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On the value of project safeguards: Embedding real options in complex products and systems

Nuno Gil [*]

Centre for Research in the Management of Projects (CRMP), Manchester Business School,
The University of Manchester, Booth Street West, Manchester M15 6PB, UK

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Abstract

This study defines a project safeguard as the design and physical development work needed to ensure, or enhance, the embedding of a real option in complex products and systems (CoPS). Safeguards operationalize optionlike strategic thinking at implementation. I examine safeguarding investments through an in-depth multiple-case study of 12 options embedded across 5 projects encompassed by an airport expansion programme. This includes options to phase out delivery (stage-option), grow capacity (growth-option), and switch operational regime (switch-option). Passive safeguards only involve design work, whereas active safeguards involve both design and physical execution. The analysis shows how the confluence between the uncertainty of option exercising and the modularity of the relevant functional elements in relation to the CoPS architecture affects the attractiveness of safeguarding. High uncertainty makes safeguarding less attractive as it can lead to sunk costs that may not pay off over the CoPS operating life. Conversely, high modularity increases the attractiveness of safeguarding because (1) safeguards can be limited to marginal investments at the interfaces between the functional elements with other CoPS subsystems, and (2) the stability of modular design rules increases the likelihood that safeguards remain valid over time. Safeguards build options into integrative CoPS. This flexibility and redundancy makes them resilient to change stemming from option exercising if uncertainties resolve favourably in the future.

Keywords: Project safeguards; Real options; Complex products and systems; Uncertainty; Modularity

1. Introduction

A real option is the right, but not the obligation, to take an action such as expanding, acquiring, deferring, or abandoning, at a specified price (the exercising cost) and for a predetermined period of time (Dixit and Pindyck, 1994; Trigeorgis, 1995; Amram and Kulatikala, 1999). An optionlike thinking framework helps when making strategic investments in complex infrastructures, such as airports, transport systems, energy supply systems, and production plants (Smit and Trigeorgis, 2001). These assets take many years to deliver and are designed to operate for a number of decades despite uncertainties about the future states of the world in which they will operate (e.g., Hughes, 1987; Morris, 1994; Miller and Lessard, 2000; Gil et al., 2006; Markard and Truffer, 2006). They are examples of complex products and systems (CoPS), a generic category of capital-, engineering-, and IT-intensive industrial goods, networks, and systems, produced in multi-firm alliances (Hobday, 1998, 2000a). CoPS, in turn, are key parts of the large infrastructural networks, or large technological

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[*] Tel.: +44 161 3063486.
E-mail address: nuno.gil@mbs.ac.uk.

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systems (Hughes, 1987), such as electricity, rail, and air travel.

CoPS are characterized by high levels of user involvement in the development process, high uncertainty in design requirements, complex supply networks, long delivery times, and highly regulated design and operational environments (e.g., Hughes, 1987; Miller et al., 1995; Hobday, 1998; Geyer and Davies, 2000). CoPS also exhibit long operational life cycles, important feedback loops from operations into development, and design innovation continuing long after project completion (Hobday, 1998). CoPS tend to have integrative architectures formed by many customised interconnected control units, subsystems, and components (ibid.). In CoPS, the project is the mode of coordinating decisions across the stakeholders (suppliers, prime contractors, regulators, government agencies and users), enabling buyer involvement, and matching of financial and technical resources (Hobday, 2000b).

Real options embedded into the CoPS definitions make them more adaptable to economically accommodating changes in the operational requirements stemming from evolution in the technological and business environment over time. The more the future is uncertain, the more it pays to keep a range of options open since the asymmetry in payoffs allows the owner of the asset to benefit from higher upside movements while limiting losses on the downside (Trigeorgis, 1996, p. 92). In publicly traded airport systems, for example, the value of a growth option as a proportion of the stock price can range between 40 and 50% (Smit and Trigeorgis, 2004, p. 388).

A key problem in operationalizing a portfolio of strategic options for a CoPS project manager operating with a limited budget and with limited information as to the value of each option is: how much should be invested in building each option in the design, or stated differently, how much should be spent on ‘buying’ each option at project birth? The more the project manager invests in building in one option, the less the manager can invest in building in other options and in the rest of the project. This study terms (project) safeguards the design and physical development work needed to ensure, or enhance, the embedding of a real option into the definition of a CoPS. The capital spent in *safeguarding* an option, i.e., ensuring that an option stays efficiently open in the CoPS, is the cost of the option. An increase in the option cost tends to increase its strategic value because it reduces the cost of exercising that option in the future, provided that the design assumptions underpinning the safeguard remain valid over time. The problem of safeguarding applies to different settings, as explained by a programme administrator with a background in automobile platform development (2005):

> “[The] Safeguarding [problem] is not new. This is a new car platform project: you design it for a life not for a day. And you know that during its lifetime there will be some changes that might impact on your design: an emissions legislation update, tougher requirements for fuel economy, etc. You make assumptions that if you had a diesel engine, it would be about this shape, size, weight. You then design your car structure to permit both petrol and diesel engines, even if you find that the car performs at its optimum level without that diesel engine [. . .] I have never seen a set of decision rules to safeguard. *The rule is built judgmentally by the person who holds the budget*. Everybody’s view is different on the decision between what is nice to have versus what we must have. *You have your wish list and then you step back from that, and think* ‘*what can I afford to do?*’ If I do not do that perhaps I can afford to leave provision to do it later. This is the trade-off.” (emphasis added)

This study investigates the rationale underlying decisions to safeguard through a multiple-case study of safeguards for 12 options across 5 projects forming part of an airport expansion programme. The options leave provision to grow capacity (growth-option), stage delivery over two phases (stage-option), and create flexibility to switch the operational regime over the lifetime of the infrastructure (switch-option) (Trigeorgis, 1996). This study defines safeguards as passive when the investment to safeguard only includes design work; if it involves design and physical work, safeguards are active. The magnitude of the irreversible investments in safeguards indicates what a firm loses if the options go unused (Taudes, 1998; McGrath et al., 2004).

2. On the value of safeguards

Safeguards manifest Simon’s principle (1962) that designers should avoid designs that create irreversible commitments for future generations. The designs of CoPS are inherently difficult to modularize and tend to exhibit strong path dependencies (Hobday, 1998, 2000a; Markard and Truffer, 2006). The challenge of economically exercising an option that had not been properly safeguarded in an integrative design could be beyond man’s problem-solving capabilities. In extreme cases, this situation could lead to premature obsolescence of the CoPS. Hence, safeguards build redundancy and flexibility in the CoPS definition, complementing the role of modularization and standardization in enabling future design modifications with incremental adaptation costs (Thomke, 1997). They also help design teams tolerate foreseeable risks of change if the option is exercised to accommodate favourable resolution of uncertainties during project delivery or in the operational lifetime of the infrastructure:

> “Safeguarding is not so much keeping my design solution generically flexible. It is about saying I can see a potential future use. It is not there now, but it will be very expensive to implement it when it comes unless I do a few things now which will have limited cost. It is about *playing it safe.* [Head of Design and Development 2005, emphasis added]

Safeguards contribute to making the CoPS definition resilient against foreseeable changes. Resilient enterprises seek to be able to bounce back speedily to their normal performance level following a high-impact/low-probability disruption (Sheffi, 2005). They build redundancy and operational flexibility in their supply chains to make them less vulnerable and brittle to disruption stemming from volatile marketplaces (Sheffi, 2005). To be resilient but lean, commercial enterprises need to balance investments in work-in-process inventories with efforts to develop products with flexible designs (ibid.) Likewise, CoPS developers need to balance investments in safeguards with investments in developing flexible designs:

> The trick is about being able to be flexible and to some extent safeguard while at the same time recognizing that *safeguarding can cost money*. So it is about how to *prudently* stop waste, but actually keep open that flexibility as needed.” [Head of Design and Development 2005, emphasis added]

Safeguards can lead, however, to a sunk cost that does not generate returns if decision-makers ‘get them wrong’, i.e., the uncertainties resolve unfavourably or they resolve favourably but the safeguards must be reworked because the assumptions became obsolete over time. Safeguards that were unnecessary from the beginning or disproportional in relation to the option value may manifest poor design practices and waste resources. Likewise, protecting supply-chains against disruptions by building big inventories is costly and leads to relaxed manufacturing, procurement, and logistic disciplines at the expense of quality products and delivery (Sheffi, 2005, p. 173):

> “Generally, we accept rework. There are many examples in this airport where people had good ideas and have buried something in the ground for future possibilities which never happened. Some will happen, but the ratio maybe 1 out of 10. If you can predict the future, then you can safeguard. But to predict the future in this sort of world. . .you get lucky sometimes, but you will not get lucky regularly.” [Project leader 2005]

From an options lens perspective, safeguards help the firm to increase the strategic value of an option. They also increase the value of the CoPS in which the options are incorporated because they endogenously reduce the cost of exercising those options in the future. They do so, however, at the expense of increasing the cost of purchasing the option in the present. I next discuss the attractiveness of safeguarding to the project manager who holds the budget at implementation.

3. The attractiveness of project safeguards

The empirical findings suggest that the decision to safeguard each option from a portfolio of options hinges on two determinants: (1) the assumed uncertainty as to whether or not the option will be exercised in the future, and (2) the modularity of the CoPS architecture in which to embed the option. This attractiveness of safeguarding goes up when the assumed uncertainty that the option will be exercised is low (in other words, there is a high likelihood that the option will be exercised). Low uncertainty is often associated with options that are likely to be exercised in the short term because the likelihood of the future diverging from scenarios foreseen upfront increases as time progresses (Sheffi, 2005). For a project manager who operates under a limited budget and has limited information about the future, it makes more sense to safeguard an option that the manager assumes will pay off soon, rather than to safeguard a risky option.

The attractiveness of safeguards also increases when the modularity of the CoPS architecture is high. This study applies, or translates (Kogut and Kulatilaka, 2004), the notion of product design modularity to characterize the CoPS architecture. Product architecture is the ‘scheme by which the function of a product is allocated to physical subsystems and components’ (Ulrich, 1995). Product architectures that are strictly modular exhibit: (1) a one-to-one mapping from functions to physical subsystems and components, and (2) physically decoupled and standard interfaces between subsystems and components. In contrast, products with integral architectures include complex mapping (many-to-one, one-to-many, many-to-many) and tightly coupled physical interfaces (Ulrich, 1995). Most products are hybrids, i.e., they include a number of functions that map to physical subsystems and components with modular architectures, and other functions that map to integral elements (Ulrich and Eppinger, 1995).[1]

Modular products and systems exhibit built-in options since parametric evolution of the module can take place without redoing the whole as long as changes conform to the design rules agreed upfront (Baldwin and Clark, 2000, p. 223). When functional elements that interact in a modular fashion with the other CoPS subsystems are readily available or can be developed, safeguarding can be attractive. In this situation, only marginal investments are required to further enhance the cross-module interfaces and reduce the costs of exercising the options built into the CoPS definition. The modularization of complex physical systems is not, however, an easy goal. Modular architectures are easier to accomplish for products based on electricity than for those based on mechanical and structural systems because of the one-dimensional flow of electrons vis-à-vis the multidimensional surfaces of the physical systems (Baldwin and Clark, 1997). Hence, major investments in safeguards may be necessary to build options into integrative CoPS.

The remainder of this paper is structured as follows. After reviewing related work (Section 4), I describe the research methods and site (Section 5). I then characterize the database of options and the infrastructures in which the options are embedded (Section 6). From these findings, I induce a framework concerning the determinants underscoring safeguards and discuss the trade-offs (Section 7). Finally, I discuss the limitations and implications for practice, theory, and policy making (Section 8).

4. Related work

The real options approach extends financial option theory to nonfinancial or ‘real’ assets by incorporating the effects of private risk and the business environment into the valuation of strategic opportunities (Amram and Kulatikala, 1999; Trigeorgis, 1996). Real option theory helps decision-makers to structure foresight and exploit exogenous uncertainties from investments put in place to capitalize on unfolding events (Amram and Kulatikala, 1999, p. 7). Five basic variables affect option evaluation (Trigeorgis, 1996): (1) the value of the underlying asset, i.e., an asset with the same risks as the project that the firm would own if the option was exercised; (2) the cost to exercise the option; (3) the time to expiry of the option; (4) the volatility of the value of the underlying risky asset; (5) the riskless interest rate over the life of the option. The value of the option increases with the value of the underlying asset, its riskyness, and longer times to expiry since the asymmetry in payoffs allows the developer to benefit from higher upside movements while limiting losses on the downside (Trigeorgis, 1996, p. 92).

Real options reasoning is an alternative to option evaluation when decision-makers cannot quantify the value of operating flexibility and strategic adaptability because either data are too unreliable, or the firm lacks the required resources and capabilities (McGrath and MacMillan, 2000). Quantification is difficult for projects with a portfolio of interrelated options as the incremental value of each option increases or decreases whether the option complements or substitutes the other options, unless interactivity between options is low (Kulatilaka, 1995a). Quantification of compound real options, i.e., when the option payoff is another option, is also difficult because options have to be looked at as links in a chain of interrelated projects (Trigeorgis, 1996, p. 104, Bowman and Moskovitz, 2001). Options reasoning can be appropriate at the birth of a project when reliable assessments of outcome performance and cost are not available, whereas option evaluation can be used later (McGrath and MacMillan, 2000).

Differences in the assumptions underpinning the theories of evaluating financial and real options are at the core of a debate about the boundaries of the applicability of real options (Adner and Levinthal, 2004; Kogut and Kulatilaka, 2004; Zardkoohi, 2004; McGrath et al., 2004). Unlike financial options, the real option-holder can act endogenously, e.g., shape the target markets and technical agendas that influence the value of an option. Adner and Levinthal (2004) posit that this difference can undermine the timely abandonment of an option when uncertainties get resolved unfavourably because of organizational bias, vested interests of stakeholders, and lack of conformity to corporate policy and to the logic of governing a portfolio of options. Hence, the use of real options may be inappropriate when firms lack rigid control systems and the outcomes of strategic opportunities are linked to the firm’s actions (Adner and Levinthal, 2004). Yet, others argue that firms need to consider endogenous actions in their valuation models (Kogut and Kulatilaka, 2004) and proactively manage implementation to preclude misuse of the theory (Zardkoohi, 2004; McGrath et al., 2004; Kogut and Kulatilaka, 2004). Scholars agree, however, that project management is a suitable environment in which to ‘translate’ (Kogut and Kulatilaka, 2004) financial pricing theory into real

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[1] Whether the architecture of a subsystem is integral or modular differs from how it interacts: a tyre has an integral architecture that interacts in a modular fashion with other subsystems in a car (Ulrich, 1995).

options because project control systems can avoid that options ‘take a life of their own’ (Adner and Levinthal, 2004).

Some pioneering work has applied the real options approach to evaluate capital investments in product platforms, large engineering assets, and large-scale IT systems (e.g., Taudes, 1998; Pindyck, 2001; Copeland and Tufano, 2004; Ford and Sobek, 2005; Fichman et al., 2005). We still know little, however, about how to efficiently operationalize optionlike strategic thinking at project implementation and what the issues are (Adner and Levinthal, 2004). The trade-off associated with safeguards – augment the option cost with a view to decreasing the cost of exercising the option in the future – is notably absent from the literature.

This trade-off is less relevant when modular products are available. In these circumstances, option-holders can exercise the built-in options by substituting one module for another and by adding new modules. Products with integrative architectures can be also modularized. The modularization process partitions the design architecture into independent modules that interact and fit together through a set of integration protocols and testing standards (Baldwin and Clark, 2000). Modularity does not come for free, however. In general, the stability of design rules ensures returns over several rounds of design work, but the costs of modularizing go up as the number of modules increases (Baldwin and Clark, 2000). Gains from over modularization can be offset by increasing the time spent in the testing and integration phase, ‘where the consequences of ignored dependencies come to the fore’ (Ethiraj and Levinthal, 2004). By definition, integral designs do not exhibit built-in options unless these are safeguarded beforehand.

The development of infrastructures with modular architectures underscores the ‘open building’ movement. Its advocates work toward the conceptualization of the built environment as a set of ‘open’ or ‘living’ entities, decoupling the physical interfaces between the base building and fit out ‘levels’ (Habraken, 1998; Kendall and Teicher, 2000; AIA, 2004). The base building includes the functional subsystems that collectively provide service space for occupancy, such as the foundations, steel/concrete superstructure, envelope (façade and roof), and supply subsystems (e.g., power, water and fresh air). The fit out includes the functional subsystems used to create interior space and make it functional, such as partition walls, ceiling, flooring, and specialized equipment (Habraken, 1998). ‘Open’ or ‘regenerative’ infrastructures are economically adaptable to a variety of ‘individual territorial claims’ and environmental transformations, enabling occupants to move in and out with different fit out subsystems (Habraken, 1998; AIA, 2004).

The study I present next induces a framework to guide decisions whether or not to safeguard as a function of the uncertainty of option exercising and the modularity of the infrastructure.

5. Methods

5.1. Research design

This study builds theory from multiple case study research (Eisenhardt, 1989; Yin, 2003). It adopts a ‘replication logic,’ analogous to that used in multiple experiments, to accomplish a high degree of certainty in the study’s findings (Yin, 2003). The units of analysis are 12 options built into five projects forming part of an airport expansion programme. The airport operator (simultaneously project developer and manager) did not use any option evaluation model, but the brief instructed project development teams to make discretionary investments in safeguards to leave open a portfolio of options. Hence, the research site manifested the intuitive, rudimentary use of options reasoning, which Amram and Kulatikala (1999) note it is common in complex investments.

I adopted an inductive approach after uncovering the prominence of the *in vivo* notion of *safeguarding* through open coding the first 15 exploratory interviews (Glaser and Strauss, 1967; Strauss and Corbin, 1990). I subsequently undertook a second stage of fieldwork during which I systematically studied in-depth investments in safeguards through 64 face-to-face interviews and analysis of archival documents. The theoretical sample varies from one extreme to the other in terms of the modularity of the interaction of the functional elements with the other infrastructure subsystems and the assumed uncertainty of option exercising. The studied options involve the substitution or addition of idiosyncratically large functional elements, such as a concrete tunnel, aircraft stand pavements, and steel mezzanines. Project teams made the decisions to safeguard at the outset of development to set up the budget, and get it approved and funded by the programme board. I focused the analysis on the safeguards associated with the civil design systems. This approach enabled me to build a rich, fine-grained database appropriate for inductive studies (Strauss and Corbin, 1990; Langley, 1999). I made cross-case comparisons through tables and graphs, and induced and tested the plausibility of the conceptual framework by iteratively playing it against case data until theoretical saturation was reached (Miles and Huberman, 1994).

Table 1
Description of case data

Project	No. of options	Discussions			Archival documentation
		Developer	Supplier	Customer	
Airfield	3	6	3	5	Functional and operational briefs, drawings and specifications, design standards, programme, corporate reports, clips from the trade and business press
Inter-terminal train	3	4	3	1	Functional and operational briefs, drawings and specifications, design standards, programme
Baggage handling system	2	6	3	2	Functional and operational briefs, drawings and specifications, design standards, programme, supplier presentations, clips from the trade and business press
Multi-storey car park	2	3	3	1	Project briefs, drawings and specifications, design standards, programme
Terminal building one	2	10	8	6	Project briefs, drawings and specifications, design standards, programme, supplier presentations, clips from the trade and business press, press releases

5.2. Data collection

The data collection focused on five projects: airfield, multi-storey car park, baggage handling system, terminal building one, and inter-terminal train system. I collected data through one-on-one interviews, archival documentation, and site visits (Table 1). After I learned to construct the e-mail addresses from the programme phone directory, I arranged the interviews myself weeks in advance. The protocol involved sending emails to individuals, attaching the research summary and authorization. I used a snowball tactic to identify interviewees (Vogt, 1999). Once I came across a potential unit-of-analysis, I asked who else could complement her/his point of view.

I addressed the issues of construct and internal validity both by triangulating interview data across three groups of respondents, and by playing interview data against archival documents and site observations (Jick, 1979). The project developer representatives included design managers responsible for managing designers and liaising with customers, project leaders responsible for managing suppliers, and programme administrators with responsibilities cutting across various projects. This group helped to characterize each built-in option. The project supplier representatives included design consultants, specialized contractors, and product manufacturers. This group provided technical information required to understand the raison d'être of each safeguard. The customer representatives included the main user airline, the baggage operating division, and the airport's retail division. This group complemented the information provided by the developer.

I conducted the scheduled interviews over 14 months' elapsed time (from May 2004 to July 2005) by regularly visiting the project teams in their offices at the airport site. The visits lasted from 1 to 5 days, and involved extensive preparation ahead to schedule meeting times and locations, brief the interviewees about the research questions, and clarify the confidential nature of the study. Interviews typically lasted 60–90 min, although a few ran longer (to two and a half hours). I discussed each safeguard in the database with at least five professionals, including a programme administrator, a project leader, a design manager, a design consultant, and a customer representative. All interviews were tape-recorded and transcribed.

During the site visits, I examined documents posted on the programme intranet, including the public inquiry requirements and programme process standards. I also studied the project briefs spelling out the functional and operational requirements, and other information such as technical and operational standards and legislation. Occasionally, I joined on-going job activities such as supplier presentations, project meetings, and work inductions.

5.3. Research site

The airport operator generated the initial brief for adding a new terminal campus to an airport operating close to maximum capacity in the early nineties, and submitted a planning application in 1995. The development of the various project designs started immediately after the planning application was approved in 2001, subject to a set of conditions. From the outset, the airport operator found it worthwhile to build into the design for the new campus opportunities to create business value that could be unlocked if uncertainties resolved favourably. This effort required foreseeing how the airline and airport industries might evolve in the future:

> "The planning application was approved in 2001 and the first phase will open in 2008: how to define and get it right when the world will change so much in between? Think just about the headlines, 9/11, SARS, and growth of self-service check-in and low-cost airlines. In this time span, we are looking to design something that is made to last: we have a natural dilemma here." [Head of Development 2005]

> "Do you back what you know? Do you try to speculate? Do you invest in a future that may never come? The difficulty here is that there is no right answer and different people take different approaches. Our approach is – and we are controlling it to a very tight budget – even if I can see a future now, I can only take it so far because if I try to speculate beyond any reality of today I am not going to be able to take people with me." [Director of Design and Development 2005]

The airport expansion programme included two consecutive phases (Fig. 1). The first 6-year phase encompassed the delivery of two partially fitted-out terminal buildings (1 and 2) connected by an underground passenger train and baggage handling systems, around 40 aircraft stands, and the car park. The second 3/4-year phase encompassed the complete fit out of the two terminal buildings, the delivery of the terminal building three, and extensions of the train and baggage systems to the third building. Further, there was a possibility to extend the train and baggage systems to a fourth terminal building and to the existing central terminal area.

5.4. Characterization of the environmental uncertainties across the five projects

Environmental uncertainties affected the five infrastructure projects (Table 2). The uncertainties were exogenous to design development, rather than stemming from iterative loops and task interdependencies intrinsic to engineering design (Pich et al., 2002; Gil et al., 2006). Sources of uncertainties included evolution of passenger growth rates, developments in aircraft and check-in technology, and new legislation introduced by the aviation regulator. These uncertainties affected primarily the projects that interfaced closely with the airline industry:

> "In general, it is very difficult to predict what you are going to need in 5 years from an airfield perspective because airlines change modes of operation very quickly. This is a very fluid environment, and airports have to be responsive organizations to keep airlines happy. It is difficult to predict which airlines will occupy a terminal throughout its life. Airlines may also change quickly their business position, for example, from low cost to full service." [Head of Airfield Design and Development 2005]

Likewise, environmental uncertainty was high during the design and development of the terminal building one due to evolution in the business needs of the main tenants, such as airlines, airport retail division, and statutory authorities. Planners foresaw new trends getting closer, such as low cost carriers, self-service check-in, and strin-

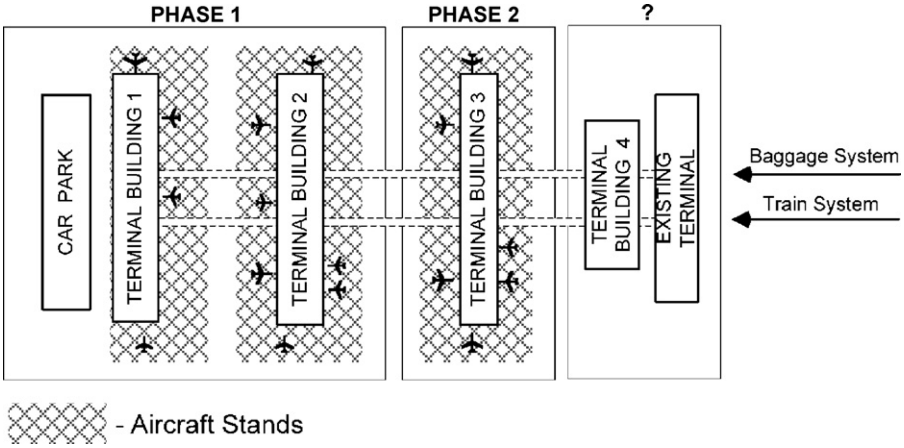

Fig. 1. Schematic layout of the new airport terminal campus.

Table 2
Summary of case data on characterization of environmental uncertainties

Case	Environmental uncertainties affecting project requirements
Airfield	*High*. Source: airline business: "We have uncertainty around the interface with the airlines because they work on a much shorter look ahead, 5-year at most, whereas we look 20–30 years into the future"
Terminal building one	*High*. Sources: (1) airline business: "it has always been known that the end-user airline would like to put all its traffic into one terminal campus. The acceptability of it being split varies in time;" (2) retail business: "In the world of retail, anything more than 3, 4 years out is strategy, therefore we can never be too rigid in terms of how we are going to use the space"
Inter-terminal Train	*Moderate*. Source: capacity requirements: "other than STO[a] and Consolidation[b] I have not seen a lot of change. . .even with these two, it was more platform, more vehicles, more of something we were providing"
Baggage handling system	*Moderate*. Source: capacity requirements: "quite a lot of uncertainty exists on user needs, but it tends to lay in volumes and throughput not functionality. The big changes [STO and Consolidation] did not affect us much apart from increasing the numbers of check-in desks and baggage chutes"
Multi-storey car park	*Low*. Source: capacity requirements "the design requirements set up by the programme brief were clear from the beginning, and the maximum car park capacity was set up by the public inquiry"

[a] STO stands for single terminal occupancy. It refers to a 2002–2003 decision in which the airport operator and main customer airline agreed that the airline would concentrate its operations in the new terminal campus after the end of the first phase, rather than remain spread across the airport until completion of the second phase as planned initially.

[b] Defined as a 'value engineering exercise on top of STO', it refers to a major change after STO to consolidate as much retail as possible in terminal 1, while reducing the floor area inside terminal 2.

gent security requirements. They understood that some project requirements needed to change to meet these trends, but could not exactly predict when the changes would be requested. These modifications were likely to ripple through design criteria for provision of floor space and services.

Environmental uncertainties were moderate throughout design and development for the baggage and train systems. Both projects aimed to deliver transport systems whose main design inputs consisted, first, of forecasts of maximum passenger and baggage throughput per year, per day, and in a 15 min peak-time; and second, operating performance criteria, such as service frequency and maximum passenger-waiting times. On one hand, the maximum throughput design capacity for the new terminal campus had been fixed in the public inquiry, and was unlikely to reduce as it was in the interest of the business to grow. On the other hand, the operating requirements for the two transport systems were tied to corporate service standards developed over time to standardize services across a number of airports owned by the airport operator. While standards go through regular cycles of upgrading, changes are rarely radical in complex systems because of strong path dependencies (Markard and Truffer, 2006). Yet, the train and the baggage systems were not required to operate at maximum capacity by the end of the first phase since by then only two terminal buildings would be in service. The exact timing for starting the second phase was a chief source of uncertainty. In contrast, environmental uncertainty was low for the multi-storey car park. Its design definition was based on principles crystallized in a corporate design standard for car parks. The maximum car park capacity was capped by the public inquiry. The project requirements were foreseen to remain stable around the need to deliver as many parking spaces as possible given the importance of parking fee revenues in any airport.

I present next the analysis of the options built into the five infrastructure projects. I use Trigeorgis' (1995) taxonomy to differentiate between stage-, growth-, and switch-options, and the lens of product design modularity to characterize the infrastructure architectures.

6. Data analysis

6.1. Characterization of the built-in options

This study characterizes the 12 options across three dimensions (Table 3): First, the strategic value of the option, or in other words, what valuable functionality the developer can add to the terminal campus from exercising the option in the future; second, the uncertainty as to whether or not the airport operator would ever exercise the option; and third, the time frame for when the airport operator may exercise the option. I discuss the exercising costs later in this paper when I examine the investments to safeguard, since the latter affect those costs. As in other studies of real options (Amram and Kulatikala, 1999), the options here are perpetual, i.e., they will stay open throughout the asset's service

Table 3
Summary of the database on the built-in options

Case	Option	Option #, type	Uncertainty of option exercising		Modularity of the relevant functional element
			6-Year delivery (Phase 1)	20–30 Years operation	
Airfield	Service either a code-F aircraft (wingspan up to 80 m) or 2-small aircrafts using same stand	(1) Switch option	*Low*: "We need them [large stands] to receive the test flights of the Airbus A380 in 2006"	*Low*: "based on our flight schedule, we foresee a very good use of the asset"	*Moderate*: aircraft stand pavements are physically integral to mechanical & electrical service tunnels, fuel pods, and head of baggage tunnels
	Service a greater number of code-F aircrafts and code-G aircrafts (wingspan up to 85 m)	(2) Growth option	*Scenario ruled out*: "large aircrafts cost a lot of money and they [airlines] do not purchase them on a whim"	*Moderate*: "it is a crystal ball to predict aircraft fleet configurations in 20 years, but we can see more code-F coming. . .code-G is still a long way off"	*Low*: adjacent stands are physically integral to one another, to the terminal buildings, and to the taxiways
	Exploit lift of usage restriction on north runway	(3) Switch option	*Scenario ruled out*: "it is not going to happen in the next 4, 5 years"	*High*: "we would like to optimize use of the runway, but it may only come in 5–10 years time after terminal opening"	*High*: taxiways are loosely coupled to the airfield, provided there is space available in the master plan of the airfield
Train system	Rule out passengers from taking shopping trolleys in the train	(6) Switch option	*Low*: planned operating regime unlikely to change before terminal opens	*Moderate*: "hard to pinpoint if Health and Safety Inspectorate's concerns in allowing trolleys in the train are plausible"	*High*: trolley ramps are modular components with few, standard physical interfaces
	Extend train system to terminal 3	(7) Stage option	*Scenario ruled out*: delivery of terminal three is excluded from first phase	*Low*: business forecasts support second phase, and consequently train extension to the terminal three	*Low*: physical interfaces between train, airfield, and terminal buildings are hard to break apart
	Extend train system to terminal 4 and beyond	(8) Growth option	*Scenario ruled out*: delivery of terminal four is excluded from first phase	*High*: "this is a lovely aspiration but . . .there is no sense of when this may occur"	*Low*: physical interfaces between train, airfield, and terminal buildings are hard to break apart
Baggage system	Grow baggage reclaim throughput capacity	(4) Stage Option	*Low*: growth of baggage throughput capacity staged over two phases	*Low*: business forecasts indicate phase 2 is vital to accommodate forecasted growth of passenger demand	*High*: baggage reclaim belts are modular components with few, standard physical interfaces
	Grow baggage storage room capacity	(5) Grow option	*Moderate*: "we do not know yet what service packages we want to offer in the future that require storing bags"	*Moderate*: "the airlines may want to use it [the storage room spare capacity] later"	*Moderate*: baggage storage equipment has few, standard interfaces, but it is risky to put cranes in the basement after opening

Table 3 (*Continued*)

Case	Option	Option #, type	Uncertainty of option exercising		Modularity of the relevant functional element
			6-Year delivery (Phase 1)	20–30 Years operation	
Car park	Increase car park capacity	(9) Growth option	*Scenario ruled out*: business development plan rules out increasing car park capacity before 2008	*Moderate*: "I am not sure if we will ever build it [the mezzanine] but it was a prudent decision to safeguard for future inclusion"	*Moderate*: expansion can come through a modular steel mezzanine, but integration costs may not be marginal
	Addition of third trolley lift	(10) Switch option	*Low*: "we are fairly certain that two trolley lifts will work"	*Moderate*: "although on paper it looks right, given that this scheme is new and critical for operations, it was probably sensible to safeguard"	*High*: trolley lifts are modular components with few, standard, physical interfaces
Terminal building one	Accommodate increase in passenger throughput capacity	(11) Stage option	*Low*: no need for more than 80% of the floor area in phase 1, unless operating brief changes	*Low*: development of the second phase assumes 100% use of the floor area in terminal one	*Low*: floor plate superstructure physically decoupled from building envelope, but it is integral to other subsystems
	Expand areas of commercially important passengers (CIP) lounge and retail	(12) Growth option	*Low*: no business need to expand floor areas before terminal 1 opens	*Low* [*Retail Lounge*] *Moderate* [*CIP Lounge*]: "someone will stick more shops about 5–10 years after the terminal opens. . .I am less confident about the CIP mezzanine"	*Moderate*: expansion can come through modular steel mezzanines, but integration costs may not be marginal because of the impacts to service quality

life. Thus, the analysis disregards the time to expiry factor.

6.2. *Growth-options*

Growth-options build flexibility in the design definition to accommodate change needed to increase capacity in response to future events that will make growth economically justifiable (Kulatilaka, 1995a; Taudes, 1998). Growth-options prevail in projects to develop technological platforms made to last, but their value becomes increasingly difficult to estimate with increasing time to expiry (Baldwin and Clark, 2000; Fichman et al., 2005). The empirical findings suggest variability in the assumed uncertainty of option exercising for these options.

The option to expand the retail area in terminal building one through the addition of a steel mezzanine, for example, had low uncertainty. Respondents observed that retail expansions are inevitable in terminal buildings as operators seek new ways to increase revenues to meet business targets over time. On the other hand, uncertainty was high regarding the growth-options to extend the train system to terminal building four and beyond, and to expand the lounge for Commercially Important Passengers (CIP). Exercising these options is a function of favourable evolution in passenger throughput demand, demand profile, and regulation over the next two decades. It is difficult, however, to exactly predict how these three factors will evolve. There were also growth-options with moderate uncertainty, such as the option to increase the number of stands for servicing large aircraft. Acquiring large aircraft will be the only way by which airlines can meet the forecast growth of passenger throughput in this airport over time because the airport operates close to the regulated cap on the maximum number of flights per year. However, airlines rarely make commitments as to the number and type of aircraft that they expect to purchase more than 5 years ahead:

> "Decisions [on aircraft stands] are based primarily on forecasts generated by our experts. To plan for the opening date is to plan to fail, so we plan for a 20, 30 years horizon. We believe in time something will happen: our demand some years ago was about 48 million passengers, now we have moved into 60 million; the average number of passengers per aircraft has gone up; 30% of flights on now are 747s, and in time we will see similar progression with A380s." [Head of Airfield Design and Development 2005]

Likewise, uncertainty was moderate on the option to grow car parking capacity. While the public inquiry capped the capacity on 4500 spaces, decision-makers opted to deliver a structure with 4000 spaces with an option to expand up to 4500 spaces. Demand for car parking is expected to grow, but it remains unclear if the option will be exercised due to the negative impacts of the construction work on the service quality of the coach station located at the ground level.

6.3. Stage-options

Unlike growth-options, stage (or time-to-build) options exhibit less uncertainty as to when they will be exercised. Execution of each stage is made contingent on a reassessment of the costs and benefits of completing that stage at the time the stage is reached (Trigeorgis, 1995). Each stage therefore represents an option on the value of the subsequent stage (intra-project compoundness) by incurring the instalment cost outlay required to proceed to the next stage. The firm has the option to abandon, or 'default', the execution of the subsequent stage if uncertainties get resolved unfavourably (Trigeorgis, 1996). The staged delivery of the new campus limited the capital investment and accelerated the date when the committed capital would start generating returns. Further, the staged delivery built flexibility to scale back design capacity if the forecast growth of passenger demand failed to materialize, or the economics of the business deteriorate. Stage-options were embedded to extend the train and baggage systems to the terminal building three:

> "Two to three years ago there was a change that said: 'we will actually build the substructure of terminal 3 in the timescale of phase 1.' We are now putting the infrastructure that extends the train system to terminal 3. However, we have always designed the system to support this expansion: its capacity, the size of the stations, the number of cars in the train, egress, ventilation. All those sort of things were understood and accommodated in the design. When it will start to operate [across the three terminals] we still do not know." [Head of train design and development 2005]

The uncertainty of option exercising was systematically low for the stage-options because the airport operator was bullish about the need to deliver the second phase. Forecasts based on 40 years of historical data consistently pointed to a 4–5% average yearly growth rate of passenger demand over the 30-year planning horizon. There was, however, uncertainty on the timescale for exercising the stage-options. In particular, developers did not foresee that the stage-options would be exercised half-way through the delivery of the first phase; as put by a respondent: "we probably would not know [in 2002] if we would build the terminal building 3 in 2011; we might have said 2013 or 2015, but we knew we had to do it to meet our service standards."

6.4. Switch-options

Switch options reflect a firm's willingness to pay a certain positive premium for a technology that can flex to different operational requirements through switching between production processes or outputs, over a rigid alternative (Trigeorgis, 1996). The empirical findings suggest that three motivations could underscore investments to incorporate operational flexibility. First, there were switch-options needed to provide flexibility if hindsight learning on actual passenger usage would suggest an operating regime more suitable than that planned. These instances were associated with situations where performance is influenced by humans acting as decision-makers or information processors, such as the options to add a new trolley lift in the car park or a trolley ramp in the train station. Designers thought that their solution would work well, yet they lacked good simulation models or prototypes to model human behaviour. This lessened their confidence on the modelling results or at least made them controversial:

> "A passenger arrives at the check-in desk with luggage on the trolley. If we provision a rack to leave the trolley, how many passengers will put it there? We do not know, so we need to leave ourselves some flexibility to run it for a while before we try to optimize. What is the best way to distribute people in the meeting and greeting area without creating big throngs of people? You can make assumptions but they may not necessar-

> ily come out correctly." [Programme Administrator 2005]

A second group of switch-options built in flexibility to accommodate foreseeable but uncommitted changes. The airport operator foresaw that two additional taxiways connecting the terminal campus to the north runway would be required to use the north runway in a mode less restricted than that currently used. While the value of this option is high because the airport operates close to maximum runway capacity, exercising this option is contingent upon the aviation regulator lifting the usage restrictions in the direction west-east. This, in turn, is contingent upon future developments in aircraft technology and aviation policy. A third group of switch-options included instances where the airport operator invested in a flexible solution to accommodate different operating regimes, such as the four aircraft stands which could serve either a large aircraft such as the new Airbus A380, or two small aircraft. In this case, uncertainty of option exercising was low because the four stands were planned to service any large aircraft using the airport, rather than having their use restricted to service the aircraft of the main airline using the new terminal:

> "We felt we needed operational flexibility to change between small and large aircraft, particularly with the aircraft stands around building 2. So we decided to MARS [Multi-Access Ramp Stand] four of them. MARS stands double the amount of services you have to provide: you mark up two smaller central lines besides the main central line, you add more stand entry guidance systems, more fuel pods, more pier services, more expensive loading bridges, etc." [Airfield Designer 2005]

The next section analyses the design architectures of the infrastructures in which to embed the options.

6.5. *Modularity of the infrastructure architectures*

In the analysis of the interaction between the civil architectures of the functional elements with the other subsystems of the infrastructure I differentiate three situations: First, exercising the options involved plugging modular elements, readily available, into the infrastructure. Second, the physical interaction between the functional elements with the other infrastructure subsystems was modularized during development. Third, the functional elements remained integral with the other infrastructure subsystems because the interdependences were too hard to break apart.

6.6. *Availability ex ante design development of modular functional elements*

The addition of modular, functional elements will be an essential part of exercising the switch-options to install a trolley ramp at the train platform and a passenger lift in the car park, as well as of exercising the stage-option to install two additional baggage reclaim belts. These elements exhibit standard technologies, and stable rules specify the interfaces with the other subsystems:

> "Our design process is different from other people's. We have a product for more than 25 years; it is not like we are making escalators and lifts for this programme. It is almost an off-the-shelf item. We just need to take the height and length, and then we design the machine they are getting. From a design point of view it is straightforward. Our machines generally sit on the edge of the structure on a rubber pad. We just need to tell people the size and depth of the pit, the electrical power, and how our control panel interfaces with fire alarms." [Supplier Director 2005]

These technologies have little stand-alone value, yet they are valuable once integrated in the infrastructures that need them. The limited group of firms that globally supply these technologies – for example, over 80% of the world market share for lifts belongs to seven companies (Mikkola and Gassman, 2003) – may be said to form a modular cluster in the same way clusters have played host to the evolution of modular computer designs (Baldwin and Clark, 2000).

6.7. *Availability ex post design development of modular functional elements*

In a second group of cases, project teams modularized the interaction between the civil subsystem of the functional element with the other infrastructure subsystems. The car park concrete structure, for example, was designed to receive the additional loads of a modular steel mezzanine to park 500 more cars without affecting the aesthetic and structural qualities of the main concrete structure. The mezzanine would sit on steel brackets inserted in the pre-cast concrete columns between the ground and first floors. Likewise, the floor plate superstructure of terminal building one was designed to embed the option to grow the retail and CIP lounges through the addition of modular steel mezzanines. Conservative assumptions were made before sizing the foundations, columns, and floor plates, to accommodate mezzanines with a range of different shapes and sizes.

6.8. Integrative infrastructure architectures

In a third group of cases, project teams were unable to break apart the physical interdependences between a functional element and the other infrastructure subsystems to make it economic to add or substitute the functional element in the future. The interdependences were either between subsystems belonging to the same project or between subsystems belonging to different projects. For example, the civil subsystem of the aircraft stands is tightly coupled to the other subsystems forming part of a stand. The stand pavement consists of a set of structural material layers topped with a thick concrete layer. This layer is integral to the tunnels that supply the utility subsystems (e.g., mechanical, electrical, fuel and baggage) to various locations on both sides of the central lane where the aircraft wheels park. Further, the physical adjacency between stands along the width direction means that one stand cannot be enlarged without reworking the adjacent stands, unless some buffer areas are built in between stands. Likewise, taxiways are adjacent to the back of the stands. This makes it hard to increase the stand length without moving the central line of the taxi way or changing the width of the taxi way.

Some physical interdependencies between the civil subsystems of the train tunnels, airfield pavement, and terminal building one were also hard to break apart. One of the principles underpinning the layout of the new terminal campus was to maximize the provision of new aircraft stands in the first phase, while staging over two phases the provision of passenger throughput capacity for the terminal buildings, baggage system, and train system. The project teams were unable, however, to find a solution for staging the delivery of the terminal building one into two modules – ‘normally, our way’ as put by one respondent – because they wanted to maximize stand capacity around the building footprint. The construction work otherwise needed to expand the building envelope of terminal building one would temporarily remove a number of aircraft stands out of service, an integration cost that the airport operator could not afford:

> “We looked to all sorts of options of how to construct the terminal building one in two phases because we wanted to accommodate 20 million [passenger throughput/year] in phase 1 and 30 million in phase 2. We locked bits off, we did funny configurations, but all had problems in terms of efficiency. Because we wanted the building to have stands on three airside sides, we could not make the building layouts work without losing stands during construction to expand, and *stands are always our most precious resource*.” [Head of Design and Development 2005, emphasis added]

These examples corroborate theory in product design. A caveat with modularization is that developers need to set limits on the depth and breadth of the modularity they wish to achieve to avoid problem-solving in an immense and amorphous space of possible designs (Baldwin and Clark, 2000; Brusoni et al., 2004). The next section pieces together these two contingencies into a conceptual framework to yield insight on the attractiveness of safeguarding.

7. Discussion: from passive to active safeguarding

Safeguards can be passive or active. Passive safeguards only involve a design development effort to generate a definition that does not rule out the firm’s ability to exercise an option in the future. This includes, first, ensuring that the space necessary to exercise the option stays available, and accordingly, document space requirements in master plan layouts and project specifications. Second, designing the subsystems that may temporarily occupy that space in a way that they can be sacrificed, i.e., can be economically relocated in the future. Passive safeguards work well when uncertainty is high because of their negligible sunk costs:

> “It [passive safeguarding] means that I’m not going to invest in anything now because it is too uncertain to make it worthwhile, but I’m going to make sure I have space that I can use if that comes along. For example, in the case of the train system, we identified a route to extend it in the future to the central terminal area but we have not built anything. I will not make any provision now apart from safeguarding space for that route, so I do not block it off if that eventually occurs.” [Director of Design and Development 2005]

Active safeguards cost more because they include both design and physical execution work. They may be attractive, first, when the cost of exercising an option without safeguards would be so onerous due to the complexity of problem-solving that it would cancel out its value. This would mean, in effect, that the option was not built into the design definition. Second, active safeguards may be attractive for increasing the option value in the sense they reduce the exercising costs:

> “I call active safeguarding when we decide to make an allowance now because not doing so would be silly.

Table 4
Summary of database on investments to safeguard

Option #	Safeguard	Investment [civil system]	Option exercising costs [civil system]	
			With safeguards	Without safeguards
1	*Active*: four Multi-Access Ramp Stands (MARS) stands to service one Airbus A380 or two small aircrafts, e.g., Boeing 737	*Low*: $\sim$£1.0 million; $\sim$0.5% increase in airfield civil budget. MARS stands have a 55 cm-deep concrete central lane, which thins to 40 cm where small aircrafts park	*No extra investment*, MARS stands have operational flexibility to park both large and small aircrafts	*High*: civil work costs three times more in airfield than in landside conditions; removing an aircraft stand from service can cost up to £1.5 million/day
2	*Active*: eight aircraft stand geometries to park code-F aircrafts, and two geometries to park Code-G aircrafts	*Moderate*: $\sim$£5.0 million; $\sim$3% increase in airfield civil budget. Construct a 12 m wide concrete lane between stands (to narrow to 7 m), and increase stand length in 20 m	*Moderate*: $\sim$£0.7–1.0 million/stand to reinforce concrete pavement in airside conditions	*Prohibitive*: "it would devastate the airport to rework stand geometries in the future"
3	*Passive*: space in master plan layout for two taxiways linking campus with north runway	*Marginal master planning effort*	*Moderate*: $\sim$£45 million to construct 2 taxiways in airside conditions	
4	*Active*: pit for installing trolley ramp	*Low*: marginal cost increase	*Low*: marginal investment to open pit	*Moderate*: underground construction work; disruption to operations at train station
5	*Active*: tunnel linking terminals 2 and 3, and offline maintenance platform at terminal 2	*High*: $\sim$£70–100 million; $\sim$100% increase in train civil budget needed to double the length of the 'cut and cover' tunnel	*Low*: incremental cost to convert offline maintenance platform into ventilation pit	*High*: "delivering the tunnel beneath operating aircraft stands and taxiways would be a massive cost"
6	*Passive*: space alignment to extend the train tunnel beyond terminal 3	*Marginal master planning effort*	*High*: "it will cost at least £600 million to construct the tunnel—whoever comes and justifies it will have to bear the big cost"	
7	*Active*: 1000 m^2 space in baggage reclaim area to install two carrousels	*Low*: $\sim$£0.8 million; $\sim$1.5% increase in baggage civil budget. Add 1000 m^2 to baggage floor area (over 70,000 m^2) in terminal 1	*No extra investment*	*High*: reconfigure terminal space; negative impacts on operations at arrivals level
8	*Active*: buffer storage area for around 1000 bags	*Low*: $\sim$£0.4 million; $\sim$0.75% increase in baggage civil budget. Add 500 m^2 to baggage floor area in terminal 1	*No extra investment*	*High:* reconfigure terminal space; high risk of impacting baggage handling operations
9	*Active*: Engineer structure to receive a 500-car park mezzanine	*Low*: $\sim$£0.3 million. $\sim$0.4% increase in car park civil budget. Reinforce foundations and columns, and insert 150 steel brackets into columns	*Moderate*: $\sim$£2–4 million to manufacture and install mezzanine	*High*: $\sim$£4–8 million "two-fold increase to dig new foundations and build columns [. . .] there is also the aesthetic cost of a more intrusive solution"
10	*Active*: construct pit lift and knock-out panel slabs along lift shaft	*Low*: marginal increase of the concrete superstructure cost	*Low*: "lift installation will just add a bit because pit and knock-out panels are there"	*Moderate*: "you would have much higher installation costs to break and reinforce the concrete"
11	*Active*: expand floor plate capacity	*High*: $\sim$£20 million; $\sim$10% increase in terminal 1 civil budget. Construct 20% of spare capacity in floor plates (kept sealed off until second phase)	*No extra investment*	*High*: technically possible, but with some impacts over operations inside terminal building 1
12	*Active*: Engineer terminal 1 structure to receive new mezzanines	*Low*: $\sim$£0.25 million, $\sim$0.1% increase in terminal 1 civil budget, reinforce foundations, columns, and beams to receive mezzanines	*Moderate*: $\sim$£1–2 million, cost of manufacturing and installing mezzanines	*Moderate*: technically possible, but with major impacts to operations at departures level

> It is where we specifically put money in the ground to safeguard something for the future so there needs to be a clear demonstration that it is better to build it today than to incur greater cost tomorrow, which is about investigating if there is a practical solution to build it in the future or not.” [Programme Administrator 2005]

Table 4 summarizes the safeguards in the civil subsystems for the 12 options. It shows how safeguards impact the exercising costs, and what the implications would be had safeguards been ruled out. The analysis uncovers a delicate trade-off. Should firms pay more at project birth for an option by investing in safeguards, or should they pay more if and when they exercise the option in the future?

Fig. 2 (right) maps the instances of passive and active safeguards over a two-dimensional space that integrates the uncertainty of option exercising and the modularity of the relevant functional elements in relation to the infrastructure subsystems. Fig. 2(left) abstracts the mapping of the safeguards into a conceptual framework.

7.1. *The attractiveness of passive safeguards*

The findings suggest that the attractiveness of safeguards is negatively related to the uncertainty of exercising the option. The more the assumed uncertainty of exercising the option, the more reluctant project managers are to spend money on safeguards in the face of budget limitations. The region around the top left quadrant in Fig. 2 manifests a situation where uncertainty is high and modularity is low. In this situation, passive safeguarding may be attractive because it ensures the embedding of the option in an infrastructure with an integral architecture, yet it limits the cost sunk in safeguards. This was the case with the decision to passively safeguard the train tunnel between terminal buildings three and four, an option unarguably too far ‘out of the money’:

> “The safeguarding was passive for expanding the train system to terminal 4 and beyond: first, a track alignment, vertically and horizontally, was safeguarded to allow a possible extension; second, the design of the maintenance facility was safeguarded to revert in the future into a running tunnel if the train is extended. We also did not put any critical system rooms at the end of the track, which would then have to be sacrificed [. . .] Will that extension be ever built? It is too early to say.” [Manager of Design and Development for the Train System 2005]

Likewise, high uncertainty ruled out active (but not passive) safeguards for two additional taxiways connecting the new terminal campus to the north runway (which would cost around £15 million, 5% of the civil system budget in the airfield project). The loose integration of the taxiways with the other airfield subsystems precludes a disproportional escalation of the costs to build the taxiways in the future. Rather, the costs will be around three times higher because the work will then be undertaken in airside conditions, which involves night shifts and stringent security requirements. The low costs needed to adapt modular architectures can explain the lack of safeguarding instances when both uncertainty and modularity were high (top right quadrant in Fig. 2). This suggests a situation of mutually exclusive investments (Kulatilaka, 1995b): why invest to further enhance an option with high uncertainty if modularity per se ensures that the cost of exercising the option will not escalate despite the lack of safeguards?

Conversely, the exercising costs can escalate if the functional elements are highly integrative, even when investments are made on passive safeguards. The exten-

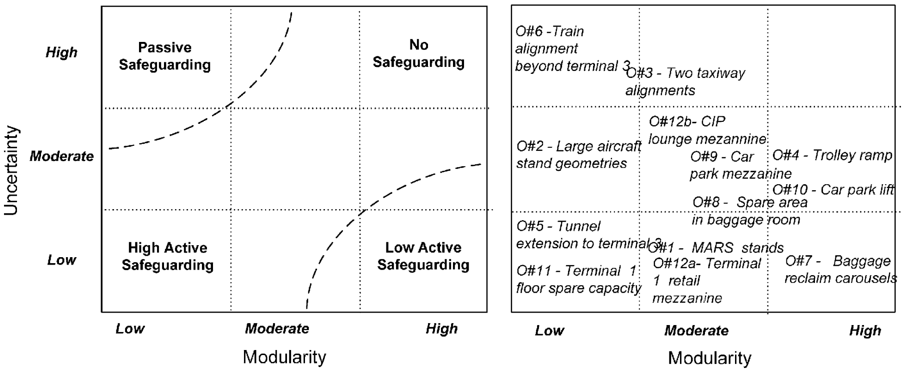

Fig. 2. Attractiveness of safeguarding according to uncertainty and modularity in theory (left) and for the empirical observables (right).

sion of the train to terminal building four and beyond was passively safeguarded by securing underground space and the tunnel alignments. Yet, the excavation of this tunnel in the future through the cut and cover method – the most economical method – is likely to be prohibitive because various aircraft stands and taxiways would have to be put out of service for the construction period. Hence, the tunnel extension will probably need to be excavated with boring machines, which costs at least six times more.

7.2. The attractiveness of active safeguards

The attractiveness of active safeguards increases as uncertainty decreases. Other determinants being equal, decision-makers are less reluctant to invest in active safeguards to embed a stage-option likely to be exercised in the short-term, than to embed a growth- or a switch-option associated with longer timescales. When both uncertainty and modularity are low (bottom left quadrant in Fig. 2), the investments in active safeguards can be very high. The airport operator, for example, invested massively to construct: (1) the tunnel connecting the terminal buildings two and three, and (2) an offline maintenance base at terminal building two to service the trains in the few years that they shuttle between the two terminals. The switch of the train system into a 3-station system requires its reconfiguration into a pinched loop mode by joining the two independent guideways into a loop configuration. The maintenance base at terminal building two can then be converted into a smoke ventilation pit, and another offline maintenance base needs to be built in the terminal building three. While this option was exercised earlier than expected, one respondent noted "the business case for the terminal building three can always collapse if passenger numbers drop after a major disruption."

When modularity is high and uncertainty is low, active safeguards can be attractive as they help to further reduce the costs of exercising the built-in options at marginal cost (bottom right quadrant in Fig. 2). Modularity also increases the attractiveness of active safeguarding as there is a greater likelihood that the assumptions underpinning the safeguards remain valid over time[2]:

> "You must never build something unless you have a reasonable confidence it is going to be required, and when it is required it will be of the same size, shape, or whatever, particularly if you are building underground. You do not want to safeguard underground buildings to discover later that it is in the wrong place when you come to use it. It is easy to waste money by safeguarding because very often you may anticipate something that will turn out either not to be needed or needed in a different place or different form." [Train system design and development manager 2005]

The availability of clusters of modular suppliers, for example, allowed decision-makers to actively safeguard the switch-options to install a trolley ramp and a passenger lift through marginal investments in the interfaces with the civil subsystems. The investments included (1) construct the foundation pits, and (2) detail the reinforced steel in the concrete floor plates of the car park to make it easier to knock down the concrete panels vertically aligned with the lift shaft in the future. In other cases, project teams modularized the interactions between the functional elements with the other infrastructure subsystems, and then invested in active safeguards to further increase design flexibility. For example, investments in active safeguards were made to structurally reinforce the civil systems (including foundations, columns, beams, and floor plates) to receive the mezzanine loads in the future. While some heavy construction work on-site will still be required to install a modular mezzanine, these costs would escalate without safeguards because the integration of the mezzanines would then involve digging new foundations and reinforcing the columns or constructing new ones. The implementation of a mezzanine which had not been safeguarded ex-ante could also have negative impacts from an aesthetic perspective.

Stylized 'decision trees' are useful to summarize choices between alternative strategies based upon a set of conceptual determinants (Terwiesch et al., 2002). Fig. 3 summarizes the decision-making process for safeguarding. High uncertainty of option exercising generally deters decision-makers from safeguarding. Passive safeguards can be attractive, however, with high uncertainty if the relevant functional elements are integral. When uncertainty is low/moderate, the attractiveness of safeguarding is a function of the availability of functional elements that interact in a modular fashion with the other subsystems of the infrastructure.

8. Limitations and outlook

The study addresses the issue of validity by strictly adopting the methodological guidelines for building theory from case study research (Eisenhardt, 1989). It provides enough details on the research protocol to allow others to reliably reproduce the fieldwork and falsify the

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[2] One respondent described this as the 'are you going to get it right?' question.

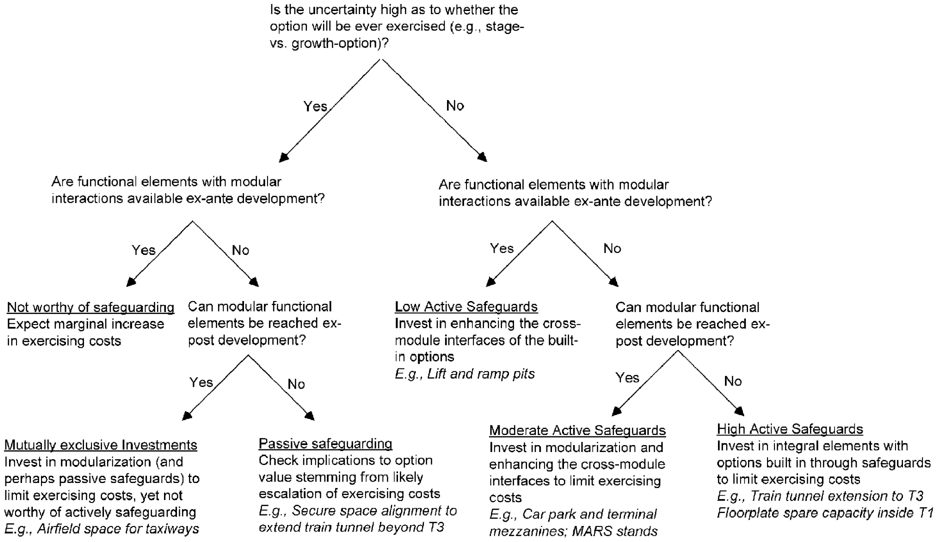

Fig. 3. Scaling the investments in safeguards.

propositions. However, the fact that the findings stem from a single airport expansion programme raises issues with reproducibility and generalizability that only further studies can address (Yin, 2003). In particular, the predominance of safeguards for growth and stage options in our data set may not always apply in CoPS development. In the case of hospitals (AIA, 2004) and high-tech plants (Gil et al., 2006; Gil and Beckman, 2007), for example, evolution in fit out technology appears to be the main source of design change. Likewise, the extent to which the notion of safeguarding applies to digital infrastructures, which are inherently more modular than physical infrastructures, remains indeterminate.

The breadth of the analysis also merits extension in at least two directions. First, the study examines the trade-off between safeguarding and exercising costs for the civil subsystems, yet embedding options involves decisions across a myriad of subsystems and components. A study of safeguarding for options across all the subsystems forming part of CoPS may yield complementary insights. It is also worth exploring in-depth how the attractiveness of safeguards is affected by the magnitude of the investments relative to the strategic value of the option.

Second, the study is focused on intra-programme options although, admittedly, ‘no project is an island’ (Engwall, 2003). For example, the new terminal campus will be connected to the outside environment by two passenger train lines. Yet, there is an option left open to connect a heavy rail line to the terminal. Although this option is associated with low modularity and high uncertainty, the airport operator actively safeguarded it. First, it constructed an underground concrete box for the train station, wide enough to accommodate the construction of a third platform; second, it extended the underground train tunnel to the western limit of the terminal land, so heavy rail from the west can be linked without unreasonable limitations on train gauge or speed in the future. These investments, referred by a manager as “purchasing a license to expand and operate in a world where sustainability matters more and more,” suggest that a complex inter-programme relationship may underpin the decisions to safeguard (Trigeorgis, 1996, p. 133). Clearly, it is worth expanding research on safeguarding into other types of options.

The link to theory in innovation studies also merits further research. Safeguards help to leave open options in integrative CoPS. Some options can relate to new technologies and evolution in the heterogeneity of customer requirements. Safeguards, I conjecture, can help to reduce the strong path dependencies and high barriers for radical innovation exhibited by large technical systems (Hughes, 1987; Miller et al., 1995; Van den Ende and Kemp, 1999; Markard and Truffer, 2006). They may also help CoPS developers, both private and public, avoid the undesirable entrapment or lock-in to sub-optimal solutions (Walker, 2000).

9. Implications to practice, theory, and policy

This study addresses calls for empirical studies that test the conformity of the practice with theoretical real-options work (Trigeorgis, 1996, p. 375; Adner and Levinthal, 2004). It contributes an analysis of an ‘intuitive' (Kogut and Kulatilaka, 2004) operationalization of strategic optionlike thinking. It also uncovers a delicate balancing act. Safeguards increase the option value, yet they get less attractive with high uncertainty and low modularity, two factors that increase the value of the option. Managing this balancing act is important to the development of CoPS. Unlike commercial products, CoPS have long operational lives and often operate within territorial monopolies (Hobday, 2000a; Geyer and Davies, 2000). Two core forces playing a role towards modularization of commercial products – competitive intensity and rapid obsolescence (Schilling, 2000) – may play a minor role in CoPS development. This can lead to a predominance of integrative CoPS and a scarcity of readily available functional modules. The long operational lives of CoPS make it important, however, to leave open options to economically accommodate foreseeable operational changes, new technologies, and business evolution. The value of project safeguards is to ensure, or enhance, the embedding of these options into the CoPS definitions.

There are also other implications for theory on the management of CoPS projects (Hobday, 2000b). Methodologically, the work contributes an in-depth multiple case study on CoPS development. Cases develop a nuanced view of reality and contribute to the effectiveness of theory (Flyvbjerg, 2001). Specifically, the case sheds light on how to make early investments on project safeguards, which can help developers (1) to generate CoPS definitions that are resilient against disruption from externalities, and (2) avoid wasting resources in unavailing safeguards likely to be designed out when the project budget becomes tight. The high-level know-how captured in the conceptual framework can also be useful to build project capabilities, overcoming difficulties to transfer know-how between projects (Davis and Brady, 2000; Prencipe and Tell, 2001; Kogut and Kulatilaka, 2001; Brady and Davis, 2004).

There are also some implications for policy-making. The fieldwork did not uncover any evidence of cost-benefit analysis informing the investments in safeguards. This confirms perhaps the difficulties of applying cost-benefit analysis to problem solving in the context of major projects (Flyvbjerg et al., 2003). Similar difficulties are known with attempts to use cost-benefit analysis to apply the precautionary principle for technology assessment. Proponents of a potentially harmful technology must show the new technology is harmless before the new technology is used (Foster et al., 2000). Yet, the debates to quantify the opportunity cost of not acting and the option value of waiting for further information before acting are more often than not marred by politics and sharp conflicts of interests (Foster et al., 2000; Glynn, 2002).

Rather, the findings suggest that safeguarding is primarily associated with *phronesis*, the context-dependent practice of consideration, judgment, and choice in real-world situations based upon experience and practical knowledge (Flyvbjerg, 2001). 'Phronesis' is often translated as 'prudence' or 'practical common sense', but Flyvbjerg's (2001) notes that there is not an analogous contemporary term. Rather, *phronesis* focuses on what is variable, on that which cannot be encapsulated by universal rules or predictive principles or rules of the praxis (Flyvbjerg, 2001, p. 57). Similarly, a respondent defined safeguarding as '*playing it safe*' and '*about how to prudently stop waste*.' Flyvbjerg (2001) argues that more *phronetic* research is needed to help social science find avenues to praxis, to clarify and deliberate about the problems and risks we face, and to outline how things can be done differently, or in other words, to help make social science matter (Flyvbjerg, 2001, p. 140). This study responds to this call.

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