USING PRODUCT AND PROCESS FLEXIBILITY TO COPE WITH PROJECT DELIVERY UNCERTAINTY

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Three factors – technical complexity of the product design, need to compress project delivery, and external-driven changes in design criteria – make the project delivery of semiconductor fabrication facilities (fabs) a challenging problem. Empirical findings on strategies to cope with this problem support a comparative study of two project management principles: the principle of investing upfront on a flexible product design and the principle of structuring a more flexible project development process. The project delivery problem is first articulated by outlining the extent of the overlap between the critical steps in the fab development process and by interpreting data to exemplify real-world profiles of external-driven uncertainty. Various strategies that implement the two principles are then analyzed. Specifically, the pros and cons are compared of committing early on by overdesigning with those of postponing critical project decisions by employing modular design definitions and by pre-fabricating building components. The study shows that the two principles are complementary. Managers may find it useful to adopt strategies that implement both principles whenever they have to deliver challenging projects.

Keywords: flexibility, uncertainty, postponement, project management, facility delivery.

INTRODUCTION

Semiconductor fabrication facilities (or 'fabs') are high-tech facilities that house the manufacturing tools necessary for the production of semiconductors. Semiconductors "are the basic building blocks of integrated circuits" or chips (Wright 2001, p. 172). Three factors combined make the delivery of fab projects a challenging problem. First, the technical complexity of the fab design results from the stringent performance requirements the fab needs to meet, regarding for example the quality of the air and the steady utility flows. To meet these criteria, designers use costly, state-of-the-art technologies. Chip manufacturing tools are complex pieces of equipment with features that change between consecutive generations due to ongoing research and development efforts. Tools require stringent environmental conditions, and hook up to a large number of utilities and support equipment. Second, the need to compress the project delivery time is critical to ensure a fab project's profitability since the first manufacturers to reach the market with a new product can benefit from higher priced sales and possible pre-empt competitive products (Burnett 1997). Third, events exogenous to the fab development process frequently cause changes in the fab design

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criteria. These events are hard to predict by fab project teams because they tend to relate to changes in the chip manufacturing technology or to changes in the forecasts of market demand for chips.

Fab development includes: (1) the design phase, comprising the design of the architectural and structural systems that define the shell, and the design of the building utility systems such as the mechanical, electrical, and piping (MEP) systems, the life safety, and the telecom systems; (2) the 'base-build' phase, comprising an array of operations such as excavating, building foundations, erecting the steel or concrete structure, and installing the architectural shell and selected interiors; (3) the 'fit-up' phase, comprising the installation of the main and lateral utility routings in the subfab by MEP contractors and the installation of the walls, floors, and ceiling of the cleanroom by carpenters; and (4) the 'tooling' phase, comprising the design of the systems to install the chip manufacturing tools and the installation of those tools. Tool installation itself includes 'pre-facilitation' and 'hook-up'. Pre-facilitation consists of extending the main routings of the utility systems that run in the subfab (including pipes, ductwork, and cables) to the space underneath the cleanroom waffle slab, above which the tool will be located. Hook-up consists of connecting the tool hook-up points with the hook-up points at the support equipment and at the routing ends left during pre-facilitation.

These phases commonly overlap in an attempt to compress the fab delivery time (i.e., the time between the start of design of a new fab and the date it can start to produce chips) (Figure 1). The design process of specific building systems overlaps with the fabrication and construction (in base-build as well as in fit-up) of parts of those systems as well as of other intertwined systems. Likewise, the design of the tool install systems overlaps with the tool installation work on site, and the tooling phase overlaps with the fit-up phase. In turn, the fab design-build-tooling process overlaps with the development process of the chip manufacturing technology (not shown in Figure 1).

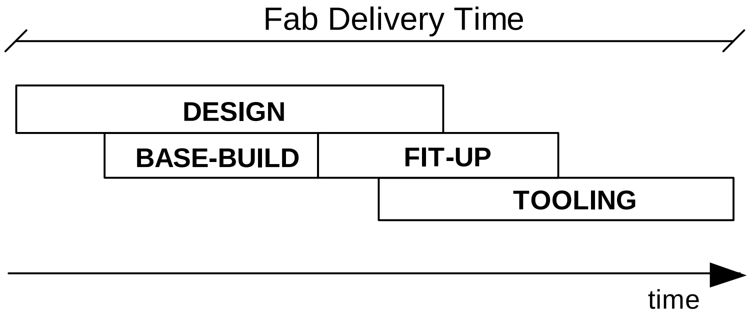

Figure 1: Fab Design-Build-Tooling Development Process

Despite the already short time in which fabs are delivered, manufacturers challenge architecture-engineering-construction (AEC) practitioners to compress it further. They also challenge practitioners 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 process and go all the way through every step of the manufacturing process without incurring defects).

Practitioners say that they constantly reexamine the project management strategies they use to cope with these challenges. They may over design features of the fab to support an early commitment strategy, as well as employ modular design definitions to support a postponed commitment strategy. This reflects an ongoing effort to implement the managerial principle of investing upfront in product flexibility as well as the complementary principle of structuring a more flexible development process. To understand better how project management strategies embody this duality of principles is the focus of this research.

This paper is organized as follows. We first briefly review related work and define the problem. An outline of the critical steps in the fab delivery process shows the extent to which these steps overlap and an analysis of data illustrates external-driven uncertainty in a real-world project. Then, we analyze various managerial strategies and discuss the extent to which they contribute to investing upfront on product flexibility or to structuring a more flexible development process. Finally, we comment on the usefulness of the two principles to guide project management decisions.

RELATED WORK

Empirical studies help to understand how project-based organizations are structured to deliver AEC projects. Some of these studies have focused on alternative strategies and methods to meet better project goals (e.g., Crichton 1966, Pietroforte 1997, Jin and Levitt 1996). Less work exists, however, on articulating the theoretical principles to guide project management practices in the AEC industry. Research in ‘lean construction theory’ is seeking to fill this gap by articulating a theory to promote understanding and to find ways to better manage project-based production systems (e.g., Koskela 1992, Tommelein 1998, Gil 2001, Gil *et al.* 2001, Koskela *et al.* 2002, Ballard *et al.* 2002, Arbulu *et al.* 2003). Gil *et al.* (2001), for example, focus on the principle of involving specialty contractors in the early design stages, and clarify the contribution of specialty-contractor knowledge to early design. The study we present next contributes to this on-going effort.

EMPIRICAL RESEARCH

We carried out empirical research in collaboration with Industrial Design Corporation (IDC), a leading design-construction firm specializing in high-tech facilities. We interviewed senior people ranging from lead designers of the mechanical, architecture, electrical, chemical, and structural specialties, to construction-, design-, and project-managers, and client representatives. We interviewed one-on-one 22 IDC design-related people, 10 client representatives, and 19 people working for contracting firms. The interviews lasted approximately one to two hours. We carried out follow-up interviews with more than 50% of the interviewees. In addition, we attended design and construction coordination meetings, and we examined the records for several fab projects, such as project proposals, meeting minutes, schedules, logs of design change orders, and project drawings and specifications. From this empirical research, we developed an understanding of external-driven project uncertainty.

UNDERSTANDING OF EXTERNAL-DRIVEN UNCERTAINTY

Two main sources of external uncertainty affect the design-build-tooling process of a fab. A first source of uncertainty 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 degree of technological innovation in the manufacturing tools.

In contrast, internal uncertainty includes design iterations that occur whenever the designers’ assumptions about the design parameters of an interrelated building system do not hold up at the time when more complete information becomes available from other specialties (assuming design criteria remain constant). Occasionally, design decisions may also turn out to be difficult for suppliers and contractors to implement so that design and construction rework is needed. The study of the effects of internal uncertainty to the fab development process merits future research but falls outside the scope of this paper.

Uncertainty Resulting from the Fab's Purpose

TD fabs house pilot lines of tools, which will be used to research and develop new chip manufacturing processes. These are the most difficult fab projects since their delivery unfolds concurrently with the research and development (R&D) processes for new manufacturing tools and for the chip manufacturing processes. 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-driven events affect the delivery of HVM fabs because these will house lines of tools fine tuned in a TD fab. Still, to gain time, major chip manufacturers such as Intel may decide to start the design of a HVM fab while the construction of the TD fab is still underway (Figure 2). As a result, external-driven events are also likely to affect the delivery of a HVM fab.

There are few manufacturers like Intel that have the financial capability to build multiple fabs in a short period. Smaller manufacturers increasingly rely on the foundry model to meet their production needs (The Economist 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 AEC practitioners design and build a foundry, the client does not know exactly what processes the fab will house. The design definition of foundries therefore needs to be flexible to accommodate an array of opportunities that may arise later.

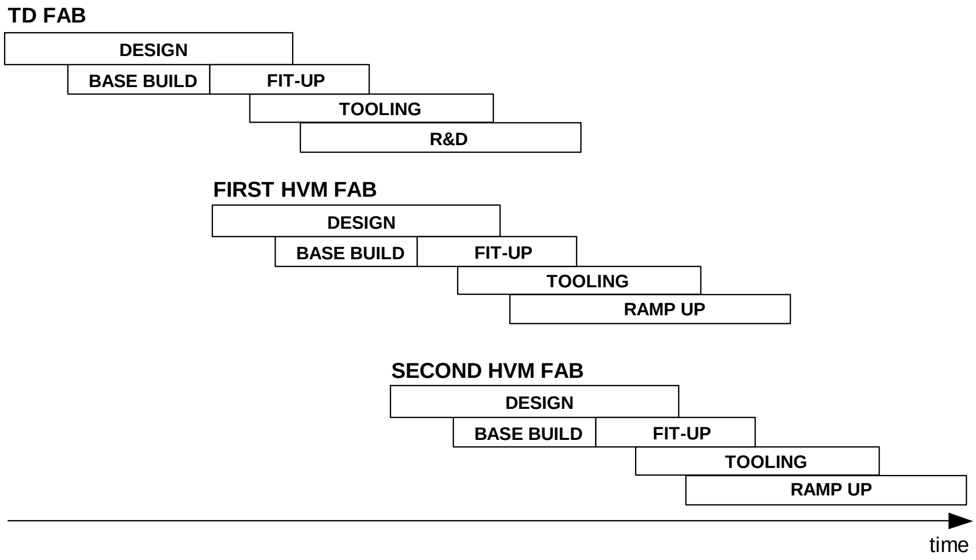

Figure 2: Cycles of Development of Fabs for a Large Chip Manufacturer

Uncertainty Resulting from Tool Innovation

Tool innovation is driven mainly by two parameters: the technological breakthroughs in terms of wafer size, and the decrease of the circuitry width on the wafer surface. Whenever the 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 change the tools less.

AEC practitioners involved in fab projects that will receive new manufacturing tools commonly work with incomplete, unreliable information on the new tools. The dates when tools are expected to arrive to the construction site (‘requested tool dock’ dates) are also more likely to slip. Such fabs will logically be more complex to deliver than fabs that receive mature manufacturing tools.

DATA ANALYSIS

Table 1 and Figure 3 show data on design work collected from a HVM fab project (Fab X). Note the extent of design work done after construction work started across the various design specialties, as well as the extent of design change work in the chemical, architectural, electrical, and instrumentation & controls (I&C) specialties.

Table 1: Work-Hours Spent in Design Work and in Design Changes (Fab X)

	Civil	Structural	Architectural	Chemical	Mechanical & HVAC	Electrical	Life Safety Systems	Instrumentation & Controls	Telecom
Programming	680	110	310	660	290	340	300	230	240
Design Before Construction	2994	2883	10548	14626	11955	10711	2944	4864	2892
Design During Construction	1137	1340	2824	4773	4433	3837	2135	3338	1967
Total Design Work	4811	4333	13682	20059	16678	14888	5379	8432	5099
Design Change Work	1716	417	2805	4993	1723	3213	794	2622	1309
Design Change as a Percent of Total Design Work Hours	36%	10%	20%	25%	10%	22%	15%	31%	26%

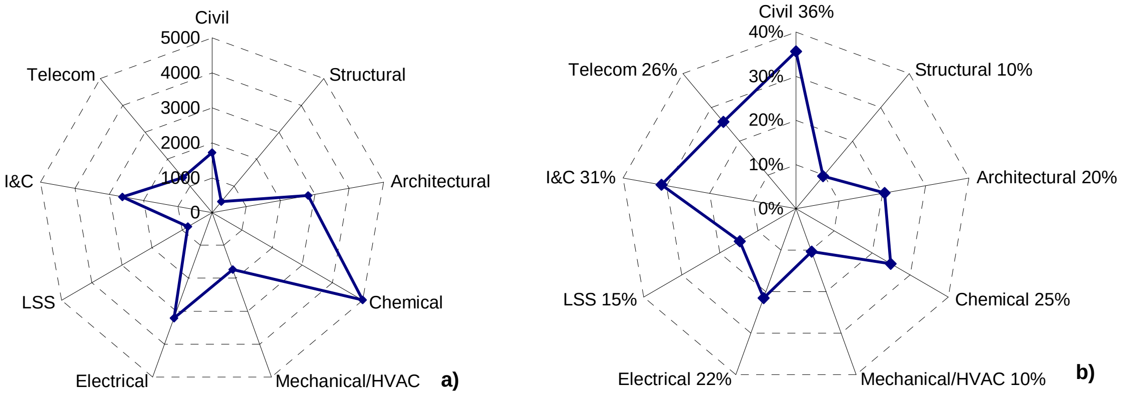

Figure 3: Design Change (a) Work-Hours per Specialty and (b) as Percentage of the Total Design Work for that Specialty

COPING WITH CHALLENGING PROJECT DELIVERY

Product Flexibility

Product flexibility is the ability of the product design to accommodate changes in design criteria that may occur after the design has (supposedly) been frozen. The following two managerial strategies implement this principle:

Strategy 1: Overdesign the Product

Designers may overdesign by choosing equipment at the high end of available alternatives because they expect design loads to increase but acknowledge that it is hard to predict when exactly increases will happen and what their precise magnitude will be. Likewise, designers may oversize cross-sections of utility routings or allocate empty space in the subfab to accommodate future increases in support equipment or changes in the tool layout in the cleanroom. Designers believe that fabs with extra capacity will more easily accommodate changes that result from the tool R&D processes and from the tool conversion cycles, and that those fabs will endure a longer operating lifecycle.

Example: Decouple Areas of Product Design

The overdesign strategy translates into three fab design types: decoupled, coupled, and semi-coupled. In a decoupled fab, designers keep constant the features of the facility 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 give the client the flexibility to later change design criteria, such as swapping the location of functional areas in the cleanroom, without being constrained by the facility's characteristics. Design features 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 will change less and, in particular, assume that the cleanroom functional areas will not move. As a result, they tie design features to each functional area. For instance, a functional area where tools for lithography will be located requires more stringent vibration criteria than others such as etching. This difference affects the thickness of the waffle slab, the spacing between subfab columns, and eventually the height of the subfab.

A semi-coupled fab exists in-between these two extreme types: designers assume the functional areas with more stringent design criteria will not move, and they design accordingly. For the remaining areas, designers decide conservatively on the design features, excluding the stringent criteria associated with the areas they assumed fixed.

Strategy 2: Intensify Communication between Project Participants

Practitioners found that effective communication helps project participants to predict which late changes are likely to occur and thereby to make more adequate design allowances in anticipation. Once changes happen, good communication helps to flow information quickly to whom it matters and thereby to minimize the detrimental impact late changes could possibly have in the work already done.

Example: Promote Meetings

Start-up meetings are a way to help project participants sharpen their ability to anticipate likely changes in design criteria. For example, during the initial stages of developing a new fab concept, a client promoted several meetings between designers, contractors, suppliers, and users of existing fabs. On-going coordination meetings also facilitate sharing of information throughout project development. In another fab project, on the client'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 (a person in charge of keeping the schedule for the tooling phase updated with the requested tool dock dates) 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 a start-up coordination meeting. Start-up 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 weekly update the schedule with the dock dates, and inform the construction manager who in turn was responsible for sharing the information with contractors.

DRAWBACKS IN IMPLEMENTING PRODUCT FLEXIBILITY

The designers we interviewed almost 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 strategies used to implement this principle however have drawbacks. First, designers overdesign primarily based on their experience and prediction of future needs. They cannot guarantee that design allowances will accommodate the hard-to-predict changes the client may request, even when the best communication procedures have been set up. For example, many changes in a fab project happen when facility operators (e.g., lab owners, tool managers) get involved in the late project stages and exercise their authority to customize the spaces that will fall under their responsibility. To preempt these kinds of changes, the owner of one project invited operators of existing facilities to participate in the early design meetings. However, these operators were not those to later work in the new facility – some of the latter operators were not yet selected or even hired at the early design stages – and as a result, many late changes still occurred.

Second, design allowances can be insufficient because the magnitude of each change is hard to anticipate. If changes occur during construction and allowances turn out to be insufficient, parts of what was built may have to be torn down and rebuilt anew. Because the remaining facility components may constrain the space of new design solutions, it may be hard at that time to find solutions that perform equally well. Especially, those changes may be costly, delay the fab delivery, and hurt fab performance.

Third, the flexibility designers embed in the 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 already included some allowances. Ultimately, designers run the risk of unknowingly developing an unnecessarily overdesigned solution. If the client later wants to lower the estimated construction cost (which frequently happens during value-engineering), designers have to cut out those allowances the client suspects are embedded in the design and does not want to pay for. New iterations and rework will then follow.

Finally, good communication does not guarantee that people have updated information, particularly in large project organizations. As an example, the previously-mentioned tool dock coordinator who was in charge of weekly schedule updates, oddly, admitted that the most reliable source of information regarding tool arrival dates were the freight carriers!

In addition, good communication procedures will not guarantee that people communicate effectively whenever they get together. As an example, we 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 get the needed information. (It is unclear if they had prepared a checklist of questions in advance of their visit so that they would know what to ask). Similar phenomena happen in meetings when people in the room fail to communicate effectively.

Despite the drawbacks of the strategies that implement a flexible product design, designers and clients acknowledge that benefits and cost savings in the long term outweigh the drawbacks. However, clients also assert that they cannot afford the extra up-front cost 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, clients and AEC practitioners together have been seeking to make the delivery process more flexible.

PROCESS FLEXIBILITY

Process flexibility is the ability to structure the project development process so that it can accommodate possible late changes in design criteria without necessitating large design allowances upfront. Project organizations implement this principle through the following two main managerial strategies:

Strategy 1: 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 (op. cit. p. 132).

Example: Modular Fab Fit-Up and Tooling

Some organizations 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 facility up to the target rates, a process that may last up to two 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 has shown 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. This practice is effective, however, only if lead times for adding tooling capacity are short.

Strategy 2: Pre-fabrication

Practitioners are looking to identify components of the building systems that can be assembled off-site and then transported to the construction site. Off-site assembly allows for increased concurrency between design and construction tasks and it can bring savings in labor hours, installation time and cost, and increased safety during assembly (Gibb 1999). Pre-fabrication supports a more flexible development process because alternative designs can be developed upfront but the choice of one design and the start of the assembly process for that design can be postponed until design criteria are more certain.

Deciding to pre-fabricate building components is not, however, a trivial decision. Once a component is pre-fabricated, it is costly to change it. The pre-fabricated module also needs to interface correctly with the structures on site. Tolerances for the pre-fabricated components and for the connecting structures must be mutually adjusted. Pre-fabricated modules need to be protected from damage during transportation, which may translate in a need to over design some features. Still, the high-tech building industry is increasingly adopting pre-fabricated solutions.

Example: Pre-fabrication of Clean Room Plenum
In a recent project, 560 modules for the clean room plenum of the fab were pre-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. Pre-assembly 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 shop fabrication of the modules and in their ease of installation. The performance quality of this solution was considered higher because of better conditions available in the shop to carry out work such as welding. The solution has been patented and can be applicable to future projects (Panelli *et al.* 2003).

FINAL COMMENTS

This study presents two complementary principles ─ product and process flexibility. Their usefulness is illustrated by applying them to structure an analysis of various strategies employed in the delivery of fab projects. The analysis yields understanding on the purposes served by the various strategies and on how they complement each other. Clearly, the list of strategies studied here is not exhaustive ─ the increasing use of Information and Communication Technologies (ICT), for example, was consciously left out for the sake of brevity.

It is worth noting that although fabs are unique high-tech buildings, the main delivery factors ─ design complexity, speeding up project delivery, and changing design criteria along project delivery ─ are increasingly common in capital projects. This study clarifies the importance of implementing strategies that embody both principles for delivering challenging projects. Project managers may find it useful to employ the theory when choosing the strategies that best suit other challenging projects.

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