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Theoretical comparison of alternative delivery systems for projects in unpredictable environments

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A project delivery process simulation is presented based upon empirical studies in the design-build environment of semiconductor fabrication facilities ('fabs'). The model captures key tasks and decisions in design, procurement and construction, as well as design criteria changes along the delivery of a R&D fab utility system. Simulation shows that to involve the specialty contractor from the project start on average expedites project delivery since it prevents delays caused by bidding and by contractors' unfamiliarity with the design product definition. Yet, in unpredictable project environments – environments in which design criteria are likely to change irrespectively the project progress status – simulation reveals that the averages of construction rework and waste increase if design is prematurely frozen. Assuming that work methods do not change and design criteria remain uncertain, results indicate that a system that combines early contractor involvement with judicious postponement of the design start reduces the average duration of the fab utility delivery in relation to the expected duration if competitive bidding was used, with limited increase in the averages of construction rework and waste. Additional efficiency is gained when specialty contractors relax conservative assumptions on anticipated site conditions. An economic model uses simulation results to assess the tradeoffs between alternative project delivery systems for the case of R&D fabs.

Keywords: Specialty contractor, simulation, change, postponement, facility delivery compression

Introduction

Researchers have long recognized that specialty contractors can contribute to the design-build process, especially if they participate early on in design (e.g. Crichton, 1966; Bennett and Ferry, 1990; Pietroforte, 1997). Specialty contractors – such as mechanical, electrical and piping or plumbing (MEP) contractors – typically install the various building systems. Increasingly, specialty contractors also detail the design and maintain the systems.

Yet, too often is the case that specialty contractors have to bid competitively a set of drawings and specifications to get to participate in the project. Bidding is a time-consuming process that delays the start of shop drawing development, fabrication, and construction activities (Figure 1a). Competitive bidding also causes development of shop drawings to last longer because the awarded contractor needs to get fully acquainted with the design product definition (he may not have done it before since he was not sure he would get the job), write requests for information, and submit shop drawings for approvals.

In contrast, if a specialty contractor participates in programming and from there onwards, the contractor is typically ready to develop shop drawings once design is completed (Figure 1b). The involvement of specialty contractors from the start of programming should not imply, however, that design has to start once programming ends. Changes of design criteria that occur during programming or design but prior to fabrication and construction cost less to implement than those that

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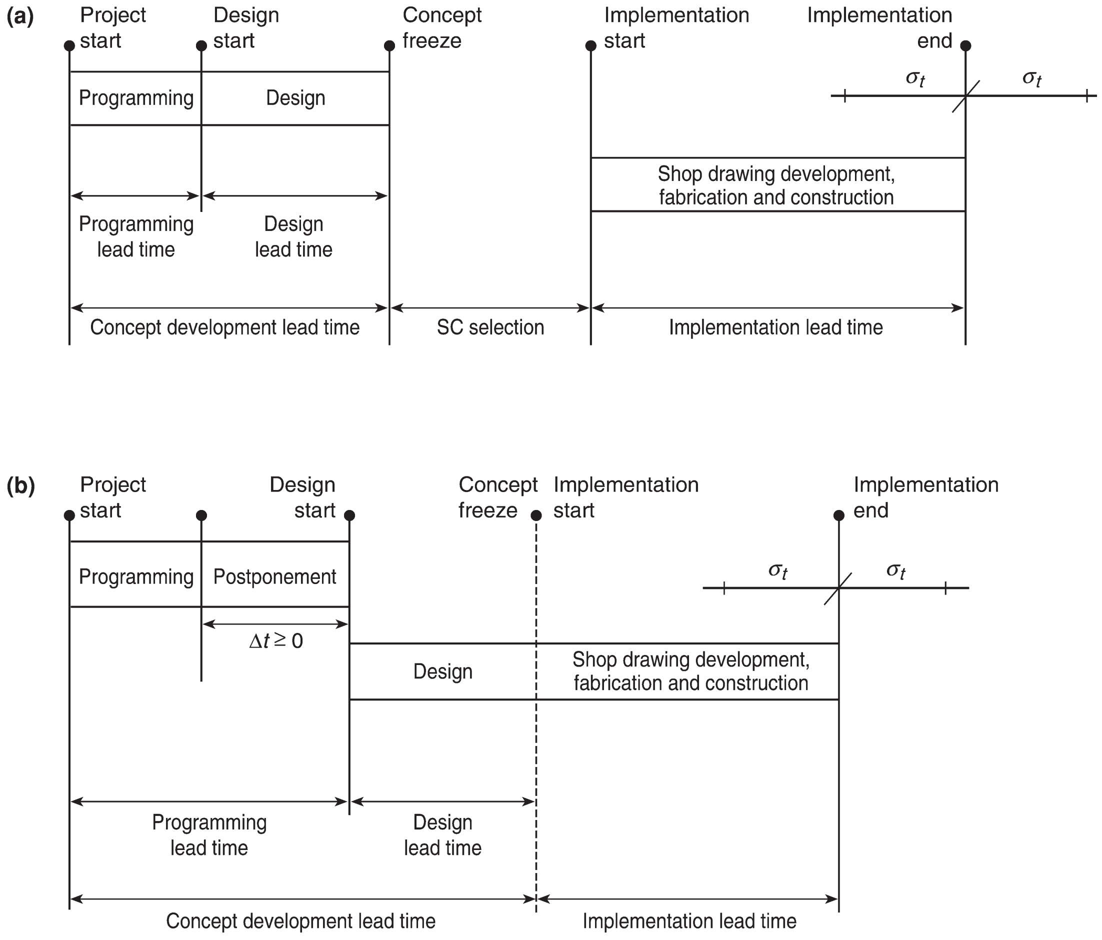

Figure 1 Alternative models of project delivery for one building system (adapted from Iansiti, 1995)

occur when any of the latter two processes is underway because more resources have then been mobilized.

Our empirical research took place in the design-build environment of 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). We found no evidence of practitioners postponing the start of design although fab design criteria invariably remain uncertainty. In contrast, empirical evidence on new product development processes in unpredictable environments shows that effective teams involve suppliers early on and postpone the moment when they freeze the design concept (e.g. Iansiti, 1995; Ward *et al.*, 1995; Thomke and Reinersten, 1998). Assuming that the role of specialty contractors in architecture-engineering-construction (AEC) projects is largely equivalent to the role of suppliers in product development projects, this paper investigates the question: How to best structure the delivery system and to involve specialty contractors early on in high-tech projects unfolding in unpredictable environments?

This paper is organized as follows. After reviewing related literature, we summarize the findings of our empirical research. We then employ a simulation model to compare alternative project delivery systems, first assuming that work methods do not change from one alternative to the next and then relaxing this assumption. Finally, we illustrate the economic trade-offs between a strategy based on early design commitment and other strategies based on postponing the start of design, for a scenario in which the specialty contractor is involved from the project start.

Related research

This work primarily relates to research in design of lean production systems as applied to the AEC industry: what has been termed ‘lean construction’ theory. To effectively structure the work, and consequently the project delivery system, is one objective in lean construction (Ballard, 2000). Involving key specialty contractors early in design is an approach taken in lean construction.

Research in new product development processes commonly uses models to gain managerial insights (e.g. Bhattacharya *et al.*, 1998; Terwiesch and Loch, 1999). Bhattacharya *et al.* (1998), for example, use an analytical model to claim that having a sharp product definition early on may not be desirable or even feasible for product development in high-velocity environments. Instead, they propose that firms delay commitments and refine gradually the product solution, according to the level of uncertainty they expect, their own risk profile, the difficulty in making changes to the product solution and the value of customer information. Similar uses of models are less frequent in the construction management domain, in which simulation studies have primarily focused on comparing alternative construction methods (e.g. Halpin, 1973; Ioannou and Martinez, 1996). Closer to the work presented next is Tommelein's (1998) use of simulation to illustrate ways of pull-driven scheduling, a lean construction technique to synchronize off-site design and fabrication with on-site construction. The use of simulation here encompasses, however, project work from design inception up to the end of onsite construction.

Empirical research

Methodology

Empirical research progressed in collaboration with Industrial Design Corporation (IDC), a leading design-construction firm specializing in high-tech facilities. We interviewed 22 IDC design-related people, 10 owner representatives and 19 trade specialists. Each interview lasted approximately one to two hours. We did follow-up interviews with all interviewees.[1] We also attended design and construction meetings, and examined records for several fab projects, such as proposals, meeting minutes, schedules, logs of change orders, and drawings and specifications.

Results

From the empirical research, we developed three main results (Gil, 2001): (1) a categorization of the contributions of specialty-contractor knowledge to early design; (2) a generic model of the delivery process of high-tech projects; and (3) a profile of the types of uncertainty that practitioners face along the fab delivery process.

Result 1: contribution of specialty-contractor knowledge to early design

The contributions of specialty-contractor knowledge to early design fall in four categories: first, ability to develop creative solutions; second, knowledge of space considerations for construction processes; third, knowledge of fabrication and construction capabilities; and fourth, knowledge of supplier lead times and reliability. Gil *et al.* (2001) describe these categories, provide examples from practice and discuss contractual, liability and communication issues, as well as means and incentives to involve specialty contractors early in design.

Result 2: understanding of a fab utility system delivery

The delivery of a fab utility system is understood as a sequence of two phases: concept development and implementation. Concept development includes programming and design. During programming, practitioners use empirical rules, historical data, and client requirements to set forth the design criteria and one or more design concepts for the utility system. Empirical rules may use, for example, preliminary information about the expected area for the cleanroom (the space inside the fab that houses the chip manufacturing tools) or about the expected number of wafer starts per month.[2] During design, designers use sophisticated computer-based tools to refine the decisions previously made for each utility system. In design, designers detail the sets of drawings and specifications for each utility system to define its loads, critical cross-sections, equipment with long delivery times and layout of routings. Implementation includes development of shop drawings, fabrication and construction.

Result 3: understanding of uncertainty in design criteria

During the long lead-times associated with the delivery of new fabs, various events – external to the fab design-build process – can affect the design criteria and the product definition of a fab, and consequently impact the ongoing design-build process. These events are hard for fab designers to anticipate because they tend to be related to changes in chip manufacturing technology and in the forecasts of market demand for chips. These events change the design criteria by altering the needs for cleanroom- and utility capacities, or by making it necessary to design utilities not initially planned. Designers grouped changes in fab design criteria as follows: first, full changes, which cause designers to redo programming and design; second, partial changes, which affect work done during design but impact less the work done during programming; and third, small changes, which have a relative small impact in the design-build process but are more frequent than the latter two. The focus of this research lies on designers' ability to accommodate externally driven full and partial changes. We leave the study of how small changes affect fab project delivery to future research.

Simulating alternative project delivery systems

The simulation model encompasses the process of programming, designing, and building a fab acid-exhaust system (Figure 2). The design-build processes of the 40–80 MEP utility systems in a fab largely determine the project duration. The study of the delivery of these systems matters because they are critical for the fab performance, the most expensive to design and build, and the most vulnerable to events external to the fab design-build process because they directly serve the chip manufacturing tools. We chose the acid-exhaust system given the depth of information that appeared to be available at the onset of this research and that we were able to collect. Admittedly, the level of abstraction of the simulation model makes it much simpler than actual projects. Simplifications, such as modelling only one utility system, were needed to keep the model's behaviour and results tractable.

Project delivery process model

The project delivery process model synthesizes the understanding we gained primarily through the interviews with practitioners. In the description that follows, words in all-caps denote geometric shapes in Figure 2. The Appendix informs on the meaning of each symbol. The PROJECT START[s] with a PROGRAMMING phase followed by a DESIGN phase. DESIGN is expressed as a sequence of three tasks: LOAD-, SECTION- and LAYOUT DESIGN. The LOAD DESIGN task represents the designers' effort to estimate the loads that the utility system will serve. The SECTION DESIGN task represents the designers' effort to size the cross-sections of the main elements using the loads. The LAYOUT DESIGN task represents the designers' effort to route the system and to locate its major equipment.[3]

If the specialty contractor is competitively bid, the model assumes two stochastic process delays: the first expresses the time the bidding period lasts after the end of DESIGN (Delay 1 in Figure 2); the second expresses the time spent by the awarded contractor familiarizing with the design product definition after the SELECT SC event (Delay 2 in Figure 2). Afterwards, the contractor decides on the length and number of spools (industry jargon for piping pieces) and accordingly PROCURE/REORDER[s] LONG LEAD ITEMS (e.g. fibreglass coated ducts and specialty items like valves) and DEVELOP[s[SHOP DRAWINGS. The operation of assembling specialty items on the spools (FABSHOP ASSEMBLY) starts once two conditions are met: first, the architect/engineer APPROVE[D the] SHOP DRAWINGS (approval is immediate if the contractor is involved from the start of PROGRAMMING but is delayed otherwise – delay 3 in Figure 2), and second, the necessary LONG LEAD ITEMS [are] IN SHOP. Then, the batches of SPOOLS ASSEMBLED are SHIP[ped] by truck, and INSTALL[ed] on site. Simulation of spool installation proceeds one routing line (called a lateral) at a time to mimic how this construction operation is most commonly executed.

Stochastic model of changes in design criteria

Jointly with practitioners, who had worked on complex R&D fabs for leading-edge microprocessors and application specific integrated circuits (ASICS), we developed a mathematical stochastic model for generating expected distributions of full and partial changes over

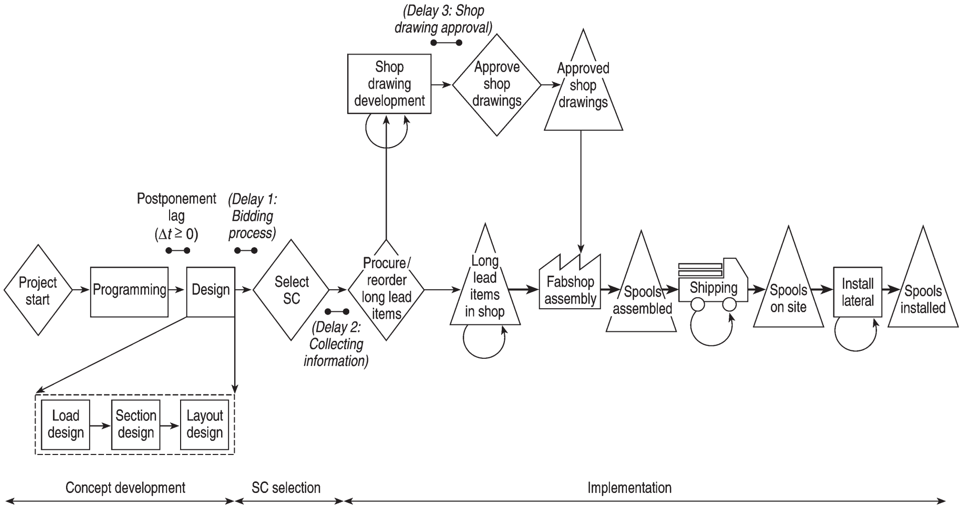

Figure 2 Project delivery process model for an acid-exhaust system with fixed design criteria (see Appendix for meaning of symbols

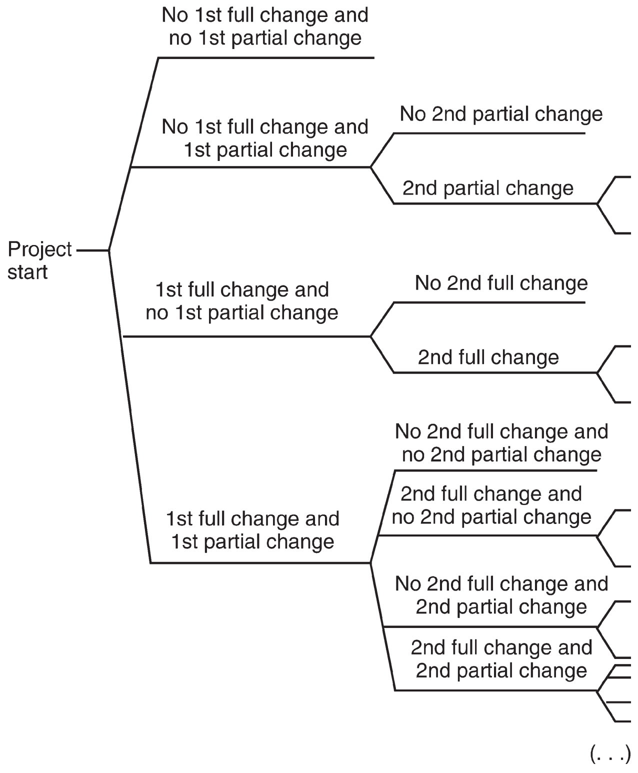

Figure 3 Partial random tree for full and partial changes

the duration of R&D fab projects (Figure 3). Our interviews with practitioners suggested that:

- full and partial changes are stochastically independent from each other;
- partial changes are more likely to occur and are likely to occur earlier than full changes;
- the occurrence of the first change conditions (affects the likelihood 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. Designers therefore deem the scenario of a first, unexpected full or partial change late in the design-build process extremely unlikely; and
- the conditional likelihood of each subsequent change decreases in relation to that of the immediately preceding change of the same type and the variability around the time when a change occurs increases between subsequent changes.

We used re-scaled and shifted symmetric beta random distributions [$a + (b - a)*\mathrm{Beta}(\alpha_1 = 2, \alpha_2 = 2)$] to express the variability around the time when full and partial changes occur. We employed the beta distribution – a parameter input distribution – since the richness of shapes that it can take with simple changes of its parameters was needed to best align the mathematical modelling with practitioners' perceptions. This flexibility is frequently exploited in simulation studies where a subjective approach to fit a distribution is needed because data is not available (e.g. Schruben and Schruben, 1999; Lu and AbouRizk, 2000).

A first set of interviews allowed 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 constants A, B and C in Table 1. Subsequently, we analysed jointly with practitioners the simulated histograms of design criteria changes to ascertain that the modelling assumptions were consistent with their beliefs. The implications of the scarcity of data to validating this research are discussed at the end of this article.

The conditional probabilities and the temporal relationships between changes of the same type, within any stream of changes, were stated as

$$P(\mathrm{change}_1) = A \tag{1}$$

$$P(\mathrm{change}_2 | \mathrm{change}_1) = \frac{A}{1 + \mathrm{B} * 1.0} \tag{2}$$

or in general:

$$P(\mathrm{change}_i | \mathrm{change}_{i-1}) = \frac{A}{1 + \mathrm{B} * (i - 1)}, \quad i \geq 2 \tag{3}$$

$$T_1 = \mathrm{C} + \mathrm{C} * \mathrm{Beta}_1(\alpha_1 = 2, \alpha_2 = 2) \text{ (days)} \tag{4}$$

$$T_2 = T_1 + \mathrm{C} + \mathrm{C} * \mathrm{Beta}_2(\alpha_1 = 2, \alpha_2 = 2) * (1 + \mathrm{B}) \text{ (days)} \tag{5}$$

or in general:

$$T_i = \mathrm{C} * \left[i + \sum_{s=1}^{i} \left\{ \mathrm{Beta}_s(\alpha_1 = 2, \alpha_2 = 2) * \left(1 + \mathrm{B} * (s - 1)\right) \right\} \right] \left(\text{days}\right), \quad i \geq 1 \tag{6}$$

Table 1 Estimates of A, B and C for the case of R&D fabs

Constant	Meaning	Full change	Partial change
A	Likelihood of a first change	0.5	0.9
B	Measure of declining in likelihood and in time predictability between subsequent changes	0.5	0.25
C	Minimum time lag before occurrence of first change [days]	20	15

where $P(i)$ is the probability of change i occurring; $P(i|i{-}1)$ is the probability of change i occurring given the prior occurrence of change $i{-}1$; A, B and C are the constants (defined in Table 1); T_i is the time when change i occurs (days); and $\mathrm{Beta}_i\,(\alpha_1 = 2, \alpha_2 = 2)$ is the symmetric beta random variable that is sampled for every value of i.

Project delivery process simulation

The project delivery process model and the stochastic model of design criteria changes were implemented with SIGMA, a discrete-event simulation environment based on event scheduling (Schruben and Schruben, 1999). Event-scheduling systems model a system by 'identifying its characteristic events and then writing a set of event routines that give a detailed description of the state changes taking place at the time of each event' (Law and Kelton, 2000 p. 205). Here, events express the start and end points of tasks and decision points, scheduling relationships model information and material flows between events, and Boolean statements model time delays and flow conditions. External-driven changes were modelled by employing cancelling relationships, depicted by dashed arrows in Figure 4.

Accordingly, a FULL CHANGE event unconditionally cancels any scheduled DESIGN task, and it schedules a new PROGRAMMING phase. Likewise, a PARTIAL CHANGE event unconditionally cancels any scheduled DESIGN tasks, and it schedules a new LOAD DESIGN task. CHANGE events also cancel implementation tasks, such as SHIPPING and INSTALL LATERAL, if the design load resulting after the CHANGE will necessitate larger spools; in this case, the [spools] IN SHOP but not yet assembled must be put aside (UNUSED SPOOLS), all SPOOLS ASSEMBLED, -ON SITE, and -INSTALLED are transformed into TORN DOWN SPOOLS, and larger spools must be PROCURE[d] once DESIGN is repeated. If any spools and valves had already been ASSEMBLE[d] when a change occurred and the spool commercial diameter remained the same, the simulation assumes contractors must REWORK all SPOOLS ASSEMBLED, -ON SITE and -INSTALLED per the new APPROVED SHOP DRAWINGS. If a FULL CHANGE does not affect the spool commercial diameter but the contractor had already PROCURE[d] the spools, the contractor must not only REWORK the SPOOLS ASSEMBLED, -ON SITE and -INSTALLED per the new APPROVED SHOP DRAWINGS but eventually also REORDER more spools if the fab will have more and longer routings.

Simulation scenarios

We used the same model to simulate a scenario in which the specialty contractor is competitively bid as well as scenarios in which the contractor is involved from programming and the start of the LOAD DESIGN may

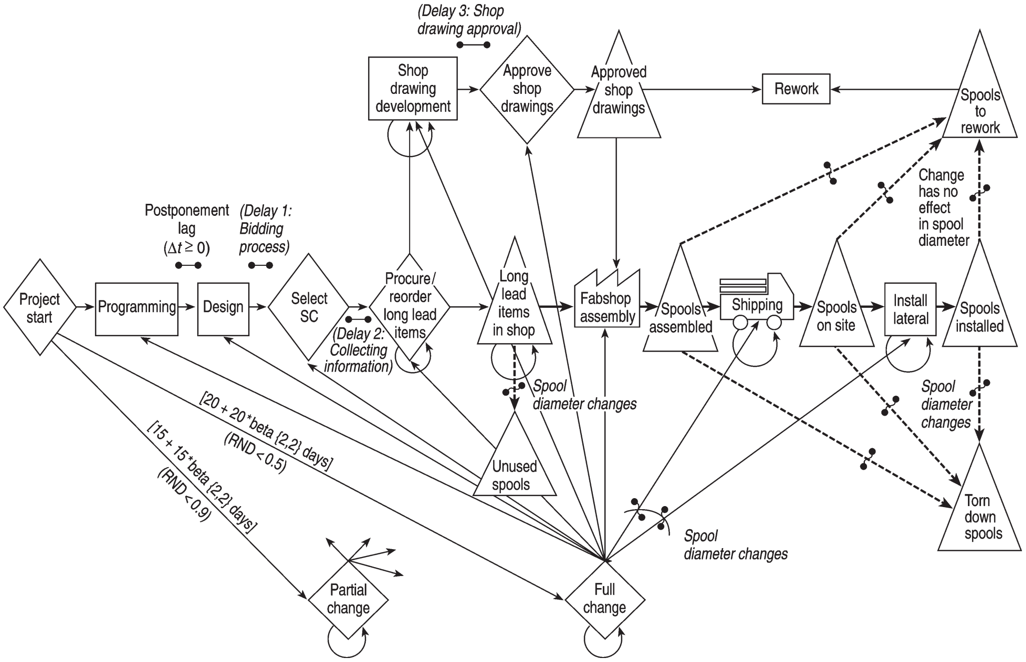

Figure 4 Project delivery process model for an acid-exhaust system with external-driven changes in design criteria (see Appendix for meaning of symbols)

or not be postponed. The only independent factors that changed between scenarios were, first, the three delays associated with the competitive bidding process based on practitioners' educated guesses and, second, the definition of a 'no earlier than' constraint on the date to start the LOAD DESIGN task for modelling design postponement. Specifically, we simulated the project delivery scenarios as follows:

Scenario 1: competitively bid specialty contractor

The SELEC SC event occurs after the end of the DESIGN phase, delayed by the duration of the bidding process – the Delay 1, which lasts between 15 to 20 days (15 + 5*Rnd[0,1]).[4] The PROCURE/REORDER LONG LEAD ITEMS follows the SELECT SC event, delayed by the time the awarded contractor spends collecting design information, issuing requests for information, and getting answers from the architect/engineer – the Delay 2, which lasts between 5 to 15 days (5 + 10*Beta{3,2}days). Then, the SHOP DRAWING DEVELOPMENT task starts and batches of LONG LEAD ITEMS [start to arrive] IN SHOP. To APPROVE SHOP DRAWINGS takes 5–10 days per batch (5 + 5*Rnd[0,1]) – the Delay 3.

Scenario 2: specialty contractors involved from the start of programming and early commitment

Delays 1, 2 and 3 are null: the DESIGN phase starts right after the end of the PROGRAMMING phase. This means that the LOAD DESIGN task starts on day 25 (PROGRAMMING lasts 25 days if no FULL CHANGE interrupts it) or on whatever day PROGRAMMING ends, if a FULL CHANGE occurred in the mean time. The PROCURE LONG LEAD ITEMS task starts right after completion of the DESIGN phase; the APPROVE SHOP DRAWINGS event occurs immediately after the end of the SHOP DRAWING DEVELOPMENT task.

Scenario 3: specialty contractors involved from the start of programming and design postponed

To develop a sense for how the length of the postponement lag influences the performance variables, we simulated 13 postponement scenarios using increments of five days to gradually delay the start of the LOAD DESIGN task from a date 'no earlier than' day 30 (corresponding to a postponement lag of approximately five days) up to a date 'no earlier than' day 90, an extreme scenario (corresponding to a lag of approximately 65 days!)

Performance variables

We applied three performance metrics: overall project duration, total length of torn down spools, and total length of unused spools (Table 2). Monitoring the overall project duration is critical since a client's major concern is to compress the fab delivery time. To assess the construction waste and rework is also critical because of the extremely high costs of qualified labour and materials involved in fab construction.

Table 2 Description of the performance variables

Performance variable	Description
Overall project duration (days)	Elapsed time from the day programming starts to the day on which the last spool is installed or reworked on site, and no more changes occur
Total length of torn down spools (feet)	Total cumulative length of spools that were assembled when a change occurred that necessitated larger spools, whether or not the assembled spools were installed
Total length of unused spools (feet)	Total cumulative length of spools that were in the fab shop but were not yet completely assembled when a change occurred that necessitated larger spools

Simulation assumptions

For clarity's sake, the simulation model reflects the following assumptions (see Gil, 2001 for details):

(1) We used practitioners' average estimates to quantify the duration of tasks and the size of batches in which shop drawings are released and spools fabricated and assembled. Given the sequential nature of the model, with finish-to-start relationships, stochastic task durations do not change the mean of the performance variables (a consequence of the Central Limit Theorem) although the variability of the performance variables would increase.

(2) The design tasks (LOAD, SECTION AND LAYOUT DESIGN) are executed only once unless the design criteria change.

(3) Resources – implicitly allocated by assuming specific task durations – are available to execute the tasks, whether contractors get involved early or later in the project, and whether or not the start of design is postponed. This assumption is discussed at the end of this article.

(4) Designers' beliefs on their ability to reuse design work after a full or partial change were matched by applying the following algorithm (Figure 5):

  (a) If the task was concluded when the change occurred:

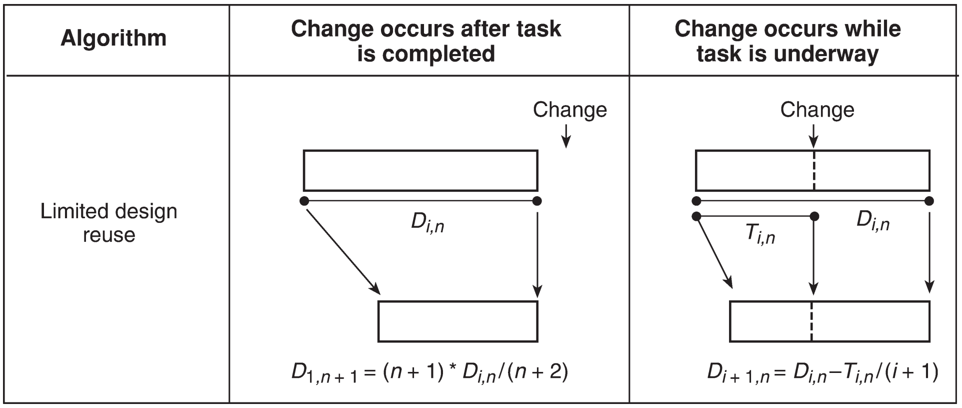

Figure 5 Representation of the design-reuse algorithm

$$D_{1,n+1} = \frac{(n+1) * D_{i,n}}{n+2}, \quad \forall n, \forall i \tag{7}$$

(b) If the change interrupted the execution of the task:

$$\begin{aligned} D_{i+1,n} &= D_{i,n} - T_{i,n} + \frac{i * T_{i,n}}{i+1} \\ &= D_{i,n} - \frac{T_{i,n}}{i+1}, \quad \forall n, \forall i \end{aligned} \tag{8}$$

where i,n is the number of times ($i = 1,2,3,\ldots$) designers have started to execute the task, given the number of times ($n = 0,1,2,3,\ldots$) designers already completely executed the task; $D_{i,n}$ is the expected duration of the task in iteration i, given that designers already completely executed the task n times, and no design change interrupts its execution (days); and $T_{i,n}$ is the time designers spent working on iteration i, given that they already completely executed the task n times, before a change interrupted its execution (days).

Analysis of simulation results

For each one of the scenarios aforementioned, we run a sample of 1000 independent, identically distributed simulations, first assuming hypothetically that design criteria were fixed, and second using the stochastic pattern of design criteria changes. The means and variances of the performance variables were calculated using the respective unbiased estimators for each sample of 1000 simulation runs. Table 3 summarizes the results of the various simulated scenarios.

Table 3 Competitive bidding vs. early contractor involvement (mean ± standard deviation ($\mu_{\text{time}} \pm \sigma_{\text{time}}$), coefficient of variation (v)) [spools 10 ft long]

Sample of 1000 simulation runs	Scenario	Description	Overall project duration (days)	Total length of torn down spools (ft)	Total length of unused spools (ft)
A	1	SC competitively bid with fixed design criteria	125 ± 4	0	0
B	2	SC involved from the project start, with fixed design criteria, and with early commitment	96 ± 3	0	0
C	1	SC competitively bid, with uncertainty	162 ± 33 V = 0.2	177 ± 847 V = 4.8	141 ± 686 V = 4.9
D	2	SC involved from the project start, with uncertainty, and with early commitment	137 ± 41 V = 0.3	1180 ± 2211 V = 1.9	298 ± 938 V = 3.1
E	3	SC involved from the project start, with uncertainty, and with postponement lag of approximately 35 days	151 ± 30 V = 0.2	483 ± 1483 V = 3.1	130 ± 630 V = 4.9

Project delivery with fixed design criteria

Lines A and B in Table 3 show the results respectively for Scenarios 1 and 2, hypothetically assuming fixed design criteria, which eliminates the occurrence of full or partial changes. In these unlikely circumstances, early contractor involvement unsurprisingly compresses the mean of the overall project duration because it eliminates the delays caused by contractor selection and by shop drawing approval; construction waste is null.

Project delivery with uncertain design criteria

Lines C and D in Table 3 show the results respectively for the Scenarios 1 and 2 with stochastic changes in design criteria. If, in conditions of uncertainty, the specialty contractor is involved early in programming and design is not postponed (Scenario 2), as opposed to a scenario in which the contractor bids the design (Scenario 1), the results show: (1) the mean of the overall project duration shortens approximately by the mean sum of the delays caused by bidding and the variability of the project duration increases slightly; and (2) the means of the two construction waste variables increase significantly but the variability of these variables decreases somewhat.

These results are explained given that design criteria changes are less likely in the course of time. Clearly, the delays associated with the competitive bidding process work as a buffer that lessens the impact of upstream uncertainty on the project delivery process, thereby reducing construction rework and waste generated. If these delays are removed (by involving the specialty contractor since programming) and the design phase is allowed to start right after the end of the programming phase and the implementation phase starts right after the end of the design phase, inevitably more changes occur while fabrication and construction are underway. Note the large variability in terms of waste generated by changes in scenarios C and D. Indeed, whereas some random realizations of the sample of 1000 simulations do not experience any change and thereby no rework, other realizations experience several changes that consequently generate significant rework and waste. This helps to understand why some R&D fab projects run smoothly whereas others are plagued by changes that generate large-scale rework and waste.

Postponement commitment strategies

Figure 6 shows two data points respectively for Scenarios 1 and 2, and 13 data points for various Scenarios 3, in which increments of 5 days increased the postponement lag from approximately 5–65 days; each data point averages 1000 simulation runs. Figure 6 informs on the trade-off faced by project teams when judiciously postponing the start of design, for a situation in which design criteria remain uncertain and in which the specialty contractor is involved from the project start. A comparison between the Scenario 2, in which the contractor is involved early on without postponement (line D in Table 3), and a Scenario 3, in which the contractor is involved early on with a postponement lag of approximately 35 days (line E in Table 3), shows that the means of the two construction waste variables decrease more than 50% if postponement is applied effectively while the mean of the overall project duration increases about 10% relative to the expected mean had postponement not been applied. However, because the variability of the overall project duration also decreases as postponement is applied, the one-standard deviation

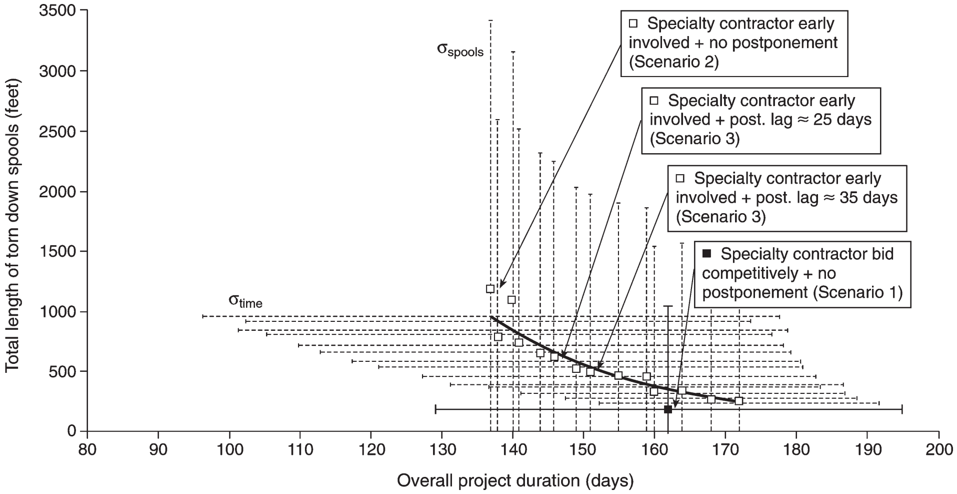

Figure 6 Overall project duration vs. total length of torn down spools for alternative project delivery systems (1000 runs for each data point)

upper limit of the overall project duration ($\mu_{\text{time}} + \sigma_{\text{time}}$) hardly increases between the Scenario 2 (line D in Table 3) and the scenario in which the design start is postponed approximately 35 days (line E in Table 3).

In addition, a comparison between the Scenario 3, in which the contractor is involved early on (with a postponement lag of approximately 35 days, line E in Table 3), and the competitive bidding scenario (line C in Table 3) shows that: (1) the mean of the overall project duration is shorter in Scenario 3 but the variability is approximately of the same magnitude; (2) the mean of the total length of torn down spools in Scenario 3 stays above the results achieved in Scenario 1 but its variability decreases slightly; and (3) the mean and the variability of the total length of unused spools are of the same order of magnitude.

Leveraging specialty-contractor knowledge in concept development

The simulated scenarios so far implicitly assumed that construction methods would not change, whether or not the specialty contractor participates in early design. The next scenario relaxes this assumption, using the same simulation model. In a competitive bidding scenario, contractors make conservative assumptions regarding the buildability of the product design definition, and regarding the extent to which the project environment will facilitate participants to follow the best construction sequences (e.g. Birrell, 1985; Bennett and Ferry, 1990; Hinze and Tracey, 1994).

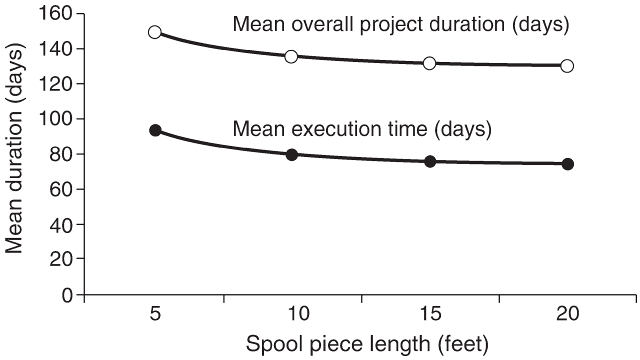

Figure 7 Influence of spool length on the project delivery process (1000 runs for each data point) [scenario 2: specialty contractor involved early on and early commitment]

We learned during our interviews with mechanical and piping contractors that the fab project delivery system affects the contractor's decision on the length of spools. In a competitive bidding scenario, contractors often select the shortest spools (around 8–10 ft long) because these are easier to slide into steel racks. In contrast, specialty contractors involved from the project start are comfortable in selecting longer spools because they understand better the product design definition and know better the other project participants. Longer spools minimize the number of required welds and they can still be slid, if specific on-site conditions are warranted. Because welding is the most crucial operation in spool installation, the number of welds is more or less proportional to the time needed to install the spools. Contractors roughly estimate that if the number of welds doubles, the time it takes to install a routing line also doubles. Figure 7 (and results in Table 4) illustrate that going from 5–20 ft compresses the mean of the overall project duration by approximately 10%. Changing from shorter to longer spools influences negligibly the means and the variability of the construction waste variables (compare results in lines F and G respectively with those in lines D and E).

Economic analysis of alternative project delivery systems

This analysis uses the mean simulation results to assess the economic trade-off between reducing construction waste and delaying the project delivery as the start of design is postponed, when the specialty contractor is involved from the project start.

The lost opportunity cost reflects the value that the manufacturer would forgo if a delay in the completion

Table 4 Influence of spool length on the design-build process (mean ± standard deviation ($\mu_{\text{time}} \pm \sigma_{\text{time}}$), coefficient of variation (V)) [scenario: spools 20 ft long]

Sample of 1000 simulation runs	Scenario	Description	Overall project duration (days)	Total length of torn down spools (ft)	Total length of unused spools (ft)
F	2	SC involved from the project start, with uncertainty, and early commitment	131 ± 39 V = 0.3	1030 ± 2007 V = 1.9	312 ± 962 V = 3.1
G	3	SC involved from the project start, with uncertainty, and with postponement (post. lag H ≈ 35 days)	149 ± 30 V = 0.20	463 ± 1432 V = 3.1	125 ± 567 V = 4.5

of the fab delivery process delayed the start of the manufacturing process, and caused an unrecoverable loss of sales. Practitioners roughly estimated the opportunity cost associated with a R&D fab between $2.5 million up to $5.0 million per day (2000 current costs). We trace the lost opportunity cost curve, first, by assuming that this cost is zero at the early commitment scenario, in which the mean of the overall project duration is the shortest possible. Then, as the postponement lag increases in 5-day intervals, the mean of the overall project duration increases somewhat and the lost opportunity cost increases (Figure 8).

The costs of the construction waste were assessed as follows. First, we assume that changes in design criteria produce construction waste with the same order of magnitude for the other 40–80 fab utility systems as they produce waste for the acid-exhaust system. This waste is quantified in terms of total feet of unused spools and of torn down spools. Second, a cost of $600/ft is used for the materials needed for any utility system, not including installation. This includes the cost of one foot of ductwork or pipe – regardless of the material (e.g. straight stainless steel, Teflon coated stainless steel, and fibreglass) – plus an allowance for the cost of specialty items, such as taps, dampers and valves. The analysis also assumes a labour cost of $400 per ft for installation.

Each trade-off cost curve adds the lost opportunity cost to the construction waste cost. The trade-off cost curves in Figure 8 combine the lower and upper estimates of the lost opportunity cost with the construction waste cost that results as the acid-exhaust waste is extrapolated for 40 and 80 utility systems. The results show that if a high-value lost opportunity cost is assumed, to postpone the start of design is economically attractive, on average terms, only if a high-value for the construction waste is also assumed. If a low lost opportunity cost is assumed, then to postpone the start of design leads to savings in cost irrespectively of the value assumed for the construction waste.

Discussion

The theoretical simulation of alternative project delivery systems indicates ‘there is no such thing as a *free lunch*’. Given the one-of-a-kind nature of R&D fabs, faster delivery implies to making commitments early on, so that procurement, fabrication and construction activities may start sooner. If design, procurement, and fabrication commitments are made early on and design criteria remain uncertain irrespective of the on-going status of the project delivery process, on average, wasted construction resources inevitably increase.

Nonetheless, simulation results suggest that a delivery system that combines early contractor involvement with judicious postponement of the design start reduces

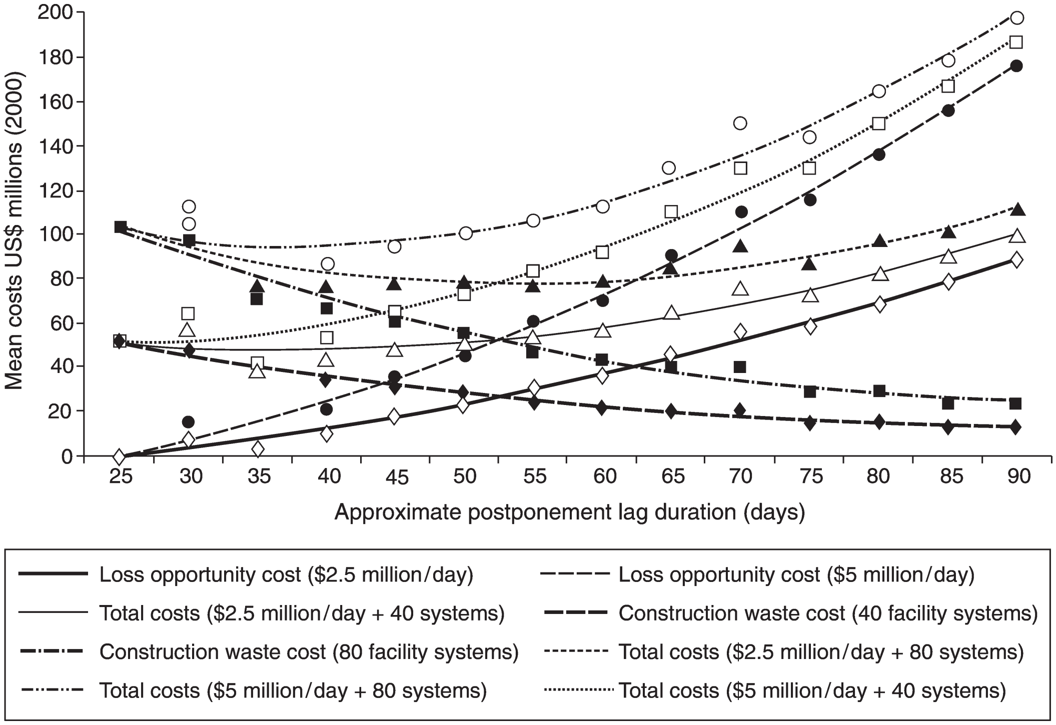

Figure 8 Economic analysis of the trade-off between minimizing construction waste and delaying the project delivery, for alternative postponement strategies [scenarios 2 and 3: specialty contractor involved from the project start]

the average project duration (in comparison with the average duration of the competitive bidding scenario) with limited increase in construction rework, if design criteria remain uncertain. It may be surprising to some practitioners to discover that total project cost can be lower with project durations slightly longer than necessary. Moreover, simulation confirms that additional opportunities to expedite fab project delivery exist for organizations that take advantage of specialty-contractor knowledge in early design. The example used here on the spool length illustrates this point. These are important benefits since construction clients are generally moving towards greater contractor involvement throughout the life of a project and towards long-term alliances with preferred contractors while shifting away from one-off contracts in which contractors would just take responsibility for building (e.g. Smy, 2003). Furthermore, a likely increase on the use of performance-based design specifications also gives room for more participation of specialty contractors in design (CIB, 2000).

Note, however, that simulation cannot guarantee that a specific project delivery system that performs best on average terms will perform best for a given real-world situation. Simulation results average a large number of realizations. In contrast, in the real world, decision-makers have to choose a delivery system without knowing if external events will change design criteria, even if they anticipate these are likely to occur. Project organizations should, therefore, commit early on or postpone critical design decisions in function of: (1) the criticality of increasing chances for shortening the project delivery, (2) the amount of control in terms of process reliability that organizations are willing to loose and (3) the risk of construction cost overruns that organizations are willing to incur. Subject-matter experts must decide which criteria matter most, and act accordingly.

Some modelling limitations merit discussion. First, the simulation model cannot differentiate the quality of a product that results out of several rework cycles *vis-à-vis* that of a product developed with mature design criteria or with the early contribution of specialty-contractor knowledge. Second, postponement is rudimentary implemented here since it delays the design start for the whole utility system. Future research should explore the possibility of postponing only the design features more likely to get affected by external events. Third, the simulation does not explicitly model the resources needed to perform the tasks. Managers, however, expressed concern that if they would let team members get involved with another project during a postponement lag, they would have difficulty later getting their teams back together because of the scarcity of skilled resources. This is a fair concern. Regrettably, project managers seem to pride themselves on working their staff at more than 100%. Under loading resources (i.e. adding a capacity buffer), an approach commonly used by Japanese manufacturing organizations, would allow designers to accommodate variability in work demand and thereby increase workflow reliability (Hopp and Spearman, 1996, p. 157).

Finally, the model can be expanded to simulate concurrently the project delivery process of various building systems and the critical hand-offs between specialties. This would enable the model to mimic better the complexity of project organizations, and thereby achieve more predictive power on the expected behaviour of real-world systems.

Validation

Validation determines whether the simulation model is 'an accurate representation of the actual system, for the particular objectives of the study' (Law and Kelton, 2000, p. 264). We addressed validation, first, by interviewing subject-matter experts with different roles in fab project delivery to assure the objectivity of the empirical research findings. Then, we walked practitioners through the initial simulation model prototype to ascertain that the rationale and assumptions on the process representation and on the patterns of design criteria changes matched practitioners' perceptions. At the end of the research, we showed to and discussed the model and the findings with practitioners to check their reasonableness. These were consistent with perceived system behaviour, which Law and Kelton (2000) call face validation.

Regrettably, hardly any data was available on the frequency and process implications of design criteria changes in R&D fab projects (although some data available on one R&D fab project was consistent with practitioners' perceptions). This limitation hindered a comparison between the model and system output data, what Law and Kelton call 'results validation'. This does not however invalidate the contribution of this work in terms of the managerial insight that judicious postponement can be employed to account for the trade-off between increasing chances of expediting project delivery at expenses of increasing the risk of rework and waste if early design criteria changes are likely. Furthermore, this research contributes a methodology that organizations can use to gain managerial insights on project delivery in unpredictable environments, after adapting the model to their specific circumstances. Clearly though, the benefits of computer simulation for supporting process analysis and decision-making cannot be exploited fully unless the AEC industry rethinks the data collection procedures it currently employs.

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Notes

1. Since many professionals interviewed worked in several high-tech design or contracting firms or even at client organizations prior to their job position at the time of the interview, the knowledge we gathered reflects to a large extent current practices in the AEC high-tech industry.
2. 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.
3. During design, designers also size and procure equipment with long delivery times but this activity was excluded from the scope of the model.
4. Rnd[0,1] – random number equally likely to occur anywhere between zero and one.

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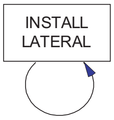
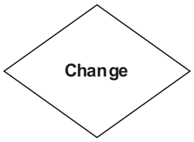
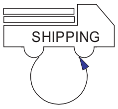
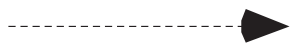
Appendix

Symbols used to represent the project delivery process

Symbol	Name	Explanation
	Task	A closed rectangle denotes a design or construction Task. A circular arrow underneath expresses that the task needs to be executed as many times as the number of batches it receives as input along the project delivery process.
	Decision point	A diamond denotes a decision point event. It represents the moment at which critical decisions are made.
	Information flow	A solid arrow denotes an information flow. It indicates the flow of information from one Task or event to the next task or event.
	Resource queue	An upward triangle denotes a resource queue. Resources result from the execution of a task or of a decision point event.
	Fabshop assembly	A symbol of a factory denotes the operation of assembling specialty items (e.g. valves and Ts) on the spools in the fabshop.
	Shipping	A symbol of a loaded truck with a circular arrow underneath denotes the shipping of materials from the fabshop to the construction site.
	Edge condition	A curly line with dots at both ends denotes an edge condition. It indicates that the edge it crosses only gets executed if the edge condition is met.
	Material flow	A solid, bold arrow denotes a material flow. It indicates the flow of materials, such as spools.
	Cancelling edge	A dashed arrow denotes a cancelling edge. It indicates that the event from which the arrow emanates cancels the task/event to which the arrow points after a time delay ($\Delta t \geq 0$), if the latter is scheduled to occur and the edge condition is met.
	Transformation edge	A dashed, bold arrow denotes a transformation edge. It indicates that a resource type will be transformed into another resource type, if the edge condition is met.