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The innovation potential of new infrastructure development: An empirical study of Heathrow airport's T5 project

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ABSTRACT

We propose a conceptual framework to analyze technology adoption in mega infrastructure projects, and assess their potential to innovating large socio-technical systems. Drawing on an in-depth empirical analysis of Heathrow airport's Terminal 5 project, we find that innovation hinges on technology adoption decisions that are governed systematically by two intertwined determinants – assessment of expected profitability and development of absorptive capacity, both of which are distributed across various interdependent actors. On an ad hoc basis, technological decisions are also affected by other factors, namely attitudes toward risk, politics, and (lack of) established standards. We reveal how a schedule-driven project framing creates an underlying boundary condition that constrains the longitudinal process of building a 'whole collective' with capacity to absorb new technologies. The innovation potential of mega projects is thus subjected to a fundamental, unifying tension: on the one hand, they offer a one-off opportunity to invest in cutting-edge technologies and innovate socio-technical systems; on the other hand, project stakeholders have limited time to develop capacity to absorb novel technologies and negotiate differences on assessments of profitability and risk. Stakeholders may therefore be compelled to agree to adopt proven technologies upfront to reduce uncertainty and mitigate risks, thus limiting the innovation potential of new infrastructure development.

1. Introduction

Large-scale infrastructure assets such as airports, power plants, or high-speed railways are complex systems and critically, they form key components of even broader socio-technical systems (or networks of systems) – for example, airports are components of air travel. The development of new assets occurs intermittently, often decades apart. Hence, when a mega project delivers a new asset it creates, presumably, a one-off opportunity to modernize and improve the performance of overarching large socio-technical systems. Once the asset is built, it can be expected to constrain innovation since future decisions have to attend to the built-in technologies, especially for elements that are tightly coupled. Studies of technology adoption grounded in mega infrastructure projects – undertakings promoted increasingly by profit-seekers (Gil and Beckman, 2009) – can thus be expected to offer insights on innovation that fill the gap between our understanding of technology adoption in firms and innovation in large socio-technical systems. Here, we explore how two qualities inherent to mega projects – temporality and plurality of stakeholders – affect their innovation potential.

Three interconnected research strands are relevant to explore technology adoption in private-led mega infrastructure projects. The first strand examines the determinants of adoption and diffusion of new technologies at the (micro) level of the firm, emphasizing the effects of expected profitability (e.g., Mansfield, 1961; Stoneman, 1983; Leonard-Barton, 1988; Gomez and Vargas, 2009) and absorptive capacity (Cohen and Levinthal, 1989, 1990). The second strand adopts a macro view to explain technological innovation in constituent parts of large socio-technical systems, including infrastructure. Some studies stress how changes are shaped by a web of socio-political and technical forces (Hughes, 1983; Bijker, 1987; Ferlie et al., 2005; Miller et al., 1995; Islas, 1997; Walker, 2000; Glynn, 2002; Peine, 2008), whereas others emphasize how changes are affected by economic forces (Davies, 1996; Markard and Truffer, 2006; Watson, 2004). The third strand investigates innovation during the production of complex products and systems (CoPS) (Hobday, 1998), which includes infrastructure assets. This meso level research explores how the project-based and multi-stakeholder nature of CoPS production affects the innovation development and adoption processes (Hobday, 2000b; Gann and Salter, 2000; Shapira and Berndt, 1997).

Our study extends extant theory by exploring the extent to which a private-led mega infrastructure project can contribute to innovating large socio-technical systems. More specifically, we ask, first: how do the key determinants of profit-seekers' decisions to

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adopt new technologies interact in these projects? And, second, to which extent can these projects contribute to innovate large socio-technical systems? To this purpose, we follow a research design based on an inductive case study (Yin, 1994). The embedded units of analysis are new technologies that could be adopted in the £4.2 bn (2008 prices) project to add a fifth terminal (T5) to the privately owned Heathrow airport; a positive decision would contribute invariably to innovate overarching socio-technical systems. We use fine-grained archival and interview data to track a sample of technological decision-making processes. We designed our research around the case study method since the phenomenon is underexplored and ill-explained in the literature (Eisenhardt, 1989; Eisenhardt and Graebner, 2007; Siggelkow, 2007).

Through this study, we contribute to extant literature with an analytical framework that elucidates how the key determinants of profit-seekers' decisions to adopt new technologies interact in a mega, private-led infrastructure project. This framework deepens our understanding of the potential of these projects to innovate socio-technical systems. Wholly consistent with prior theories on innovation in large socio-technical systems and CoPS, we find that the project-based decision to adopt (or not) a new technology is a collective outcome involving all key actors that would see their activities impacted by the innovation, either during project delivery or after hand-over to operations. We argue that decision outcomes are governed systematically by the interaction of two intertwined determinants – assessment of expected profitability and development of absorptive capacity, both of which are distributed across various interdependent stakeholders. We also show that on an ad hoc rather than systematic basis, and as a function of the characteristics of the new technologies, decision outcomes can be affected by other factors, including attitudes to risk, politics, and (lack of) established standards.

Importantly, our study advances theory on innovation in large socio-technical systems by uncovering how a mega schedule-driven infrastructure project constrains the time that key actors have to develop capacity to 'absorb' new technologies and assess their profitability and risk, and critically, constrains the time these actors have to reconcile differences in assessments. A sense of urgency to make an adoption decision can spur project stakeholders to agree collectively to freeze adoption decisions on proven technologies upfront, wary of the difficulties to reverse any detrimental consequences of adopting alternative but novel technologies without derailing the project plans. This reveals a fundamental and unifying tension limiting the potential of schedule-driven projects to innovate socio-technical systems that could only be uncovered by a deeper investigation of this phenomenon. On the one hand, these projects create one-off opportunities to adopt new, cutting-edge technology that can modernize large socio-technical systems. On the other hand, constrained timescales can make it attractive to agree on adopting vintage technologies during project front-end strategizing to reduce uncertainty and risk. Overall, these insights enhance our understanding of the potential of new mega infrastructure projects to change large socio-technical systems.

2. Technology adoption: in firms, large socio-technical systems, and mega (infrastructure) projects

Seminal literature on the adoption and diffusion of innovation focuses on factors driving the adoption of new technologies at the level of the profit-seeking firm (Rogers, 1983; Stoneman, 1983). Extant (micro) studies argue that the firm's decision is affected by two key factors: first, the assessment of the expected profitability of the new technology, which factor in both the expected benefits, e.g., savings, new revenues, economies of scale, flexibility and network effects, and the estimated costs, e.g., price, manpower training, human resources, adaptation or substitution costs (Davies, 1969; Fudenberg and Tirole, 1985; Geroski, 2000; Antonelli, 1989; Katz and Shapiro, 1994; Arvanitis and Hollenstein, 2001). Unsurprisingly, profitability assessments differ across firms due to heterogeneity in the diffusion of innovation within the firm's environment (Griliches, 1957; Mansfield, 1961; Canepa and Stoneman, 2003) and heterogeneity among firms in terms of size, status, age, and risk attitude (Karshenas and Stoneman, 1993, 1995; Geroski, 2000; Hollenstein, 2004). A second key determinant is a firm's capability to identify and recognize the value of external information, and to assimilate and exploit it to commercial ends (Cohen and Levinthal, 1989, 1990). A firm's absorptive capacity, which depends on its endowment of human and technological knowledge capital (Cohen and Levinthal, 1989) and on internal routines developed for this purpose (Lewin et al., 2011), equips it to recognize potentially valuable new technologies, understand how they can be exploited, and find ways to mitigate the risks of innovation (ibid). Firms build absorptive capacity through investments in R&D, learning from education, communication, and training initiatives promoted by external parties (Cohen and Levinthal, 1990), and past experience with earlier versions of the new technologies (Colombo and Mosconi, 1995). The firm's absorptive capacity influences its decision to position itself either as an innovator and early adopter, or as an imitator that prefers settling for vintage technologies (Lewin et al., 2011).

Micro studies of innovation point to other factors influencing a firm's decision of whether and when to adopt new technologies. Perceived uncertainties, for instance, can increase the anticipated downside risks with respect to performance, with some firms choosing to be first-movers and others waiting for improvements to materialize that will reduce uncertainty (Rosenberg, 1976). Path dependences in the form of interdependencies and compatibilities among established technologies and standards (David, 1985) also increase adaptation or substitution costs, which combined with constraints in financial liquidity can hold up adoption of new technologies (Stoneman and Kwon, 1994; Mansfield, 1988). Further, technological decisions are also affected by comparisons with what other firms do and how they behave (Massini et al., 2005).

In contrast, (macro) studies of innovation in socio-technical systems emphasize how technological decision-making processes are distributed across interdependent actors who need to negotiate differences on assessments of profitability and risk as a prerequisite to innovate (Davies, 1996; Edquist, 1997; Joerges, 1998; Markard and Truffer, 2008). This literature argues that collective outcomes are influenced by each actor's in-house capabilities which shape its own assessments of expected profitability, in particular the drives to realize economies of scale and scope (Lundvall, 1988; Glynn, 2002; Watson, 2004) within an existing context characterized by established practices, usage patterns, regulations, safety norms, and technical standards (Miller et al., 1995; David and Greenstein, 1990). To complicate things, these actors often have limited in-house capabilities and capacity to recognize and absorb new technologies because they acquire technology infrequently, often relying on third-parties to overcome knowledge asymmetries, map alternatives to their needs, and deal with vendors (Prencipe, 1997; Flowers, 2007). Adding to this framing, socio-constructivist studies posit that to adopt new technology and overcome a 'reverse salient' (Hughes, 1983) – the (sets of) components that lag behind others due to uneven growth of large socio-technical systems – actors need to mobilize the resources capable of transforming established routines and practices (Bijker, 1987; Ferlie et al., 2005; Peine, 2008). Politics and power struggles are inherent to this 'domestication' process (Geels, 2004) due to cross-firm differences in social and cognitive boundaries, path dependencies, and sunk costs (Pinch and Bijker, 1987; Bijker, 1995).

These insights extend into (meso) studies of innovation in complex products and systems (CoPS) – the capital, engineering and IT-intensive assets integral to the socio-technical systems (Hobday, 1998, 2000b; Miller et al., 1995). CoPS projects potentially provide a point of entry of new technology into the socio-technical system, and therefore can shape and can be shaped by the system (Geyer and Davies, 2000; Hobday, 2000a). In CoPS projects, stakeholders need to reconcile differences in perceived risks of project inefficiencies or ineffective operations associated to decisions to adopt new technologies (Miller et al., 1995; Hobday, 2000b; Divr and Lechler, 2004). Difficulties to reach jointly inter-firm, multi-lateral agreements can be compounded by uncertainty and ambiguity in the project requirements (Miller and Lessard, 2000), inadequacy of codified knowledge, limited opportunities for prototyping (Cacciatori, 2008), lack of routines for inter-project transfers of tacit knowledge (Gann and Salter, 2000; Prencipe and Tell, 2001), and inadequate feedback loops between project teams and operational staff (Geyer and Davies, 2000).

Surprisingly, these research strands have seldom intersected in innovation studies, and have been hardly applied to explore innovation in mega infrastructure projects – undertakings that deliver the backbone of modern cities (Hodson and Marvin, 2010) and are essential for economic growth and social welfare (Hansman et al., 2006). Broadly, extant studies argue that technological change in infrastructure sectors is shaped by national policies, path dependencies, vested interests of powerful constituencies, legal issues, and politics (cf. Edwards et al., 2007). Changes are also affected by the private developer's commercial logic or scarcity of public resources (Markard and Truffer, 2006; Edwards et al., 2007) and by standards established to ensure inter-compatibility across systems (van der Vleutn and Kaijser, 2006). But we still know little about how the determinants of profit-seekers' technological decisions play out in private-led mega infrastructure projects, and whether these intermittent projects introduce innovations into the large socio-technical systems of which their outputs will then become part of. These are the two questions that motivate this study.

3. Methods

3.1. Research setting and design

Our empirical setting is the £4.2 bn project to add a fifth terminal (T5) to the Heathrow airport that was granted planning consent in November 2001. This was an appropriate setting for exploring how the profit-seekers' determinants to adopt new technologies play out in a mega infrastructure project since British Airport Authority (BAA), the private airport owner, had committed in the planning application to design the new terminal in close co-operation with its several future tenants including British Airways (BA), the main airline moving to T5, the UK's Border Agency, the organization managing border control, and Heathrow Ltd., the BAA's subsidiary acting as T5 landlord. Hence, BAA's T5 team, the business unit that 'owned' the project budget and led delivery, needed to negotiate technological decisions with these mutually interdependent organizations within a context of well-established norms and practices.

Importantly, the last time BAA had opened a new terminal at Heathrow airport was in 1986 (T4), and future tenants saw in the T5 project a one-off opportunity to modernize their operations. For BA, T5 meant consolidating all its operations in a single hub for the first time in its history; for the Border Agency, the T5 project was instrumental to help it overhaul security practices at Heathrow airport, especially in the aftermath of the 9/11 attacks in 2001; and for Heathrow Ltd., T5 could be seized as a catalyst to improve service across all terminals of the airport, and thereby respond to evolution in air travel, including new safety regulation, new aircraft design, and pressure to reduce flight connection times. Unsurprisingly, all these actors wanted to have an active role in the design of T5 and scrutinize key technological decisions.

Our research design is an inductive case study with embedded units of analysis to improve the richness and accuracy of the conceptual insights (Yin, 1994). In this approach, each unit of analysis – a new technology that could be potentially adopted – is treated as an experiment in replication logic and used to confirm or disconfirm the inferences drawn from the other units (ibid). To yield more generalizable and robust insights (Eisenhardt and Graebner, 2007), we embedded our units of analysis across four subprojects representing over 50% of the T5 project activities – the airfield, the baggage handling system, the substructures, and the inter-terminal train. For this study, we define technology broadly so as to encompass new high-tech systems and technical designs with potential to be applied to the T5 design or delivery process. We selected our sample from a large group of technologies considered in the project, which we identified in the early stages of the fieldwork. Following recommendations to ground the insights of process-focused inductive studies on a diverse sample (Siggelkow, 2007), we built a sample that includes positive and negative decision outcomes – thus the sample includes technologies that were adopted and others that were not. We excluded new technologies that the government mandated to adopt, e.g., Iris recognition immigration system. Informed by macro studies and CoPS literature (Hobday, 2000a; Brady and Davies, 2010), we chose to form a sample that varied in the time that stakeholders took to make collective decisions. Thus, some units of analysis illustrate decisions reached in the early project stages and others show rather protracted negotiation processes. And considering that a firm's capability to absorb a new technology and assess profitability is impacted by the extent the adoption would impact overarching socio-technical systems, we included deliberately in our sample new technologies that would have low or moderate impact, as well as technologies that could be framed as a breakthrough for a broader sector if they were adopted in T5. The need to build a fine-grained database for each unit of analysis also influenced the final selection for the sample. Table 1 summarises key characteristics of the sampled technologies and respective decision-making processes.

3.2. Data collection

Data collection was part of an independent research programme to build theory on new infrastructure development, grounded on in-depth fieldwork. To this purpose, we generated and interrogated data (Strauss and Corbin, 1990) from the T5 project from different cognitive lenses – engineering, economics and management of innovation, and organization science. Fieldwork on mega projects is notoriously difficult because they unfold under the public eye and developers are, understandably, reluctant to share sensitive and confidential data, whilst tending to deliver innocuous and benign press releases, such as 'the project is on time, within budget', 'another milestone has just been achieved'. Exceptionally, however, the first author was given a security pass and restricted access to the T5 project intranet, as well as authorization to contact project staff; cold calls were done to contact other actors, e.g., BA. The bulk of the fieldwork was undertaken between May 2004 and June 2007, when the schematic and detailed design progressed concurrently with manufacturing and construction works.

For each unit of analysis, we tracked the decision-making processes going back to the project start in 2002. Whilst the new terminal was scheduled to open only in March 2008, the T5 design was largely frozen across all the subprojects by mid-2006, effectively closing off opportunities to adopt new technology since late adoptions would involve unacceptable risks of budget or schedule overruns. We used two primary data sources: archives and

Table 1
Summary of the characteristics of the sampled technologies and decision-making processes to adopt/reject.

New technology	Summary description of the technology	Subproject context and budget	Key actors proposing the innovation	Key actors to buy into the innovation	Novelty of technology at project onset	Potential impact to large socio-technical systems	Timing and duration of the decision-making process	Decision outcome
Radio frequency identification (RFID) for baggage handling system	Chip tags attached to baggage so that they can be tracked and data stored and retrieved	Baggage handling system ~£300 m	Technology vendors, third-party consultants (IT industry body)	Baggage subproject team, BA, Heathrow Ltd.	Mature technology, but yet to be applied in air travel	High: fundamental change to baggage handling operations	Decision reached in 2002, less than a year after project start	Not adopted
IT baggage reconciliation system	Tracking and management system to ensure all baggage in the hold of the aircraft is accompanied by a passenger on the aircraft		Joint effort between subproject team and operator (BA)	End-users (BA baggage handlers)	Incremental development of existing systems	Moderate: some impact to baggage handling operations at Heathrow airport	Decision reached in 2005, three years after project start	Adopted
High-performance (F7) concrete mix	Super-strength concrete mix with extremely high flexural strength	Airfield ~£660 m	BAA's Pavement Task team	Airfield subproject team; Heathrow Ltd., civil engineering contractor	Incremental development of existing systems	Low: operations at Heathrow airport remain business as usual	Decision reached in 2002 right at the project start	Adopted
Technical design for aircraft stands	Pavements with varying thickness of the concrete slab, thicker at the central lanes and thinner elsewhere		Airfield subproject team	Heathrow Ltd.; BA	Novel technology, but proponent downplayed impacts	High: potential to set new precedent in the world of airports	Decision reached in 2005, three years after project start	Adopted (in last batch of stands)
CCTV-based vehicle occupancy security system	Remote security system for the train cars based on a network of surveillance cameras and communication protocols	Inter-terminal train ~£90 m	Train subproject team	Train subproject team; Heathrow Ltd.; Department of Transport	Evolved into radically novel development (for threat assessment)	High: potential to overhaul security policy in the world of airports	CCTV-based solution abandoned in production design in 2004, two years after project start	Not adopted
IT production and control system (ProjectFlow)	IT system to support implementation of just-in-time, pull-based production approach	Relevant to many T5 subprojects	Joint effort between T5 logistics team; civil engineering contractor; technology vendor	T5 subproject teams, T5 main contractors	Novel, unproven departure from established practice	Debatable: project-based change, but with potential to change established practice in UK construction industry	ProjectFlow adopted for civil works at project start, but not by other contractors	Abandoned midcourse

IATA: International Air Transport Association, a global trade organization whose mission is 'to represent, lead and serve the airline industry'.

interviews. We gathered our archival data from sources of information internal and external to the project. The internal sources included design briefs, drawings, standards and by-laws, project specifications and execution reports, videos and Power-point presentations, articles published on T5 monthly publications (The Site newspaper, the TeamTalk briefing packs for managers, and the T5live! electronic newsletters) and interviews with T5 administrators in the specialized press (Building Magazine, Construction News) and mainstream press (Financial Times) located through searches on-line using T5 project as the keyword. The external sources included articles about T5 in two professional journals – New Civil Engineering (published by the Institution of Civil Engineers) and Ingenia (published by the Royal Academy of Engineering) – and articles about T5 and emerging technologies for airports published in the leading trade magazines (Passenger Terminal World, Airport Business, and International Airport Review).

We triangulated archival data with excerpts of 58 one-on-one interviews during which we discussed the adoption of the focal technologies. Our interviewees had project roles ranging from top management to technical staff in order to obtain complementary perspectives, fill gaps in understanding, cross-check specific issues and mitigate potential biases of individual respondents. We discussed the case history for each focal technology with at least one representative from each key project stakeholder involved in the decision-making process. All interviews were tape recorded, transcribed, and organized into a digital database. The interview protocol included open-ended questions that asked respondents to describe the process of adopting new technologies and target questions on related opportunities and barriers. The Appendix provides a list of the core questions and job roles of the respondents. When salient issues emerged around one technology, such as particular barriers or contradictory views, we interrogated the respondents about these issues in follow-up interviews. Interview data were supplemented with insights from many informal conversations that took place whenever the first author was on site.

3.3. Data analysis

In inductive research, close adherence to empirical data and their analysis by means of prior and emerging theoretical constructs and relationships aims to provide the discipline that guides the reasoning toward the development of adequate and impartial conceptual insights (Eisenhardt and Graebner, 2007). Thus, to make sense of our data, we started by building chronological stories for each case, triangulating the respondents' interpretations against archival data. We then conducted within-case analyses. For coding the data, we used sensitizing codes and logic derived from the research streams selected as our cognitive frames of reference for this study (Van de Ven, 2007). The within-case analyses helped to develop a preliminary understanding of how technological decision-making was distributed across interdependent actors.

With no a priori hypotheses, we then conducted cross-case comparisons to probe into which constructs and patterns of relationships would hold consistently across the units of analysis. We used cross-case comparative tabular displays to unscramble our empirical findings and cluster and process our data (Miles and Huberman, 1994). As we iterated between data and emerging logic, we gradually built a more objective characterization of the process of adopting new technologies in mega infrastructure projects, and of their potential to innovate large socio-technical systems. As we cycled between data and theory, we crystallized our understanding of the project timescale as an underlying boundary condition to innovation. In the course of refining and validating our insights, we also unearthed the need to distinguish between determinant factors that govern decision-making systematically, and other factors that do not influence decisions systematically but rather on a case-specific and ad hoc basis. These insights underpin the framework that we present after analyzing our data.

4. Analysis: project-based opportunities to innovate large socio-technical systems

The T5 project was a suitable setting to explore whether a mega infrastructure project can contribute to innovating large socio-technical systems. For BAA, the sustainability of its monopoly on the major London airports hinged in part on its capability to improve service at the Heathrow airport, which scored repeatedly low in international surveys of passengers' satisfaction. Strap lines for T5 framed it as a 'world-class gateway into Europe' and 'the world's most successful airport development', showing BAA's effort to suggest to the lay observer its commitment to change and innovation. In turn, British Airways planned to exploit the move to T5 to reengineer ground operations and generate efficiencies critical to compete with the rise of low-cost carriers and global airline alliances. Because T5 was the largest construction project in the UK at the time, BAA and the UK's government jointly saw it as a unique opportunity to change deep-seated practices in the construction industry, a sector generally perceived as inefficient and conservative (Miozzo and Dewick, 2002). Further, Heathrow's iconic status made T5 a desirable project for vendors of new technologies for airports – a global market estimated around £80 bn by Passenger Terminal World. Extolling the innovative ethos of T5, one project director remarked:

> *T5 looks set to be remembered as one of the most remarkable engineering stories of the 21st century with innovative IT and engineering solutions at the very front of the achievement.*

To develop and manage design and execution of all the subprojects, BAA set up a 200-staff business unit (the 'T5 team') with some staff seconded from specialist suppliers. The T5 team's role was akin to that of other systems integrators in CoPS (Hobday et al., 2005). Hence, in co-operation with a myriad of project stakeholders, the T5 team consolidated the facility and operational requirements into design briefs that defined the scope of the works (Fig. 1). To encourage inter-firm co-operation and a problem-solving attitude, the suppliers were brought in under an 'open-book' contract, which limited their commercial risk by guaranteeing reimbursement for all legitimate costs plus an agreed overhead and profit margin (Gil, 2009). Critically, BAA announced publicly in 2003 that T5 would open in March 2008, creating a strong schedule-driven (and constrained) project environment.

Our data confirm that decisions to adopt new technologies in a mega infrastructure project are systematically distributed across key stakeholders, and they need to factor in often misaligned assessments of expected profitability. Our data also show that stakeholders tend to differ in their in-house capability to 'absorb' innovation at the project onset. To try to overcome differences in assessments, the proponents of the innovation invest in educating other stakeholders by offering to share knowledge and additional information. Proponents appear to do so on the presupposition that their effort will increase the other actors' absorptive capacity, which may make them more amenable to consider adopting the proposed innovations. But in a multi-stakeholder, schedule-driven project like T5, conflicting interests and unmovable deadlines limit the stakeholders' eagerness and time to learn about new technologies, as well as to negotiate differences on assessments. This constrains the opportunity to adopt novel technologies, which, in turn, limits the potential of these projects to innovate large socio-technical systems. Next we analyze our data illustrating this conceptualization.

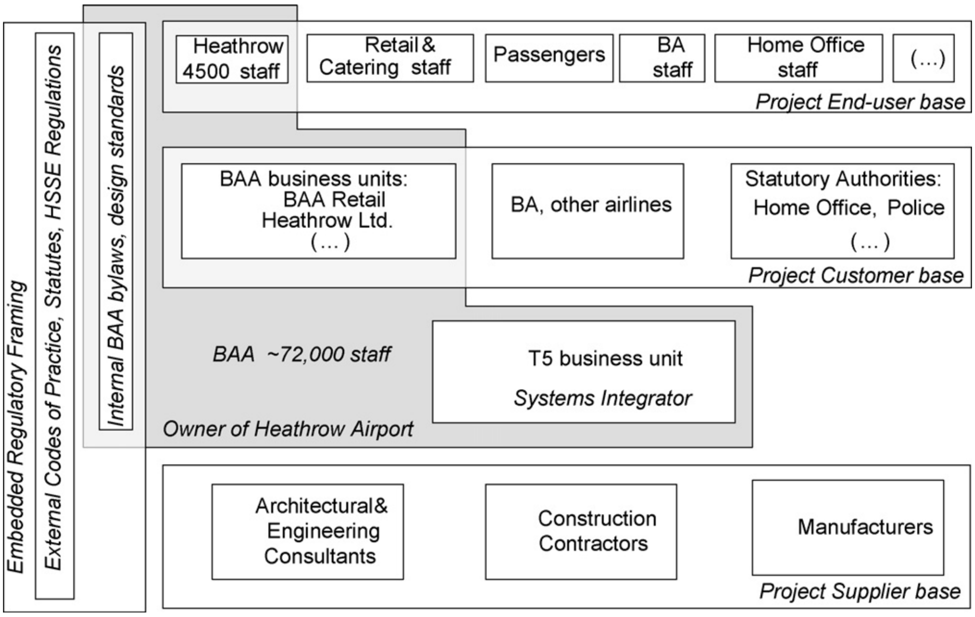

Fig. 1. T5 stakeholders and embedded framing relevant to technological decisions.

4.1. Expected profitability: differences and evolution in assessments across project stakeholders

BAA plc. budgeted the T5 project at £4.2 bn (2005 prices), which created a sense that the firm, which was listed on the London stock exchange, was 'betting the house' since its turnover was around £1 bn and market capitalization was less than £6 bn. To deliver the new terminal on time and within budget was critical for BAA so it could start paying off the capital and interest on the debt incurred to finance it. Aware of the challenge, BAA encouraged subproject teams to scout for new technologies which could save on costs, bring higher revenue, or improve customer satisfaction. Our findings suggest, however, that the technological decisions were not governed by one single actor's assessment of profitability in terms of cost-benefit and risk analyses. Rather, the decisions depended systematically on whether the actors whose operations would be affected by the new technology succeeded in reconciling their assessments in the project time. Interestingly, we observed significant heterogeneity across the stakeholders' initial assessments, which required them to negotiate their differences as the project unfolded. Table 2 summarises, for each technology, information on the capital cost, perceived benefits and risks for the subproject teams accountable for the budget, as well as the perceived benefits and risks for the future operators.

The findings suggest that the assessments of the capital costs tended to be fairly homogenous among the T5 subproject teams and operators because they built on shared information. The exception was the disagreement regarding the cost of training contractors' staff to use ProjectFlow, which some contractors reckoned were underestimated by the T5 team. By contrast, the assessments of the perceived benefits and risks could vary significantly as a function of the stakeholders' in-house expertise, attitudes to risk, and embedded commitments. In particular, assessments of benefits could vary dramatically since some new technologies (e.g., new concrete mix, new aircraft stand design) aimed to bring project efficiencies (benefiting directly the subproject team that owned the budget), whereas others (e.g., new reconciliation system, CCTV system) aimed to improve operations after project handover.

The new design for the aircraft stands is an excellent example. This technology was championed by the airfield subproject team interested in reducing construction costs. Historically, the pavement at Heathrow for a row of adjacent aircraft stands was designed as a continuous concrete slab with uniform thickness. The subproject team proposed instead to vary the thickness of the slab, making it thicker where the aircraft wheels park (the area subjected to high loads) and thinner under the aircraft wings, at the inter-stand clearways, and at the head of stands. This new solution, they argued, required less excavation and concrete works, which could save around £40–60 m in delivering the aircraft stands without compromising (in their view) operational performance. At the project onset, the operators contested this assessment of benefits, stressing that stands were designed to operate for 50 years. In their view, uniform slabs were the only way to 'safeguard' (Gil, 2007) the economical adaptation of the stand geometry if the user-airlines were to reconfigure their aircraft fleet in the future. But the subproject leader disputed the operators' assessment:

> *We do it [continuously] because we perceive it would take otherwise massive work to change the stand configuration in the future. But the probabilities to move stands are low. In one terminal, we're now changing them for the first time in 25 years! And we replaced the pavements anyway as we had to move the fuel connections, change underground services, and the pavements had deteriorated a bit.*

The RFID technology for baggage tagging offers a second illustration of differences in expected profitability. SITA, the leading supplier of IT applications to air transport, identified the opportunity to replace, or at least supplement, the established bar-code technology with RFID, pointing to initiatives ongoing in other international airports. Backed by reports from the International Air Transport Association (IATA) that estimated the annual costs of mishandled bags at around £1.6 bn, SITA argued that RFID could bring substantial operational savings. It also argued that its high reliability could reduce mishandled and lost luggage (the average costs of each mishandled bag were around £83 compared to £4 for bag handling) as well as reduce baggage handling errors from fifteen to less than five per cent. BA and Heathrow Ltd. representatives on the project agreed that the new technology was relevant for their businesses. Together, both firms competed against other airport hubs for advertising the lowest times to connect an inbound flight with an outbound flight, a metric affected by the ability to unload and load bags quickly without mishandling. The two firms did not

Table 2
Assessments of expected profitability and risk for the new technologies.

Characteristics	RFID for baggage handling	New reconciliation system	New concrete mix for airfield pavements	New design for aircraft stands	CCTV solution for inter-terminal train	ProjectFlow for construction works
Capital cost	Very high ~£30–50 m	Marginal ~£1.6 m	R&D cost marginal relative to budget for the airfield subproject	Insignificant	Evolving Cost estimate increased over time: *cost of solution became prohibitive* [subproject leader]	Relative Marginal relative to the T5 construction budget, but perceived high by some contractors
Potential direct benefits for the subproject team accountable for the budget	No	No	Significant savings: (i) reuse of gravels; (ii) 25% reduction of cement, water, aggregates; (iii) reduction of 14,000 truck movements	£20–30 m savings in the £180 m subproject budget for the concrete surface	No	Ongoing debate "We oscillate between getting sacked and being the saviors of the universe" [Leader of the Demand Fulfilment team]
Perceived downside risks for the subproject team	Ongoing debate Very high for T5 team, but not for technology vendor	Moderate Risk of delays in integrating two IT systems	Low Technology had been tried and tested in R&D	Low New paver machinery will make execution feasible	Evolving Risk of integration evolved from marginal to high	Ongoing debate: *Investment is wasteful if people cannot make ProjectFlow work* [T5 leader]
Potential benefits for the future operators	Ongoing debate *I don't think RFID by itself can solve our problems* [Heathrow Ltd.] vs. *RFID lowers need for lost baggage retrieval* [vendor]	Very high (except for baggage handlers) Minimize misrouting of bags; enhanced real-time visibility and traceability	No	No	Very high Reduce requirements for operational staff	Yes, but indirect Savings in construction work release capital to invest elsewhere in the T5 project
Perceived downside risks for future operations	Very high (except for technology vendor) No tried and tested application in air travel; RFID standards unresolved; pay off only if RFID takes up	High Threat of industrial action by BA baggage handlers	Minimal Operator relies on technical competence of project staff	Ongoing debate *Flexibility of possible future conversion will be lost* [Heathrow Ltd.] vs. *push back is just reflection on how it was made in the past* [subproject leader]	Evolving Risk to operations evolved from low to high as project design unfolded	Not applicable

dispute that RFID technology was more reliable than bar coding, yet they expected a negative profitability. They argued that, consistent with literature on network externalities (Katz and Shapiro, 1994), the financial case would not stand up unless more major international airports adopted the new technology. For example, a Heathrow spokesman noted that tags were expensive – "each tag needs to cost less than 10 cents, it's no way near that". Furthermore, an expert seconded to the subproject team saw significant flaws in the vendor's commercial logic:

> *I don't buy them [the benefits] because the reasons for lost bags are numerous. And I don't think RFID can solve the problem. A lot of the problems we've with lost bags are that we don't get the message through due to equipment failures – the RFID tag can be on the bag, but if we don't get the message, we still have a problem.*

The sharp differences in the expected profitability informed BA's and Heathrow Ltd.'s joint decision to rule out right at the project onset the possibility of becoming early adopters, and contributing to generate epidemic effects (Mansfield, 1961) and increasing returns (Arthur, 1989) for RFID technology. Still, our data show instances when the key actors' assessments of a new technology were almost all in harmony. One example is the baggage reconciliation system. This technology aimed to replace the system that BA baggage handlers used to scan bags in the sorting area before putting the bags onto the containers to be loaded on the aircraft. The innovation would integrate the reconciliation and baggage handling systems, allowing data sharing between the BA handlers and check-in staff for the first time. Handlers would be given handheld terminals which were faster, more reliable, robust, and ergonomic compared to the ones they used, and had enhanced data-capture features that would minimize misrouting of bags and enable the segregation of baggage according to passenger flight class. From the early stages of design, the subproject team, the key suppliers (Vanderlande Industries and IBM) and BA agreed that the benefits largely offset the costs. A new system would help BA meet new targets for system-generated errors and delays that could bring savings of up to £10 m annually. We discuss later how it took nonetheless three years to talk the baggage handlers into the new technology, a prerequisite to go ahead with its adoption and fulfil the aim to use the T5 project to innovating BA's baggage handling operations at Heathrow airport.

Our analysis also shows how attitudes to risk could lead, occasionally, to sharp differences across stakeholders' assessments of a new technology. In the case of the new aircraft stand design, the airfield subproject team needed over two years to persuade the future operators that their perceived risk from having limited flexibility to adapt the aircraft stands in the future was illusory. Even more striking were the differences in the risk assessments of the RFID technology across stakeholders: the operators' aversion to risk – an attitude typical of imitators (Rogers, 1983; Massini et al., 2005) – was influenced by fiascos with airport openings attributed to innovation in baggage handling systems. As a result, they insisted on a 'pizza-bin' approach (Clark and Wheelwright, 1993) that consisted of using only proven off-the-shelf technologies:

> *We don't prototype, that's one of the lessons we learned. If we've got a problem, we try using existing technology to solve it. We don't want to be another Denver* [T5 production leader].

This risk-aversion attitude made it virtually impossible for the RFID vendors to talk sceptic operators into RFID – as the T5 production leader quipped: "RFID? Great theory. Let someone else test it first." Yet, our data also show instances in which the assessments of profitability converged over time. To understand this, we examine next the interaction with efforts to build up the stakeholders' absorptive capacities.

4.2. Developing stakeholders' absorptive capacity over project time: R&D, education and communication

Our analysis indicates that each individual stakeholder's assessments of profitability, irrespectively of whether they were positive or negative, reflected systematically its understanding of the new technology at a point in time. Our data also indicate that each stakeholder's in-house capacity to understand the broader impacts of adopting new technology could evolve over project time. Consistent with theory (Cohen and Levinthal, 1990), the proponents of the innovations tended to build up their own absorptive capacity by investing in internal R&D and other routines for knowledge-creation (Lewin et al., 2011). Concurrently, they sought to enhance the absorptive capacities of other relevant actors, driven by the presupposition that effort would make it easier to reconcile differences in technological assessments. To this purpose, the proponent would involve occasionally a subject-matter expert. Table 3 summarises our data.

We observed that the proponents of innovation, mindful of the need to forge cross-stakeholder consensus around technological decisions, used systematically a combination of different communication channels to try to educate other actors. One good example is the new concrete mix. Even before the T5 project received planning consent, BAA and BA discussed whether to prepare the new terminal for receiving larger and heavier aircraft such as the Airbus A380. BA was not disclosing its purchasing plans ("never subscribed to the concept 'buy now while stocks last'", as put boldly by the CEO), but BAA experts reckoned that purchasing A380 aircraft was the only way through which the airline could grow capacity at the Heathrow airport, which operated close to the cap on the number of air traffic movements. The projected 28 t wheel loads for the A380 represented a 20% increase relative to a fully loaded and fuelled Boeing 747. If the airfield subproject team stuck to the established F5 mix, the concrete slabs would be over 800 mm thick, and thus difficult and expensive to lay down. Anticipating the emergence of this 'reverse salient' (Hughes, 1983), even prior to T5 project approval, BAA invested in an internal R&D programme to explore new concrete mixes – a conventional way to develop absorptive capacity (Cohen and Levinthal, 1990). Over three years, the BAA Pavement Task team performed tests and full-scale trials to understand the sensitivities and requirements of the new mix. When the design for the new airfield started, the T5 team knew enough to document the specifications for the new F7 mix and educate the contractor selected to do the job.

Crucially, the promoters' effort to educate other actors, or put differently, to try to develop their absorptive capacity, did not guarantee that the latter would change their position toward a new technology, and arguably, that their absorptive capacity even increased at all. A good example is ProjectFlow, an IT application for improving the reliability of construction planning. The technology built on a paper-based workflow method ('Last Planner') which BAA had been using in projects since 1998 with positive results (Lane and Woodman, 2000). At the onset of the T5 project, as part of the Integrated Demand Fulfilment Strategy, the T5 team commissioned a specialist technology provider (SPS) to develop a more advanced IT application jointly with Laing O'Rourke (LoR), the civil engineering contractor which was the first to move on site. The T5 team, aware that it was asking suppliers to depart from well established practices, sought to educate them by discussing ProjectFlow in the TeamTalk pack and T5live! newsletter. It also produced a booklet explaining what ProjectFlow 'was and wasn't', and the ProjectFlow evangelist in T5 delivered presentations of the benefits achieved in early applications, e.g., savings of 36% (£1 m) in pile cage fabrication. From the T5 team's point of view, using ProjectFlow was essential to improve construction productivity and reduce site congestion, stressing that its adoption by LoR had brought 'tens of millions of savings' to the project. Notwithstanding these forceful efforts, none of the other suppliers followed suit ("ProjectFlow betrayed the concepts in Last Planner, argued one supplier). Whilst it is unclear whether the suppliers' capacity to absorb this new technology effectively increased (we discuss later how politics created a disincentive for other suppliers to even care to learn about ProjectFlow), the fact is that the aspiration of using the T5 project to innovate work planning practices in the UK construction industry fell apart.

Exceptionally, efforts to develop stakeholders' capacity to absorb a new technology could revert the innovator's own stance. The example is CCTV, a technology that the train subproject team built into the design brief in 2002, but later deemed ill-suited. In order to meet a statutory requirement for maintaining segregation between departing and arriving passengers, the security system for the train cars needed to ensure that no objects would be left unattended. The relevant actors reckoned that a remote security system would drastically reduce the operational costs and increase reliability (the train itself was driverless). If adopted, this innovation would overhaul security policy at Heathrow airport, with potential ripple effects to major airports worldwide. And when the train cars started to be manufactured in 2004, a decision was made to add cabling for the CCTV cameras. However, the train subproject team later changed its position:

> *Until we consulted the Department of Transportation, we hadn't appreciated the requirement involved in threat assessment. Initially, we thought we needed a detection system, later it became clear that threat assessment was needed as well* [Subproject leader].

Specifically, the subproject team learned that CCTV technology for threat assessment was still in its infancy. New and complex algorithms for scanning a scene, detecting a potential threat, filtering false alarms, and notifying the operator were already on the market, but independent trials suggested that the applications exhibited a propensity to generate many false alarms and required a dense network of cameras to be effective. Concerned with reliability, and anticipating expensive licensing fees and maintenance, the key actors agreed collectively to opt for a man-based solution in 2004.

Crucially, our data show that pre-set project milestones and deadlines constrained the time available to the proponent of an innovation for trying to develop other actors' absorptive capacity. The proponents' efforts presuppose that uneducated actors are open to listen to the innovators' point – a reasonable logic. In the case of the baggage reconciliation system, for example, an expert on Heathrow baggage systems (who had a reputation of being 'quite impartial and independent' in his own words) was brought in to work closely with the baggage handlers as the deadline to agree changes to user-interfaces and output reports loomed up. This finding points to a fundamental tension between the aspiration to adopt cutting-edge technology in a mega project and the need to keep it on schedule, which limits the time to build a whole collective (Miller, 1993) capable to absorb a new technology and agree

Table 3
Building absorptive capacity over project time.

Characteristics	RFID for baggage handling	New reconciliation system	New concrete mix for airfield pavements	New design for aircraft stands	CCTV solution for inter-terminal train	ProjectFlow for construction operations
Proponent's communication and education channels	RFID-on-Baggage summits, IATA Baggage-Go teams, articles, visits to RFID-enabled airports, industry fairs	Show and tell workshops; end-user meetings; training sessions; informal talks	Project meetings; project specifications	White paper; project meetings	Project meetings; briefing documents	Internal presentations; briefing documents; meetings; fliers; articles in project publications
Involvement of subject-matter experts	Not observed	Yes Heathrow airport specialist on baggage systems seconded to T5 team to educate everyone: *I need to galvanize users and developers* [subject-matter expert]	Not observed	Yes Airfield subproject leader's expert status key to dispel concerns: *This is a technical field, and I'm the specialist here* [airfield project leader]	Not observed	Yes Leader of Demand Fulfilment (DF) team had expert status: *Every time they push back, I say 'you're not looking across the whole* [DF leader]
Overall evolution of adopters' capacity to absorb technology	Unclear *We want to see it [RFID] used in other airports. When it's a success, we employ it* [T5 Production Leader]	Positive *Ground handlers are now happy with the new handhelds* [Subject-matter expert]	Positive *We had to operate at edge of possible, but we were always confident we could do it* [T5 contractor]	Positive *We're now looking into it for some aircraft stands, but won't do it across* [Heathrow Ltd. rep.]	Positive *When you get to the nitty-gritty of what segregation means, it means a whole host of different things to different people* [T5 subproject leader]	Unclear *We need to change the project organization, but people [T5 leaders] don't understand that* [ProjectFlow evangelist]
Chronology of key related events	2002, T5 team/BA rule out RFID adoption 2003, Las Vegas Int. airport invests $125 m in RFID application 2004, Hong Kong Int. airport invests $50 m in RFID application 2008, RFID adopted in Milan, Lisbon airports	2002, T5 stakeholders agree need for new system 2003, BA leaders start talks with baggage handlers 2005, T5 team gives go ahead to design in the new system 2006, BA completes labor talks	1998, BAA initiates R&D project to develop new concrete mix 2002, start laying new F7 mix on site 2005, 35% of airfield completed using F7 mix 2007, BA commits to buy A380s	2002, Start discussions of new aircraft stand design 2004, first batch of conventional stands completed 2005, new design adopted in second batch	2002, CCTV documented as preferred option 2003, wiring looms installed in train cars 2004, agreed not to pursue CCTV-based-solution	1998, BAA adopts paper-based version 2002, ProjectFlow adopted in civil subproject 2005, T5 team drops effort to diffuse innovation

multilaterally to adopt it. We next examine how this tension played out systematically in the T5 project.

4.3. Negotiating innovation adoption: a race against the project schedule

The T5 schedule included 70 intermediate milestones ('70by07') and other deadlines for key design and technological decisions – the so-called 'Last Responsible Moments' (Gil and Tether, 2011). The progress of the subprojects was reviewed quarterly and the public announcement of the opening date placed enormous pressure on the T5 team. The team also shared a sense that the project schedule was tight after an internal review in 1999 shaved off one year from the original plan. Still, risk simulations and global benchmarking suggested that the target was achievable. But, by 2005, the T5 team's sense of urgency to freeze the design became overwhelming:

> *We're about 15 months from commissioning. Design needs to be finished because we‘ve to build it. And the only way to drive this forward is to get ownership of areas, and get more dictatorial rather than consensual management. The tipping point should have happened, I suggest, 6 months ago!* [T5 Construction leader].

Our data indicate that the framing of a mega infrastructure project as schedule-driven creates an underlying boundary condition that constrains the time to build up the stakeholders' capacity to absorb innovations and negotiate differences in assessments. The sense of urgency impels project managers to ask for decisions to be made as early as possible so as to ensure there is enough time left to detail, implement and test the new technologies, whilst leaving prudently a buffer for accommodating risk. The pressure to deliver on time also creates a sense that adopting a new technology adds risk of further adaptation and derailing the project schedule. To compound the difficulties to adopt new technologies, collective decisions that involve many equally legitimate stakeholders are unsurprisingly difficult to achieve quickly. Table 4 summarises data on how this tension played out systematically across our sample, limiting the T5's potential to innovate overarching socio-technical systems.

The new reconciliation system provides a good illustration of how innovation adoption was repeatedly a race against the project schedule. The original deadline to make an adoption decision was end of January 2005. All key actors agreed it was critical to start integrating quickly the reconciliation system with the baggage handling system (the testing and commission of which was scheduled to start in 2005) to allow for unexpected delays. But the new technology was difficult to shoehorn in the project. On the one hand, the proponents struggled to communicate adequately its features wary that similarities to a system in use elsewhere could be unfairly perceived as an infringement of intellectual property rights – a concern which complicated their effort to educate the end-users. On the other hand, the proponents needed to get the end-users'

Table 4
Negotiating differences in assessments over the project time.

Characteristics	RFID for baggage handling	New reconciliation system	Concrete mix for airfield pavements	New design for aircraft stands	CCTV solution for inter-terminal train	ProjectFlow for construction operations
Key obstacles to innovation adoption at the project onset	Adopters' wariness of (1) vendor's logic; (2) lack of global standards, and (3) absence of network and epidemic effects	End-users' worries with job security	Adopter's concern with lack of qualified concrete paver equipment	Established preconceptions, mental models, and design practices in adopters' world	Adopters' wariness of: reliability of the new technology	Adopters' sunk costs and wariness of innovation proponents' logic
Evidence of potential benefits at project onset	Scarce	Plenty from similar systems in place at other airports	Plenty from BAA internal R&D programme	Scarce	Scarce	Documented cases on a vintage technology
Change in adopters' assessments over the project time	No Adopters remain unconvinced of the business case	Yes Handlers become convinced that retraining will keep their jobs	Yes R&D findings effective to get rid of any technical concerns	Yes Adopters buy into reasons why on balance loss of flexibility is not a big issue	Yes (but on reverse) Adopters lose faith in business case	No Adopters remain unconvinced of the business case
Ad hoc impact of particular risk attitudes to negotiate differences in assessments	Adopters' risk aversion amplifies concerns with new technology	Not observed	Not observed	Adopters' risk aversion amplifies concerns with new technology	Not observed	Not observed
Ad hoc impact of politics to negotiate differences in assessments	Not observed	Yes Negotiation affected by threat of industrial relations actions	Not observed	Not observed	Not observed	Yes Negotiation affected by proponent's political ineptitude
Ad hoc impact of established standards, or lack of	Lack of global standards contributes to put off adopters	Not observed	Not observed	Need to rewrite Heathrow standards complicates decision to adopt	Lack of established standards contributes to put off adopters	Not observed
Final contribution to innovating large socio-technical systems	No	Yes Modernization of baggage handling operations	Limited No visible impact to airfield operations	Yes Major change to the design of airfield systems	No	No

approval. When BA was yet to commit to the technology in April 2005, a crisis erupted, as a T5 leader explained: "If for any reason [BA] don't make a decision now, we'll be in a situation where we won't have a complete system". Facing a political ultimatum, as the T5 team was keen to adopt the new system but had no contingency left to fund it, BA released ten percent of the funding but stopped short of fully endorsing it. Thanks to the IT supplier's ingenuity, a deadlock was averted; using a flexible architecture, the supplier built 'hooks' in the software of the baggage handling system whilst holding on to coding until BA endorsed it finally in July 2005.

Occasionally, a prolonged process to negotiate inter-stakeholder differences in assessments could lead to a suboptimal outcome. The example is the new aircraft stand design. The first two handover of stands were scheduled for May and October 2004. It was critical for BAA to meet these deadlines since a delay would trigger a tightening of the price caps on the airport levies. The airfield team insisted that expensive, uniformly 'thick' slabs were an 'old' practice from the days when airports were publicly-owned, arguing it was time to shift to a new 'paradigm' (Dosi, 1982) in aircraft stand design. But they were not naïve about the effort and time required to do so: "It may take 2 years or more to get it approved!" exclaimed the sub-project leader. To overcome the adopters' worries about the loss of flexibility – unfounded in the proponent's view – the latter collated historical data showing that: (1) the cost of removing a stand from operations was marginal since the airport had spare capacity for parking aircraft; and (2) the chances of this scenario occurring were low. To further persuade other actors on the merit of the innovation, the T5 team highlighted that other elements connecting to the stands, including gates, air bridges, fuel pods and baggage chutes, did not have built-in flexibility either. It also pointed to advances in paving equipment to brush off perceptions that inefficiencies from varying the thickness of the slabs would outweigh the savings. Ultimately, the team leader's commitment to the change ("*I'm* challenging the way we build stands") and his team's efforts paid off. The innovation was adopted in the last batch of aircraft stands – reportedly, the first time ever in a major international airport – setting a new precedent.

However, our findings also reveal instances where either the proponent failed to build up other actors' absorptive capacity in time to design the innovation in T5, or arguably, the capacity was there in the end, but it was still not a sufficient condition to reconcile sharp differences across the parties' assessments of the new technology. An excellent example of this is ProjectFlow. Despite the T5 team's efforts to educate the contractors about the proven merits of the new technology ("a couple of times we let the system revert to traditional ways of working to show people what could happen", confided the ProjectFlow evangelist on T5), the presumably educated contractors remained unconvinced. They asserted that ProjectFlow was only fit to handle bulk materials. When the Demand Fulfilment team shared examples of successful applications to manufactured products, suppliers insisted that their bespoke modules did not fit well with a pull system. For example, one supplier, mindful of the costs sunk in its own logistic system, said "We're aligned with the principles, but won't implement them in the way they're suggesting". The suppliers also pointed out drawbacks, insisting ProjectFlow was easy to cheat ("you tell it you do less than you think [you can do] just to make sure you accomplish 100% of what you say") and vulnerable to misuse ("just because I put an order in, I've now something to come back to you with").

In hindsight, the T5 team partly attributed the failure to forge consensus – and ultimately to change practices in the UK construction industry – not to deficiencies in the technology, but to the building suppliers' conservative mindset:

> *The construction industry changes course slowly and [ProjectFlow] demands a real change in attitudes (...) Production, assembly, transportation activities are broken down in many codes, and people aren't measuring the whole. When we deliver presentations, we get a lot of skepticism (...) The challenge is how to make the message pass, to tell them 'this is what needs to happen* [ProjectFlow sponsor].

Uniquely, the RFID case tells of key adopters agreeing to rule out a technology with massive potential to change the airport and airline industries early on in the project, hardly giving its proponent a chance to bring them up to speed on its merits. Both BA (which would have to pay for the tags and check-in printers) and the T5 team (which would have to pay for other infrastructure) reckoned that there was no way the RFID technology would become the de-facto dominant, standard technology in baggage handling by the time T5 opened. This conviction, combined with an imitator's aversion to adopt an unproven technology (Massini et al., 2005), the risks of which were difficult to discern, ruled out any chance to adopt RFID in T5. In this regard, our data suggest that the decision was prescient since a global ISO standard remained unresolved in 2008, with IATA admitting 'everyone is waiting for everyone else'.

On an ad hoc rather than systematic basis, and consistent with socio-constructivist studies (Hughes, 1983; Bijker, 1995), the outcomes of technological decisions were also shaped by politics. In the case of the reconciliation system, for example, the decision to adopt the new technology got tangled with internal politics between BA top management and the unions – BA had agreed to ballot the staff on a range of changes to operations at the Heathrow airport, but staff kept complaining:

> *"[BA] made their decision to employ process engineers to develop the operations in T5, and when they spoke to the unions side about it in constitutional forums, it was an imposition (...) They have dehumanized a system with complete reliance upon technological advances"* [Union representative].

Concerned about the baggage handlers' threat of industrial action, BA management delayed the decision to adopt the new technology until the handlers were reassured that retraining would avoid loss of jobs. Likewise, the T5 team attributed its failure to get other suppliers to buy into ProjectFlow also to politics, especially its failure to anticipate suppliers' aversion to adopt a tool when its key evangelist was not a BAA-badged employee, but rather was on a main contractor's payroll. Although the T5 team rebranded later the system to BAAProjectFlow, this eleventh-hour action was deemed too late to be effective. We discuss next how these findings illuminate our understanding of adoption of new technologies in mega infrastructure development projects and the potential of these projects to innovate large socio-technical systems.

5. Discussion

Our inductive study suggests that decisions to adopt new technologies in a private-led mega infrastructure project are systematically determined by the longitudinal interaction of two intertwined factors – assessment of expected profitability and development of absorptive capacity, both of which are distributed across interdependent project stakeholders. To increase the odds of reconciling differences in assessments of a new technology in the project time, its proponent invests in educating other actors, many of which lack in-house capabilities to assess novel technologies at the project onset – understandably, in light of the intermittent nature of mega projects. The proponent's effort to build a 'whole collective' (Miller, 1993) to comprehend the new technology and its impacts does not guarantee, however, that a de facto 'collective' absorptive capacity emerges, and even if it does, it may be still insufficient to overcome differences in assessments, i.e., educated actors can agree to disagree. Fig. 2 and Table 5 outline this conceptualization. At the project onset, each stakeholder holds its own level of expected profitability and absorptive capacity. Both dimensions are bound to evolve overtime through processes of education and negotiation constrained by preset project milestones. Final agreements can lead to decisions to adopt novel technologies and innovate overarching systems, or instead to adopt proven technologies, forsaking the opportunity that the capital project creates to innovate large socio-technical system.

Table 5
A framework of new technology adoption in mega infrastructure projects.

Key determinants of technological decisions in new mega infrastructure development projects		
	Stakeholders' assessment of expected profitability	Stakeholders' development of absorptive capacity
Critical mechanisms in realizing the determinants	Cost-benefit analysis Risk analysis	Internal and external R&D Communication Education and learning initiatives Involvement of subject-matter experts
Time logic	Project milestones and deadlines constrain time left to refine assessments	Actors need to develop absorptive capacity before project design freezes
Multi-stakeholder logic	Differences in assessments need to be negotiated and bargained for	The absorptive capacity of the whole collective needs to inform decisions
Other factors that can affect the interaction of the main determinants on an ad hoc basis		
Risk-aversion attitude	Can influence assessments negatively	Can affect willingness to develop absorptive capacity
Project politics	Can influence perceived legitimacy of assessments	Can complicate process to develop the whole collective's absorptive capacity
Lack of adequate regulation/ standards	Delays materialization of network/epidemic effects	Can affect willingness to develop absorptive capacity in project time

Consistent with micro studies of technology adoption (Lissoni, 2000; Arvanitis and Hollenstein, 2001; Gomez and Vargas, 2009), our conceptualization posits that decisions to adopt new technology are informed by intertwined assessments of expected profitability and absorptive capacity. But in the context of mega projects, we contend that stakeholders may hold heterogeneous technological assessments at the project onset, and that decisions to adopt new technologies and innovate large systems hinge on whether the actors develop a whole collective with capacity to absorb the innovation before preset deadlines. In agreement with studies of large socio-technical systems (Geels, 2004; Davies, 1996; Hughes, 1987; Markard and Truffer, 2006) and innovation in CoPS (Prencipe, 1997; Geyer and Davies, 2000; Hobday, 2000b), we emphasize those decisions to acquire new technologies in one-off mega projects are outcomes of conflicted and negotiated processes wherein stakeholders differ in their capabilities and incentives to innovate. On an ad hoc basis, outcomes can be affected by other factors including risk attitudes, politics, and (lack of) established standards.

A central contribution to studies of innovation in large socio-technical systems is to unearth how the schedule of a mega

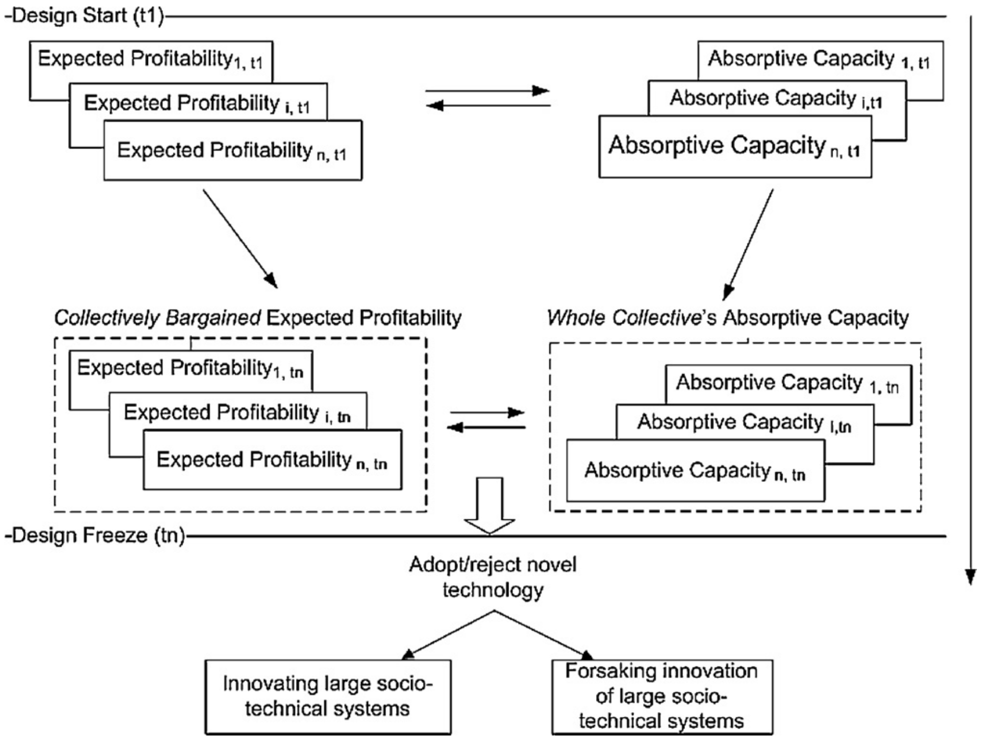

Fig. 2. The technological decision-making process in mega infrastructure projects (i, j) = (*project stakeholder*, *project time*).

infrastructure project constitutes an underlying boundary condition that limits its potential to innovate these systems. Indeed, prior studies emphasize that innovation is protracted in socio-technical systems (Markard and Truffer, 2008) and in CoPS projects (Prencipe, 1997; Hobday, 2000b). Yet, the scheduled-constrained nature of the potential contribution of mega projects to innovation had remained elusive. Our study proposes that, irrespectively of the novelty of the new technology relative to the project context, technology adoption decisions face a race against time. Underlining this race is a fundamental and unifying tension between the pressure to freeze design at the project front-end – framed invariably as best practice in project management manuals (PMI, 2004) and scholarly studies (Morris, 1994; Miller and Lessard, 2000; Brady and Davies, 2010) – and the time-consuming process of building a whole collective with capacity to agree on their adoption. A constrained timescale can make key actors reluctant to adopting unproven technologies, which may be perceived to increase the risks of derailing the project, and consequently, unwilling to seize the opportunity to innovate large socio-technical systems. This risk-aversion can be compounded by a sense of imponderability and incomprehensibility of the functioning of complex systems, in which seemingly minor decisions can trigger combinations of small failures with unintended consequences (Tenner, 1996) or even lead to unforeseen disasters (Perrow, 1984).

Taken together, these insights contribute to explain why vintage instead of novel technologies may be adopted in mega projects despite efforts of individual actors to seize the one-off opportunity that these undertakings create to modernize overarching socio-technical systems. Occasionally, the awareness that the next capital investment will be decades away can encourage the key actors to agree collectively to incur calculated risks. To be effective, the proponent of the innovation needs to start working as early as possible in attempting to build up other actors' capacity to assess the innovation and its impact to broader systems. However, technological decisions remain distributed, and the innovator has no guarantee other actors are even willing to listen in the project time. Furthermore, even if they listen, educated, capable actors may feel as confident to invest in a new technology as to reject it. These insights are significant because, in contrast to manufacturers' chances to adopt new technology over successive generations of consumer products (Krishnan and Bhattacharya, 2002), the non-adoption of new technology in a mega project can delay the modernization of overarching socio-technical systems for decades to come.

In relation to studies of innovation in CoPS (Hobday, 1998; Gann and Salter, 2000), the contribution of our work is to frame mega projects as heterogeneous rather than homogeneous contexts for innovation. Whilst technological decisions tend to be invariably the outcomes of negotiated and conflicted processes, differences exist between holding negotiations between two actors and negotiating differences among a large group of actors, each assessing the benefits and costs of a new technology and its impacts differently. In particular, we show that the stakeholders' attitudes toward risk which invariably shape decision-making in mega projects (Flyvbjerg et al., 2003; Perrow, 1984; Miller and Lessard, 2000; Shapira and Berndt, 1997) can vary significantly for the same technology. Thus, the greater the number of actors involved in the decision-making process, the more complicated and conflicted it becomes, as well as more vulnerable to politics. Interestingly, we find that whilst financial liquidity is known to affect technological decisions (Mansfield, 1988; Stoneman, 1983), a fixed project budget is not necessarily a hard constraint. When a subproject team has limited contingency left to fund the innovation, inter-subproject budget transfers can be negotiated; operators can also fund capital costs. These devices build budget flexibility, which contrasts with the greater rigidity that the schedule imposes.

Importantly, our study suggests that subject-matter experts can be instrumental to build multilateral consensus over the project time. This insight adds an individual dimension to macro studies of technology adoption and non-spread of technologies, which claim groups and professions can have conflicting objectives toward innovation (Hughes, 1983; Bijker, 1987; Geels, 2004; Walker, 2000; Burkhardt and Brass, 1990; Ferlie et al., 2005). Here, we show that individual experts can be pivotal to dispel myths, refute objections, overcome inertia to change, counter-argue, balance pros and cons, and reveal unwarranted assumptions. But to be effective, their job roles must grant legitimacy and objectivity to their views. This insight adds an individual dimension to claims that organizations with a greater learning-related scale, related knowledge, and knowledge diversity, i.e., absorptive capacity, are more likely to favor new technologies (Fichman and Kemerer, 1997; Rice and Rogers, 1980). Significantly – and in line with recent studies on the micro foundations of absorptive capacity (Volberda et al., 2010; Lewin et al., 2011) – we show that the expert's contribution can also be instrumental to make informed *non-adoption* decisions on new technologies.

Finally, our study responds to recent calls for in-depth empirical studies of technology adoption (Robertson et al., 2009). The advancement of knowledge requires that contextualized studies complement impartial testing of hypotheses deducted from propositional theory, following a hypothetic-deductive research design (Ketokivi and Mantere, 2010). Our inductive study provides original insights. Extant studies argue that innovation can be difficult for firms operating in complex systems (David, 1985; Dosi, 1982; Islas, 1997; Nelson and Winter, 1982; Markard and Truffer, 2006) unless reverse salients provoke policy interventions that build absorptive capacity and positive profitability. Consistent with work on the challenges of adapting new technologies (Leonard-Barton, 1988) and on the non-spread of innovations in complex systems (Ferlie et al., 2005), we reveal that it can be challenging to negotiate the adoption of innovation within a constrained project schedule. This is true especially if powerful constituencies become wary that the innovation threatens their professional knowledge and status, and the decision process then becomes tangled with politics.

6. Conclusion

This study extends work on innovation of large socio-technical systems by examining the potential contribution of new mega infrastructure projects. As typical of inductive studies, there are limitations to generalize our insights (McGrath, 1982). We should not lose sight that this study is grounded on a schedule-driven airport expansion promoted by a profit-seeker monopolist. It is important to keep our contribution grounded on these characteristics (Ketokivi and Mantere, 2010). First, a pre-set schedule underpins all mega projects, but not all deliveries face an immovable completion date. Some do, such as in projects that deliver infrastructure ahead of scheduled events like the Olympic Games or World Cups, but developers shy away from committing to hard opening dates in others if possible, e.g., London Crossrail. It thus merits investigating whether non schedule-driven mega projects have an enhanced innovation potential. And, second, many mega projects are not private-led even if evidence indicates that private infrastructure ownership is on a steady rise (Donahue, 1989; Gil and Beckman, 2009) – a socio-economic evolution that adds relevance to our study. Unsurprisingly, expected profitability is a key determinant of innovation in a profit-seeker – led mega project. But it merits further research that can test the validity of our framework in state-led mega infrastructure developments.

Overall, our study has important implications for policy and management of innovation. It suggests innovators should not take for granted that new mega infrastructure projects will contribute to innovating overarching socio-technical systems. Whilst the capability to innovate is essential for the private firm to survive in a competitive market (Teece et al., 1997), there is no clear-cut extension of this logic to large systems and natural monopolies where inertia to overcome embedded commitments can lead to undesirable entrapment in inferior technologies (Watson, 2004; Barlow and Koberle-Gaiser, 2008; Geyer and Davies, 2000; Markard and Truffer, 2006, 2008). Adding to this line of reasoning, we show that technological decisions in mega projects can be fundamentally schedule-constrained. If there are no regulatory turning points or initiatives to support technology take-up, innovators need to anticipate the difficulties and start early to persuade and bargain with the whole collective. Policy-makers should give heed to this insight given that, first, mega projects have the potential to generate desirable technological spillovers (Hobday, 2000a) as well as support economic growth and modernization of societies (Lundvall, 1988; Mowery and Langlois, 1996); and second, public welfare is often at stake in new infrastructure development.

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Appendix: Core interview questions.

See Table A1.

Table A1
Job roles of the key informants.

Technology	Job roles of the key informants (number of interviews)		
	T5 team	Project suppliers	Future operators
RFID for baggage handling system IT baggage reconciliation system	Subproject production leader (2); subproject leader (2); design manager (1); development manager (1); assistant subproject leader (1); operations manager (2); systems integrator (1)	Systems manager (1); senior systems architect (1); site manager (1) designer (1)	Project director (2); chief architect (1); head of development (2); seconded designer (1); quality manager (1)
High-performance concrete mix Technical design for aircraft stands	Subproject leader (1); design manager (1); development manager (1); head of development (2)	Senior designer (1); design engineer (1); designer (1)	Project director (2); chief architect (1); head of development (2); seconded designer (1)
CCTV-based vehicle occupancy security system	Subproject leader (1); design manager (1); head of design (1); development manager (2)	Designer (1)	Operations manager (2)
IT production and control system (ProjectFlow)	Logistics manager (3) Logistics director (1) Project leader (2) Construction leader (1) Production leader (1) Subproject leader (1)	Project director (4) Logistics manager (2)	Not applicable

- Which new technologies were considered for potential adoption in the T5 project?
- Why were some technologies built into the design of the project and others rejected?
- Describe the novelty of the technology in the world of airports?
- Describe the costs of adoption, adaptation and operation of the new technology, as well as future revenues stemming from its adoption?
- Describe the process of negotiating technology adoption?
- Which organizations were involved in the decision-making process leading to adoption/rejection of a new technology?

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