Embodying Product and Process Flexibility to Cope with Challenging Project Deliveries

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Abstract: Four factors make it challenging to manage semiconductor fabrication facility ("fabs") projects: technical complexity of the product design, need to compress the project duration, need to reduce upfront costs, and unexpected project changes. The strategies employed by practitioners to cope with these challenges form an intricate puzzle. We empirically develop a framework that provides a structure for helping to solve this puzzle, which comprises two principles: investing upfront in a flexible product design and structuring a flexible process. Empirical findings reveal that project teams make commitments early on by overdesigning but also postpone critical decisions by differentiating the scope of their work. Project teams employ other strategies such as increasing communication, using modular architectures, engaging in four-dimensional computer-based modeling, and fabricating components and subsystems off-site. Our analysis yields understanding on the purposes and performance tradeoffs of these strategies, and on how they embody the two principles. Project managers may find the framework useful when deciding which strategies best suit other equally challenging projects.

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Introduction

Studies of problems related to the management of engineering and construction projects that unfold in conditions of uncertainty are increasingly common (Ibbs 1997; Hanna et al. 2002; Touran 2003). While the literature may suggest a scholars' preference towards studies of the impacts of change orders to project performance, the perspectives adopted vary. For example, Hanna et al. (2002) characterize quantitatively the impacts of change orders on contractors' productivity. Ford (2002) and Touran (2003) investigate the use of budget contingencies by project managers. Ibbs et al. (2003) study the appropriateness of using specific contractual arrangements for managing projects in conditions of uncertainty. Peña-Mora and Park (2001) develop a planning method to help project managers cope better with change orders in fast-track projects. Other scholars have focused on the impacts of change orders on the project design process. For example, Slaughter (2001) investigates alternative strategies to increase the robustness of a building design to changes in design criteria. Hegazy et al. (2001) propose an information model to store design information, record design rationale, and manage design changes.

Our work contributes to this literature with a qualitative empirical study focused on the operational strategies and methods adopted by project teams to cope with uncertainty during semiconductor fabrication facility ("fabs") projects. Fabs are high-tech facilities that house the manufacturing tools necessary for the production of semiconductors or chips, which "are the basic building blocks of integrated circuits" (Wright 2001, p. 172). Qualitative empirical studies on managerial practices to deliver construction projects are not new (Crichton 1966; Bresnen and Fowler 1994; Pietroforte 1997), but our work is different. First, it focuses on one family of large-scale construction projects seldom studied in the literature. Second, our study focuses on the operational methods and strategies employed by fab project teams during both design and construction. Hence, our study relates to work that adopts a systematic production management perspective to study project-based organizations that operate in the construction industry, what is termed "lean construction" (Tommelein 1998; Gil et al. 2001; Ballard et al. 2002; Koskela et al. 2002). Specifically, our work contributes empirical understanding, from a production viewpoint, on the role played by managerial strategies that embrace flexibility in construction projects with uncertain design criteria.

Research has been conducted on the role of flexibility in commercial product development projects. Thomke and Reinertsen (1998) illustrate three major strategies for increasing product development flexibility in turbulent markets: adopting inherently flexible technologies (e.g., computer-aided design), structuring processes for lowering the cost of change (e.g., defer commitments), and designing flexible product architectures (e.g., using modular product structures). Other scholars have advocated the need to integrate lean and agile paradigms for streamlining manufacturing supply chains when product demand is uncertain in volume and variety (Cusumano 1994; Naylor et al. 1999). Lean construction scholars are aware that project development processes

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need to be flexible to accommodate changes stemming from uncontrollable external sources (Koskela et al. 2002). This need underpins lean design methods such as deferring design commitments until the "last responsible moment," using set-based design, and sizing and locating buffers to absorb variability (Ballard et al. 2002). More in-depth empirical studies are needed, however, to validate the usefulness and practicality of these methods.

Four main factors contribute to the challenges in managing fab projects (see Chasey and Merchant 2000 for a detailed analysis of the challenges in delivering the next generation of fabs). First, fab designs are complex because production of leading-edge chips is a complex manufacturing process that involves various state-of-the-art tools. These tools hook up to a large number of utilities and support equipment, require steady utility flows and stringent environmental conditions to operate, and are constantly changing between consecutive generations. Second, the speed with which to bring a fab online is critical to ensure the project's profitability since manufacturers that reach the market first with a new product can benefit from higher-priced sales and possibly preempt competitors (Burnett 1997). Third, reduced costs upfront matter in a competitive business environment. Finally, the need to design and build the fab before the chip-manufacturing technology has been developed generates frequent but hard-to-anticipate changes in the course of the project.

Our empirical research reveals that practitioners involved in fab projects simultaneously employ various managerial strategies that embody two complementary principles: the principle of product flexibility and that of process flexibility. Product flexibility is the ability of the product design to accommodate changes in design criteria after the design has (presumably) been frozen. While this definition is close to the concept of "robust design" used in the literature on developing new manufacturing products and on design theory (Taguchi and Clausing 1990), its aim is conceptually different. Robust design methodologies aim to design products whose performance quality is insensitive to stochastic variation in the manufacturing process, in the parts, and in how customers use the product (Kazmer and Roser 1999). In contrast, product flexibility aims to allow project participants to make commitments early on in order to expedite the project, even though they expect the project customer to request late changes in design.

Process flexibility is the ability to structure the project process so that it can accommodate late changes in design criteria and in intermediate schedule milestones without necessitating large allowances upfront in the product design. Process flexibility is akin to concurrent engineering principles that aim to compress the development time for manufacturing products but the conceptual aim is different. Concurrent engineering overlaps the concept development phase with the implementation phase by delaying the end of concept development and accelerating the start of implementation (Iansiti 1995). This facilitates timely exchanges of information between the two phases and can help to compress the product development project duration but, in the absence of careful management, it can deteriorate the performance of the product development process (Krishnan 1996). In contrast, process flexibility delays tasks in design, shop fabrication, and on-site construction for selected building systems until the project customer is more certain of the design criteria, while it accelerates similar tasks for other systems unlikely to be affected by changes, without compromising cost or program.

We grouped the observed practices in three categories (Table 1):

Table 1. Managerial Strategies Embodying Product and Process Flexibility

Main principle	Product flexibility	Process flexibility	Product–Process flexibility
Managerial strategies	Overdesign	Differentiation of works Off-site fabrication Four-dimensional computer-based modeling	Intensify communication Modular buildings Design reuse

1. We empirically identified one strategy that primarily embodies product flexibility in fab projects: (1) **Overdesign**. Designers overdesign by choosing equipment at the high end of available alternatives because they expect design loads to increase, yet they acknowledge that it is hard to predict when increases will happen and what their magnitude will be. Likewise, designers oversize cross sections of utility routings or allocate empty space to accommodate future needs for extra capacity.
2. We empirically identified three strategies primarily embodying process flexibility in fab projects: (1) **Differentiation of Works**. Design-criteria changes in the course of the project do not affect all building systems equally. An analysis of real-world data on a fab project illustrates this, and is discussed later in this paper. Architecture, engineering, and construction (AEC) practitioners are aware of this phenomenon and seek to identify, early on in a project, which building systems (and in particular which specific characteristics of those systems) are more and less susceptible to be modified if design criteria change. This differentiation of works guides the decision on whether to commit early on or to delay the design, fabrication, and on-site construction for specific building systems. (2) **Off-site fabrication**. The AEC practitioners increasingly investigate which building components can be fabricated off-site. Off-site fabrication allows for more concurrency between fabrication, assembly, and on-site construction and it can bring savings in labor hours, installation time and cost, and improve safety and quality (Gibb 1999). Off-site fabrication supports a more flexible project process because alternative designs can be developed upfront but the choice of one design and the start of its fabrication process can be postponed until design criteria are more certain. Off-site fabrication aims to standardize components and their interfaces with the other parts, so that practitioners can rely on the components fitting and functioning together once they are brought to the construction site (Pavitt and Gibb 2003). (3) **Four-dimensional (4D) computer-based modeling**. The management of three-dimensional building space is difficult whenever the product design is complex or likely to change during design development. Physical interferences, such as components getting in each other's way or blocking an area needed for other uses, remain commonly unnoticed until they surface in the field. Project organizations have traditionally built large-scale physical models to help anticipate possible interferences. These large-scale models are useful but they have numerous limitations: they prototype only a small chunk of the work, represent only a selected few product features, cannot easily be taken apart to be viewed from many different angles, and are available only to those that can get physically near it. Computer-based 3D and 4D models overcome many of these shortcomings. Four dimensional

means that time-based information on construction tasks and on scheduling logic is integrated with the 3D product model (Koo and Fischer 2000).

3. We empirically identified three strategies that contribute about equally to embody product and process flexibility. Of course, strategies in the first two categories can contribute to embody the other principle to some extent (e.g., off-site fabrication can result in some overdesign if adverse transportation conditions are expected) but they tend to do so unequally. (1) **Intensify communication**. Effective communication between project stakeholders helps designers to anticipate the changes that are likely to occur and make more adequate design allowances at the early project stages. Once changes happen, effective communication helps team members to transmit information quickly to those for whom it matters so that they can minimize the detrimental impact of late changes on work completion. Partnering initiatives exemplify efforts to improve communication between project participants (Larson 1997). (2) **Modular Buildings**. Ulrich and Eppinger (1995) define "product architecture" as the scheme by which the functional elements of the product are arranged into building blocks and by which these blocks interact. In modular product architecture, the functional elements of the product match specific building blocks and the interactions between blocks are well defined and generally fundamental to the primary functions of the products. Modular architectures allow design changes to be made to one block without generally requiring changes to the other blocks for the product to function correctly (Ulrich and Eppinger 1955, p. 132). The concept of modular architectures applies to modular buildings and building subsystems. (3) **Design reuse** exploits the short cycles allowed by computer-aided tools for modifying digital models, drawings, and specifications, when design criteria change. It also allows for adapting a former product design quickly when the customer wants to build the same product in a different location. The use of purposefully developed electronic libraries for design reuse is common practice in the design of system-on-chip architectures (Jacome et al. 1999) and an exciting research topic in construction (Ball et al. 2001). Design reuse adds flexibility to the design process for accommodating changes, but overdesign is a prerequisite to making it effective if design criteria are likely to remain uncertain in the course of the project.

Clearly, the strategies described in these three categories are not exhaustive but illustrate the usefulness of the framework for promoting understanding on how project teams may cope with uncertainty and complexity. The remainder of this paper is organized as follows. We first substantiate the challenges in managing a fab project by outlining the delivery phases and by analyzing real-world project data on external-driven uncertainty. Then, we use the framework to yield understanding on how project teams instantiate the aforementioned strategies. Finally, we discuss performance tradeoffs associated with the various practices and the need to embody both product and process flexibility for coping with challenging projects.

Fab Project Environment

Data Sources

In-depth empirical research was carried out by the first author in collaboration with Industrial Design Corporation (IDC) in Portland, Ore., a leading design-construction firm specializing in high-tech facilities. He conducted field research over a 30 month period, including three visits to IDC's main office that lasted 1 week each, and two summer internships that lasted 2 months each. During the internships, he worked first as an assistant to the tool dock coordinator for one fab tooling project, and then as an assistant to the construction manager for another fab project. The tool dock coordinator and the construction manager acted as "key informants" during the summer internships and introduced the first author to co-workers. To assess the validity of the empirical findings, experiential data was triangulated by method.

First, we conducted 85 semistructured interviews, each approximately 1–2 h long, with a sample of experts that included 22 lead designers and design/construction/project managers, 19 specialist contractors, and 10 customer representatives. We used an interview protocol to question practitioners about the critical decisions they make in concept development and implementation, the patterns of likely customer-requested changes, and the impacts of changes to project performance. We selected interviewees by using theoretical, "purposive sampling," and specifically, a variant called intensity sampling, which is sampling of a selection of "participants who are experiential experts and who are authorities about a particular experience" (Morse 1994, p. 228). All interviews were tape recorded except a few made over the phone, and the recordings were subsequently transcribed. No proprietary or confidential information was disclosed unless permission was granted by the fab owner.

Second, for several fab projects that were ongoing at IDC, the first author attended design and construction meetings, collated clippings from professional publications, and examined archival data, including proposals, meeting minutes, schedules, and logs of design changes. He ethnographically gathered further data during the internships (Van Maanen 1977): He observed project participants in their daily work routines, worked for the "key informants," spent days shadowing designers, foremen, and construction/project managers, had spontaneous conversations, and cultivated relationships with several people. Occasionally, he accepted invitations to lunch or meet after work.

The empirical qualitative data was synthesized in a systematic way and commented on in a cross-case display for five design specialties (structural, mechanical, chemical, electrical, and architectural) (Miles and Huberman 1994). For the sake of brevity, we report here on only two empirically developed constructs: (1) an outline of the critical phases in fab delivery and (2) the sources of external uncertainty in fab projects. Gil (2001) presents a technical and financial brief on fab projects and further details the cross-case display.

Construct 1: Outline of Critical Phases in Fab Projects

Fab project delivery comprises the following phases:

1. **Programming** includes the definition of the fab performance requirements, such as the type of product to manufacture [e.g., microprocessors, chipsets, state-of-the-art dynamic random access memory (DRAM) chips, or chips for domestic appliances], the target capacity in terms of the average number of wafers to produce every month, and a preliminary list of manufacturing tools to install. [Wafers are the basic units of production in a semiconductor fab. They are disks of (usually) silicon, on which the semiconductors are etched. Wafers are then sliced into what we know as semiconductor chips.] With the help of rules of thumb and historical data, designers

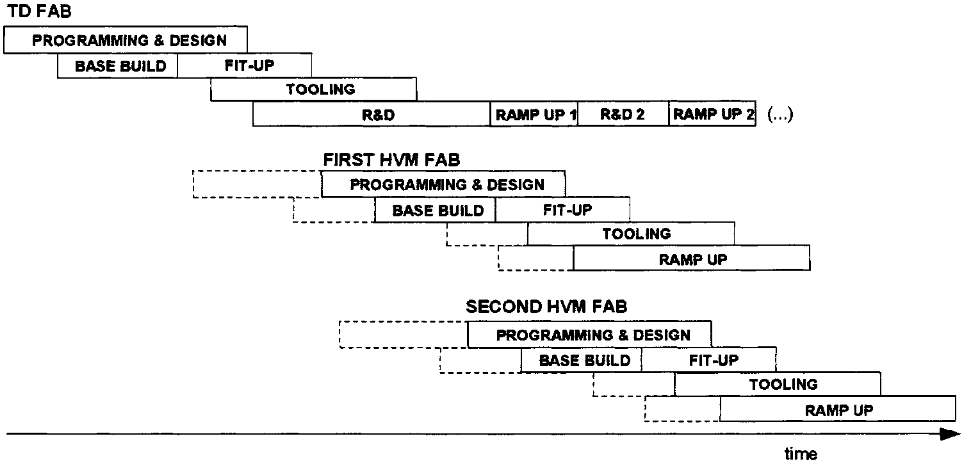

Fig. 1. Development of fabs for a large chip manufacturer

convert these requirements into the design criteria that govern the design decisions.

2. **Design** includes the design of the architectural and structural systems that define the shell as well as the design of the fab utility systems such as the mechanical, electrical, and piping (MEP) systems, and life safety and telecom systems.
3. "**Base-build**" includes an array of construction operations such as excavating, building foundations, erecting the steel or concrete structure, and installing architectural elements.
4. "**Fit-up**" includes the installation of the main and lateral utility routings in the subfab, as well as the installation of the walls, floors, and ceiling of the cleanroom.
5. "**Tooling**" includes the design of the systems to install the tools, the installation of the tools in the cleanroom, and the installation of their support equipment (e.g., vacuum pumps, heat exchangers, and gas cabinets) in the subfab. During tool hookup, MEP contractors connect the multiple tool connection points with the points of connection for the numerous chemicals, gasses, drain lines, safety/environmental sensors, and exhaust lines.
6. "**Ramp-up**" includes the increase of factory production up to the target production rates while the chip manufacturing processes are progressively fine tuned and the demand for the chip materializes.

These phases overlap in an attempt to compress the fab project time (i.e., the time between the start of programming for a new fab and the date when the fab can start to produce chips) (Fig. 1). The programming and design of some building systems overlaps with the fabrication and construction of parts of those systems (base-build and fit-up) and with the work from other building systems. Likewise, tooling overlaps with the fit-up phase, and within tooling the design of the tool install systems overlaps with the tool installation work on site. In turn, the fab design–build–tooling process overlaps with the development of the chip-manufacturing technology.

Construct 2: Sources of External Uncertainty

Two main sources of external uncertainty affect the fab design–build–tooling process. A first source is the fab's purpose: fabs can be: (1) technology development (TD) fabs, (2) high-volume manufacturing (HVM) fabs, or (3) foundries. A second source is the need to design a fab for several generations of chip-manufacturing technology (fabs are expected to receive from two to five generations of technology over a 20 year period) not knowing what the future requirements will be. In contrast, the sources of internal uncertainty include: (1) unexpected design iterations when initial assumptions on design parameters do not hold after design information that is more complete becomes available; and (2) design and construction rework due to design choices that are hard to implement on site. The scope of our work is limited to the study of operational strategies employed by practitioners to cope with external changes. While the literature is rich on studies of the impacts of internal iteration to project performance and of appropriate tools to cope (e.g., Austin et al. 1999; Korman et al. 2003), it is less so in relation to external uncertainty.

Uncertainty Resulting from Fab's Purpose

The TD fabs house pilot lines of tools, which are used to research and develop new chip manufacturing processes. These are the most difficult fabs to deliver since their delivery unfolds concurrently with the research and development (R&D) processes for new manufacturing tools and for the chip-manufacturing process. Changes related to these two R&D processes are likely to affect the fab design criteria and impact the fab design–build–tooling process. In contrast, fewer external events affect HVM fab projects because these will house lines of tools fine tuned in a TD fab. Still, to gain time, major chip manufacturers may decide to design one or more HVM fabs while the construction of the TD fab is still underway (see Fig. 1). As a result, external events may also affect the delivery of an HVM fab.

Few manufacturers have the financial capability to build multiple fabs in a short period. Many manufacturers rely on the foundry model to meet their production needs ("Face value. Foundry father" 2001). Foundries are fabs that produce products for other manufacturers who have the chip manufacturing knowledge but may not (want to) have the financial or technological capability to mass produce the chips. When project teams design and build a foundry, the customer does not know exactly what processes the fab will house. The design of foundries needs to be flexible to accommodate an array of opportunities that may arise later.

Uncertainty Resulting from Innovation in Chip-Manufacturing Technology

Innovation in chip-manufacturing technology is mainly driven by two parameters: the technological breakthroughs in terms of

Table 2. Work Hours Spent in Programming, Design, and Design Change Work (Fab *X*)

	Civil	Structural	Architectural	Chemical	Mechanical and HVAC	Electrical	Life safety systems	Instrumentation and controls	Telecom
Programming	680	110	310	660	290	340	300	230	240
Design before construction	2,994	2,883	10,548	14,626	11,955	10,711	2,944	4,864	2,892
Design during construction	1,137	1,340	2,824	4,773	4,433	3,837	2,135	3,338	1,967
Total design work	4,811	4,333	13,682	20,059	16,678	14,888	5,379	8,432	5,099
Design change work	1,716	417	2,805	4,993	1,723	3,213	794	2,622	1,309
Design change as a percent of total design work hours	36%	10%	20%	25%	10%	22%	15%	31%	26%

wafer size and the decrease of the circuitry width on the wafer surface. Whenever manufacturers worldwide agree to increase the size of wafers, the design features of many tools change significantly, as do the tools' performance requirements. New tools may require higher utility loads as well as disproportionally more support equipment. Changes in the circuitry width are much more frequent and result in the so-called "tool conversion cycles." These cycles affect the design features of the tools less.

Teams involved in fab projects that receive new manufacturing tools commonly work with incomplete, unreliable information on new tools, because these tools may still be under development. The dates when tools are to arrive to the construction site ("requested tool dock" dates) are also likely to slip. Such fabs will logically be more complex to deliver than fabs that receive mature manufacturing tools.

Data Analysis

Design Changes

Table 2 shows data on design work collected from an electronic log of customer-requested changes in a HVM fab (Fab *X*) available at IDC's project database. Note the extent of design work done after the start of construction across the various design specialties and the extent of design change work in number of hours and percentage wise. Fig. 2 details the additional hours of design change work caused by each change that affected the electrical specialty in the course of the project. Data show that, first, the amount of additional design change work varies considerably between changes and between specialties for the same change, and second, the number of changes in any month varies considerably between months.

Schedule Milestones Changes

Fig. 3 illustrates how the actual and the originally scheduled tool arrival rates differed in tooling a TD fab project (Fab *Y*) with 140 new-generation tools in an initial time window of 7 months. The data source is a digital folder kept by the tool dock coordinator (a person in charge of keeping the schedule with the requested tool arrival dates up to date), which contains all the weekly updated versions of the project schedule. The actual variation in the tool arrival weekly rate was higher than that initially scheduled. This unplanned variation in weekly rates, such as the unexpected picks in Weeks 16 and 28, matters because the work force on-site has to be flexible enough to accommodate the shifts in production rates.

Fig. 4 illustrates the (or lack of) reliability of the requested tool arrival dates for a selection of five tools in project *Y*. The

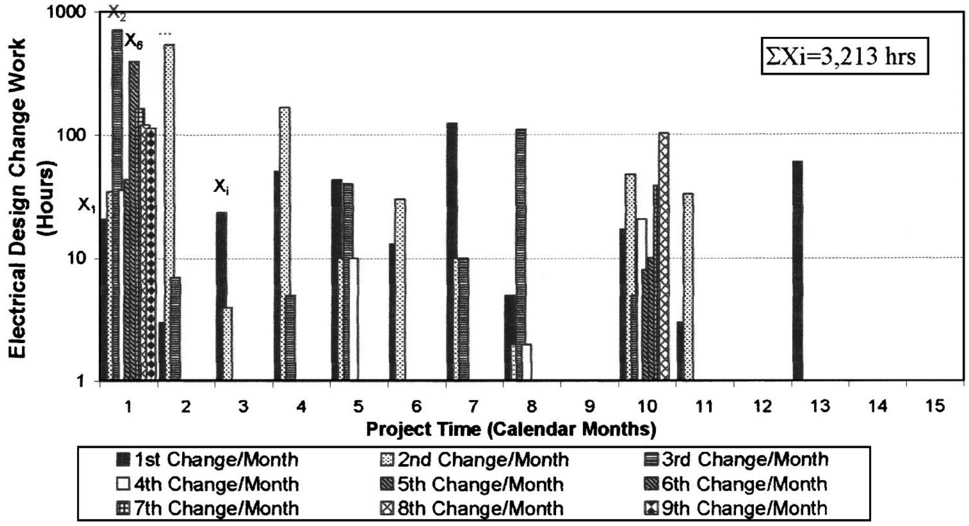

Fig. 2. Impact of customer-requested changes in additional work-hours over duration of project for electrical specialty (fab *X*)

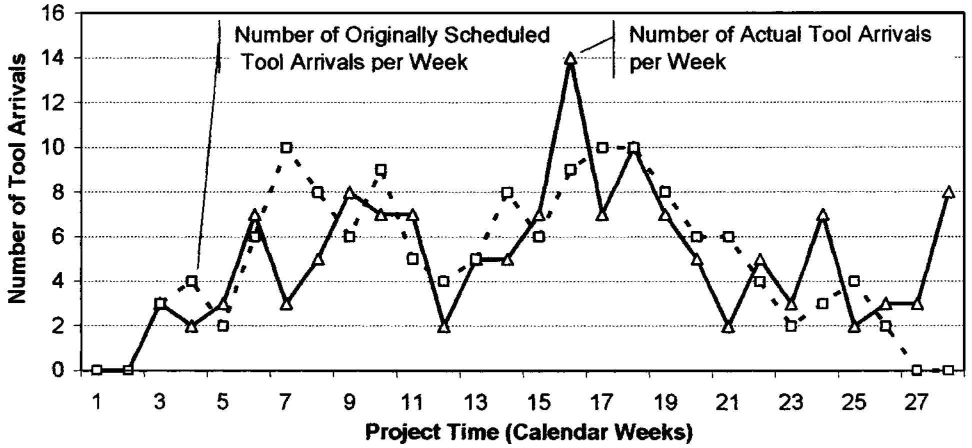

Fig. 3. Originally scheduled tool arrivals versus actual tool arrivals (fab *Y*)

graph depicts the evolution of the difference between the requested tool arrival date and the actual tool arrival date as the project unfolded. Hence, a positive value along the *Y* axis in a specific week means that the tool actually arrived later in relation to the date that was scheduled for its arrival in that week, a negative value along the *Y* axis in a specific week means that the tool arrived earlier in relation to the date that was initially scheduled. Logically, the planning horizon is shorter for the first tools to arrive on site (Tool A in Fig. 4), whereas it spans more of the project duration for the later tools (tools D and E). For example, Tool E arrived approximately 90 calendar days late in relation to the date that remained scheduled from the project start until Week 11 (with an exception in Week 9). After Week 11, the requested tool arrival date for Tool E was delayed several times until, in Week 23, it was finally scheduled an arrival date that corresponded to the actual tool arrival date in Week 25.

More than 80% of the requested tool arrival dates slipped at least once and many several times, frequently for more than 60 days in total. Several reasons explain this: (1) the tool supplier committed to an early requested tool arrival date but miss it; (2) the tool failed the qualification tests at the supplier's facilities; and (3) the tool experienced shipping delays. Note the occasional effort (steep downward slope of Tool B in Fig. 4) to align the requested tool arrival dates with more realistic ones. Although one might expect the accuracy to be smaller when forecasting dock dates further out into the future, this accuracy varied by tool (Tool D's arrival was forecasted more accurately than Tool A's). Occasionally, some tools arrived earlier than scheduled (Tool C), which can be as disruptive as a late tool arrival. Furthermore, the curve for Tool C does not show a null difference on the week when it arrived. This means that the schedule information was not always kept up to date: the tool arrived on a particular week but the scheduled date for the week when the tool arrived was not updated.

Product and Process Flexibility

Chip manufacturers currently look for reducing a fab project duration (including design, construction, and tooling) to less than 18 months. The Semiconductor Industry Association (2000, p. 11) is looking for solutions to reduce the fab construction time (defined as the number of months from the first concrete pour to the time the first piece of manufacturing equipment is ready for qualification) to less than 11 months; and to reduce the time elapsed from the first concrete pour to the first full output of wafers to less than 16 months. Note that on a fab project with a cleanroom

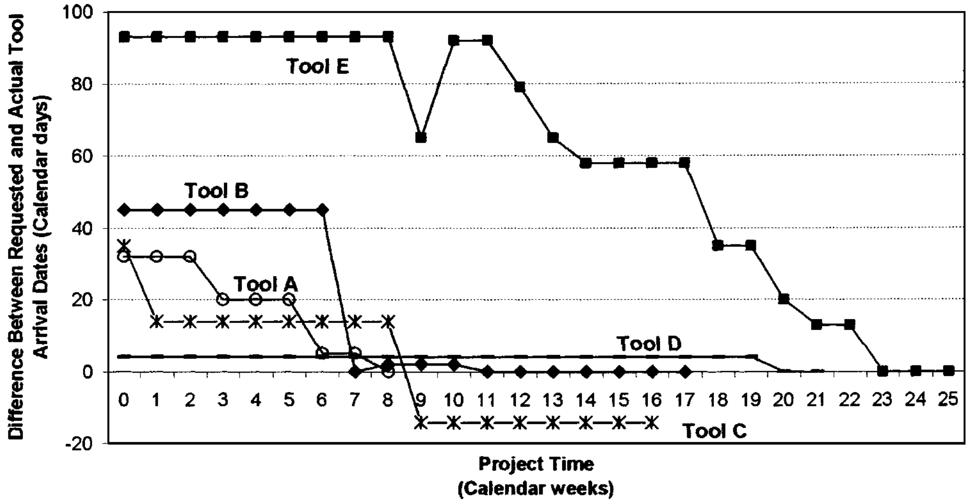

Fig. 4. Evolution of scheduled requested arrival dates for tooling project (selection from data sample of 122 tools) (fab *Y*)

varying between 80,000 to 200,000 ft^2, more than 1,000 construction workers may be on-site daily during the construction and tooling phases. The cost of designing, building, and tooling a large fab can exceed 2 billion United States dollars (Harris and Zachary 2000).

Despite these short cycle times, manufacturers challenge design and construction teams to compress them further. They also challenge teams to deliver, under tighter budgets, fabs that once in operation exhibit increasingly higher production yields (yield refers to the percentage of chip wafers that start through the manufacturing process and go all the way through without incurring defects). Project managers say that they constantly reexamine the strategies for coping with these challenges. The examples provided next illustrate this effort.

Embodying Product Flexibility

One main managerial strategy embodies the principle of product flexibility: to overdesign the product.

Strategy 1: Overdesign Product

Example: Decouple Areas of Product Design. The overdesign strategy translates in practice into three alternative fab designs: decoupled, coupled, and semicoupled. Decoupled fab designs are rare. In a decoupled fab, designers keep constant the features of the fab systems across the various cleanroom functional areas, such as the span between subfab columns and the diameter of critical cross sections of utility routings. Decoupled designs allow the customer to later change design criteria, such as swapping the location of functional areas in the cleanroom, without being constrained by the fab's characteristics. Design characteristics in a decoupled fab are conservative because they have to satisfy the most stringent criteria of all functional areas pooled together. In contrast, in a coupled fab, designers assume that design criteria change less and, in particular, assume that the cleanroom functional areas do not move. As a result, they tie design characteristics to each functional area. For instance, a functional area where tools for lithography are located requires more stringent vibration criteria than others such as etching. This difference affects fab design parameters, such as the thickness of the waffle slab, the spacing between subfab columns, and eventually the height of the subfab. A semicoupled fab exists inbetween these two extreme types and is the one used most often. In this case, designers assume that some functional areas with stringent design criteria will not move and design accordingly, whereas other functional areas may be overdesigned.

Embodying Process Flexibility

Designers and customers argue that benefits and cost savings of a flexible product design in the long term outweigh its up-front cost and risk of rework. However, customers face increasing pressure to reduce up-front costs because shareholders demand that their fabs are not—nor appear to be—more expensive than the fabs of competitors are (or appear to be). Accordingly, project teams seek methods to make the fab project process more flexible. Three main strategies primarily embody process flexibility.

Strategy 1: Differentiation of Works

Example 1: Intel's Process Specific Support Systems Strategy. Intel uses the work differentiation strategy to highlight to all project teams that there are a group of process-specific support systems, such as chemical pumping systems, whose characteristics are likely to change with major design criteria changes. Project teams are instructed to consider this information during programming and delay design and implementation commitments for these systems. To be used effectively, this strategy requires some design modularity and standardization of the interfaces between building systems.

Example 2: Tool Prefacilitation. To speed up tool installation, project teams often separate tool installation in two phases: "prefacilitation" before the tool arrives on site, and "hook up" once the tool and its support equipment move into their final positions. For utility systems judged unlikely to be affected by late changes, contractors extend ("prefacilitate") some main routings that run in the subfab (except for approximately the last 5 ft) to the space underneath the cleanroom slab above which the tool will be located. During hook-up, contractors connect the tool hook-up points with the hook-up points at the support equipment and at the routing ends left during prefacilitation. Tool prefacilitation decouples the installation work from changes on the tool arrival date. This helps to stabilize the number of construction craft workers and to balance out the work so that the scheduled dates to prefacilitate the tools can remain the same despite changes in the tool arrival dates.

Strategy 2: Off-site Fabrication

Example: Off-site Fabrication of Air Plenum Body. In a recent project, 560 modules for the clean room plenum of the fab were fabricated in a shop and then assembled on site. These modules included the air barrier layer, the ceiling grid, the framework between the two layers, the fire sprinkler system, the air transfer ducts, the balancing dampers, and all of the normal components of the ceiling grid. Off-site fabrication brought significant savings in labor hours, installation time and cost, and increased safety during installation. Savings were largely associated with the efficiency gained in the off-site fabrication of the modules and in their ease of installation. The performance quality of this solution was reportedly considered higher because of better conditions available in the shop to carry out work such as welding. The solution has been patented and is available to future projects [Panelli et al., "Modular clean room plenum," U.S. Patent No. 6,514,137 (2003)].

Strategy 3: Four-Dimensional Computer-Based Modeling

Example: Fab Pilot of Multidimensional Computer Aided Design System. As the density of tools in the fab cleanroom increases, it is increasingly important that project teams compare the impacts of alternative cleanroom layouts (developed by industrial engineers) to the fab design and construction. Intel recently piloted a program that developed a 4D fab model for the base build phase that included all the civil, structural, architectural, mechanical, and process systems and equipment, as well some of the electrical systems. A construction schedule was integrated with the 3D model as well as with some routines for automatic line and cable routing, and with automatic estimation of construction costs based on material and labor unit pricing. A method to measure the cost savings and avoidances was developed by using a third party Quantity Surveyor. The use of the model facilitated the search for design alternatives. It also helped to unearth and eliminate many physical conflicts and interferences between building systems in design, and reportedly saved more than the overall cost of its implementation within 90 days of the pilot program's start (Garrett and Garside 2003).

Embodying Product and Process Flexibility

Some strategies contribute to make the fab product design more robust to likely changes in design criteria while at the same time they increase the flexibility of the project process to accommodate changes.

Strategy: Intensify Communication

Example 1: Increase Meeting Frequency. Start-up meetings at the early design stages are a way to help project teams sharpen their ability to anticipate changes in design criteria, which can lead to more sensible overdesign decisions. Start-up meetings were extensively promoted by a customer to get together designers, specialist contractors, component suppliers, and users of existing fabs in the initial stages of developing an innovative fab concept for accommodating a new generation of tools. Ongoing coordination meetings also facilitate sharing of information: In another fab project, on the customer's side, more than ten area coordinators shared the responsibility for tool installation, each coordinator in charge of a cleanroom functional area. Several tool managers, each one in charge of the information exchanges and negotiations with a few tool suppliers and designers, reported directly to each area coordinator. The dock coordinator met twice a week with the move-in contractor and with tool managers. Freight carrier representatives in charge of delivering the tools participated in these meetings via telephone. Three times a week, the tool dock coordinator participated in an ongoing coordination meeting. These meetings brought together area coordinators, tool managers, and the fab manager. During the meetings, the dock coordinator reported past and future tool arrivals and tool managers updated everyone present about changes in tool dock dates. The dock coordinator would then report the alterations to the construction manager who in turn was responsible for sharing that information with contractors.

Example 2: Move People Around. At Intel, the design of a HVM fab is largely a "copy exact" of the design of the TD fab in which the chip production lines were first developed (McDonald 1998). To prevent the recurrence of design-related problems that arose during construction of the TD fab, Intel assigns people to keep track of these problems, document them, and fly between the two job sites to make sure the information flows quickly to the HVM fab project team. Likewise, before the start of any tool install phase, chip manufacturers often organize (and pay for) visits of tool install designers and contractors to tool suppliers' facilities so that the former can ask questions to tool suppliers and observe the tools. These visits are important because sometimes changes happen in the location, in the number, and in the type of tool hook-up points in relation to the specifications and drawings provided initially to tool install teams. Such changes may seem unimportant to suppliers because they are unlikely to affect the tool performance but may have costly implications in terms of on site (re)work if the tool was already prefacilitated.

Strategy 2: Modular Buildings

Example: Modular Fab Fit-Up and Tooling. Some manufacturers divide the fab space in various modules, each one corresponding to a fitted up and tooled quadrant in the cleanroom, and supporting a set of tools that on their own may constitute a chip-manufacturing line. New modules are progressively designed, fitted up, and tooled throughout the process of ramping the fab up to the target rates, a process that may last up to 2 years. In doing so, the manufacturer can initially tool up the fab sparsely and postpone other decisions related to fit-up and tooling. Wood's (1997) analytical model shows that modular tooling decreases risks associated with obsolescence of capital equipment and inventories since it allows for more accurate matching of fab capacity with demand and technology. The main advantage to this strategy is to make fab building space readily available once demand for new chips is verified, whereas a corporate decision to start a new fab site would be a lengthy process. This practice is only effective, however, if lead times for fitting up and tooling are short. It can result in less efficient use of capital assets if the production output is small during the early stages.

Strategy 3: Design Reuse

Example: "Copy Exactly Technology Transfer Method." To minimize the time required to transfer technology from a TD fab to a HVM fab without compromising design quality and expected production yields, Intel has instituted the "copy exactly technology transfer method" ("copy exact"). In terms of the fab design, the method recommends to "exactly copy everything about equipment and its installation down to diameters of piping and number of bends" (McDonald 1998). Because of the numerous factors involved in fab design and complex interdependencies between fab systems, manufacturers have a limited understanding of how seemingly minute details of the fab design may influence the chip-manufacturing yield. By instructing designers to reuse the fab design, manufacturers expect to not only expedite the design process but also increase the chances of replicating the yields already obtained at the TD fab. Reusing the fab design also makes it easier for manufacturers to transfer people who operate and maintain an existing fab to the new one. Overdesign may be a prerequisite for effectively reusing the design solution since early commitments are made. Design reuse requires the support of computer-aided design tools for quickly adapting the features of an existing design to local conditions, including differences in regulations, in available workforce skills and machinery, and in utility characteristics.

Product–Process Flexibility Tradeoffs

Interviewees unanimously advocated a flexible product design as the most effective principle to cope with the fast delivery of a technologically complex product (fabs) in conditions of uncertainty. The degree of flexibility in product design can vary: First, project teams can design and build extra fab space and utilities with bigger capacities in anticipation of change—clearly the most costly method upfront. Second, they can design and build space for production needs likely in the future but delay the installation of the utilities until the requirements are identified and quantified. Third, they can merely allow space for a future expansion of the fab building—clearly the least costly method upfront.

Irrespectively of the approach adopted, project teams need to anticipate the future performance requirements to prevent the fab design from compromising future uses. This is a difficult task. First, designers overdesign based primarily on their experience but some changes are hard to anticipate. For example, many changes in a fab project happen when fab users get involved in the late project stages and exercise their authority to customize the spaces that will fall under their responsibility. To preempt these changes, one chip manufacturer invited users of existing fabs to participate in the early design meetings in one project. However, these users were not those to later work in the new fab—some of the latter had not yet been selected or even hired at that stage—and as a result, many late changes still occurred. If changes occur during construction and allowances tum out to be insufficient, parts of what was built may have to be torn down and rebuilt anew. Because the remaining fab components may constrain the space of new design solutions, it may be hard to find solutions that perform equally well.

Second, the flexibility designers embed in the product design may not be exercised because some may be excessive. Designers from one specialty may base their allowances on the information they receive from other specialties. It may be unclear that the received information included some allowances. Ultimately, designers may unknowingly develop an excessively overdesigned solution. If the customer later wants to lower the estimated construction cost (which frequently happens during value engineering), designers have to cut out allowances that the customer suspects are embedded in the design and does not want to pay for.

The tradeoffs associated with overdesign—the strategy favored by designers—motivate project managers to employ strategies for embodying process flexibility. The latter inevitably also come with performance tradeoffs. For example, deciding to fabricate building components off site is not a trivial decision. Tolerances for the prefabricated components and for the connecting structures must be mutually adjusted. Prefabricated modules need to be protected from damage during transportation, and this may translate in a need to overdesign some features. Likewise, the time gained by tool prefacilitation tradesoff with increasing the risk of rework: first, tool features may change after preliminary information was handed over to tool install teams and the teams only find out once the tool arrives on site; second, the assigned tool location occasionally has to change; and third, if a dock date slips after the tool was prefacilitated, the prefacilitated systems may unnecessarily obstruct the work.

Finally, strategies that embody product and process flexibility also have pros and cons. Increasing communication frequency can be time consuming without guaranteeing that project performance will improve (Patrashkova-Volzdoska et al. 2003), especially if people feel intimidated to speak (Gil et al. 2001). As an example, one tool dock coordinator who was in charge of weekly schedule updates, oddly, admitted that the most reliable source of information regarding the tool arrival dates were the freight carriers! We also learned that tool installers who visit the tool suppliers' facilities before the start of a tool install job occasionally fail to ask the right questions and thus fail to obtain the needed information. It is unclear whether they had a checklist of questions prepared in advance of their visit in order to know what to ask.

Implications for Practice and Research

This study empirically develops a framework based on two principles—product and process flexibility. We validate the usefulness of the framework by applying it to analyze various strategies employed in fab projects. The analysis yields understanding on their purposes and performance tradeoffs. Of course, the list of strategies studied here is not exhaustive—the increasing use of information and communication technologies (ICT) to improve and accelerate information exchanges between project participants, for example, was consciously left out for the sake of brevity. Likewise, we left out innovative contractual and procurement agreements to support the involvement of specialist contractors and suppliers from the early design stages. The framework nonetheless lends itself to promote understanding on how ICTs or contracts can embody product or process flexibility, and thereby help to align future ICT and contractual initiatives with strategic aims. Project managers may find it useful to employ this framework when choosing the strategies that best suit other challenging projects.

Our work also shows that fab project managers are mindful of embodying principles of product and process flexibility—if and where that flexibility creates value—when deciding which operational strategies to adopt. Scholars in lean construction have developed methods to make project processes flexible to accommodate changes in design criteria (e.g., Ballard et al. 2002). Our work contributes empirical evidence on the practical use of some of these and other methods, and on the reasons for project organizations to adopt them. Further research should characterize better the resources and effort required to implement each method, and how the methods in turn can impact the performance of the project-based production system, in terms of spent resources, project duration, and product quality. That understanding can help project teams to make better-informed operational decisions at project start.

The empirical evidence reported here relates to fab projects. Fabs are unique high-tech buildings but the main factors affecting their delivery—design complexity, need to speed up project delivery, need to reduce upfront costs, and changes in design scope and in intermediate milestones along project delivery—are increasingly common in large-scale engineering and construction projects. Clearly, further investigation is needed of the applicability of the framework to analyze operational strategies that are employed to deliver other construction product families. In doing so, the current framework may be inductively developed into a theoretical proposition and related to efforts that contribute to a theory of production applied to project-based systems. Such a theory could help to explain current practices and rationalize project managers' choice of operational strategies to support challenging projects.

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