Design Reuse and Buffers in High-Tech Infrastructure Development: A Stakeholder Perspective

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***Abstract*—This study investigates the implementation of design reuse and buffers in developing the infrastructure of high-tech production facilities *Design reuse* entails using the same systems architecture from one project to the next. *Design buffers* involve building slack into a proven systems architecture to absorb foreseeable change requests. Choosing the appropriate amounts of reuse and slack is dependent on the uncertainty in the manufacturing technology over the infrastructure life cycle. While proven infrastructure designs can economically accommodate incremental changes in technology, adaptation costs escalate when sufficient buffers are not built-in and changes are radical. We uncover opposing stakeholder interests in determining the extent to which reuse or buffers are used. Design reuse is attractive to the client to reduce the risk that a facility fails to perform, but limits the designer's job to tedious customization work. Design buffers are attractive to the designer to do original problem-solving and limit the risks of being unresponsive to uncertainty, but not to the client who is not guaranteed that the investments will pay off. We find that inequalities between the two stakeholders in the governing power on design decision-making compound the difficulties in assessing and implementing the reuse versus buffers tradeoff.**

***Index Terms*—Design buffers, design reuse, infrastructure development process, project stakeholder management.**

I. INTRODUCTION

FEW ideas are more central to the literature on the management of large engineering (capital) projects than the notion that the client—the business or governmental institution that governs the project [7]—needs to invest time and effort upfront defining design requirements [4], [46]. As Morris [43] suggests "The history of the management of projects has demonstrated consistently the importance of a *comprehensive definition* of the project, and of spending time *planning at the 'front end*'" (p. 221, emphasis added). To improve project performance in terms of product design quality, development effort, and lead time, clients are exhorted to: invest in "careful" project definition and task planning [43], analyze risks and opportunities [40], work collaboratively to develop the project "mission" [66], and involve end users at the onset [11]. A critical focus of this work is contingency planning for the variety of environmental uncertainties that may beset the project. Uncertainty denotes factors poorly described by quantifiable probabilities [33].Uncertainties are foreseeable when decision-makers know and can speculate about the factors beforehand, yet cannot say exactly if and when they will occur [59].

Scholarly analyses suggest that developers complement instructional or prescriptive recommendations (e.g., risk management, task scheduling, scenario planning, stochastic networks) with other strategies when uncertainty, size, and complexity are important contingencies [13], [45], [59]. When flexibility is needed to respond to novel situations and adjust under uncertainty, developers need to combine trial-and-error learning, i.e., the capacity to replan [59], with set-based exploration. The latter involves the pursuit of multiple candidate solutions that gradually narrow to converge to a single-point solution [58]. Trial-and-error learning is preferred when problems are novel, designs can only be imperfectly tested (e.g., through simulations, mock ups, prototypes), and rework costs are low [59]. Another stream of literature focuses on the organizational aspects of managing under uncertainty. It encourages project organizations to develop capabilities to cope with inevitable changes [19], [30], including cross-stakeholder communication [7] and integrated governance [10].

Our study adds to the literature an empirical investigation on the implementation of two other strategies for managing project definitions under uncertainty: design reuse and design buffers. *Design reuse* here means to repeatedly use the systems architecture of an infrastructure in developing subsequent production facilities. The reuse of proven solutions is attractive to reduce uncertainties and the risk that complex facilities fail to perform, as well as to speed project delivery. The application of design reuse is well known at the component level—some component specifications in Toyota have not changed in 12 years [64] and Rolls-Royce engines repeatedly reuse well-understood technology [44]. Yet, we know little about how to efficiently scale it up. This is an important problem as global manufacturers seek to reuse proven infrastructure designs to build enterprise resilience, i.e., flexibility to speedily ramp up and return to normal performance after a disruption, such as an earthquake, a terrorist attack, or a change in technology [52]. If facilities around the world have "identical" infrastructures, it is easier to transfer know-how and staff across because less retraining of staff and process requalification are required.

On the other hand, *design buffers* aim to build slack in the systems architecture of a proven infrastructure to lessen or absorb the impacts of foreseeable changes in design requirements during and after project delivery. The tradeoff between sacrificing optimality in the present to reap the benefits of cheaper rework in the future is again well known at the

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Manuscript received January 1, 2006; revised August 1, 2006. Review of this manuscript was arranged by Department Editor J. Pinto. This work was supported in part by the Fundação para a Ciência e Tecnologia. The work of N. Gil was supported by the Fundação Luso-Americana para o Desenvolvimento.

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Digital Object Identifier 10.1109/TEM.2007.900805

component level [14], [52]. Tolerance margins, or buffers, are systematically designed to absorb the resolution of problems that developers may anticipate but project complexity makes it hard to rule them out *ex-ante*. Buffers are especially effective when the cost of building extra component capacity is low versus the high risks of system failure [52]. In helicopters, for example, up to 25% reserve margins can be added to the specifications of key components to accommodate late changes in resolving vibration problems without impacting interdependent systems [14]. Likewise, buffers are built into the systems architecture of complex infrastructures to lessen the impacts of future changes. In extreme, buffers can preclude infrastructures from reaching obsolescence prematurely [56]. Again, we know little how to do it efficiently.

We approach our study with theory development from a multiple case-study research [16], [70], using stakeholder management literature to guide data collection and interpretation. This approach is both appropriate to study underexplored areas [16] and fully understand the context within which capital project management takes place [18]. It also allows us to circumvent the difficulties associated with collecting large quantities of hard empirical data on infrastructure projects due to client concerns with its commercial sensitivity. Each case entailed the design of the infrastructure for a new semiconductor fabrication facility ("fab") project.

We find that the right balance between implementing design reuse and buffers is contingent on the degree of foreseeable uncertainty in the manufacturing technology at the project outset. Changes in manufacturing technology are likely over the infrastructure life cycle. As a result, complex physical infrastructures invariably exhibit residual capacity to ensure the infrastructure is adaptable to changes. While this residual capacity is enough to accommodate incremental changes in manufacturing technology, newly built-in buffers in the proven infrastructure definition are needed to ensure its economical adaptability to radical changes in production technology.

Less intuitively, we find that the implementation of design reuse and buffers is complicated by the ties that bind the two strategies to the legitimate but opposing interests of two key project stakeholders: the client and the infrastructure design supplier. The reuse of infrastructure designs is attractive to the client to speed up delivery, reduce risk of delays in ramp up, and build enterprise resilience. Yet, design reuse limits the high-tech designer's job to tedious customization work for making the existing designs fit the local environment and evolution in manufacturing technology. Design buffers, in turn, are attractive to the designer to engineer original solutions at limited risk in the face of foreseeable uncertainty. Yet, the client may not want to make the investments without a guaranteed payoff.

These ties make it hard for the two stakeholders to be collectively rational in making choices under urgency when one party asymmetrically holds the governing power on design decision-making, even if the parties are engaged in a long-term relationship and trust each other. Our findings on the deleterious effects of inadequate strategic implementation on the performance of the infrastructure project suggest that the client and designer need to work better together to reconcile their interests. This involves acknowledging conflicts of interest upfront and setting joint policies for decision-making on design reuse and buffers.

The rest of the paper is organized as follows. We first describe the application of the stakeholder management research to the study of projects (Section II) and our research methods and setting (Section III). We, then, present an empirical analysis of adopting the two strategies across three projects (Section IV), and summarize the insights in a conceptual model (Section V). Finally, we discuss the limitations of the study (Section VI), outlook (Section VII), and the contributions to theory and practice (Section VIII).

II. THE APPLICATION OF STAKEHOLDER MANAGEMENT RESEARCH TO PROJECT MANAGEMENT

Stakeholder management research [61] has its roots in Freeman's [22] work on the impact on corporate performance of managing stakeholders. A stakeholder is "any group or individual who can affect, or is affected by, the achievement of the organization's objectives" [22, p. 46]. At the core of stakeholder management work is the notion that "economic value is created by people who voluntarily come together and cooperate to improve everyone's circumstance" [23]. The job of the firm is to manage and reconcile the conflicts between divergent interests of stakeholders [29]. "Stakes" are a share in an undertaking that can range from a simple interest to a legal or moral claim of ownership [2]. Stakeholders are driven by the utility of their actions in helping them to achieve their interests [48].

Stakeholder analysis involves three steps: 1) identify role-based stakeholder groups; 2) determine interests of individuals within each group; and 3) evaluate the type and level of stakeholder power [42]. Role-based stakeholder groups are defined by shared self-interests (e.g., wages, job security, and satisfaction) that homogenize attitudes, concerns, and priorities of individuals in the group. Groups are made less homogeneous when interests are influenced by "symbolic predispositions" or learned affected responses to symbols acquired early in life (e.g., prejudices, basic values) [31], [49]. Stakeholder analysis is most valuable when role-based stakeholder groups can be found in which the individuals perceive their stakes similarly [67].

The power of a stakeholder involved in a relationship with a firm refers to its capability to exert influence on the firm to act in a prescribed way, whether or not there are legitimate claims [42].[1] The stakeholder can be internal to the firm, such as a group of employees, or external, such as a supplier. Power inequalities when stakeholders' interests conflict increase the likelihood of reduced cross-stakeholder synergy and creativity [28]. Power inequalities can coexist with relationships exhibiting positive levels of trust [26], [27]. Trust is based on fair dealing and sense of reciprocity. It manifests confidence that 1) the behavior of another will conform to one's expectations and 2) that another will act in goodwill [47]. Yet, trust does not imply that outcomes be divided equally between parties [27].

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[1] This builds on Weber's notion that in a relationship among social actors, power is the probability that one actor, A, can get another actor, B, to do something that B would not have otherwise done.

The purpose of stakeholder research—to understand and inform corporate governance and management—applies readily to project management [7], [8], [66]. Role-based stakeholder groups include the project client, (design) suppliers, institutional agencies, and local communities. The notions that "firms should treat stakeholders as ends" [31] and that "the interests of all legitimate stakeholders have intrinsic value" [6] equate to the notion that the reconciliation of stakeholders' interests can impact project performance positively. The increasing growth in partnering efforts, such as engaging project participants to get together in informal settings and in collectively agreeing and signing off a project charter, denotes one way as to how clients can promote a culture of collaboration to help stakeholders reconcile their interests [35].

Our study focuses on two role-based stakeholder groups common in capital projects: The client who commissions the work, invests capital, and may select the first-tier suppliers, and the engineering design supplier who delivers the work through a "social process" that inherently involves changes, negotiations, ambiguity, and uncertainty [1, p. 187]. We know little about this multifaceted client–designer relationship in capital projects although fewer and fewer clients keep capabilities to design infrastructure in-house.

Both stakeholder groups are primary stakeholders, i.e., ones without whose ongoing participation, the organization cannot survive [6]: a project organization would have difficulty progressing if it lacked either the client's capital or the design supplier's know-how. The client holds an equity stake and, thus, has direct ownership of the project output. The design supplier receives contractual fees for its services and is professionally liable, so also holds an economic stake but not necessarily an ownership interest. In our research, we can claim relative homogeneity of priorities across individuals within each role-based group because of the shared economic and equity stakes [67].

Clients of capital projects are high on the three dimensions of Mitchell *et al.*'s [42] theory of stakeholder salience. First, the claims of clients are legitimate because of the damages they suffer if the project goes wrong. By definition, stakeholders perceive legitimate claims as proper and appropriate within some socially contracted system of norms, values, beliefs, and definitions [65]. Second, clients' claims are urgent because the project goals can be irremediably compromised if suppliers fail to meet them in a timely fashion [43]. Third, clients of big projects have a lot of clout stemming from their knowledge of the business, such as undisclosed budget contingencies and program float. This makes clients a definitive stakeholder—they have a clear mandate to attend and give priority to their claims [42].

Design suppliers are high on only two dimensions of stakeholder salience: first, their claims are legitimate because they contribute know-how and skilled resources that the client cannot easily replace. Second, their claims are urgent because project goals can be irremediably compromised if the client does not attend to requests to allocate more resources or freeze the design in a timely fashion [43]. Yet, design suppliers—like most small suppliers to big corporations [37]—lack governing power. Thus, suppliers have limited capability to exert influence on another firm to act in a prescribed manner [27]. The relative powerlessness of design suppliers makes them dependent stakeholders—their claims are legitimate and urgent, yet they have little power to enforce their will [42].

We next introduce the setting in which we apply the stakeholder lens to longitudinally examine the relationship between a client and its infrastructure designer across three projects.

III. METHODS

We developed theory through a longitudinal multiple-case study research [16], [70] in the semiconductor industry. Constructs from stakeholder theory served as a template to iteratively collect and make sense of case data [25], [60]. The embedded units of analysis are decisions to reuse proven infrastructure designs for new high-tech facilities without building in new buffers in the systems architecture. Infrastructure design includes the base-building systems (e.g., foundations, steel/concrete structure, cladding, and roof), the utility systems (e.g., chemicals, power, water), and the tool installation systems necessary to hook up the chip manufacturing equipment (tools) to the utilities. Fab development goes through multiple cycles until the infrastructure and tools are integrated into a single operating system [55].

We followed a "replication logic" analogous to that used in multiple experiments to penetrate the logic behind observed process phenomena without betraying the richness and complexity of the data [70]. The choice of the cases follows the methodological guidelines for building theory from case study research, which recommends building a small sample along a range of "polar types" [16]. The repetitive nature of the problem combined with our window of opportunity to collect data enabled building three in-depth case stories about what happened and who did what when [34]. The sample includes one case about the development of a new fab infrastructure slated to receive a radically new generation of tools, and two follow-on cases (one within the same country and another offshore) about the development of fab infrastructures targeted to first receive tested tools and convert later to the new technology. We limited the study to the analysis of two stakeholders' viewpoints. While we acknowledge that other perspectives could contribute to deeper understanding of the empirical observables, it would be hard to feature more stakeholders without losing depth—a tradeoff inherent to qualitative studies [68].

A. Research Setting

Our study examines three projects to design fab infrastructures (Alpha, Beta, and Gamma) commissioned by a chipmaker (the Client) from a design supplier (the Designer). The Client was a global player that developed chip manufacturing processes in technology development fabs and then rolled them out to high-volume manufacturing fabs. The Designer was a much smaller company—albeit a recognized leader in its sector—that supplied the designs of fab infrastructures for process-intensive technology industries.The Client had been commissioning infrastructure designs mainly to the Designer for more than 10 years, whereas the Designer worked for more than ten chipmakers.

TABLE I
SUMMARY OF THE ALPHA, BETA, AND GAMMA INFRASTRUCTURE DEVELOPMENT PROJECTS

Project Case	Facility Purpose	Facility Location	Technological Uncertainty in Production Technology (†)	Reuse of Proven Infrastructure Designs	Buffers in the Proven Infrastructure Design
Alpha	Technology development	Home country	Super high: infrastructure receiving the new generation of 300 mm-wafer tools, some still under development (§)	High, reuse of the key parameters in the systems architecture of the 'old' fabs, e.g., cross-section, cleanroom layout, subsystem capacities	Little, e.g., no extra space in the basement, few spare valves per pipe length, no additional height in the cleanroom or subfab.
Beta	High-volume Manufacturing	Home country, but different city	High: infrastructure first receiving the latest developments of 200mm-wafer tools; prospect to convert manufacturing lines later to 300mm-wafer tools	Extreme, the infrastructure design should *literally* reuse the Alpha design documents	The same as above
Gamma	High-volume Manufacturing	Overseas	High: infrastructure first receiving the latest developments of 200mm-wafer tools; prospect to convert manufacturing lines later to 300mm-wafer tools	Extreme, the infrastructure design should *literally* reuse the Alpha design documents	The same as above

(†) We follow Shenhar and Dvir's (1996) classification in terms of level of technological uncertainty
(§) Wafers are silicon-based discs on which semiconductors are etched and cut into individual chips. The radical change toward wafers with a diameter of 300mm offered 240 percent more chips per wafer relative to the current 200mm-wafers, estimated to give a 30% cost advantage over smaller wafers.

Alpha involves the development of the infrastructure for a new technology development fab, reusing the key parameters in the systems architecture of the "old" fabs. Beta and Gamma involve the development of the infrastructures for high-volume manufacturing fabs, literally reusing the Alpha design documents (Table I).

Four contextual factors are intrinsic to infrastructure development projects: the technical complexity of the design definition, the urgency to complete the design, the high-reliability targets for the infrastructure performance, and the pressure to reduce the costs of physical delivery. Fab projects as a whole represented a \$1.5–2-billion (2000 prices) investment, about 80% of which went to procure tools; 10% to build the fab infrastructure (base-build and core utility systems); and 10% to hook up roughly 150 tools and support equipment (see Fig. 1). At the time, chipmakers sought to deliver fabs in less than 16 months elapsed time from groundbreaking to first full loop of wafers out, with a target of 99.5% operational reliability [50].[2] Fast delivery enabled chipmakers to reach market first with new products, preempting competitors and benefiting from higher selling prices. To avoid losses of market share and financial penalties, chipmakers were keen to avoid the delays to ramp-up production in the technology development fab and to scale up the operations in the high-volume manufacturing fab [61].

Evolution in the manufacturing technology was necessary to fulfill the basic premise in the technology roadmap for semiconductors. This premise, termed Moore's law, recommended doubling the number of functions (or transistors) per chip every 1.5–2 years to reduce the cost per function and promote market growth for faster integrated circuits [50]. Radical changes were associated with increasing the diameter of the wafers and happened in a 10–15-year cycle: the transition from 150 mm- to 200 mm-wafer tools occurred in the late eighties, and the transition to 450 mm-wafer tools was already planned for 2015. Incremental changes were associated with the introduction of new technologies that further shrunk the width of the line circuits. The latter changes were ongoing to the extent tool sets were completely replaced after 4 years on average. However, fab infrastructures were constructed to last at least 20 years.

Technological uncertainty in the tools was "super high" [54] in Alpha as the infrastructure would be part of one of the first fab projects worldwide leading the industrial transition from 200 mm- to 300-mm-wafer tools. Thus, the manufacturing technology hardly existed at the outset of the infrastructure development process. Technological uncertainty was high in Beta and Gamma because the 200-mm-wafer tools used newly developed copper-based metallization technology to shrink line

[2] Defined as [(total hours/year of operation) − (total hours/year of utility interruption) × (outage or out of specification)] divided by [(total hours/year of operation)].

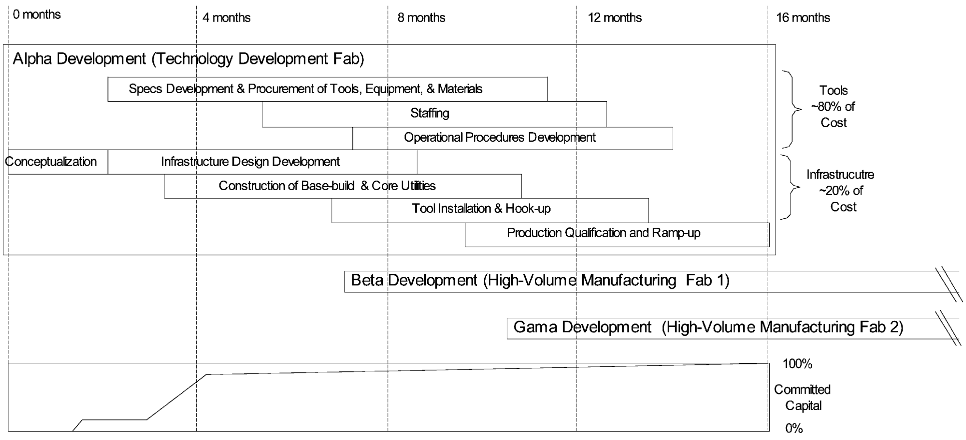

Fig. 1. Target planning timeline for the client capital expansion program.

circuits from 0.18 μm (current) to 0.13 μm. Beta and Gamma also had the additional uncertainties of local customization.

The delivery of a fab infrastructure started off with a conceptualization stage during which the Designer was instructed to reuse existing documents for compiling a planning report, including site facts, design criteria, schematic drawings and specifications, tool layouts, utility matrices, cost estimates, and a delivery schedule. After the Client approved the report, the infrastructure design was developed using computer-based simulations and computer-aided design (CAD). Design work was broken down into more than 15 work packages, such as excavation, steel/concrete structure, cladding, utilities, and cleanroom partitions. These packages were released gradually allowing design, off-site manufacturing, and on-site construction to progress in parallel. Concurrently, Client teams developed specifications to procure the tools, support equipment (e.g., pumps, boilers, gas cabinets), the automated system to handle wafers, and materials (wafers, spares, and consumables); other Client teams proceeded with staffing arrangements and development of the future operational procedures. Tools were docked on site once the construction of the cleanroom was advanced enough so tools could be moved in and hooked up to the core utilities.Tooling overlapped, in turn, with the ramp-up stage during which the Client troubleshot and ramped up production to reach the target yields.[3]

B. Data Collection

We undertook the field study between January 1999 and August 2001. In 1999, the industry went through the last year of a slump in market demand for chips that forced chipmakers to defer capital projects. In 2000, the industry started off with a nearly 30% growth rate that led chipmakers to step up plans to deploy new fabs. By December 2000, however, growth had slowed to just 2%, which led chipmakers to put some fab projects on hold again (Designer's Alumni Bulletin, 2001). This was a typical pattern for an industry long characterized by the overlay between short up and down cycles of market demand with sharp and discontinuous changes in technology, competition, and government regulation [15].

Field research included three 1-week visits to the Designer's main office and two summer internships by one of the authors over 30 months. The first internship took place on the Alpha site where a team of designers developed the core utility and tool installation designs; the second internship took place at the Designer's main office where two teams of designers reused the Alpha documents to develop Beta and Gamma. Three senior members of these teams, who we identified through a network of personal relationships, acted as "key informants." Our strict data collection protocol involved transcribing all the interviews, organizing the transcripts into a database, and organizing case write ups. We conducted 52 formal semistructured interviews with 22 design representatives and 10 client representatives; each project was discussed with at least three Client and five Designer representatives. Interviews lasted approximately 1–2 h, and respondents were assured of the confidential nature of the study to respect commercial sensitivities.

We handled the issues of construct validity by interviewing three categories of respondents: 1) client decision-makers, including facilities, operations and project managers, and administrators of the capital program; 2) design managers with a broad view of the entire infrastructure development process and change impacts; and 3) design leads with deep knowledge of one system and some understanding of the interdependent systems. To reduce the risks of chance associations and systematic biases, we interviewed design leads across five key specialties: chemical, architectural, structural, electrical, and mechanical.

We handled the issues of internal validity by triangulating interview data against archival documents and site observations [32]. We used different methods to collect field- and post-field data: we attended project meetings and collated clippings from professional publications and press releases, and examined archival data, including project briefs, proposals and reports, design drawings and specifications, and meeting minutes. We were given access to a digital log of design changes for the Beta project. We also gathered data ethnographically by observing project participants in work routines, shadowing design leads/managers, and holding innumerous spontaneous conversations [69].

[3] Yield refers to the percentage of product that starts through the manufacturing process and goes all the way through without incurring defects.

TABLE II
EFFECT OF THE FORESEEABLE UNCERTAINTIES ON THE THREE INFRASTRUCTURE PROJECTS

Uncertainties	Alpha	Beta	Gamma
Chip Market Fluctuation	Downturn in market demand for chips led to interruptions to infrastructure work in 1998	Business case robust enough to respond to sharp variations in projections of market demand for chips - progress was unaffected	Market downturn at end of 2000 put infrastructure work on hold; tooling strategy was later changed to 300mm-wafers with 0.09-micron line circuits
Technology developments	Actual tooling costs escalated 75% in relation to budget due to difficulties in installing the new 300mm-wafer tools	High number of design change requests to adapt the proven infrastructure to new installation requirements associated with incremental evolution of 200mm-wafer tools; designers expressed concerns that the conversion to 300mm-wafer tools would be difficult	
Local customization	This was not an issue because the new design reused 'old' infrastructure designs from fabs at the same location	High number of design change requests to adapt the Alpha documents to different site-specific conditions	High number of design change requests to adapt the Alpha documents to different country- and site-specific conditions

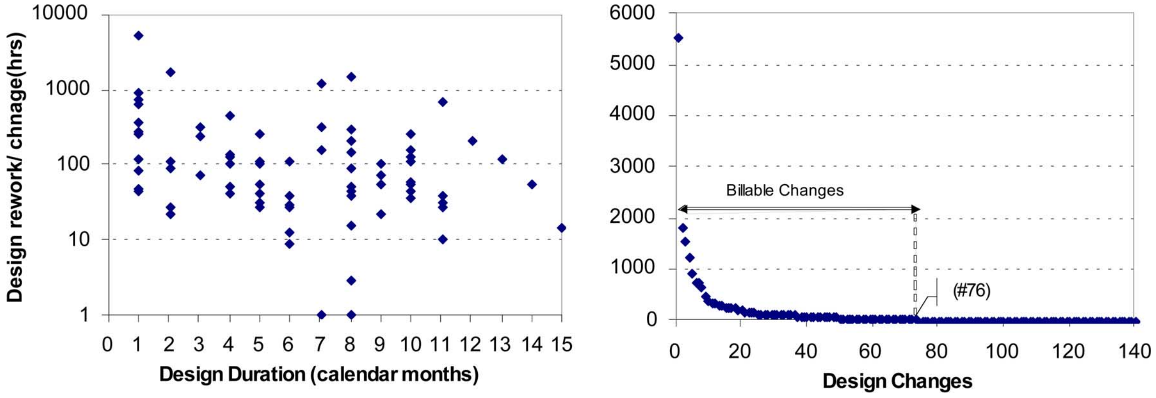

Fig. 2. Changes to customize beta design documents to site-specific conditions in (left) chronological sequence and (right) ordered by rework impact. Each dot represents the cumulative rework impact stemming from a design change across all design disciplines.

We used open coding techniques to analyze the database: our final list of codes—labels for assigning units of meaning to data [60]—was generated iteratively as we reviewed the database. We started off with a list of high-level aggregated codes generated from previous studies in project management (e.g., flexibility, rework, redundancy). This list was complemented with inferentially-meaningful codes in terms of stakeholder interests (e.g., meet life-cycle needs, uncertainty adaptation, original problem-solving), which emerged from the first reading of the respondents' descriptions. We then cycled between rereadings of the interview transcripts and archival material specifically for codes, and development of the cross-case displays of exemplars [39]. We used Microsoft Word to annotate the original data files, and cut and paste quotes into matrices in new documents—the codes were organized in rows and the cases in columns. Early in this process, we temporarily decomposed the data coded in the matrices between conceptualization and design stages. In a subsequent cycle, we partitioned the codes that were conceptually inclusive of too many differentiated instances (e.g., flexibility) into more descriptive subcodes (e.g., design reuse and buffers). This systematic process enabled us to identify patterns, remove ambiguities, answer the questions emerging from the coding effort, and develop a graphical model of the theoretical propositions. We checked the theoretical validity of our work by: 1) making cross-case comparisons; 2) engaging the second author (who was kept blind about the original coding) in cross checking the tabular and graphical displays; and 3) presenting and discussing the emerging conclusions with practitioners and academics. Figs. 1–2 and Tables I–IV present a summary of compelling exemplars, which we picked from the final matrices to illustrate the discussion in the next sections.

IV. DATA ANALYSIS

A. *Foreseeable Uncertainties in the Fab Infrastructure Development Process*

We identified three main sources of foreseeable uncertainty in developing fab infrastructure (Table II). First, there was the cyclic nature of the market demand for chips, which made it hard for the Client to exactly predict changes in market behavior 1 or 2 years in advance. Thus, the Client would put on hold or downsize infrastructure projects when an unanticipated downturn happened, or rapidly launch a new project or scale up

TABLE III
SUMMARY OF DATA EXEMPLARS ON CLIENT INTERESTS AND PREFERRED STRATEGIES BY STAGE

		Alpha	Beta	Gamma
Conceptualization	Interest: Speed Delivery	*“If we could we would build it overnight, build like hell”* (Client Facilities Manager 2000)	*“We plan to bring this fab on line in record time”* (Client vice-president 2000)	*“It is better to have something [manufacturing space], even if it is not good enough, than nothing because it is now that it is needed”* (Client Project Manager 2000)
	Interest: Eliminate Uncertainty/ reliable design	*”We allow change a little bit because this is a Technology Development fab, but we have to start with something that is proven”* (Client Project Manager 1999)	*“If a fab design works, then we know it will still work when we reuse it”* (Client Facilities Manager 2000)	*“We reuse everything to make sure we are going to get the same yields”* (Client Project Manager 2001)
	Strategy: Reuse Proven Designs	*“This design is not substantially different from the standard design: It is still a X foot floor to ceiling height subfab, Y inch exhaust ducts, etc.”* (Design Manager 2000)	*“We did not have time to change, although we knew we were copying a design that was flawed”* (Client Facilities Manager 2000)	*“We copied problems and copied solutions, whether they were efficient or inefficient”* (Client Operations Manager 2001)
Design	Interest: Uncertainty Adaptation	*“Our tool sets and layouts have to change up to the last minute.”* (Client Programme Manager 2000)	*“We have an appetite for change and tolerate change because we started designing it [Beta] without completing the [Alpha] fab.”* (Client Programme Manager 2000)	*“We do not want to violate the notion that this is a design reuse, but we have to adapt the design to site-specific conditions.”* (Client Project Manager 2001)
	Strategy: Change Design	*“Our 2-3 inch vacuum lines turned out to be 4-6 inch, and our 6 inch exhaust lines 8-12 inch - we ran out of space and had to encroach on space reserved for other purposes”* (Tool Install Designer 2000)	*The Client requested 80% additional design (re)work: ~20,000 work-hours in site-specific changes and ~35,000 work-hours in services during construction* (Digital Log)	*“We started with a package of 1,500 drawings. It ended up that all sheets had changes because it is a different soil, different weather conditions, and different country codes“* (Design Manager 2001)

an ongoing project in the face of an upturn. The financial crisis of 1998, for example, triggered a downturn that put Alpha on hold. Late in 1999, the Client reactivated Alpha and shortly after launched Beta and Gamma in reaction to a foreseen boom for 2000–2001.

The second source of uncertainty was technology developments from both tool manufacturers and the Client’s R&D teams. Technological uncertainty was especially high in Alpha. The Designer and Client anticipated radical changes in the development of the 300-mm-wafer tools, including increases in utility consumption rates, height, and footprint area. They also anticipated needs for new utilities and for an automated wafer handling system (boxes full of 300-mm wafers were too heavy to be transported manually). The overlap of Alpha with the development of the new generation of tools made it hard, however, to plan for these changes: many vendor equipment data sheets were still not available, some tool suppliers were not yet selected, and tool suppliers’ nondisclosure policies could make it hard for the designer to gather preliminary information.

The third source of uncertainty was late requests from the Client end users (fab operating and maintenance staff) to customize the infrastructure design to different country- and site-specific conditions. The Client invited prospective end users to attend conceptualization and design meetings and provide feedback, but end-user attendance was not guaranteed if they perceived limited opportunities to influence design decision-making at that stage. The Client also invited end users from other fab sites, but they often had limited input because they lacked know-how about the site- and country-specific legislation and practices. We next examine the ties between the two role-based stakeholders’ interests and implementation of design reuse and buffers.

B. Client Preference: Design Reuse and Then Adaptation to Uncertainty

At the conceptualization stage, the infrastructure development process was driven by the Client’s interest to *speedily develop a reliable infrastructure* (see rows 1–3 in Table III). The Client reckoned that the benefits stemming from reusing proven designs—eliminate uncertainties and speed conceptualization—outweighed the rework penalty at the design stage, i.e., it would rather rush and be wrong [36]. The complexity of the infrastructure—with a large number of interacting variables, difficulty identifying and measuring the relationships among the variables, tight tolerances, and integral systems—limited the Client’s ability to predict the effects of changing the systems architecture on the time and effort later required to ramp up production. Hence, to attempt to match the inputs (e.g., utility flows, temperatures, pressures) between fabs, the Client

TABLE IV
SUMMARY OF DATA EXEMPLARS ON DESIGNER INTERESTS AND PREFERRED STRATEGIES BY STAGE

		Alpha	Beta	Gamma
Conceptualization	*Interest:* Meet facility life-cycle needs	*"I would have liked to design a fab to accommodate tool replacements."* (Design Manager 2000)	*"I wrote a memo to prevent repetition of some bad decisions, but unfortunately they are copying the warp."*(Design Manager 2000)	*"There will be a lot of pain to convert this fab to 300mm-wafer technology."* (Design Lead 2001)
	Strategy: Develop custom design	*"This design is basically the same for the last 20 years…we had a discussion early on to change and no one at the other side would even want to consider that."* (Design Manager 1999)	*"They need to make some fundamental changes [in the Beta design] but I wouldn't be surprised if it takes one or two more projects before they realize it."* (Design Lead 2000)	*"The Alpha design is our grandfather and the Beta is our father, but the assumption that you can reuse them is wrong."* (Designer Project Manager 2001)
	Strategy: Build design buffers	*"There are places where you should not try to save money, where you should build redundancy and leave safety margins to avoid future nightmares."* (Design Lead 1999)	*"We tried to reuse the design of a larger fab [instead of Alpha] but he [the Client] did not want to spend that amount of money."* (Design Manager 2000)	*"Where the client has not determined which vendor tool will be used, use the tool with the larger footprint. This will be a placeholder for a worst case tool set."* (Designer Analysis Report)
Design	*Interest:* Rework avoidance	*"We, designers, do not like change; more meetings [with the Client] means more changes and not able to make it faster."* (Design Lead 2000)	*"The Client should stop the game and work towards a more rational outcome."* (Design Lead 2000)	*"I would like the Client to commit [on the tool layout] but he never commits."* (Design Manager 2001)
	Strategy: Freeze design	*"We are constantly forcing the Client to decide at meetings."* (Design Lead 2000)	*"I want the Client to tell me if I can trust the drawings. I do not have the time to validate decisions."* (Design Manager 2000)	*"At a certain point I ask the Client to freeze the layout."* (Mechanical Designer 2001)

instructed the Designer to reuse "everything that could affect the process or how it was run unless it was either impossible to do so or there was an overwhelming competitive benefit to introducing a change," including "everything about equipment and its installation down to diameters of piping and the number of bends" (Client Policy document).

Stakeholder interests invariably change over time as projects move from birth to maturity [9], and decision-makers change rules and behaviors as they get close to achieving their goals [3]. The three cases "literally replicated" [70] this theoretical pattern of dynamic change. As the infrastructure development process reached the design stage, the Client systematically became interested in *adapting the design to newly resolved uncertainties* (see the last two rows in Table III.) The amount of rework was contingent on whether the requests to change the design were caused by incremental or radical modifications at the source.

Radical modifications primarily affected Alpha because many requirements to install the 300-mm-wafer tools and the automated wafer-handling system were not compatible with the assumptions embedded in the "old" designs. For example, upstream cross sections of the routings for the core utilities had to increase to accommodate much higher consumptions and the floor layouts had to change to accommodate disproportionate increases in the amount of support equipment needed for some tools. As a result, the Client contracted a design team to stay on site providing "services during construction." This meant reworking the existing infrastructure documents and coordinating changes with those performing the physical work. Reportedly, the actual cost to install the tools escalated 75% in relation to the original budget.

On the other hand, Beta and Gamma were beset by incremental changes. First, there were the requests of the end users to change selected features of the Alpha documents to account for different site- and country-specific conditions, such as soil conditions, inputs controlled by local authorities (e.g., electrical voltages), and local codes/legislation. Second, there were change requests to accommodate evolution in the characteristics of the 200-mm-wafer tools (e.g., differences in size, number, and location of hookup points). While the Client pushed hard the idea of standardization through the development of jigs for the backs of the tools—"promoting the washing-machine idea" as put by a Client representative—tool interfaces were constantly evolving because global tool suppliers were not necessarily responsive only to the Client. These incremental changes rarely impacted, however, the systems architecture of the infrastructure; as a Client representative commented: "our designs have to change because of site adjacencies and relationships with manufacturing, but we are pretty rigid with the size of the box—there are things we consider crucial and do not want to touch."

It is worth noting that the cumulative impact of the incremental changes on design rework could be very high. The effort to develop the Beta design by reusing the Alpha documents, for example, was originally estimated around 4000 h in conceptualization and 70 000 h in design work. The actual effort, however, was significantly higher. First, there were 140 additional changes to customize the new documents to the Beta site-specific conditions (Fig. 2, left). While most changes were incremental (only four changes had impacts above 1000 work hours of design), 76 changes had enough impact to be billable. Altogether, the billable changes added around 20 000 work hours to the estimated design effort (Fig. 2, right).[4] Subsequent services during construction for adapting the Beta design documents to late changes in the manufacturing technology added 35 000 more hours.

Despite the extra work required to accommodate the changes, the Client did not push out the target dates for design completion, which forced the Designer to systematically work overtime under pressure. We next examine the Designer's behavior under these circumstances.

C. Designer Preferences: Buffer-Proven Designs and Then Design Freeze

Unlike the Client, the Designer was interested in developing a custom infrastructure to *best meet the fab life-cycle needs,*i.e., best solving the problem of engineering an infrastructure that remained "state-of-the-art" for at least 10 years, lasted 20 years, and could economically accommodate full replacements of each toolset every 4 years (see rows 1–3 in Table IV.) Hence, the Designer preferred to conceptualize and compare alternatives, or to some degree adopt a wait and be late strategy [36].

The know-how acquired by the Designer from working on first projects for new clients (where it found it easier to introduce technological leaps) as well as on upgrades of existing infrastructures to accommodate tool replacements gave it confidence to propose step changes in existing designs. It did so for Alpha, but the Client turned down its proposal: "Although I've done many more fabs than the Client, my opinion does not count if I cannot convince the Client. I only argue three times, because in the long term I do not want to alienate the Client. At some point I decide he is right." The Designer particularly disliked reusing "as-built" drawings and specifications to conceptualize Beta and Gamma because it replaced original problem-solving—a core expectation of knowledge workers who need, above all, challenges to get motivated [12]—with tedious work to customize the design to different site-specific conditions and evolution in tools.

Rather, the Designer preferred to make step changes and build incremental buffers in the proven system architectures (e.g., add basement space, increase the subfab height, oversize utility cross sections, and design tool installations for worst case scenarios) to limit the risk of failure in the face of foreseeable uncertainty, technical complexity, and urgency. The Designer's logic was that allowances increased the adaptability of the infrastructure at marginal cost, although it admitted "it was difficult to guess requirements that far out":

> Part of my job is to be the client's watchdog, tell the client 'your cost is driving up because you decided to do this. . ..' I do not believe the cost in over design is that much even at reasonably high return rates . . . what I was asked to save by reducing the number of valves when I did one fab, I spent in one single weekend fixing a small problem because I had to shut down two gas systems that are supposed to work 24 hours (Design Manager, 2000).

Of course, design allowances proactively helped to meet the Designer's interest in reducing rework. The Client acknowledged both the merits of buffers and its marginal cost, but it contradicted itself by prohibiting the Designer from making step changes. The Client worried that business analysts could penalize its stock price if capital infrastructure-spending appeared disproportionately high against competitors' costs. It was also cognizant of wasteful allowances made in the past when fabs "could accommodate almost any tool anywhere":

> In the past our fabs were costing anywhere between \$3,600–3,700/sq.ft when industry average was in the range of \$3,000/sq.ft. *It may have been the wisest thing to do*, but *we cannot afford* to have 30%–40% more cost than our competitors in this worldwide benchmarking environment we live in. (Client Facilities Manager, 2001, emphasis added).

On Alpha, for example, the Client opted—against the Designer's advice—to rule out some allowances, such as requesting a smaller central trench rather than a basement floor. The Client later acknowledged that the lack of buffers made the installation of the 300-mm-wafer tools very inefficient.The opportunities to engineer technological leaps in the infrastructure were even fewer at the design stage because the main features of the systems architecture were crystallized in the first design packages handed over to the trade contractors. Accordingly, the Designer shifted its interest to *avoiding rework* and to a preference to *freeze the infrastructure definition* (see rows 4 and 5 in Table IV.) The burden of putting up with tedious rework—which made the infrastructure systems architecture increasingly convoluted or "spaghetti-like"—reinforced the Designer's belief on the merit of built-in buffers.

D. Inequalities in Design Decision-Making Power Under Cross-Stakeholder Trust

The analysis of power differences is the third step in stakeholder analysis [42]. In a buyer–supplier relationship, buyers are typically more powerful because of greater relative supplier dependence [27]. Supplier dependence increases: 1) the less the buyer needs the resources or performance provided by the supplier, and 2) the more organizations are available to provide the same resource or performance [62]. Here, the client–design supplier relationship emerged as one of half-partnership, half-competition—neither party could do well without the other, but

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[4] In project management practice, "death by a thousand cats" is an expression used to refer to the cumulative deleterious impact to performance caused by a large number of incremental changes.

they had to find mutually acceptable solutions to arrive at compromise points [53].

Unarguably, the Client was committed to the more than 10-year-old relationship with the Designer; as put by a Client representative "this [fab design] is still a people's business . . . we need to like each other." Given that there were a few other design suppliers capable of doing the job, the Client's stance created in the Designer an expectation of continuity known to encourage trust [27]. Further, the Client promoted other initiatives that reinforced three key dimensions of trust: caring, openness, and reliability [38]. First, the Client cared about the welfare of the Designer by awarding other types of work to the Designer to help it through downturn periods. Second, the Client openly shared information and listened to the Designer by paying for colocating client and design teams at the project sites, for seconding Designer staff to the Client, and for visits of the Designer to tool suppliers. And third, the Client was reliable by showing consistency between what it asked the Designer to do and what it did, allowing the Designer to bill for rework hours at the latter's discretion. The rework done using overtime helped the Designer to reward its staff at the end of good years, to encourage best staff to take unpaid sabbaticals in downturns, and to get laid-off staff to come back in upturns.This also kept the Client confident that individuals would stay for the next project, a major concern given the scarcity of skilled resources in the industry: "People say 'I'm not going to do it again' but they get such a buzz: it's like drug, where else can people go with such a pressure?" (Client Director).

The investment in trust-building did not preclude the Client from systematically exercising its governing power to induce the Designer, whose fees were around \$15–20 million per project,[5] to implement the Client's strategic preferences.Indeed, all three cases systematically showed that the Client induced the Designer to do something (reuse proven infrastructure designs) the latter would otherwise not do. While inducement is a means of influence chosen when one party has moderate trust on another [26], it was a destabilizing factor in the relationship. The Designer—"a flea in the tail of the dog" as one Designer manager described it—complied to secure the resources and reputation that working with the big Client conferred, yet was not persuaded by the arguments.

The Designer was not, however, totally powerless as power differences exist at various levels of analysis [37]. It had some decision-making power around the less conspicuous, technical issues as for any knowledge-intensive professional service [12]. Hence, we found instances where the Designer built buffers, such as by overengineering the foundations and choosing to design for equipment capacities at the high end. Further, the Designer tried to persuade the Client to let it make step changes in the systems architecture of the "old" fab infrastructures: "We [the Designer] routinely present opportunities for improvement, but he [the Client] will want to stick to a proven concept unless we can prove that there are major gains to achieve . . . it's unnerving to him, it's a comfort issue." This denotes that the Client's effort to build trust paid off as persuasion is the choice of parties with a high level of trust as a means to influence [26]. The Designer's trust in the Client was perhaps best illustrated by its comfort in beginning rework immediately after tacitly receiving a change instruction from a Client manager. The Designer launched rework at risk (without a formal contract) to avoid holding the project up, knowing that the Design Change Board could take up to 5 weeks to sign off the bill.

Trust and cross communication help stakeholders to mutually understand underlying premises and blame each other less when disagreements occur [22, p. 30]. These factors were fundamental to speed infrastructure development, but they did not eliminate the power inequalities and the different views of the world. We systematically found Designer staff ignoring the raisons dêtre of design reuse, although the Client's policy documents were available on-line with unrestricted access. Likewise, the Designer did not appear cognizant that production shutdowns caused by infrastructure upgrades only had major financial penalties (around \$2.5–5 million/day) when they caused an irrecoverable loss of chip sales. As a result, the amount of design rework vis-à-vis the marginal cost of the would-be buffers left the Designer with the realization of a gap [41] between how it wished the infrastructure development to unfold and how it actually unfolded:

> We designers are desperately deluding ourselves that everything will be all right. It is not going to happen, it's a game. The client should stop the game and work towards a more rational outcome because people at the bottom of the work are getting really frustrated. It's not worth the cost (Design Lead, 2000).

The use of the stakeholder research lens helped to understand how differences in interests and power inequalities compound the difficulties in making a strategic tradeoff in a volatile environment. We next summarize our findings in a conceptual model.

V. TOWARD BALANCING IMPLEMENTATION OF DESIGN REUSE AND BUFFERS IN HIGH-TECH INFRASTRUCTURE PROJECTS

The spare capacity that complex infrastructures typically exhibit enabled the Client to repeatedly use the systems architecture of the "old" infrastructure definitions over more than 10 years. Various incremental changes inevitably had to be made to adapt the proven definition to the evolution in the 200-mm-wafer manufacturing technology. Such customization work got more cumbersome over time as the cumulative effect of incremental changes gradually exhausted the residual capacity of the original definition. This approach still worked for Beta (the Gamma fab was later put on hold), although the Designer disliked the customization work and presaged a difficult conversion to 300-mm tools.

In contrast, the reuse of the "old" infrastructure definitions contributed to the escalation of costs to install the new 300-mm-wafer generation of tools in Alpha. This suggests that there are limits to the extent a proven infrastructure definition without new built-in buffers can be efficiently reused under foreseeable radical changes in manufacturing technology.Further, the reuse

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[5] To put it into perspective, the most expensive tools reached \$10 million each (2000 prices). The Designer fees constituted a tiny fraction of the overall Designer's annual income, but were very important in the context of the high-tech subsidiary.

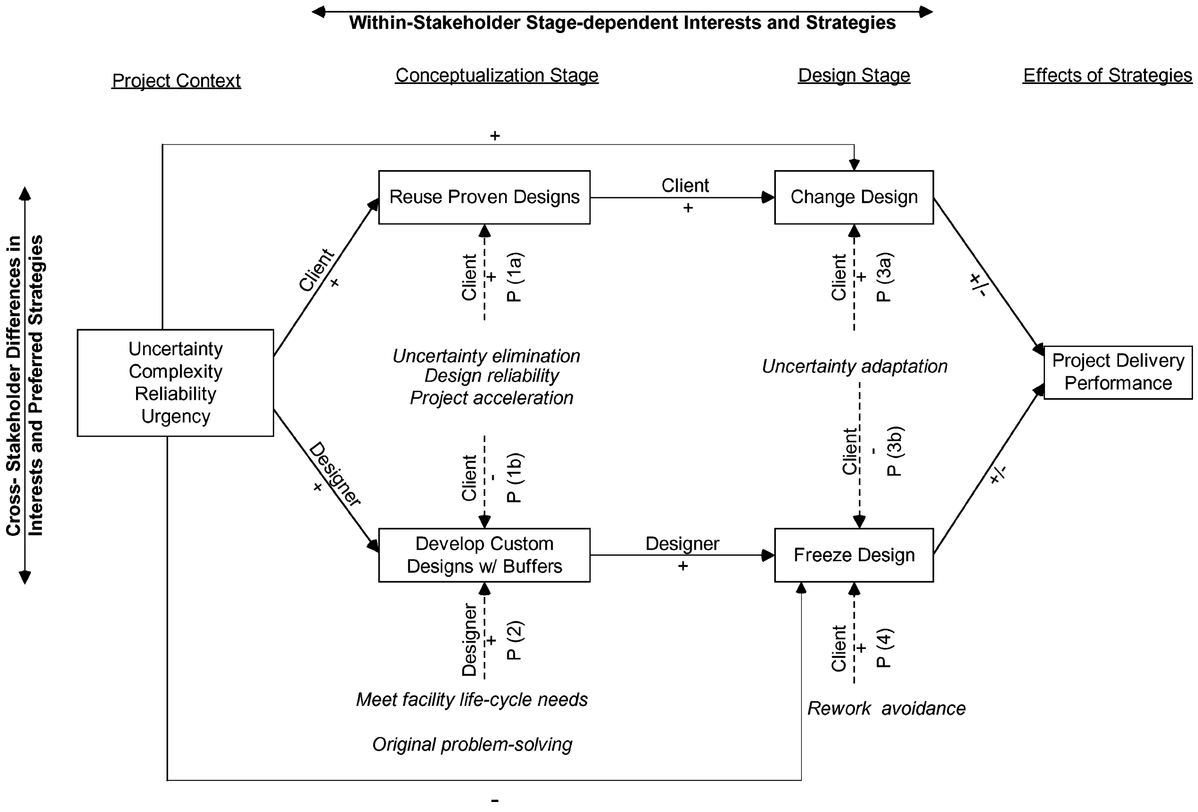

Fig. 3. Model of project stakeholder interests and preferred strategies with propositions.

of the Alpha documents across the board to develop Beta and Gamma—when the design-reuse policy exempted features of the infrastructure unrelated to the manufacturing process—systematically led to a disproportional number of late incremental changes that could otherwise have been avoided. These findings corroborate the theory grounded on component data: proven solutions offer a starting point that speeds delivery and reduces rework if design criteria are comparable, but, otherwise, provide a bad approximation and delay convergence to a solution [36]. Less intuitively, these findings show a dynamic pattern of cross-stakeholder conflict of interests and suggest preferred strategies underscoring infrastructure development, which Fig. 3 summarizes.

At the conceptualization stage, the Client instructs the Designer to reuse proven infrastructure designs due to its interests in eliminating uncertainty (as well as in guarding against operational inflexibility across the enterprise), design reliability, and accelerating the project (proposition 1a); further, the Client rules out the Designer's proposals for developing custom designs with buffers (proposition 1b). In contrast, the Designer would rather guard against the risk that the infrastructure will fail to economically adapt to foreseeable uncertainties over the facility life cycle by buffering custom infrastructure designs (proposition 2). At the design stage, the Client systematically requests changes to adapt the design to the newly resolved uncertainties (proposition 3a), ruling out a design freeze (proposition 3b). In contrast, the Designer would rather freeze the design to avoid rework and complete the job in a timely fashion without resorting to long hours (proposition 4).

This rudimentary understanding of the ties between stakeholder interests and implementation of design reuse and buffers helps improve the performance of high-tech infrastructure projects. It highlights the importance of the stakeholders working together from the outset to reconcile their interests and agree on a shared objective and cost function before implementing design reuse and buffers. Otherwise, differences in views of the world and interests married with inequalities of power greatly increase the chances that the *pendulum swings too far* to one side. When this happens, wasteful investments in redundant infrastructures can be made if foreseeable changes are incremental, or adaptation costs can escalate if proven designs without buffers are reused when foreseeable changes are radical.

VI. LIMITATIONS

Science development should seek to complement the systematic hypothetico-deductive scientific model based on large samples with theory grounded in context-dependent knowledge [20]. Cases help to develop a nuanced view of reality and to clarify the deeper causes behind a given problem and its consequences; as put by Flyvbjerg [20]: "a discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and a discipline without exemplars is an ineffective one." Building theory from case study research comes, however, with issues about reproducibility and generalizability [16], [70]. We addressed these issues by strictly adopting the methodological guidelines for qualitative research.

First, the grounding of our insights on data about a single dyadic relationship in the distinctive semiconductor industry follows recommendations to choose atypical or extreme cases because they are likely to activate more basic mechanisms with strategic importance [20]. In effect, a designer observed that the Client's "fear to move away from original concepts to avoid risks" was typical of the mature food and pharmaceutical manufacturers. Yet, case study research is generalizable to theoretical propositions not to populations [70]. Hence, we need more studies to test the external validity of our propositions in industrial sectors exhibiting different patterns of overlay between evolution in production technology and infrastructure development. We conjecture that the lack of reconciliation between client- and design suppliers' interests is likely to negatively impact the performance of new infrastructure projects.

Second, we provide enough details on the research method protocol, including the procedures we used to collect and analyze data, to enable others to reliably reproduce our study on the global client—infrastructure designer relationship. Third, we summarized the insights from our in-depth field study in an induced theoretical model. The model depicts both the conditions under which the empirical observables occurred, as well as the propositions relating the different theoretical constructs to one another. This output clearly lends itself to falsification through further hypothesis-testing as well as case study research.

VII. OUTLOOK

Our findings on the inappropriateness of reusing infrastructure designs without built-in buffers under radical uncertainty resonate with observations by high-tech practitioners that question whether radical changes have outdated the strategic reuse of manufacturing processes [61].Yet, it merits further investigating, first, how building new buffers in proven infrastructure designs would impact on the speed to ramp up production and shift production across fabs with different system architectures. Mathematical models suggest that the reuse strategy in manufacturing can still be optimal if learning is difficult (the need to overcome discrepancies between different fabs), the lifecycle short, demand growth is steep, and the level of initial knowledge is low [61]. Second, how the convoluted infrastructure designs that emanate from one rework cycle after another actually impact on the speed to ramp up and shift production.And third, how to develop and sustain common cross-stakeholder know-how in developing infrastructure for production facilities, especially when radical leaps in the manufacturing technology are 10–15 years apart.

Finally, we know little about how to organize capital client and infrastructure designers so the interests can better converge from the project outset. Client—supplier relationships, where the former holds the governance responsibility, are not rare in the computing and automotive sectors, but these suppliers primarily develop modular rather than integral designs [5], [17]. Further, the best performing enterprises in these sectors tend to keep product development, a strategic capability, in-house [17] or outsource it to integrated suppliers through strategic alliances with joint governance [10], [24]. To yield deeper insights about how to best organize and manage the stakeholders in new infrastructure development, future studies can, for example, break down the role-based stakeholder groups into smaller categories such as procurement, project managers, and the various design specialties. It is also worth exploring the intersection of the stakeholder management lens with other theories such as transactional costs and the resource-based view of the firm.

VIII. CONTRIBUTIONS TO THEORY AND IMPLICATIONS TO PRACTICE

We believe that there are four ways in which our work contributes to extant theory: First, it pioneers in-depth analysis of role-based project stakeholders. This approach adds depth to the longstanding notion of stakeholders in the project management literature [7], [8], [66] and breadth to the organization-stakeholder research tradition [22], [23], [63]. Second, it induces an important cross-stakeholder conflict of interest underscoring high-tech infrastructure development. This insight adds a new dimension to project studies on the floating of design requirements and implementing strategy [43], [55], [57]. Third, our account sheds light on how power inequalities negatively influence strategic implementation notwithstanding stakeholders' efforts to build trust. This addresses a growing number of calls for overlaying the power(lessness) dimension in studies on the performance of project organizations [7], [21]. Fourth, we shed light on how proven facility infrastructures can accommodate incremental changes in manufacturing technology, but may require step changes when foreseeable changes are radical. This complements analytical work on the contingencies for efficiently reusing manufacturing processes [61].

There is also a contribution to methodology. There are still few studies that build process theory through in-depth case study research in the world of capital projects. Clients' concerns with commercial sensitivities can make it, however, extremely difficult to get hold of statistically-significant process data. This, in turn, can put off scholars from doing research on capital projects despite their socioeconomic importance [40]. We show that although confidentiality agreements can make it hard for scholars to rapidly provide detailed stories, in-depth case research enables to theorize on the management of projects.

Finally, there are some important contributions to practice. On its own, the semiconductor industry, a world market of $213-billion sales in 2005, is already looking for the foreseeable radical change in manufacturing technology for 2010–2015. The insights here matter. More efficient resolution of stakeholder conflicts will also make the industry more attractive to the professions that develop capital infrastructure—this addresses the clients' concerns about the increasing lack of skilled resources [51]. Further, recent data tells that of over 120 high-tech chemical plants built in 2005 with price tags of $1 billion or more, one was built in the United States and 50 in China because of tax benefits and subsidies to attract investment (SAS, 2005). As global manufacturers become aware of the need to build enterprise resilience, they also need to understand how to efficiently reuse infrastructure blueprints under uncertainty.

ACKNOWLEDGMENT

The authors acknowledge Prof. G. Winch, the Associate Editor, and the anonymous reviewers for helpful comments on earlier drafts of this article. They also acknowledge the sponsorship of two confidential firms. Any opinions, findings, conclusions, and recommendations expressed in this material are those of the authors.

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