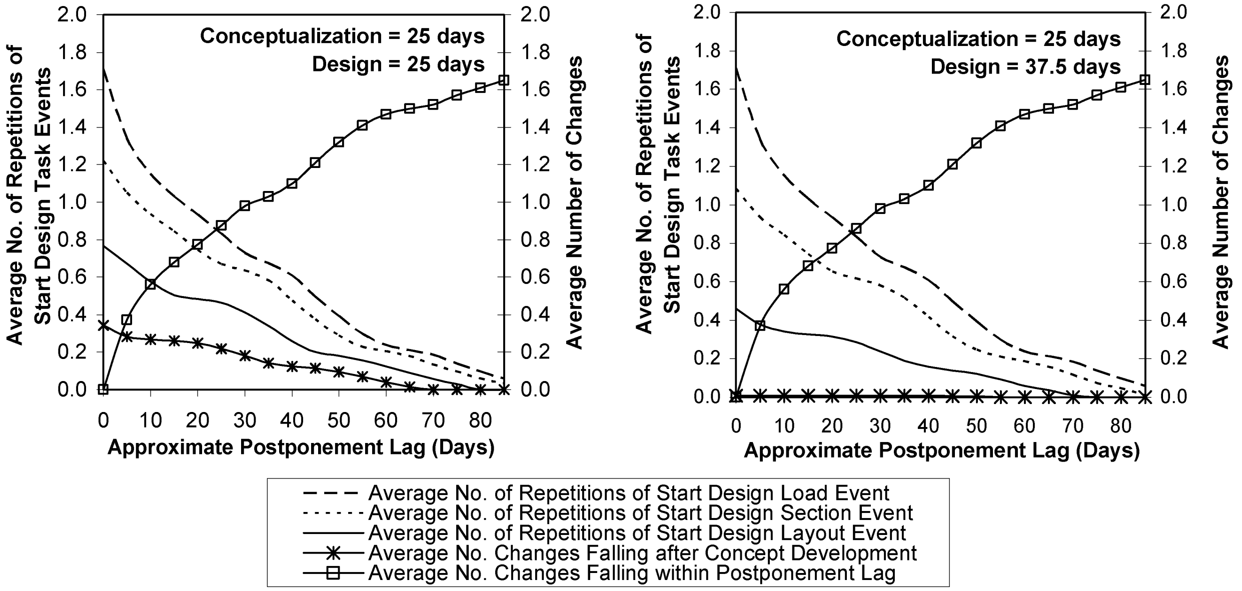

Fig. 8. Variation of the means of repetitions of start design task events and change occurrences for alternative postponement lags (1000 runs per data point).

phases commonly overlap in large software projects [13], [31]. It matters to investigate how design postponement plays against various degrees of concurrency between design and implementation.

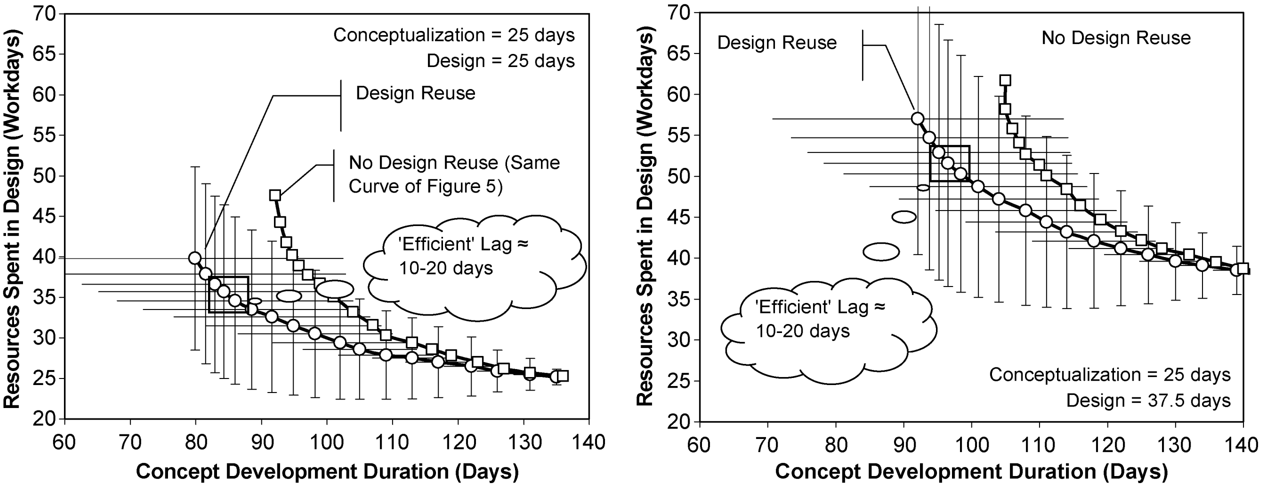

Fig. 9. Concept development duration versus resources spent in design, for different rework algorithms and numerical assumptions on the postponement lag and task durations (1000 runs for each data point).

Third, the simulation cannot reproduce design team's practice of over-engineering selected features in the design solution. While clients agree that developing an over-engineered solution can be an effective strategy to accommodate unplanned changes [25], they often contradict themselves by stating that they cannot afford to do so because it costs too much money upfront. Future research should examine this tradeoff.

Another concern involves taking the individual design project as the unit for probabilistic analysis. Difficulties in allocating resources—a factor not modeled—can impede the implementation of postponement. Design managers expressed concern that if they let skilled designers get involved with another project during a postponement lag, they would have difficulty getting their design teams back together later (e.g., see Repenning 2001 for the effects of fire-fighting in a multi-project environment). We include no provision to represent this possibility. Instead, our model assumes sufficient capacity in the system to move resources as required. As we show, postponement allows for reducing the overall number of resources and, thus, frees up capacity in the organization that employs those resources, thereby creating more flexibility in allocating them. It remains nevertheless indeterminate how situations of design resource scarcity influence the appropriateness of postponement in conditions of external uncertainty and urgency.

Our simulation uses a stochastic pattern of major foreseen external changes as input. Changes occur sporadically in the project's life with declining probability and are implemented even if design is far developed. It is uncertain, for example, how the results would be affected if the model accounted for smaller changes requested by clients and end-users. While smaller external changes are perceived as less critical and their execution may be conditional upon the state to which the design work has progressed, they downgrade process performance if they happen in very large numbers (e.g., [27], [52], and [54]).[6] Likewise, the model excludes client-requested changes associated with turn-over in client administrators. Studies show that priorities and strategies as well as project budgets/contingencies are likely to change when players change, especially in large engineering projects commissioned by public organizations and on a smaller scale by private organizations (e.g., [41] and [42]). These limitations could not be overcome because reliable stochastic inputs were not available, except for the one we developed empirically. They limit however the interpretation and generalizability of the results. We recommend replicating this study into other project contexts—which involves understanding what stochastic inputs need to be integrated with similarly or more complex process constructs.

VII. IMPLICATIONS TO PROJECT MANAGEMENT PRACTICE AND THEORY

Our front-end question asked: Why do clients of large engineering projects opt for an early commitment strategy when they deem inevitable major design changes once (un)foreseen external uncertainties get resolved? Our simulation model suggests that a client's decision to postpone design hinges on a combination of four factors: 1) client's urgency to complete concept development; 2) client's ability to foresee the timing and likelihood of externalities; 3) client's willingness to accept rework risk; 4) the design team's ability to reuse design work. Our simulation experiments show that when clients opt for early commitment in conditions of high external uncertainty, they increase the upside risk of reducing the concept development duration at the expense of increasing the downside risk of design reworking if external events unfold, i.e., they opt for a strategic learning approach [46]. Our study shows, however, that clients bear a high design rework risk when doing so unless they improve their ability to plan for foreseen uncertainties and to judiciously instruct changes to the design team, especially if design reuse capabilities are low. Moderate design postponement emerged as a viable option—provided that clients accept to relinquish some of the upside risks of early commitment—because it reduces the average amount of expected design rework without increasing the risk of overrunning the concept development schedule and budget in relation to the equivalent risk were

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[6] Practitioners often term this phenomena "death by a thousand cats."

commitments made earlier. This tradeoff ought to underpin efforts to operationalize postponement in large engineering design projects.

To rationalize the decision of committing early versus postponing, clients need to develop or rebuild project capabilities, like qualified suppliers do to achieve "economies of repetition" [12], i.e., establish organizational routines and learning processes to assess upfront the likelihood and timing of foreseen uncertainties and to assess the design rework impacts if unplanned events should occur. British Rail Operator's recent decision to take track maintenance projects back in-house after realizing contractors were not coping well with external uncertainty illustrates this point [6]. Likewise, some owners-manufacturers have built up capability to manage supply chains for construction materials in-house, rather than leaving it up to their contractors-suppliers [65]. Clients should also improve the links between business and project processes to enhance interproject learning and their ability to foresee external events. They can learn from the effective use of lateral relations [21], gate keepers [1], and process models [2] to transfer information between project teams in R&D and new product development environments, even if less scope for routinized learning exists in large engineering projects [27], [44]. These recommendations have been spelled out for project contractors and suppliers [22], [49] but hardly so for clients.

There is a contribution to project management theory. We explain observable phenomena in large engineering design projects by factoring in the degree to which client-driven external changes affect the concept development process. External uncertainty does not equate to technical uncertainty or project size. This suggests one additional contingent dimension that may contribute to improve the completeness of work in project management typologies [46], [59] and in project failure [31]. Likewise, project management work, such as in contracts [14] and in project management software [36], should investigate how to improve existing tools so they can cope better with the impacts of external uncertainty.

APPENDIX
COMPUTATIONAL ASSUMPTIONS

The numerical simulation experiments reflect the following computational assumptions:

1) Each task has a deterministic duration. Given the sequential nature of the model, with simple finish-to-start relationships, and the large number of experiments, stochastic task durations do not change the averages of the performance variables (a consequence of the *strong law of large numbers*), although the variability of the performance variables increases somewhat.
2) The design stage is done only once unless a major change occurs to focus the experiments on the effects of external changes. Internal design iteration would result in a longer design process, an implication captured in the numerical sensitivity analysis over stage durations.
3) Resources are available to execute the tasks whether or not design is postponed. In practice, obtaining sufficient resources later on may not be trivial, as we discuss in the limitations and outlook section.
4) Practitioners' beliefs on their capability to reuse work after an external change resembles the logic underlying learning curves, which assumes: 1) the amount of time required to complete a task is proportionally less each time the task is undertaken; 2) this amount of time decreases at a decreasing rate; 3) the reduction in time follows a predictable pattern [7, p. 446]. Because no quantitative data was available on the actual gains achieved by the design team from reusing work, we hypothesized two algorithms: the first assumes the design team cannot reuse design work after a major change; the second aligns experiments with designer's beliefs on their capability to reuse design work if a task was concluded when the change occurred

$$\mathrm{D}_{\mathrm{n}+1} = \frac{(\mathrm{n}+1) * \mathrm{D}_{\mathrm{n}}}{\mathrm{n}+2}, \qquad \forall \mathrm{n}$$

where $\mathrm{D}_{\mathrm{n}+1}$ is the expected design task duration in iteration n+1, given that the task was completely executed n times, if no change interrupts its execution [days].

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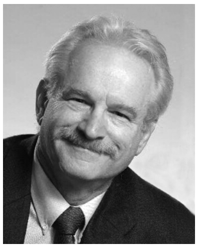

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Prof. Schruben is a fellow of the Institute for Management Science and Operations Research.