Problem-Solving Base Building under Uncertainty and Ambiguity: Multiple-Case Study on an Airport Expansion Program

Nuno Gil[1]; Sara Beckman[2]; and Iris Tommelein[3]

Abstract: This multiple-case study induces alternative strategies to coordinate the overlap of tasks to detail and physically execute base building with tasks to conceptualize the business-critical fit out. Base-building subsystems provide service space for occupancy, whereas fit-out subsystems make the space functional. Our empirical findings on problem-solving base-building design under uncertainty and ambiguity stem from a number of projects in an airport expansion program. They suggest that base-building subsystems show low sensitivity to incremental changes in fit out as their definitions are seldom optimized to eliminate slack. Yet, base-building subsystems show high sensitivity to radical changes in fit out when the architectures of the two subsystems are integral to one another. Three strategies for problem-solving base building stand out: (1) iterate design when preliminary information about fit out is ambiguous, or precise but unstable; (2) physically decouple the architectures of base building and fit out; and (3) design buffers in base building when preliminary information about fit out lacks precision but it is not ambiguous. These buffers can be designed out if uncertainties in fit out resolve favorably before starting the physical execution for base building.

DOI: 10.1061/(ASCE)0733-9364(2008)134:12(991)

CE Database subject headings: Fast-track construction; Infrastructure; Uncertainty principles; Airports and airfields; Flexibility.

Introduction

The application of the overlapped approach to the delivery of large engineering (infrastructure) projects has become common in recent years. This approach consists of freezing the design definition for the upstream subsystems of a project so as to progress them into design detailing and physical execution, while leaving the design definition for the downstream subsystems fluid. The approach aims to incorporate flexibility in the delivery process for economically adapting the downstream design to changes in the project requirements over time. Its application exploits the sequential order for delivering the subsystems dictated by physical constraints. For example, the foundation works precede the erection of the structural steel/concrete frame, and the installation of the electrical and mechanical services precedes the interior decoration. The overlapped approach is particularly appreciated by infrastructure promoters operating in business environments subject to frequent evolutions in technology, usage patterns, and customer needs (Gil et al. 2005, 2006).

The term concurrent engineering refers to a particular realization of the overlapped approach. It consists of freezing parts of a design definition so as to progress them into the detailed engineering stage, while other parts of the design definition remain fluid in a conceptual stage, i.e., it refers to an overlap between interdependent design tasks (Bogus et al. 2005, Maheswari et al. 2006). In the world of project management practice, the term "fasttracking" characterizes a situation in which the design activities overlap the interdependent construction activities (Pena-Mora and Lee 2001). Some practitioners argue that the fast-tracking approach shortens the overall project duration, but research shows that the validity of this assertion is contingent upon the efficiency of the feedback (Pena-Mora and Park 2001) and change management processes (Lee et al. 2005).

Scholars have long used analytical models to investigate the tradeoffs with the application of concurrent engineering (Krishnan et al. 1997; Terwiesch and Loch 1999; Joglekar et al. 2001). Their work employs stylized process models for the sake of tractability, which assumes a situation of overlapping two interdependent engineering design tasks. In contrast, hardly any studies explore the tradeoffs associated with overlapping interdependent design and construction tasks. An exception is Pena-Mora and Park (2001)'s dynamic planning methodology. Their work builds upon the system dynamics paradigm to help planners identify feedback processes needed to effectively handle uncertainty and develop reliable plans for fast-tracking projects. Yet, it does not investigate the characteristics of the interdependencies between the design and construction activities when they overlap. It also does not address how alternative product design architectures affect the implementation of the overlaps.

The aim of this multiple-case study is to induce a conceptual framework that spells out characteristics of the design-

[1]Senior Lecturer (Associate Professor), Manchester Business School, The Univ. of Manchester, Booth Str. East, Manchester, M15 6PB, UK (corresponding author). E-mail: nuno.gil@mbs.ac.uk

[2]Senior Lecturer, Haas School of Business, Univ. of California Berkeley, S545 Student Services Bldg., Berkeley, CA 94720-1900. E-mail: beckman@haas.berkeley.edu

[3]Director, Project Production Systems Laboratory, and Professor, Engineering and Project Management Program, Civil and Environmental Engineering Dept., Univ. of Californa Berkeley, 215-A McLaughlin Hall, Berkeley, CA 94720-1712. E-mail: tommelein@ce.berkeley.edu

Note. Discussion open until May 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on September 14, 2006; approved on July 1, 2008. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 134, No. 12, December 1, 2008. ©ASCE, ISSN 0733-9364/2008/12-991–1001/$25.00.

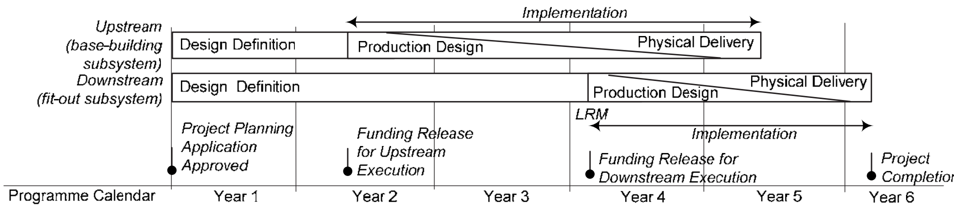

Fig. 1. Application of overlapped approach to the infrastructure development process

construction overlap problem, integrating the product and process design perspectives. Specifically, this work sheds light on four questions: (1) which are the functionalities performed by the subsystems designed in the up- and downstream tasks?; (2) to what extent are the architectures of the subsystems interdependent?; (3) at which process stages do the deliveries of the up- and downstream subsystems overlap?; and (4) which strategies help to coordinate the information exchanges needed to concurrently deliver the subsystems?

In the remainder of this paper, we first characterize the problem of overlapping design and construction tasks, and illustrate its application on our research setting. After discussing related work and the research method, we induce the conceptual framework by playing empirical data against the theoretical constructs. Finally, we discuss the implications of our multiple-case study to theory and practice.

Making Sense of Applications of Design-Construction Overlap

We borrow terminology from open building design (Habraken 1998) to make sense of observed applications of the design-construction overlap: this literature conceptualizes infrastructures as a set of "environmental level," i.e., interrelated configurations of physical elements and decision clusters that occur within a dependency hierarchy. The *base-building* level corresponds to the subsystems providing service space for occupancy, such as the foundation, steel/concrete superstructure, envelope (façade and roof), and supply subsystems (e.g., power, fresh air, exhaust, drainage, gas, telecom, water). The *fit-out* level corresponds to the subsystems creating and articulating interior space in the base building and making it functional, including wall partitions, flooring, ceiling, and specialized equipment (e.g., check-in counters, baggage screening machines). This literature also recommends that designers decouple the physical interfaces between the two levels so that the base-building subsystems can be adapted to a variety of "individual territorial claims" (Kendall and Teicher 2000). This principle aims, in part, to transfer the construction process from building to manufacturing. It also aims to promote "regenerative" infrastructures, i.e., infrastructures that can efficiently respond to transformations in the environment and enable occupants to move in and out with different fit-out subsystems over time (Habraken 1998). From this perspective, the overlapped approach can be interpreted as a project management response to the need to conceptualize "open" infrastructures that can economically cope with transformations in the environment, some of the latter likely to occur as early as in the course of project delivery. Specifically, this approach overlaps the implementation (production design and physical execution) of the base-building subsystems with the design definition of the fit-out subsystems (Fig. 1).

In our research setting, the promoter of the airport expansion program applied the overlapped approach to deliver the new, high-end terminal campus. Its aim was to create process flexibility that would allow for economically adapting the design definition of the terminal facilities to foreseeable evolutions in air products and services during the six year period it would take to deliver the new facilities. A design postponement policy allowed project managers to delay the freeze of the design definition for selected fit-out subsystems to a "last responsible moment" (LRM), while concurrently progressing with implementation for the base-building subsystems. The LRMs were defined as the latest possible dates at which the design definition for the fit-out subsystems could be frozen, without increasing the overall project costs or delaying the baseline schedule. The enactment of the policy created a number of "early overlaps" (Joglekar et al. 2001) in the sense that the design definition for the base-building and fit-out subsystems started at the same time, but the fit-out design definition continued while base building moved into implementation.

In the development of the multistory car park for the new terminal, the freeze of the design definition for the forecourt canopy on the top level of the car park was postponed about 18 months relative to the end of the design definition for the concrete superstructure. This lag allowed time for architects to generate a concept that met the design brief, which spelled out that the forecourt should have a "wow factor." Likewise, in the development of the baggage handling system, the freeze of the design definition for the baggage screening subsystem (involving around 20 machines, the more expensive ones costing $3 million each) was postponed about two years relative to the end of the design definition for the conveyor belts. Developers felt they could not reliably predict, 2 years in advance, how rapidly technology and United States legislation would move from the X-ray machines that were endorsed by the Department of Transportation toward two-dimensional (2D) and 3D CT-scanning machines.

In both cases, base-building design progressed based upon preliminary information about fit out. Preliminary information is "uncertain" if the problem solver understands enough of the structure of a situation to be able to define a range of values that will contain the final solution, but lacks the knowledge to be precise (Schrader et al. 1993). Preliminary information is "ambiguous" if the problem solver has limited knowledge both of the variables themselves and of the problem-solving mechanisms required to increase understanding of the situation. In the canopy example, preliminary information was ambiguous as the outcome of creative design processes can be genuinely unpredictable (Gehry 2004). In the baggage screening example, preliminary information was uncertain but not ambiguous since developers released a preliminary, but exhaustive, set of procurement alternatives for the baggage screening machines.

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

Related Literature in Concurrent Engineering and Modularity

This study uses two theoretical constructs—concurrent engineering and modularity—for the analysis of the empirical findings. Literature in concurrent engineering has long studied the problem of overlapping interdependent design tasks from an "information processing" view. This assumes that an information-sender task upstream overlaps an information-receiver task downstream (Eastman 1980, Clark and Fujimoto 1991, Bogus et al. 2005). This view has been supported by analytical models that investigate the circumstances under which the benefits stemming from the flexibility to change the output of the upstream design task outweigh the costs of reworking the output of the downstream design task (Krishnan et al. 1997; Loch and Terwiesch 1998; Terwiesch and Loch 1999; Bogus et al. 2005). Krishnan et al. (1997) characterized preliminary information along two dimensions: (1) "upstream evolution" refers to the speed of refining information from a preliminary set-based form to a final single-point value (i.e., slow resolution of uncertainty slows the evolution of information); and (2) "downstream sensitivity" refers to the relationship between the gradual narrowing of upstream information and the duration of the downstream iterations (i.e., a downstream task is highly sensitive when long rework cycles are needed to adapt to upstream changes). The overlapped approach is suitable when upstream evolution is fast and downstream sensitivity is low, in which case the gains in the quality of the upstream solution outweigh the cost of reworking the downstream design (Loch and Terwiesch 1998).

Interestingly, concurrent engineering studies have hardly explored the reverse situation in which the downstream task is the information sender and the upstream task is the information receiver. This is, however, a situation highly relevant for understanding the application of the design-construction overlap in infrastructure projects. Here, physical construction for the (upstream) base-building subsystems overlaps the design for the (downstream) fit-out subsystems. Releases of unreliable, preliminary information from fit-out design can generate costly rework for base building.

One way to resolve this problem is to physically decouple the up- and downstream subsystems or, stated differently, to "modularize" (Baldwin and Clark 2000) their architectures one against the other. Design architecture is the "scheme by which the function of a product is allocated to physical components" (Ulrich 1995). Product architectures that are strictly modular exhibit a one-to-one mapping from functional elements to physical subsystems, and these subsystems exhibit decoupled interfaces. In contrast, products with integral architectures include complex (many to one, one to many, or many to many) mapping and tightly coupled interfaces between subsystems (Ulrich 1995).

We next discuss how these theoretical constructs informed data collection and analysis for our research.

Research Method

The dearth of conceptual work on the construction-design overlap vis-à-vis the maturity of research on concurrent engineering (design-design overlap) motivated us to conduct a multiple-case study, a suitable method to investigate underexplored topics (Eisenhardt 1989). Case studies can also reveal contextual factors important to make sense of observed phenomena, which matters when researching the development processes underlying capital projects (Engwall 2003). We opted for a qualitative study so as to overcome the reluctance of the private infrastructure promoter to share quantitative data about design changes due to their commercial sensitivity. Our research is inductive as the insights from qualitative case studies, which lack statistical significance, poorly fit the hypothetic-deductive approach (Yin 1984, Eisenhardt and Graebner 2007). However, conceptual frameworks induced from case studies help to develop a nuanced view of reality, which contributes to advance science. As put by Flyvbjerg (2001): "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." In particular, single-setting research can lead to a "deep understanding" of a situation, helping to "see new theoretical relationships and question old ones" (Dyer and Wilkins 1991).

Our units of analysis are situations of early overlaps across four distinct projects. These units are treated as a series of experiments that can (dis)confirm emerging conceptual insights (Yin 1984, Eisenhardt 1989). We drew from constructs in concurrent engineering and modularity to iteratively: (1) collect empirical data; (2) perform theoretical coding; and (3) play emerging theory against data (Miles and Huberman 1984). We resorted to graphical mapping and tabular displays to make cross-case comparisons and test the plausibility of our conceptual relationships (Strauss and Corbin 1990). Data collection was part of a broader research program on the management of large-scale projects (Gil et al. 2008). This program involved 72 in-depth, semistructured interviews lasting 1–2 h, as well as analysis of archival documents, including clips from trade and business press, program procedures, project reports, and videos. We used semistructured interviews so as to provide respondents with flexibility to address the issues, cognizant that our constructs were grounded in the concurrent engineering problem.

Research Setting

Four projects in the airport expansion program provided the industrial context for this study (Fig. 2). Project management adopted a formal stage-gate system (Cooper 1990). The project teams could move a work package from one stage to the next after completing a set of deliverables that demonstrated "fitness to proceed." The design definition stage consisted of developing and integrating a set of functional subsystems using specialized software and a computer aided design (CAD) platform. Once the project teams demonstrated a degree of design completion and supplier involvement sufficient to support a cost and program certainty at 95%, the program administrators released funding to begin implementation. This stage included the production of shop drawings, manufacturing, assembly, and construction. Since each work package included a large number of drawings, the physical execution of the first batches of drawings happened concurrently with the production of drawings for other parts of the work package.

In the face of the 6 year lead time to deliver the facilities vis-à-vis the fast-changing nature of the needs of the project customers (e.g., airport operations and retail groups, statutory authorities, airlines), the postponement policy aimed to ensure that "time and resources are not wasted developing schemes that are almost certain to change" (as spelled out in the policy document). Table 1 shows a sample of the early overlap situations which the policy enabled.

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

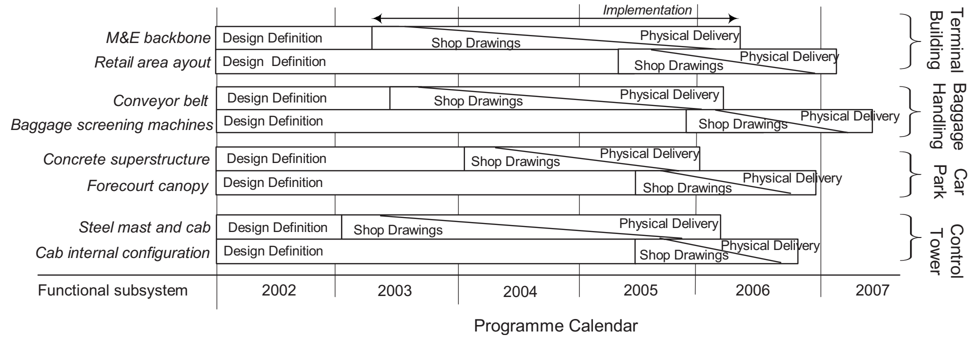

Fig. 2. High-level program for early overlapping of functional subsystems

Analysis

We start the analysis of our data by examining the patterns of the releases of preliminary information on the design of the fit-out subsystems in light of theory in concurrent engineering. We investigate: (1) the speed of evolution of downstream uncertainty (Krishnan et al. 1997); and (2) the magnitude of downstream ambiguity (Schrader et al. 1993) (Table 2). We coin the term "progressive" to characterize a process pattern in which the architecture of the fit-out subsystem is frozen early on, but the designs of the subsubsystems and components are firmed up over subsequent releases. The director for design and development explained this process:

> "The idea about flexibility of approach or 'progressive fixity' is that I'm not going to make all my decisions at the same time, but will do them in a way that gives me some certainty that the decisions are consistent with what I promised to deliver. Hence, I'm going to rank and chunk the decisions a little bit like Russian dolls. They can stagger because they work within a shell of control."

When the fit-out developers adopted this progressive approach, e.g., in the design of the layout for the retail area in the main building concourse, the speed of resolution of uncertainty and ambiguity was relatively fast for the high-level architecture (e.g., location of retail blocks and circulation areas). However, the speed of resolution slowed down dramatically for the definition of: (1) the subsubsystems (e.g., number of units inside a retail block; exact area and configuration of each unit); and (2) the components (e.g., exact building services required by each retail unit). Hence, the information releases were "precise" and "stable" (Terwiesch et al. 2002) at the high-level architecture, but the details were both "imprecise" and "unstable."

In other cases, the ambiguity in the design of the fit-out subsystems was low from the onset of development. This means that the fit-out developers had defined a set of options at the onset that remained stable throughout. This notwithstanding, the resolution of the uncertainty about the suitable option within the set could be slow. Stated differently, preliminary information could be stable but not precise (Terwiesch et al. 2002).

In one example, deciding whether to install x-ray or CT-scanning baggage screening machines (a binary set) took over three years. First, the fit-out developers wanted to wait for foreseeable changes in United States legislation; second, the fast speed of technological evolution made it attractive to procure the machines as late as possible; and third, the baggage security division of the airport was interested in aligning the configuration of the new system with that to be adopted for the systems to be installed in the other terminals of the airport, and the latter were due for replacement in 2007.

In a second example, releases of preliminary information put forward single or precise solutions which were likely to change later. The layout of the inside of the control tower cab went through 22 design versions over three years. Changes were needed to accommodate evolution in the radar technology and the feedback from the controllers who were concurrently visiting other new towers around the world and receiving training on using the new equipment in a mockup room. In this case, the developers understood that the fit-out design was prone to change, but they could not anticipate what the exact nature of those changes would be.

We next use theory in modularity to investigate the adaptation costs of the base-building subsystems.

Base-Building Adaptation Costs

When the architectures of the base-building and fit-out subsystems were integral (Ulrich 1995), the base-building subsystems were highly sensitive to radical changes in fit out as they affected the interfaces agreed upon upfront (columns one and two in Table 3). Conversely, the base-building adaptation costs were low if the two subsystems interacted in a modular fashion.

In contrast, the sensitivity of the base-building subsystems was low to incremental change in fit-out components, even when the interaction between the two subsystems was integral, because the base-building subsystems were rarely optimized to eliminate excess capacity. In effect, the base-building designers tended to pragmatically make design decisions and choices on the conservative side so as to produce solutions which lend themselves to standardization of dimensions. These uncomplicated solutions were attractive because they were easier to physically execute, as well as were capable of accommodating unexpected increases in the design loads without needing rework. For example, after the structural designers ran the computer simulations to assess the loads on each steel/concrete element, they conservatively sized the cross sections for the beams, columns, and floor plates; subsequent efforts to standardize the cross sections for constructability were again carried out on the conservative side. The rationale for this approach was explained as follows by a program administrator:

> "In a car program, the infrastructure is massively optimized because an extra few kilos of weight adds a few pounds of money and that matters massively, impacts manufacturing cost, fuel economy, safety, etc. Here, it is not worth the relationship between the amount of time

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

Table 1. Sample of Data on Early Overlaps of Interdependent Subsystems

Case: upstream/downstream subsystems	Implementation lead time for base-building subsystems	Uncertainties affecting design of fit-out subsystems	Interdependency between base-building and fit-out subsystems
Upstream: backbone mechanical and electrical elements; downstream: retail area layout	~3 years to procure specialized items, prefabricate modules off site, transport, and assemble on site	"In the world of retail, we can never be too rigid about the layout because consumer spending is quite volatile." (retail director)	"Even if you are just changing the location of a toilet block, you have to resolve a problem… we had big problems with moves of catering units because ducts need to be fully accessible" (design manager)
Upstream: baggage conveyor belt; downstream: baggage screening machines	$\sim 2\frac{1}{2}$ years to manufacture, assemble, test, and commission	"You want to leave it to the last responsible moment to get the machines with the quickest throughput times and best price" (security representative)	"Baggage handling systems have been traditionally modular …. Provide us the volume and we will install our kit of parts." (production leader)
Upstream: car park concrete superstructure; downstream: forecourt canopy	~1 3/4 years to build the concrete superstructure	"We have always felt that they wanted something more dramatic than the original canopy design." (structural designer)	"The thickness of the forecourt top slab constrains the maximum momentum load on the base of the posts supporting the canopy" (project leader)
Upstream: control tower mast and cab steel structure; downstream: cab internal layout	~3 years to build the control tower mast and cab	"You are absolutely convinced that things will change when your human factor experts look to the layout later" (head of engineering)	"We are in version 22 of the controller's desk layout (02/06). This gives you an idea of the flexibility of the [base-building] system; we went to a flexible design from day one" (head of engineering)

and effort to optimize the engineered solution and the value that you can get."

The ability of the structural design solution for the car park to accommodate a very late change in the geometry of the forecourt canopy exemplifies this pattern. The change was requested when concrete pouring for the top slab (the forecourt slab) was only two months away. This meant that the project manager was expecting the civil engineering contractor to release the shop drawings detailing the reinforcing steel that would go into that slab within four weeks, in order to keep on schedule. The new proposed design involved a radically different (relative to the original solution) geometry for the canopy consisting of a dramatic wave-shaped cross section supported on single posts. The structural designers ruled out this solution because it increased the moment loads imposed by the post connections beyond the maximum design capacity of the slab. They argued that a hypothetical change to the slab thickness would ripple through the entire design of the concrete subsystem for the car park (Fig. 3). Hence, engineers, architects, and client representatives jointly agreed to support the dramatic wave-shaped cross section on diagonally strutted posts. This reduced the self-imposed loads, and designers resolved the design challenge by increasing the amount of local reinforced steel under the post connections close to the upper limit allowed by the design code.

We also repeatedly observed a pattern of upstream sensitivity to the lack of precision of downstream information (columns three and four in Table 3). Base-building designers would nonetheless move forward and avoid "starvation for information" (Terwiesch et al. 2002) by making working assumptions. They felt confident that their assumptions would hold in light of their experience in tackling similar problems—"we aren't doing rocket science here," emphatically noted one respondent to explain her familiarity with the problems associated with the design of the airport facilities. This capability to make robust assumptions was also illustrated by a designer's conceptualization of the electrical subsystem for the main building concourse:

> "The shell-and-core design we have now [November 2004] is fundamentally what we tabled in 2002 when we didn't know what was actually going in each floor. So we forecasted consumption levels for each area and designed a system that retained total layout flexibility. Since then, we've collected new consumption figures whenever there's a change: the overall load has never been a problem, but sometimes we need to take local loads to a different transformer if we have dramatic changes." (emphasis added)

We next examine the alternative coordination strategies used for resolving base-building design under uncertainty and ambiguity.

Problem-Solving Base Building under Uncertainty and Ambiguity

Our empirical findings (summarized in Table 4) extend the applicability of the coordination strategies commonly used in concurrent engineering into the management of the design-construction overlaps, but also suggest important dissimilarities that we discuss next.

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

Table 2. Analysis of Preliminary Information Releases Sent by Fit-Out Developers

	Preliminary Information about fit-out			
Case	Speed of uncertainty resolution	Precision	Stability	Exemplar
Upstream: backbone mechanical and electrical elements; downstream: retail area layout	~2002, fix high-level blocks (color-code circulation versus retail areas) ~2004, fix user allocation (e.g., shops, duty-free, catering, toilets) ~2005, fix exact subdivision (i.e., which retail brand goes in which space, and what are the exact service requirements)	Progressive	Progressive	"We fixed the big retail blocks about 3 years ago (2002), and gave working assumptions about the inside shop functions. We fixed the location of catering units 1 1/2 ago, and 1 year ago we fixed the third-party demising lines. Last month (March 2005), we gave detailed information about the use of units, but I cannot guarantee that it will not have to change again." (retail director)[a]
Upstream: baggage conveyor belt; downstream: baggage screening machines	The same two options (CT-scan OR X-ray machines) remained open over ~3 years	Moderate (binary set)	High	"Early on our colleagues in security gave us the impression that technology was going to move from X-ray towards CT scanning… we have just now (April 2005) started the acquisition process, and machines will not be delivered until 2007" (baggage production leader)
Upstream: car park concrete superstructure; downstream: forecourt canopy	•Early 2003, first design solution •Summer 2004, first review •Spring 2005, second review	High (single point)	Low	"The original scheme had canopies that were aligned and studded between …there was a feel that it was not good enough. The design had already gone through some change in a previous review, and we were not completely surprised that it changed again" (structural designer)
Upstream: control tower mast and cab steel structure; downstream: cab internal layout	~22 versions between 2002 and Summer 2005	High (single point)	Low	"We are in version 22 of the layout. We started off with a circular layout with control desks outside and supervision in the center, we then had middle high desks but no podium, then a rotating podium, then a fixed podium (. . .) In July 2005, we firmed the final concept" (head of engineering)

[a]'Third party demising lines' here only indicate the location of the walls separating retail from public areas.

Table 3. Analysis of (Upstream) Adaptation Costs for Base-Building Subsystems

Case	Cost to adapt base-building subsystems			
	If fit-out information is not stable		If fit-out information is not precise	
	How flexible is base-building design to fit out deviations?	Does flexibility of base-building change after design definition?	Starvation: can base-building development continue based on preliminary information?	Duplication: can base-building developmentprepare for multiple outcomes?
Upstream: backbone mechanical and electrical elements; downstream: retail area layout	Contingent on whether it is an incremental or radical change "We can flex to accommodate small changes, but we need to agree on major constraints" (M&E director)	Yes, rework costs go up dramatically "We must freeze design 6 months before we start to prefabricate; after, change is costly" (project director)	Yes. The problem is not novel "We are dependent on what others do, but we can proceed with general layout" (concept guardian)	Difficult, program lag is too long "The need to procure specialized items with long lead times forces design commitments" (design director)
Upstream: baggage conveyor belt; downstream: baggage screening machines	Very, the interaction between conveyor belts and screening equipment is modular "The baggage hardware is a kit of parts that we can adjust" (production leader)	Not much, rework is local "Reworking the conveyor belts if we get it wrong costs perhaps £20,000, not a big risk" (production leader)	Yes. Working assumptions can be made "We can make educated guesses based on existing machines" (production leader)	Difficult, program lag is too long "We have to assume one type of machine to manufacture a temporary conveyor and start testing" (designer)
Upstream: car park concrete superstructure; downstream: forecourt canopy	Moderate, but changes cannot impact slab depth since some physical interfaces are not decoupled. "The local design rework is not very complicated" (project leader)	Concrete subsystem remains flexible until shop drawings are done "There's a bit of capacity in loads and cross-sections" (head of structural design)	Yes. The problem is not novel "We had to make a lot of assumptions" (structural director)	Within limits, options for alternative canopy designs can stay open until very late "When detailing the steel reinforcement you have ability to fine tune" (structural designer)
Upstream: control tower mast and cab steel structure; downstream: cab internal layout	Very, but modular interfaces must be respected "Fit out uncertainty was OK as long as it did not request more space inside the cab" (structural designer)	No, but modular interfaces must be respected "The technology that goes inside changed, but did not impose structural changes" (structural designer)	Yes, modularity decouples the subsystems "You can make assumptions, but you have to work close to your client" (structural designer)	Yes, but for a limited time "We looked to various cross-section possibilities for the mast: a triangle, a circle, a square, but quickly reduced options" (design manager)

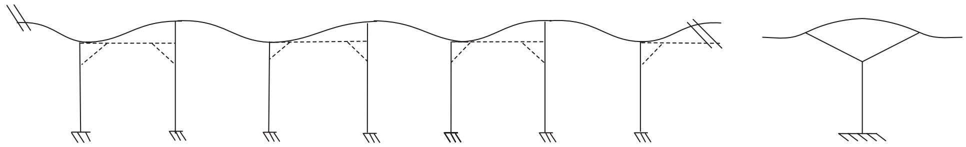

Fig. 3. Schematic longitudinal and cross-sectional views of canopy (dashed lines represent struts negotiated in last design iteration)

Attractiveness of Iterative Design Coordination

Program administrators recognized upfront that parts of the base-building subsystems would change over time, and some degree of "trial and error investment" (Sommer and Loch 2004) was inevitable. A program administrator put it bluntly:

> "The idea of building £4 billion worth of infrastructure over 5 years when the business cycles move at a different speed and not going around the loop a couple of times because the client changes his mind is nonsensical. We need to narrow the number of design alternatives to get a budget approved, but *we will not be able to get it right the first time—change is a fact of life*" (emphasis added)

We found instances of this strategy when the cost of reworking the base-building design was low relative to the benefits spelled out in the business case for the late change request. In the case of the main concourse building, for example, a radical late change in the retail area layout caused major rework in the design of the backbone mechanical and elecrical (M&E) subsystems. The motivation was a compelling shift in the commercial strategy of the retail group toward the consolidation of the "shopping experience" in the new terminal. Recent intelligence on airport retail activities had suggested this approach would significantly increase the revenues from the retail activities.

As the projects unfolded, the iterative strategy became less and less attractive because the implementation of the late change requests would involve much higher costs of adaptation and risks of project delays. To offset these negative effects, project managers would back up base-building developers over negotiations with fit-out developers with a view to restrict the design space for fit-out solutions in the late stages of the base-building implementation. This is exactly what happened when the architects proposed the change for the forecourt canopy.

Attractiveness of Designing in Buffers in Base-Building Definition

We observed investments in design buffers to shield base-building subsystems from rework otherwise necessary to accommodate changes between releases of preliminary fit-out information. This tradeoff between sacrificing product optimality in the present to reap the benefits of cheaper rework in the future is not new (Eckert et al. 2004; Sheffi 2005). Tolerance margins, or buffers, are invariably designed in complex engineering subsystems to absorb emergent changes that designers anticipate but find hard to eliminate upfront, especially when the cost of building extra capacity is low against high risks if the system should fail (Sheffi 2005). Developers recognized that buffers came with an upfront cost without a guaranteed payoff, yet accepted that the tradeoff was part and parcel of applying the overlapped approach:

> "Over-engineering does not necessarily come free; it can come with a premium. You win some you lose some. Still, it is often better to make a design decision that keeps momentum on-site than to try to fine tune because material cost may be small, but prolongation cost to have someone standing around can be significant" (Design Manager for Main Terminal Building 2005)

Buffers were particularly attractive when the base-building adaptation costs would be high unless working assumptions included reserve margins to accommodate foreseeable change in fit out. This tradeoff was clear in sizing the M&E backbone subsystems. Designers employed formulas based on the theory of fluids to estimate the design loads. These formulas required input information about both the consumption needs and the pressure losses, which designers tended to estimate on the conservative side. They then added 25% redundancy to the estimated loads to size the capacities of the equipment and the cross sections of the backbone M&E routings running inside the vertical service cores (the first ones to be physically executed). This built-in flexibility was important to adapt to late changes of the floor arrangement drawings should they occur at a later time (e.g., increase in catering or restrooms). Conversely, they applied an iterative strategy without buffers to design the M&E branches running under the flooring as they expected fit-out uncertainties to be resolved by the time they would start executing these branches.

Attractiveness of Modularizing Interaction between Functional Subsystems

Our sample is rich both in cases where designers decoupled the physical interfaces between base-building and fit-out subsystems, as well as in cases where the subsystems remained integral. In the case of the baggage handling system, for example, conveyor belts and baggage screening machines interacting in a modular fashion with each other were readily available at the outset of development. This happens frequently when technology can only be provided by a small group of firms that form a modular cluster (Baldwin and Clark 2000): fewer than five suppliers worldwide had the capability to deliver such a large-scale baggage handling system. Occasionally, the designers succeeded in developing functional elements that exhibited modular interaction during the project time. For example, designers physically decoupled the interfaces between the base-building subsystems of the control tower (mast and cab steel superstructure) and the fit-out subsystems going inside the cab. Specifically, they conceptualized a peripheral M&E core embedded in the steel walls of the mast, which connected at the top of the mast to three concentric rings running horizontally under the floor plate of the cab. They also conceptualized a self-standing steel podium which sat on top of the floor plate. This design approach made the base-building subsystem economically adaptable to the ongoing evolution of the layout of the control room inside the cab.

In other cases, however, the architectures of the base-building and fit-out subsystems remained integral despite efforts to decouple some interfaces. For example, while the M&E subsystems were designed as a kit of modules prefabricated off site, the de-

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

Table 4. Analysis of Coordinating Strategies to Problem Solve Base-Building Design

Case	Iterating Design of base-building subsystems	Buffering design definition of base-building subsystems	Modularizing interaction base-building/fit-out
Upstream: backbone mechanical and electrical elements; downstream: retail area layout	Yes "We constantly updated load forecasts, and occasionally departed from original design" (concept guardian)	Yes, but some buffers were later designed out "Our initial design allowed us to locate anything anywhere, but we removed allowances later on" (design manager)	The interaction between electrical/retail architectures was modularized, but not the one with the mechanical subsystem "The bus bar, a plug-in electrical system, has some ability to transfer loads, but the mechanical guys don't have that luck" (electrical designer)
Upstream: baggage conveyor belt; downstream: baggage screening machines	Yes "Should we get assumptions wrong, we will rework the conveyor belts" (production manager)	No evidence	The baggage handling hardware was available ex-ante development with modular interactions "We are a kit of parts that we install in a volume" (production manager)
Upstream: car park concrete superstructure; downstream: forecourt canopy	Yes, to some extent "At one stage, the designs had a 600 KNm moment that the slab could not take." (structural designer)	No evidence of buffers built on purpose, but there was residual slack	Integral interaction between the two subsystems' architectures
Upstream: control tower mast and cab steel structure; downstream: cab internal layout	No Substituted by buffers and modularity	Yes "Bear in mind you do not want cable trays to be too full, you allow 50% anyway just on keeping it tidy" (head of engineering)	The interaction between the two architectures was modularized "Our brief was to develop a steel design for the cab so the controllers' desk system on top could change" (structural designer)

signers succeeded in modularizing the interaction between the architectures of only the electrical and retail subsystems. The electrical solution was based on a bus bar system, which made the electrical design adaptable to changes in the retail layout. Conversely, the interaction between the mechanical and retail subsystems remained integral. Hence, the costs to adapt the mechanical design to late changes in the location of the restrooms were very high, to the extent that some prefab modules had to be discarded and the parts later installed on site in a traditional fashion.

We next summarize our empirical findings into a decision tree.

Conclusions

Fig. 4 summarizes the choices for resolving base building under ambiguity and uncertainty into three strategies: (1) iterative; (2) modularization; and (3) buffering. The iterative strategy is suitable when the information on fit out is ambiguous. Adaptation costs are limited if the changes are restricted to a base-building subsystem which interacts in a modular way with the fit-out subsystem. Conversely, they can escalate if the changes affect a base-building subsystem integral to fit out, unless the base-building designers constrain the design space for the fit-out solutions.

If the fit-out design is uncertain but not ambiguous, modularizing its interaction with the base-building subsystems is one option to limit the costs to adapt the base building. Functional elements with modular interactions can be available ex-ante or be developed. In the case of the control tower project, for example, designers sought to develop modular systems in the face of the high risks to the developer's business stemming from an inflexible base-building design. Two reasons suggested that adaptation costs would be extremely high. First, only authorized workers could access the construction site of the control tower and their productivity on site was low due to stringent security requirements (aircraft wing tips came within 2 m of the edge of the site). Second, a delay in handing over the control tower to the air traffic authority would have an impact on the date when the regulator would let the airport owner increase the airport levies.

If modularity is not an option because of design complexity, a tradeoff emerges between investing in a buffering or an iterative strategy. Two considerations matter in assessing this tradeoff. First, can buffers be designed out if uncertainties resolve favorably before implementing the base-building design? Second, does fit-out uncertainty exist at the architecture level (which will likely lead to high adaptation costs), or at the component level (which will likely lead to limited adaptation costs)? A buffering strategy exhibits two trajectories that differ according to whether buffers stay throughout or are removed before implementation. Buffers can only be taken away efficiently, i.e., with marginal rework, if uncertainties are resolved before the beginning of physical execution. Base-building developers, for example, designed out some buffers in the M&E backbone subsystem because the final floor arrangement drawings were released before starting prefabrication for the related M&E modules. In contrast, developers physically executed the buffers designed into the cross section of the service cores of the control tower mast. We next summarize the implications of our work.

Implications to Practice and Theory

Some challenges to compress the time it takes to execute base building in infrastructure projects can be insurmountable due to

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

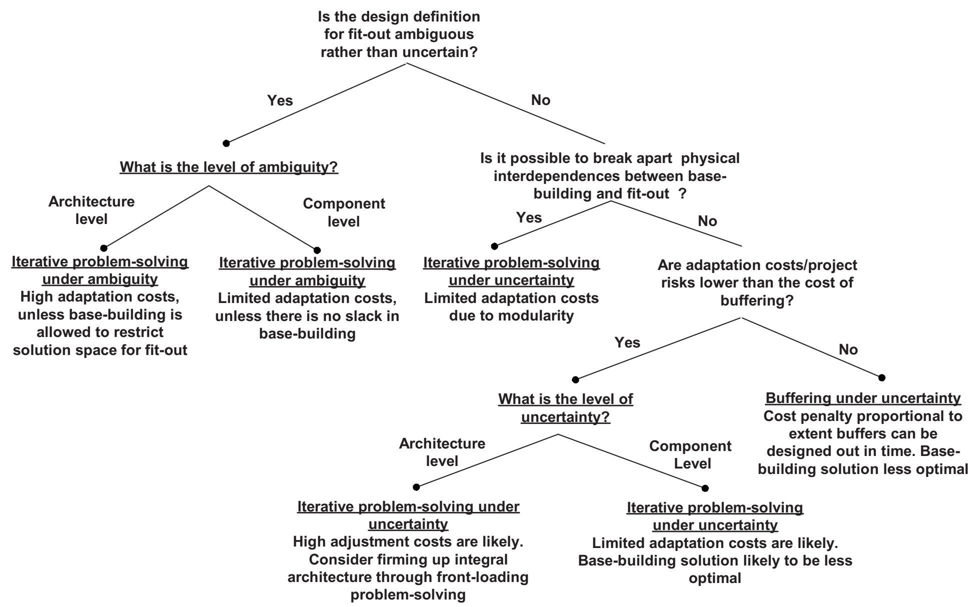

Fig. 4. Choosing between coordination strategies based on iteration, modularization, and buffering

the mammoth scale of the works, inadequate site accessibilities, scarcity of skilled labor, and stringent health and safety regulations. Yet, fast-evolving business circumstances of infrastructure promoters and technological evolutions in fit-out subsystems are unlikely to slow down. This means that a promoter of new infrastructure, interested in flexibility to make late changes, may not have an alternative but to ask developers to overlap fit-out design definition with the design detailing and physical construction of base building.

Our in-depth, multiple-case study highlights a number of facets of this "fast-tracking" approach for flexibility purposes. First, it shows how base-building subsystems in integral infrastructures may be adaptable to incremental changes in fit-out subsystems because of slack, but costly to adapt to radical changes. This insight matters for practice. The promoter of a new infrastructure typically produces a design brief describing its operational and functional requirements when commissioning the works to design consultants. If the promoter can better spell out the extent to which preliminary information about fit out is ambiguous or uncertain, or both, and when the fit-out concept is likely to become frozen, it may be easier for base-building designers to determine the most suitable coordination strategies needed in order to efficiently overlap design with construction. This theoretical proposition merits further validation.

Second, our study proposes that modularizing the interaction between base building and fit out can contribute to efficient implementation of design-construction overlaps. Practitioners may want to invest more in developing base-building subsystems that interact in a modular fashion with the fit-out subsystems and their components. These investments go beyond efforts to prefabricate modules off site (Gibb 2001; Blismas et al. 2006); they include investments to decouple physical interfaces and simplify mapping between functions and physical elements.

Finally, our study proposes two coordination strategies for moving base-building work forward with risky preliminary information about fit out when the two subsystems are integral. One option involves building buffers into the design of base-building subsystems to make them adaptable to economically accommodate late changes in the unresolved fit-out subsystems. Alternatively, base-building designers must accept the need to iterate in the course of design if their assumptions turn out to be invalid when uncertainty in fit out is resolved.

It remains indeterminate whether an efficient implementation of fast tracking can reduce the overall project duration, another proposition meriting further deductive work.

References

Baldwin, C. Y., and Clark, K. B. (2000). *Design rules: The power of modularity*, Vol. 1, MIT Press, Cambridge, Mass.

Blismas, N., Pasquire, C., and Gibb, A. (2006). "Benefit evaluation for off-site production in construction." *Constr. Manage. Econom.*, 24(2), 121–130.

Bogus, S. M., Molenaar, K. R., and Diekmann, J. E. (2005). "Concurrent engineering approach to reducing design delivery time." *J. Constr. Eng. Manage.*, 131(11), 1179–1185.

Clark, K., and Fujimoto, T. (1991). *Product development performance: Strategy, organization, and management in the world auto industry*, Harvard Business School Press, Boston.

Cooper, R. G. (1990). "Stage-gate systems: A new tool for managing new products." *Bus. Horiz.*, 33(3), 44–54.

Dyer, W. G., and Wilkins, A. L. (1991). "Better stories and better constructs: The case for rigour and comparative logic." *Acad. Manage. Rev.*, 16(3), 613–619.

Eastman, R. M. (1980). "Engineering information release prior to final design freeze." *IEEE Trans. Eng. Manage.*, 27(2), 37–41.

Eckert, C., Clarkson, P. J., and Zanker, W. (2004). "Change and customization in complex engineering domains." *Res. Eng. Des.*, 15, 1–21.

Eisenhardt, K. M. (1989). "Building theories from case study research." *Acad. Manage. Rev.*, 14, 532–550.

Eisenhardt, K. M., and Graebner, M. E. (2007). "Theory building from cases: Opportunities and challenges." *Acad. Manage J.*, 50(1), 25–32.

Engwall, M. (2003). "No project is an island: Linking projects to history and context." *Res. Policy*, 32(5), 789–808.

Flyvbjerg, B. (2001). *Making social science matter*, Cambridge University Press, Cambridge U.K.

Gehry, F. O. (2004). "Reflections on designing and architectural practice." *Managing as designing*, R. J. Boland, Jr. and F. Collopy, eds.,

J. Constr. Eng. Manage., 2008, 134(12): 991-1001

Stanford Business Books, Stanford, Calif., 19–35.
Gibb, A. G. F. (2001). "Standardization and pre-assembly—Distinguishing myth from reality using case study research." *Constr. Manage. Econom.*, 6(3), 307–315.
Gil, N., Beckman, S., and Tommelein, I. (2008). "Upstream problem-solving under uncertainty and ambiguity: Evidence from airport expansion projects." *IEEE Trans. Eng. Manage.*, 55(3), 508–522.
Gil, N., Tommelein, I. D., and Schruben, L. W. (2006). "External change in large engineering design projects: The role of the client." *IEEE Trans. Eng. Manage.*, 53(3), 426–439.
Gil, N., Tommelein, I. D., Stout, A., and Garrett, T. (2005). "Embodying product and process flexibility to cope with challenging project deliveries." *J. Constr. Eng. Manage.*, 131(4), 439–448.
Habraken, J. (1998). *The structure of the ordinary. Form and control in the built environment*, J. Teicher, ed., MIT Press, Boston.
Joglekar, N. R., Yassine, A. A., Eppinger, S. D., and Whitney, D. E. (2001). "Performance of coupled product development activities with a deadline." *Manage. Sci.*, 47(12), 1605–1620.
Kendall, S., and Teicher, J. (2000). *Residential open building*, E & FN Spoon, London.
Krishnan, V., Eppinger, S. D., and Whitney, D. E. (1997). "A model-based framework to overlap product development activities." *Manage. Sci.*, 43(4), 437–451.
Lee, S., Peña-Mora, F., and Park, M. (2005). "Quality and change management model for large scale concurrent design and construction projects." *J. Constr. Eng. Manage.*, 131(8), 890–902.
Loch, C. H., and Terwiesch, C. (1998). "Communication and uncertainty in concurrent engineering." *Manage. Sci.*, 44(8), 1032–1048.
Maheswari, J. U., Varghese, K., and Sridharan, T. (2006). "Application of dependency structure matrix for activity sequencing in concurrent engineering projects." *J. Constr. Eng. Manage.* 132(5), 482–490.
Miles, M. B., and Huberman, A. M. (1984). *Qualitative data analysis: A sourcebook of new methods*, Sage, Thousand Oaks, Calif.
Pena-Mora, F., and Lee, M. (2001). "Dynamic planning and control methodology for design-build fast-track construction projects." *J. Constr. Eng. Manage.*, 127(1), 1–17.
Pena-Mora, F., and Park, M. (2001). "Dynamic planning for fast-tracking building construction projects." *J. Constr. Eng. Manage.*, 127(6), 445–456.
Schrader, S., Riggs, W. M., and Smith, R. P. (1993). "Choice over uncertainty and ambiguity in technical problem solving." *J. Eng. Technol. Manage.*, 10, 73–99.
Sheffi, Y. (2005). *The resilient enterprise. Overcoming vulnerability for competitive advantage*, MIT Press, Cambridge, Mass.
Sommer, S. C., and Loch, C. H. (2004). "Selectionism and learning in projects with complexity and unforeseeable uncertainty." *Manage. Sci.*, 50(10), 1334–1347.
Strauss, A. L., and Corbin, J. (1990). *Basics of qualitative research: Grounded theory procedures and techniques*, Sage, Newbury Park, Calif.
Terwiesch, C., and Loch, C. H. (1999). "Measuring the effectiveness of overlapping development activities," *Manage. Sci.*, 45(4), 455–465.
Terwiesch, C., Loch, C. H., and De Meyer, A. (2002). "Exchanging preliminary information in concurrent engineering: Alternative coordination strategies," *Org. Sci.*, 13(4), 402–419.
Ulrich, K. (1995). "The role of product architecture in the manufacturing firm." *Res. Policy*, 24, 19–440.
Yin, R. K. (1984). *Case study research: Design and methods*, 1st Ed., Applied Social Research Methods Series, L. Bickman, ed., Vol. 5, Sage, Beverly Hills, Calif.

J. Constr. Eng. Manage., 2008, 134(12): 991-1001