Modular Designs and Integrating Practices:
Managing Collaboration through Coordination and Cooperation

ABSTRACT

Collaboration in large-scale projects introduces challenges involving both coordination (the ability to collaborate) as well as cooperation (the willingness to do so). Existing research has shown how modular designs can improve coordination by locating interdependencies within rather than between different modules. Based on an in-depth case study of collaboration in a large-scale infrastructure project, our study highlights an effect of modularity on collaboration that previously has been overlooked. Specifically, we show that while modular designs may help overcome coordination challenges by reducing interdependencies between modules, they can in turn hamper collaboration by emphasizing specialization within modules. Therefore, though existing work typically perceives modularity and integration as opposites, we clarify how they can also act as complements. In particular, we show how firms need to complement modular designs with integrating practices that stimulate cooperation. Overall, we contribute to the literature on collaboration and modularity by explaining when and how organizations can combine modularity and integration.

INTRODUCTION

Collaboration in large-scale projects typically involves a high degree of complexity, presenting many challenges for the actors involved. While we know that effective collaboration requires both coordination and cooperation (Heath and Staudenmayer, 2000; Kretschmer and Vanneste, 2017), it is less clear how interdependencies that emerge in complex projects affect these dynamics. To address this, we provide a contingent view to understanding collaboration (Van de Ven et al., 2013), focusing on coordination and cooperation. Following Gulati et al. (2012), we consider coordination in terms of the ability to collaborate, while cooperation refers to the willingness to do so. We investigate these contingencies through an in-depth study of a complex project and the interdependencies that arise in such settings. A better understanding of such collaborations is key, given that the complex structures and resulting interdependencies in large-scale projects have long been associated with organizational failure (Floricel and Miller, 2001; Shenhar, 2001; Flyvbjerg et al., 2009).

Existing work has shown how complexity can be decreased by developing modular systems architectures (Ulrich, 1995; Baldwin, 2008). This approach focuses on modularity in design (Baldwin and Clark, 2000) by locating interdependencies within, rather than across, individual modules (Simon, 1962). In such architectures, organizations can focus on a relatively limited set of interdependencies at different levels within the overall architecture, a principle known as information hiding (Parnas, 1972). However, there has been limited consideration of the challenges that modularity may create for complex collaboration when needing to address unanticipated interdependencies. We analyze this issue by considering how coordination and cooperation challenges co-evolve in complex projects. In particular, we show how modular designs may improve coordination, but can also hamper cooperation, and address what integration mechanisms can be used to overcome this.

Based on in-depth investigation of collaboration in a major infrastructure project, we consider the degree to which projects rely on modular or integral designs. Our study explains when modular design principles (e.g. systems decomposition, standardized components and interfaces) need to be complemented with practices that emphasize integration (e.g. co-location and team identity focus). In particular, these practices allow stakeholders to make visible interdependencies that typically cannot be anticipated in advance. This combination of modular designs and integrating practices helps stakeholders address challenges related to both coordination (by emphasizing information transparency) and cooperation (by aligning incentives). At the same time, our data also reveals challenges as mechanisms that emphasize integration, may bring about unforeseen coordination problems in terms of managing interfaces with other projects. Therefore, we show when and at what level organizations can use modularity and integration mechanisms and how these support both coordination and cooperation.

Our empirical setting, the construction of Terminal 5 (T5) of London Heathrow Airport, provides an opportunity to build theory about how organizations manage interdependence through coordination and cooperation, and the various formal and informal integration mechanisms required to manage this. Other work studying T5 has considered the role of modular designs in relation to project safeguards (Gil, 2007) or risk management and design flexibility (Gil and Tether, 2011), with the latter study focusing on how cooperation influences the emergence of modularity. Our study takes a different perspective by considering how modular designs are used in complex collaborations, focusing on the interplay between cooperation and coordination and the practices used to ensure collaboration.

Overall, our paper reveals how firms can use modular designs to manage interdependence, but need to be aware of unanticipated effects modularity may introduce. In particular, our study highlights an effect of modularity on collaboration that previously has been overlooked. Specifically, we show that modular designs may help overcome coordination challenges by reducing the number of interdependencies across projects. However, this can in turn hamper collaboration by unexpectedly inducing specialization within projects. Organizations can help alleviate this by also focusing on integrating practices that operate at the inter-project level. Therefore, we contrast with existing research that typically considers modularity at one end of a spectrum with integration at the other end. Instead we highlight how modular designs need to be complemented with practices that emphasize integration to address unanticipated interdependencies. This is crucial when modularity improves coordination within projects but hampers cooperation across projects. Therefore, this study contributes to existing research by providing a contingent approach to understanding how firms can manage complex inter-organizational collaboration. In particular, we examine coordination and cooperation as key contingencies of collaboration and consider how these need to be managed over time and across levels.

We report our study as follows. The next section briefly discusses relevant background literature on coordination and cooperation in inter-organizational collaborations. We focus in particular on how firms attempt to achieve coordination by managing interdependence through modular product designs and the extent to which this is mirrored at the organizational level. We then describe our empirical setting, focusing on how interdependence was managed through coordination and cooperation. Next we discuss our findings in light of existing work on interdependence and collaboration, followed by concluding remarks and directions for future research.

BACKGROUND LITERATURE

This paper focuses on how firms manage inter-organizational collaboration, particularly how interdependencies need to be managed in such settings. Organizational interdependence generally refers to the degree to which two or more activities interact to jointly determine an outcome (Sorensen, 2003). Organizations can therefore be considered vehicles to manage interdependence, given the need to integrate subtasks created by the division of labor among actors comprising the organization (Victor and Blackburn, 1987). In turn, organizations need to integrate these subtasks, requiring coordination mechanisms such as plans, procedures, or schedules (Perrow, 1967; Van de Ven et al., 1976). Integration refers to the process of combining different subsystems into a unified whole (Lawrence and Lorsch, 1967) and is a key organizational challenge in complex collaborations (Staudenmayer et al., 2005; Jones and Lichtenstein, 2008; Srikanth and Puranam, 2011). Depending on the complexity of the organization, such integration mechanisms vary based on the type of interdependence (Thompson, 1967). Organizational complexity increases in accordance with the degree of interdependence. As they grow, organizations usually create sub-divisions to manage this growing interdependence. However, divisionalization in turn creates additional interdependence between these newly formed sub-units, reflecting a general challenge faced by organizations.

Simon's (1962) seminal work on the architecture of complex systems provides a useful perspective to consider how organizations can reduce interdependence. Given an overall architecture that is nearly, as opposed to fully decomposable, system designers should locate interdependencies *within* individual subsystems, such that each subsystem is relatively independent. This allows actors to focus on interdependencies within the particular subsystems or modules relevant to them, while being able to ignore others. This principle is also referred to as information hiding (Parnas, 1972), allowing actors to treat other subsystems as a "black box". More recent work on collaboration and modular designs has considered the role of modular governance architectures (Manning and Reinecke, 2016) and how design rules affect partner selection (Hofman et al., 2016) to understand how interdependence can be managed.

Product complexity affects interdependencies among tasks and forms of organization (Hobday, 1998). The complexity of a product refers to the number of interdependencies and hierarchical relationship among its component parts. The increasing complexity of a product has been used to identify different types of systems, such as assembly, system and array (Shenhar and Dvir, 1996; Shenhar, 2001; Davies et al., 2009; Davies and MacKenzie, 2014). Building on this research, a distinction can be made between standardized products produced in high volumes and high-value complex product systems (CoPS) produced as projects or in small tailored batches (Hobday, 1998; Davies and Hobday, 2005). In the most complex system and array products, dedicated project organizations are established to coordinate, schedule and integrate the activities of a large network of components and subsystem suppliers (Gholz et al., 2018), as shown in the pioneering work of Sapolsky (1972) on the Solaris missile program. Focusing on the importance of systems integration, existing work has examined how modularity has been used to minimize uncertainty and reduce the coordination costs of producing complex products, such as airplane engines and chemical plants (Brusoni and Prencipe, 2001; Brusoni et al., 2001). However, the seamless inter-organizational coordination promised by modularity is rarely achieved in the production of such complex systems. The organization of different parts of the system can involve different cultures of coordination (Whyte, 2015). The organization responsible for leading the coordination of these complex projects has to develop capabilities in systems integration (Brusoni and Prencipe, 2001; Hobday et al., 2005). These are based on organizations' ability to know more than they themselves make, including understanding how components, subsystems and interfaces are connected (Brusoni et al., 2001). The end-stage of a project can be a key challenge, when systems of hardware, software and people have to be integrated into a functioning operational system (Zerjav et al., 2018; Whyte et al., 2016). In turn, firms may develop integrated solutions (Davies, 2004; Davies et al., 2006; Ceci and Prencipe, 2008; Ceci and Masini, 2011), based on capabilities to offer an integrated bundle of products and services.

A related line of work, drawing on the notion of "mirroring", has considered collaboration and complexity in terms of the relationship between the design of the product and its organization. Initial work on modular designs assumed, sometimes implicitly, that the design of the product is mirrored in its organization (Henderson and Clark, 1990; Sanchez and Mahoney, 1996). While this is a useful baseline assumption, an emerging line of work has considered this relationship more explicitly, referring to this as the "mirroring hypothesis", attempting to understand when product design choices are mirrored at the organizational level, and when not (Colfer and Baldwin, 2016; Sorkun and Furlan, 2017). We draw on this work analyzing the relation between product and organizational design choices, focusing in particular on the relationship between cooperation and coordination and how they influence these choices.

While existing research has made important progress for our understanding of the ways in which organizations can manage complexity and interdependence, important questions remain. In particular, a key assumption in the existing literature on modular designs and the management of complexity is that modularity facilitates coordination (Baldwin and Clark, 2000; Sanchez and Mahoney, 1996; Langlois, 2002) or even provides a substitute for it (Sturgeon, 2002). At the same time, existing work has also shown that modular designs may be an imperfect substitute for organizational coordination (Staudenmayer et al., 2005; Zirpoli and Becker, 2011; Tiwana, 2008). The latter line of work has emphasized the ongoing need for organizational actors to manage interdependence, in spite of the use of modular designs. Although we know that modular designs may help reduce interdependence, existing work has paid little attention to the way the use of modularity relates to not just the ability to coordinate, but also incentives to cooperate. Disentangling these two elements is important, since they jointly determine how collaborations evolve (Heath and Staudenmayer, 2000; Gulati et al., 2012). Therefore, we adopt a contingent perspective that focuses on coordination and cooperation, and consider how modularity and integration mechanisms can achieve effective collaboration.

DATA & METHODS

Data sources and analysis This study was part of a broader research project examining the development of Heathrow Terminal 5 (T5) that focused on organizational learning and capability development. We adopted a qualitative single-case design (Yin, 2003) to understand how firms manage cooperation and coordination challenges in a large-scale, high complexity setting. This allowed for an in-depth analysis of the way interdependencies were managed in the T5 project. Our study was grounded in an analysis of both primary and secondary data. In terms of primary sources, we conducted 39 interviews, focusing on senior decision makers relevant to our setting. The interviews were done in two separate rounds, the first taking place in 2005/2006 and the second one in 2009. The first round occurred during the project's construction stage, while the second round took place after the terminal's completion. The first round enabled us to collect data as the production process unfolded and thus reduce the validity threat posed by post-hoc rationalizations. The second round was focused on gathering more reflective data about how the strategies deployed to manage complexity worked over the life of the production process, which helped us gain insight into how the strategies were saw for managing complexity in the first round affected the final product.

The interviews were typically conducted by a team of two researchers. All informants agreed to have the interview taped and transcribed. Prior to each interview we sent our informants a short description of the research project and an overview of themes for discussion. The interviews followed a semi-structured approach, with more or less emphasis on each topic depending on the informant's background. Secondary sources consisted of written reports including documents used by T5 stakeholders themselves (e.g. the T5 Agreement and T5 Handbook), as well as other materials such as books and trade journals. Table 1 contains an overview of our data gathering stages and data sources.

<<<INSERT TABLE 1>>>

As an inductive study, we iterated between our data collection and theoretical framing, which is further reflected in our data analysis. Following Van de Ven (2007), we tried to engage closely with our informants where possible. We summarized our initial findings in an interim report, which was shared with our informants for corrections to our interpretations. We then conducted the second round of interviews, both to refine our initial understanding of the case and get additional reflection. When conflicting accounts of a particular issue were given, we checked this with multiple informants from different organizations. We coded the interview transcriptions using several general categories (e.g. modularity, integration, technology). We also sent out a final case summary to our informants, to further check our interpretations with the informants.

Heathrow Terminal 5 (T5): overview and case selection Our case focuses on the construction of Heathrow airport's Terminal 5 building, located near London, UK. Terminal 5 opened in March 2008, following a six year construction period starting in 2002.[1] In contrast to many other large-scale infrastructure projects, the T5 project was completed within budget and ahead of time.[2] Overall, the construction of T5 has been considered a success by the key stakeholders involved in its delivery, in particular BAA (British Airports Authority, the main project sponsor and client), Laing O'Rourke (LOR, one of the main contractors in the T5 project), and BA (British Airways, the main operator of T5 upon delivery). The project's construction phase involved two main activities: infrastructure and buildings from 2001 to 2008, and the integration of systems

[1] The construction of T5 was preceded by a protracted planning process involving the longest public inquiry in UK history; however the issues during this pre-construction phase are largely beyond the scope of our empirical analysis.
[2] The successful delivery of the project followed a protracted planning process, which took more than a decade and was initially overshadowed by problems on the opening day with the operation of the baggage handling system, which we briefly refer to in the Findings section.

and retail from 2006 to 2008. A large network of suppliers participated in the project, which was divided into four groups of activities: Buildings, Rails and Tunnels, Infrastructure, and Systems.

An advantage of analyzing complex inter-organizational collaboration is that our key constructs (collaboration, cooperation, and coordination) are clearly manifested in large-scale, capital-intensive projects such as our setting (see e.g. Gil and Beckman, 2009). The specific setting of T5 is particularly well suited to improve our understanding of how organizations manage complex collaboration for several reasons. T5 constitutes a large-scale program (with a final cost of £4.2 billion) comprising a great number of main projects, sub-projects, assemblies and components, with many potential interdependencies: the overall project (also referred to as "program") consisted of 16 main projects, 147 sub-projects, and used over 11000 pre-assembled components.[3] Most importantly, the program was based on changes in industry practices that strongly emphasized cooperation, while also making use of tools and processes (derived from other industries such as automotive) that attempted to improve coordination. Our setting therefore greatly facilitates analysis of how these processes unfold, allowing us to draw implications for our overall question of how firms manage complex inter-organizational collaboration, particularly how interdependencies affect coordination and cooperation.

FINDINGS

This section highlights two key elements used to manage interdependence and complexity in the delivery of the T5 project. First, the T5 agreement, a legal document codifying a set of behaviors

[3] In terms of the size of the project, considering T5 as merely a terminal building could be misleading, since its handling capacity is equivalent to Europe's fifth largest airport, with a main terminal, two satellite terminals, and a control tower.

for T5 project participants. This agreement stimulated cooperative behaviors, in particular by focusing on "integrated teams", which emphasized team identities, incentive alignment and co-location. Second, coordination was facilitated through the Single Model Environment (SME), a tool and process for sharing design information and updates for project participants.[4] The SME facilitated the use of modular designs, which focused on standard components, interface compliance, and pre-fabrication. Table 2 summarizes these main elements and provides illustrative quotes.

<<<INSERT TABLE 2>>>

(1) Stimulating cooperation through incentive alignment

A key mechanism for stimulating cooperation in the T5 project was the T5 Agreement, focused on providing a less adversarial approach to managing collaboration. Rather than transfer risk on to its contractors, BAA (British Airports Authority, the main project sponsor and client) realized that they effectively held all the risk on the project. This implied that problems arising, due to unforeseen complexity and interdependencies, would ultimately be their responsibility. By removing that burden from the supply chain, suppliers could work as part of an integrated team and focus on finding solutions to resolve issues that emerged during the project.[5]

[4] The SME is similar to Building Information Modeling (BIM), a term that has since become frequently used in large scale infrastructure projects.

[5] It is important to emphasize that the knowledge to establish this different type of collaboration had been built up in previous projects. In particular, BAA's involvement in the Heathrow Express rail link project laid the basis for a new way of collaboration. The usual solution to failures is for the client to sue the contractor for breach of contract. At one point the Heathrow Express project was 24 months behind schedule. BAA then recognized that *'there are two ways to get major problems sorted out. You either get people round the table with clearly aligned objectives or you take them to court. And when you take them to court you're likely to be there for years and years and no one wins'.*

The incentives to cooperate, and necessary ability to coordinate were set out in framing documents, which were developed and formalized at the outset of the project. The most important of these, the T5 Agreement, a legal document that included cost-reimbursable contracts, was based on processes outlined in a more informal document called the T5 Handbook. The T5 agreement was devised to create a different way of collaborating that allowed project members to cooperate based on integrated project team working and, as highlighted by a senior manager, was designed to "*fundamentally influence the behaviors that you then get to enable people to want to come together, rather than the reality: the minute anything goes wrong, that they're all going to take their positions and draw their pistols."*

The incentives of the various stakeholders were aligned as a result of this. Focusing on the roles of different firms collaborating in a particular project, one interviewee summarizes the alternative approach as follows: *"(...) they're incentivized on the performance of the integrated team; i.e. the completion of all the work. So every time that they delivered beneath the agreed cost, the savings were shared three ways. So we shared, one part went to the supplier, one part went to BAA and one part was put in the incentive fund and these ratios varied in different areas."*

At the same time, it is important to recognize that the willingness to adopt the T5 Agreement would vary across organizations and over time as the project progressed: *"So a third of them completely get it because they see reputational and future value (...). There's a third of them who say they get it, but actually when you really test and you diligently explore, it's evident that* *they currently don't; they're still on a journey of transition (...) And there's a third of them who actually definitely don't want to get it, because you know what, we like the old game thank you very much."*

Achieving cooperation through integrated team working

While the T5 agreement laid the foundation for changes in the way different stakeholders collaborated, it remained limited to a formal agreement. Whether the formal contract translated to behavioral changes of the different actors was unclear. While implementing the T5 agreement in practice, the T5 project management put a large emphasis on the use of "integrated teams".

Creating "integrated teams" BAA's main role in the T5 project was to create an environment where their suppliers could focus on providing solutions. Integrated project teams had been formed to run every individual project. The formation of each integrated project team was driven by the participants' skills and previous experience. In some teams, the project team leader was from BAA, while in others the leader was from the lead designer or contractor. In the roof project, the project team leader role was taken by the lead designer during the design phase, but handed to a construction manager employed by the contractor during delivery. Members of the integrated teams came from a range of companies from large corporate suppliers to specialist firms and individual consultants, and their involvement was based on an assessment of ability to behave 'constructively' rather than adversarially.

Challenges shifting to integrated team working. While the shift to integrated teams generally worked for the T5 program as a whole, stakeholders faced multiple issues in changing their existing ways of working. Collaboration between the main contractors and an engineering design consultancy illustrates these challenges.

The contractor Laing O'Rourke (LOR) made frequent use of digital prototyping, which was driven in part by the desire to use sub-assemblies for concrete reinforcements, which could be built off-site rather than the standard industry practice of bringing "loose rebar" to the construction site. Working as the designers in a team led by LOR, Mott McDonald was responsible for creating reinforcement design drawings for the production of sub-assemblies. However, at one point, designs produced by Mott McDonald for the reinforcement of structural elements were behind schedule and was hampered due to the many redundant feedback loops between designers and constructors. Consequently, LOR faced the possibility of being unable to meet its objectives for T5. The LOR team met with BAA and explained that the project would fail unless Mott Macdonald could accelerate the delivery of detailed designs. BAA responded by asking LOR, as the leader of the integrated team and working in the spirit of the T5 Agreement, to take responsibility for the project. LOR subsequently worked with Mott McDonald to solve the problem by using 3-D modeling. Rather than building physical prototypes, the team created digital prototype designs for rebar concrete. The team worked together to carry out the detail design in the digital model. However, this was a cultural shift for both companies: the teams from LOR and Mott Macdonald both had to learn the new co-operative behaviors required by the T5 integrated team project working approach. Efforts to work more closely were initially met by considerable resistance: *"Working in a collaborative environment was, to say the least, a huge culture shock. About 9 months into the program I recommended that we actually got out of the framework."*

Overcoming this inertia was a significant leadership challenge for both firms, which was achieved by BAA and other stakeholders continuously communicating and reinforcing the importance of the new behaviors: *"It was about behaviors. It was about managing change." "(...) Our role in BAA is to almost continually reinvigorate, tease out and reinforce that learning, the culture, the way we work together."*

Managers also focused on generating bottom-up driven change, and let co-workers influence each other directly: *"If you can get, you know, a few of those guys converted and, you know, talking in the right way, the guys who have been in the industry for a long time, then peer to peer communication carries a lot more weight than me standing up there... We tried to encourage it, you know, tried to move guys from one area to another to go and talk to each other."*
Another manager elaborates: *"We [LOR] invested heavily and worked with our supply chain to support these approaches. Nobody's really done it and made it successful, so people and suppliers were quite resistant."*

Over time, the Mott MacDonald team recognized the benefits of this approach and worked closely with LOR to implement it. As a result, the process of producing detail design drawings of reinforcement sub-assemblies was reduced from six weeks to five days.

Specialization based on co-location and project team identity. Another aspect of integrated team working was the focus on the team identity, as opposed to the firm with which the employee was associated. The quote below illustrates this focus on emphasizing the team identity: *"But if you look at all of our people you can, you can't tell, distinguish between, you know, who are the, which company you work for generally. If you walked onto the architectural floor plate for instance you wouldn't be able to tell who was being paid by me and who was being paid by them."*

The breakdown of the T5 program helped to create project teams that were focused on delivering specific tasks. A key challenge here was to balance the project or sub-project's ability to focus on their own tasks as well as the dependencies with other projects in the overall program.

"The subproject level is the level we worked and, and therefore the level we organized the delivery of work and what that meant was that people were managing things on a scale that they could comprehend (...) But what we did, I think we built the project, subproject identity so strong that they were very inward-looking and actually lost the focus on the interfaces with the other projects and so for a period we really struggled at managing those interfaces."

Another manager clarifies: *"I've talked about not focusing enough on the interfaces…the way we organized ourselves meant that actually we were very, looking inward at the subprojects and not at the interfaces."*

To address the issue of teams becoming too fragmented, managers realized the need to also maintain focus on external interfaces: *"So, you've got buildings, infrastructure, rail and tunnels all coming together in one space and to just, just to add to the, the sort of, you know, the complexity, in schedule terms (...) it is a highly critical area. (....) I might see the way we did it at T5 to be a success but maintain your focus on, outwards at your interfaces as much as you do in terms of building your team inwards."*

In addition, as we further elaborate on in the next section, the SME also functioned as a tool to make design information more explicit and keep track of different interfaces.

Finding solutions through integrated team working: Air Traffic Control Tower

The Air Traffic Control (ATC) tower provides another illustration of integrated team working, particularly how it overcame product integration challenges: *"The control tower has, has got to be an example of where the integrated team and the T5 agreement, actually having hit a fundamental technical challenge (...) guaranteed, at any other job, lawyers would have been involved in solving the problem but (...) the guys got around the table and they sorted it out and, you know, experts were brought in from different places to try and help, help with a solution."*

One major challenge was that the ATC tower needed to be erected near Terminal 3 in the middle of Heathrow airport. Members of the integrated project team responsible for the ATC tower recognized that they could not use traditional methods, which would have required regular and uninterrupted delivery of concrete. It was not possible to have a large number of vehicles carrying concrete in a critical part of a live airport and could only operate during the 5 hour night-time closure window. Therefore, a new technique was required and a steel tower would be constructed using prefabrication. The tower could be constructed and transported to the site in 12m lengths completed fitted out with necessary components, such as stairs and lift cores. However, the project came to a standstill when attempts were made to bolt the first mast sections together, but did not provide adequate steel tolerances. The manufacturing process was misaligned with the design and the entire batch of components became unusable. These issues were estimated to lead to significant cost overruns and delays for the project, while the risk for

BAA was even more significant. Interruptions to the tower would delay the opening of the airport terminal by up to one year. As one manager highlights: *"When things go wrong, that's when the quality and robustness of the team is tested and that's when you either come together to solve a problem or break apart. (...) There's a danger that you revert to a traditional approach with the supplier."*

However, rather than following a traditional adversarial approach focused on determining who was liable for the mistake, BAA assumed these risks, following the principles laid out in the T5 Agreement. In line with this, the members of the integrated project team got together to find a solution, rather than focusing on apportioning blame and developed an improved manufacturing process. The project made up most of the delay and BAA incurred about half of the initially estimated costs. This illustrates how ultimately BAA carried the risk for cost and time delays and used the T5 Agreement to bear the risks and encourage contractors to find a solution.

(2) Facilitating coordination through information transparency

The previous sections focused on the way cooperation was stimulated through the T5 agreement and its emphasis on integrated teams. However, as we highlighted earlier, it is important to consider collaboration not just in terms of incentives to cooperate, but also in relation to the ability to coordinate. We now focus on the role of coordination in T5, which was facilitated through the Single Model Environment (SME), a common repository of digital information. This ensured that the work undertaken by different teams was coordinated to fit within the overall T5 program objectives. The SME aimed to prevent inaccuracies when information was shared between partners in the integrated project teams who needed to view it in the various design, production and construction phases.[6] The use of the SME was *'to make it possible for all of the companies involved in the project to have access to a single design model, to be able to interrogate it, to be able to take a section from it, do their work and plug it back in'*.

Coordinating design through the Single Model Environment (SME).

A key role of the SME was to develop informational transparency for stakeholders working on interdependent subsystems: *"(...) the benefit of a single model was that everybody could see it. And although we had all the major design teams working in a co-located environment, other than some very key and specialist members of the supply chain, the others were dispersed around the country."*

Similar to adapting to behavioral changes generated by the T5 Agreement, adopting practices necessary to make use of the SME was an on-going challenge: "*Getting them to change their behavior is a very difficult task. (...) there are still pockets of resistance. (...) this whole idea of a single model environment was alien to them. I just could not get them to buy into it without sort of dragging them kicking and screaming into it."*

The SME was complemented by T5's emphasis on modular designs, focusing on standardized components, off-site construction, and interface compliance. Modular designs helped manage the

[6] BAA developed the SME not only to assist design coordination and drawing production, but also to help plan T5's construction and future maintenance.

high levels of complexity and interdependence encountered in a large-scale project as T5, described in further detail below.[7]

Systems decomposition and standardized components. One aspect of T5's emphasis on modular designs involved systems decomposition and the usage of standardized components. Here, mature technologies were emphasized, to reduce uncertainties about how they needed to be integrated. Making use of standardized components increased predictability, thereby reducing the risk of rework. One manager describes the use of standardized components as follows: *"When you're talking about large scale projects, levels of complexity multiply enormously. And just to handle the complexity, having something that is standardized, (...) is an advantage. (....) And the more you can understand and know about and measure in general terms, and plan as groups, and integrate together, the greater certainty you can generate."*

In T5 decisions about design were informed by the maturity of the technology, and the focus was to minimize risk: *"in order to approve some of the designs that we're implementing actually I have some strategies around minimizing risk and one of them is not to put any unproven technology into my terminal so with all the high tech solutions that we have, we look at their maturity."*

[7] Just as the T5 agreement emerged gradually based on knowledge developed in previous projects, the emphasis on standardized components similarly arose from earlier experiences. An important part of BAA's strategy to improve its project processes was implemented in 1995 when a new standardized process for delivering capital projects was developed called 'Continuous Improvement Project Process' (BAA Project Guide, 1995). As well as improving processes, BAA's approach was devised to achieve efficiencies based on the principle 'design it once, build it multiple times'. This "component-led" design approach was achieved by creating standardized and replicable products and components, ranging from whole buildings to specific modules such as standardized toilets.

In contrast to the maturity of proven technologies, in other areas, notably the baggage handling system, there was a high degree of technological change and decisions were deliberately delayed: *"The baggage handling system on T5 is a £239 million baggage handling system. It's the biggest baggage handling solution on the face of the planet."*

The value of using more mature standardized technologies was further highlighted in the problems associated with the operation of the state of the art baggage system that caused problems during the opening of T5. The baggage system was particularly challenging, because it was a more integral product that could not be easily modularized: *"And we still leave baggage out on its own (...) because baggage is a system in its own right and doesn't split easily into design, manufacturer and assembly as other bits do."*

Prefabrication and just-in-time delivery. In addition to using standardized components, another element of modular designs is reflected in the use of off-site and prefabricated construction, based on just-in-time delivery to the work site. One informant reflects on this as follows: *" (...) we set about managing the whole construction methodology around offsite fabrication, modularization, building sub-assemblies, creating a facility which was about a mile away from the site where these sub-assemblies could be brought together and assembled into a larger sub-assemblies, and then transport it to the site on a just-in-time basis."*

Design preparation and interface compliance. One of the areas of risk in a delivery program is in commissioning, when the systems begin to go live. One informant emphasizes the importance of managing interfaces upfront where possible: *"I built a thing called the interface test center. For any electronic system to be installed in the terminal it had to prove all its dependences and* *interfaces offsite in the test center before it was allowed to be installed on site. So that way rework and misconfiguration and misbuilds were dramatically reduced."*

The interface test center played an important part in the management of software-based interfaces, i.e. digital interfaces. However, interfaces could also be physical, based on a variety of systems that needed to inter-operate: *"(...) By interface, I do not merely mean the functional or information interfaces as we might call them, but I also mean the physical interfaces between systems, for example, this one needs a bracket here, a socket there and a cable there. (...) environmental, safety, you know, any dimension of delivering a project there may well be an interface between two systems or streams of work and we have to manage those."*

Reducing interdependencies through design changes: T5 roof project

One example where the role of integrated team work and product design choices can be seen in the construction of the roof of the T5 building. A key product decision was how to design the roof, when it needed to be redesigned after planning, as one of the managers recalled: *"They said, we've got it, we've got it! And I went, ah, that's fantastic. He said, 'but the bad news is [laughs] that the inspector has written a whole page waxing lyrical about the roof, and it doesn't work.' "*

Many options for the roof were considered, but the eventual decision to design the building roof as a large "shed", rather than a more complex integral design, strongly reduced the number of interfaces with other projects, enabling the roof design to be decoupled from and proceed ahead of numerous other interdependencies, such as decisions about placement of retail and the baggage handling system. Once the roof was redesigned in such a way that it had the minimum interfaces, the roof project team was able to get on with the design, as the architect indicates: *"it was then we were allowed to practice in a way that I've never practiced before and I would like to practice again, which is you don't have to concern yourself with documents this thick, and all that, Is dotted, Ts crossed. And the most important thing is that the people around the table, who speak for their own firms, understand what you're talking about and get it, and can go back and do their work, and we all are all literally again in one room. We were constantly building large-scale models of the roof, and then we started to integrate through model building, how the roof actually negotiates the substructure."*

To better understand and minimize the risks of erecting such a large roof, the T5 roof team – including designers, suppliers and fabricators – pre-erected the main roof structure off-site about 300 kilometers north of Heathrow, making large gains in terms of delivering this task ahead of schedule. The roof of the main terminal building is 156m long and was assembled from prefabricated steel elements. Each 156m steel beam was made up of 30m-long sections, which had to be transported the Heathrow site and bolted together. When Hathaway, T5's roofing contractor, started working on the project in June 2000, it assumed that the roof would have to be assembled on site. However, Hathaway was encouraged by the architect in the team to adopt off-site prefabrication techniques and came up with the solution of fabricating the roof skin in modules, which were put on before the roof was lifted into place.[8]

[8] Pre-assembled roof cassettes of a standard size (3 x 6m) were developed so that 10 cassettes could fit on a lorry at once. Hathaway built 12 prototype cassettes using different materials and tested their acoustic performance. A specially constructed factory produced over 3,000 cassettes for the main terminal and 950 cassettes for the satellite building. The pilot test produced lessons about how to mitigate the risk. The main roof contains 22 sections which were assembled and pre-fabricated into the largest pieces that could be transported to the site. This reduced the

At a high level, the SME functioned as a coordination mechanism allowing through centralizing and making visible disparate sources of data across projects. At the same time, within sub-project it was not always used to guide decision-making: *"whilst the single model environment was quite important to us, we were really abstracting from the single model environment the fundamental coordinates of the building, and then we were imposing, if you like, onto the single model environment, the shell of the building, which others operated within. So we were quite controlling in the way that we used the single model environment."*

Case Synthesis

To synthesize how product and organization level design choices in T5 are related, Figure 2 depicts a 2x2 framework that considers (1) the degree to which these are mirrored, (2) whether these design choices act as complements to achieve collaboration, and (3) how these choices both influence and are driven by cooperation and coordination. The framework considers the extent to which the product or organization is more modular or more integral. By plotting these on two perpendicular axes, we can distinguish four quadrants. Two quadrants illustrate situations where the product and organization show a high degree of mirroring. In Q1 this corresponds to mirroring based on a more modular product and organization, while Q4 refers to a more integral product and organization. Conversely, the other two quadrants exhibit a low degree of mirroring. In Q2 we see a more integral product and a more modular organization, while Q3 constitutes a more modular product and more integral organization. Importantly, *a priori* each quadrant may

---

amount of work that had to be done onsite under hazardous conditions. The central 117m arch section of the roof was assembled at ground level and then raised 40m into its final position. Overall, the project team estimates that at least three months were saved by this pre-emptive risk management approach.

be complementary, in that the combination of product and design choices can help manage complex collaborations.[9]

<<<INSERT FIGURE 2>>>

Q1: Modular Product and Modular Organization. Q1 constitutes low or medium complexity settings, where interdependencies are generally relatively predictable for more modular products. In T5 this was approached through mirroring in terms of product and organizational modularity and is complementary at the overall project (i.e. program) level. The T5 program focused on modularity through decomposition, where the overall project was decomposed into four main groups (Buildings, Rails and Tunnels, Infrastructure, and Systems), each of which in turn consisted of several main projects, amounting to 16 projects in total. These 16 main projects were decomposed to minimize interdependence between these projects. In turn, the organization of T5 mirrored these four groupings and 16 main projects. The key focus here was on inter-project interdependencies. The ability to coordinate these was facilitated by the SME, which made inter-project interfaces and interdependencies more visible. Incentives to cooperate between projects was enabled by the T5 agreement, as inter-project challenges could be resolved knowing that the main client took overall responsibility in terms of risk. Overall, here we find that coordination and cooperation are complementary to establish collaboration.

[9] We purposely use relative terms (such as more modular vs. more integral, and the degree of mirroring), as these are not binary concepts, but rather should be considered as part of a continuum.

Q2: Integral Product and Modular Organization. Q2 constitutes medium-high complexity settings, given that the site or frequency of interdependencies is hard to anticipate for more integral products. This typically requires an organization with a high degree of architectural knowledge, such as in the case of advanced technologies that need to be developed by independently operating teams. [10] This can be challenging given the high degree of interdependence of more advanced technologies, combined with the need for interaction between teams. The failure of implementation of the baggage system provides an illustration of these challenges. Here, the product was more integral and could not be easily modularized into clearly separable components. By contrast, the organization was relatively modular, in particular given the arm-length approach of British Airways (the main operator of T5), which had not signed the T5 Agreement. We find that in T5, this approach was generally not complementary, given the way the project emphasized modularity and integration. In particular, because of the focus on integrated teams that worked autonomously, the ability to coordinate between teams, which is key for integral products, was limited. Likewise, in terms of incentives, the high degree of cooperation required for integral products was more difficult to achieve for independently operating teams. Overall, here we find that coordination and cooperation are weakened due to a mismatch between product and organization, leading to ineffective collaboration.

Q3: Modular Product and Integral Organization. Q3 constitutes low-medium level of complexity, since product interdependencies are relatively predictable for more modular products. In our setting, we find that this approach is complementary in particular at the level of

[10] An example of developing an integral product through a modular organization is the B52 stealth bomber, as described in Argyres (1999).

individual projects, as opposed to the overall program level. In T5, product modularity was emphasized through the focus on standardized components and intra-project interfaces, as well as prefabricated assemblies, both of which eased coordination. At the same time, integrated organization remained necessary when unexpected interdependencies emerge, and which were incentivized to cooperate and find solutions. This was important in particular for architecturally novelty, where mature components were combined in potentially new ways. The roof project provides an example of this combination of a more modular product combined with more integral organization. This project also illustrates how design choices enable product design to become more modular (i.e. interdependencies with other projects were significantly reduced when the roof design was changed to a “shed”), and emerged as a result of integrated team working. Overall, collaboration was established through coordination mechanisms, while cooperation helped overcome unanticipated coordination challenges.

Q4: Integral Product and Integral Organization. Q4 is characterized by a high degree of complexity, since interdependencies are high and complex interdependent products are developed by integral organization. This approach is complementary for projects that rely on architecturally and technologically novel solutions. The Air Traffic Control (ATC) Tower provides an illustration of a complex product system, where integral teams were required to deal with challenges that emerged as project evolved. Here, the high degree of mirroring (based on integral designs) was complementary based on the way coordination and cooperation were achieved in T5. The ability to coordinate was aided by the SME, which was crucial as ongoing coordination was required given the integral nature of product. Incentives to cooperate were facilitated by co-location and risk sharing, which was necessary given the high degree of cooperation required within integral projects. Here, collaboration was established through iterative and mutually reinforcing cycles of coordination and cooperation.

Overall, the framework helps illustrate how multiple approaches to mirroring were used in T5 and that these influenced coordination and cooperation in different ways. We show that a combination of higher and lower degree of mirroring was used, and that either can be complementary depending on the hierarchical level. A high degree of mirroring was used at both the overall program level (Q1), as well as for specific projects (Q4). A low degree of mirroring could also be used (Q2), but can be highly risky, in particular given the way coordination and cooperation were achieved in T5. Q3 was the most prominent way in which complementarities were achieved between modular product designs and integral organizations. These differences in the way interdependencies were managed highlight the need to take into account multiple levels of analysis, in particular the overall program vs. individual project level. We describe the underlying processes that drive these multi-level interactions next.

DISCUSSION

Overall, our findings indicate the challenges organizations face when the complexity of the collaboration requires the use of modular design principles. While modularity can help by reducing interdependence, thereby improving coordination, it may also induce specialization within projects that subsequently hampers collaboration. Figure 3 provides a schematic overview of the key processes underlying our setting, outlining how the ability to coordinate and incentives to cooperate drive these.

<<<Insert Figure 3>>>

Here we distinguish between the overall program level (the T5 project as a whole) and individual projects, such as the roof building or ATC. At the program level, there was a focus on information transparency, which was enabled through the SME. This shared digital model made visible inter-project interfaces, which in turn provided the ability to coordinate. Incentives to cooperate were stimulated through the T5 Agreement. At the project level, coordination was facilitated through modular product designs, in particular standardized components and prefabrication. In turn, cooperation was stimulated through integrating practices, especially co-location and a focus on team identity. While these product designs and organizational practices helped coordination and cooperation respectively, they also increased specialization within projects. To address the consequences of this, such as a growing focus on intra-project interfaces, there was an increased need for integration at the inter-project level. The coordination and cooperation principles enabled by the SME and T5 Agreement made this high-level integration possible.

The dynamics observed in our setting contain several implications for our understanding of how to manage complex inter-organizational collaborations. Specifically, we highlight three ways in which our findings contribute to the existing literature on how firms manage inter-organizational collaboration, and the underlying mechanisms used to manage interdependence.

First, we draw on existing work that has considered collaboration in terms of cooperation and coordination (Heath and Staudenmayer, 2000; Gulati et al., 2012; Kretschmer and Vanneste,

2017) and focus on these contingencies in terms of incentives to cooperate and the ability to coordinate. In so doing, we show how firms can effectively combine the two, but that this process needs to carefully managed given that mechanisms that facilitate collaboration at one level may hamper it at another level. Specifically, we show that the key principles outlined at the program level (information transparency and client-led risk management) help achieve coordination and cooperation at the level of individual projects. However, the ways in which such outcomes were achieved (modular product designs and integrating practices) may in turn increase intra-project specialization, thereby hampering coordination *between* projects. Therefore, it is vital to also focus on integration at the inter-project level, where ongoing attention to the general principles articulated at the program level remains crucial. Thus in the complex collaboration observed in our setting, coordination and cooperation can be either mutually reinforcing or oppositional (see also Farjoun, 2010), implying that outcomes need to be distinguished from the underlying processes.

Second, our findings help explain when interdependencies that emerge in complex collaboration can be managed through a combination of both modular designs and integrating practices. This contrasts with existing work that has suggested that modular product designs pose a substitute, or minimize the need for organizational coordination (Sturgeon, 2002; Langlois, 2002). Instead, in this setting modular designs need to be complemented by practices emphasizing integration (co-location, strong team identity). Therefore these findings are in line with multi-level work that has underscored the importance of organizational coordination, in spite of the use of modular product designs (Brusoni and Prencipe, 2006; Staudenmayer et al., 2005). We build on this by showing the importance of considering at which level (intra-project as opposed to inter-project) coordination and cooperation takes place. Our findings also connect to research on "mirroring" that has investigated under what conditions modular products are produced by modular organizations (Cabigiosu et al., 2013; Colfer and Baldwin, 2016). We extend this work by providing a contingent perspective that shows when this mirroring between product and organization is complementary in establishing effective collaboration. In particular, we show that both higher and lower degrees of mirroring can achieve collaboration. However, their effectiveness depends on the hierarchical level, that is the intra or inter-project level, as well as the focal project's maturity, such as the degree of architectural or technological novelty (Furlan et al., 2014).

Third, our study adds to existing literature that has highlighted the importance of information hiding (Parnas, 1972), a critical element of modular designs that helps manage complexity.[11] In particular, our case points to the importance of information *transparency* to aid coordination, as well as the challenges that emerge in achieving such transparency. The digital model observed in our setting helped geographically dispersed actors coordinate subsystems, which was facilitated by information transparency rather than information hiding. The latter is effective for systems characterized by a high degree of modularity, which is very difficult (if not impossible) to achieve *ex ante* for innovative systems. Therefore, the emphasis on modular components in the context of our setting applies to more mature technologies that were "off the shelf" rather than customized. In contrast, information transparency is crucial when architecturally or technologically novel components were used and standardized interfaces were absent. The key

[11] Information hiding is a key principle for modularity in software development, where standardized interfaces allow software developers to not know about the contents of other software modules while working on their own subsystem, provided standardized interfaces are in place.

challenge in these situations is to ensure that the shared digital model does not become de-coupled from the physical designs these models represent. This can occur when the different actors are unable or unwilling to use the digital model as intended, thereby highlighting the importance of stimulating their usage (Whyte 2013, 2015; Whyte and Harty, 2012).

CONCLUDING REMARKS

Our study highlights how firms manage inter-organizational collaborations through a combination of mechanisms that support coordination and cooperation. We show how such coordination and cooperation is achieved and requires both modularity and integration depending on which level of the collaboration they operate at. In particular, our study shows that when sub-units specialize, higher-level integration mechanisms based on coordination and cooperation are subsequently required to counterbalance increasing specialization. Therefore, our study suggests that modular designs and integrating practices can be mutually reinforcing in the context of coordination and cooperation, as opposed to the traditional conceptualization as being opposing ends of a continuum (e.g. Ulrich, 1995; Fixson and Park, 2008). At the same time, the mechanisms observed in our case (especially in relation to cooperation and coordination) show the challenges involved in combining the two. Overall, we contribute to existing work by providing a contingent perspective that considers collaboration in terms of both coordination and cooperation, focusing on the role of modularity and integration to achieve effective collaboration.

Our study also has implications for practitioners. In particular, the combination of modular product components and practices emphasizing integration appear to be a potent way to manage the complexities that invariably arise in inter-organizational collaborations. While the overall approach to managing interdependence may also work in other settings, it is crucial to keep in mind the idiosyncrasies of this setting that may complicate its implementation in other areas. This is an important limitation to our current study.

We see a number of areas for future research. First, our setting points to the difficulties identifying interdependencies in complex evolving projects. A better understanding of the processes firms can employ to identify such interdependencies, both *ex ante* and during the project, seems like a promising area for further work. Second, our findings also point to the difficulties in getting project participants to adopt new behaviors, such as the integrating practices described in our setting. Future work might examine how different contract specifications and other mechanisms promote or hinder the adoption of such practices.

REFERENCES

Argyres, N. S. (1999). The impact of information technology on coordination: Evidence from the B-2 “Stealth” bomber. *Organization Science*, 10(2), 162-180.

Baldwin, C. Y. (2008). Where do transactions come from? Modularity, transactions, and the boundaries of firms. *Industrial and corporate change*, *17*(1), 155-195.

Baldwin, C. and Clark, K. (2000). *Design Rules, The Power of Modularity.* MIT Press, 1.

Brusoni, S., & Prencipe, A. (2001). Unpacking the black box of modularity: technologies, products and organizations. *Industrial and Corporate Change*, *10*(1), 179-205.

Brusoni, S., & Prencipe, A. (2006). Making design rules: A multidomain perspective. *Organization science*, 17(2), 179-189.

Brusoni, S., Prencipe, A. and Pavitt, K. (2001). Knowledge specialization, organizational coupling and the boundaries of the firm: why do firms know more than they make? *Administrative Science Quarterly*, 46(4): 597–621.

Cabigiosu, A., Zirpoli, F., & Camuffo, A. (2013). Modularity, interfaces definition and the integration of external sources of innovation in the automotive industry. *Research Policy*, *42*(3), 662-675.

Ceci, F., & Masini, A. (2011). Balancing specialized and generic capabilities in the provision of integrated solutions. *Industrial and Corporate Change*, *20*(1), 91-131.

Ceci, F., & Prencipe, A. (2008). Configuring capabilities for integrated solutions: evidence from the IT sector. *Industry and Innovation*, *15*(3), 277-296.

Colfer, L.J. & Baldwin, C.Y., (2016). The mirroring hypothesis: theory, evidence, and exceptions. *Industrial and Corporate Change*, 25(5), pp.709-738.

Davies, A. (2004) Moving base into high-value integrated solutions: a value stream approach, *Industrial and Corporate Change*, 13(5), 727-756.

Davies, A., Brady, T. & Hobday, M. (2006) ‘Charting a path toward integrated solutions’, *MIT Sloan Management Review*, 47(3), 39-48.

Davies, A., Gann, D. and Douglas, T. (2009) ‘Innovation in Megaprojects: Systems Integration at London Heathrow Terminal 5’, *California Management Review, Special Issue: ‘Infrastructure Privatization’,* 51(2), 101-125.

Davies, A., & Hobday, M. (2005). *The business of projects: managing innovation in complex products and systems*. Cambridge University Press.

Davies, A. and Mackenzie, I. (2014) ‘Project complexity and systems integration: Constructing the London 2012 Olympics and Paralympics Games’, *International Journal of Project, Management,* 35(4), 773-790.

Farjoun, M. (2010). Beyond dualism: Stability and change as a duality. *Academy of Management Review*, *35*(2), 202-225.

Fixson, S. K., & Park, J. K. (2008). The power of integrality: Linkages between product architecture, innovation, and industry structure. *Research Policy*, *37*(8), 1296-1316.

Floricel, S., & Miller, R. (2001). Strategizing for anticipated risks and turbulence in large-scale engineering projects. *International Journal of project management*, *19*(8), 445-455.

Flyvbjerg, B., Garbuio, M., & Lovallo, D. (2009). Delusion and deception in large infrastructure projects: two models for explaining and preventing executive disaster. *California management review*, 51(2), 170-193.

Furlan, A., Cabigiosu, A., & Camuffo, A. (2014). When the mirror gets misted up: Modularity and technological change. *Strategic Management Journal*, *35*(6), 789-807.

Gholz, E., James, A. D., & Speller, T. H. (2018). The second face of systems integration: An empirical analysis of supply chains to complex product systems. *Research Policy,* 47, 1478–1494.

Gil, N. (2007). On the value of project safeguards: Embedding real options in complex products and systems. *Research Policy*, *36*(7), 980-999.

Gil, N., & Beckman, S. (2009). Introduction: Infrastructure Meets Business: Building New Bridges, Mending Old Ones. *California Management Review*, *51*(2), 6-29.

Gil, N., & Tether, B. S. (2011). Project risk management and design flexibility: Analysing a case and conditions of complementarity. *Research Policy*, *40*(3), 415-428.

Gulati, R., Wohlgezogen, F., & Zhelyazkov, P. (2012). The two facets of collaboration: Cooperation and coordination in strategic alliances. *Academy of Management Annals*, *6*(1), 531-583.

Heath, C., & Staudenmayer, N. (2000). Coordination neglect: How lay theories of organizing complicate coordination in organizations. *Research in organizational behavior*, *22*, 153-191.

Hobday, M. (1998). Product complexity, innovation and industrial organisation. *Research policy*, *26*(6), 689-710.

Hobday, M., Davies, A. and Prencipe, A. (2005) Systems integration: a core capability of the modern corporation, *Industrial and Corporate Change*, 14(6), 1109-114.

Hofman, E., Halman, J. I., & Van Looy, B. (2016). Do design rules facilitate or complicate architectural innovation in innovation alliance networks?. *Research policy*, *45*(7), 1436-1448.

Jones, C., & Lichtenstein, B. B. (2008). Temporary Inter‐organizational Projects. In *The Oxford handbook of inter-organizational relations*.

Kretschmer, T. & Vanneste, B. (2017), Collaboration in Strategic Alliances: Cooperation and Coordination. In Mesquita, L., Ragozzino, R. and Reuer, J.J (Eds.*), Collaborative Strategy: Critical Issues for Alliances and Networks*, Edward Elgar.

Langlois, R. N. (2002). Modularity in technology and organization. *Journal of Economic Behavior and Organization*, 49(1): 19–37.

Lawrence, P. R., & Lorsch, J. W. (1967). Differentiation and integration in complex organizations. *Administrative science quarterly*, 1-47.

Manning, S., & Reinecke, J. (2016). A modular governance architecture in-the-making: How transnational standard-setters govern sustainability transitions. *Research Policy*, *45*(3), 618-633.

Parnas, D. L. (1972). On the criteria to be used in decomposing systems into modules. Communications of the ACM, 15(12), 1053-1058.

Perrow, C. 1967. A Framework for the Comparative Analysis of Organizations. *American Sociological Review*, (April, 1967), 194-208.

Sanchez, R. and Mahoney, J. (1996). Modularity, Flexibility, and Knowledge Management in Product and Organization Design. *Strategic Management Journal*, 17:63-76.

Sapolsky, H. (1972). *The Polaris Missile System: Bureaucratic and Programmatic Success in Government*, Harvard University Press.

Shenhar, A. J. (2001). One size does not fit all projects: Exploring classical contingency domains. *Management Science*, *47*(3), 394-414.

Shenhar, A. J., & Dvir, D. (1996). Toward a typological theory of project management. *Research Policy*, *25*(4), 607-632.

Simon, H. (1962). The architecture of complexity. *Proceedings of the American Philosophical Society*, 106 (6): 467-482.

Sorenson, O. (2003). Interdependence and Adaptability: Organizational Learning and the Long-Term Effect of Integration. *Management Science*, 49(4): 446-463.

Sorkun, M. F., & Furlan, A. (2017). Product and Organizational Modularity: A Contingent View of the Mirroring Hypothesis. *European Management Review*, *14*(2), 205-224.

Srikanth, K. and Puranam, P. (2011). Integrating distributed work: comparing task design, communication, and tacit coordination mechanisms. *Strategic Management Journal*, 32: 849–875.

Staudenmayer, N., Tripsas, M., Tucci, C. (2005). Inter-firm Modularity and the Implications for Product Development. *Journal of Product Innovation Management*, 22(4): 303-321.

Sturgeon, T. (2002). Modular production networks: A new model of industrial organization. *Industrial and Corporate Change,* 11(3): 451–496.

Thompson, J. D. (1967). *Organizations in Action*. McGraw-Hill, New York.

Tiwana, A. (2008). Does technological modularity substitute for control? A study of alliance performance in software outsourcing. *Strategic Management Journal*, 29: 769–780.

Ulrich, K. (1995). The Role of Product Architecture in the Manufacturing Firm. *Research Policy*, 24:419-44.

Van de Ven, A. H. (2007). *Engaged Scholarship: A Guide to Organizational and Social Research*, Oxford University Press.

Van de Ven, A.H., Delbecq, A.L. and Koenig, R. (1976). Determinants of coordination modes within organizations. *American Sociological Review*, 41, 322-338.

Van de Ven, A. H., Ganco, M., & Hinings, C. B. (2013). Returning to the frontier of contingency theory of organizational and institutional designs. Academy of Management Annals, 7(1), 393-440.

Victor, B. and Blackburn, R. S. (1987). Interdependence: An alternative conceptualization. *Academy of Management Review*, 12 (3): 486-498.

Whyte, J. (2013). Beyond the computer: Changing medium from digital to physical. *Information and Organization*, 23(1), 41-57.

Whyte, J. (2015) Cultures of Coordination and Control: Digital Information and New Forms of Project Organizing, in van Marrewijk, A. (ed) *Inside Megaprojects: Understanding cultural practices in construction projects*, Copenhagen Business School Press, pp. 69-102.

Whyte, J. and Harty, C. (2012) Socio-material Practices of Design Coordination: Objects as Plastic and Partisan, in Leonardi, P.M., Nardi, B.A. and Kallinikos, J. (eds) *Materiality and Organizing: Social Interaction in a Technological World*, pp. 196-216.

Whyte, J., Lindkvist, C. and Jaradat, S. (2016) Passing the baton? Handing over digital data from the project to operations, *Engineering Project Organization Journal*, Vol. 6 (1) 2-14.

Yin, R. K., (2003). *Case study research, design and methods*, 3rd ed. Newbury Park: Sage Publications.

Zerjav, V., Edkins, A., & Davies, A. (2018). Project capabilities for operational outcomes in inter-organisational settings: The case of London Heathrow Terminal 2. *International Journal of Project Management*, 36(3), 444-459.

Zirpoli, F. and Becker, M. C. (2011). The limits of design and engineering outsourcing: performance integration and the unfulfilled promises of modularity. *R&D Management*, 41: 21–43.

FIGURES AND TABLES

Characteristics of Stage	Stage 1: Oct 2005 – June 2006	Stage 2: July-Oct 2009
Objectives	Explore general dynamics in T5 project focused on 1) usage of digital technologies to manage risk and complexity, 2) capabilities and learning	Focus on the interaction between digital technologies (e.g. SME) and behavioral mechanisms (e.g. T5 Agreement)
Primary sources: interviews	Interviews (total 30) LOR (19), BAA (10), BA (1)	Interviews (total 9) LOR (3), BA (1), BBM (1), GO Ltd (1), Severn Trust (1), Rogers Stirk Harbour & Partners (1), Volkswagen (1)
Secondary sources	Business press and trade journals Internal documents (e.g. T5 Agreement and Handbook)	Business press and trade journals Internal documents (e.g. T5 Agreement and Handbook) Research papers and books on T5

Table 1: Data collection and sources

T5 agreement: Stimulating cooperation through incentive alignment	
Topic	**Description / illustrative quote(s)**
Codifying the T5 handbook: Risk and incentive alignment	*"what we wanted to do was to create a form of contract, the T5 Agreement, that actually converted risk into being a positive"* *"But also they're incentivized (i.e. T5 project participants) on the performance of the integrated team; i.e. the completion of all the work."*
The T5 agreement in practice: integrated team working	
Challenges in shifting to integrated team working	Efforts to work more closely were met by considerable resistance from both Mott MacDonald side and LOR. Overcoming this inertia was a huge leadership challenge for both organizations, which was achieved by continuously communicating and reinforcing the importance of the new behaviors. *"This is the way we're going forward. We are going to use digital prototyping, and this is why and this is what it gives us. We are going to go to sub-assemblies and we are going to optimize reinforcement fabrication to drive down labor costs and labor levels on the project. And we are going to use ProjectFlow and you are going to plan your work and be held accountable for delivering it. And here are the reasons why."*
Co-location and team identities	*"But if you look at all of our people you can, you can't tell, distinguish between, you know, who are the, which company you work for generally."*
Single Model Environment: Facilitating coordination through information transparency	
Coordination, complexity and informational transparency	A key function of the SME was to facilitate coordination among actors that were often dispersed in different parts of the country: *"the SME, it's primary intent was to coordinate the designs of all parties and a design integration and a design review process so that there was one view of the truth, one absolute statement design*
Challenges implementing the SME	*"If I were doing the same project again, or any other project for that matter, I would insist on everybody using the same software. Because it's very complicated trying to adapt people's designs which are done under one sort of*

	software umbrella and to fit into a single model." *"You've still got to have lots of rules and regulations, and somebody has got to be in charge of this bloody model otherwise the whole thing will become a complete mess."*
Modular designs: standard components, pre-fab construction, interface compliance	
Standardized components to manage costs and complexity	*"So there's modularization of building fabric and there's modularization and standardization of enormous amount of context which is not necessarily basic shell, but is stuff that passengers always interface with. Whether it be balustrading, whether it be staircases, whether it be escalators, whether it be seating, whether it be information screens, they're all standard components."*
Off-site, prefab construction and just-in-time development	*"We built part of the structure in Yorkshire with the architects, with the structural engineer, with the crane driver, to make sure that the 120 lessons [and associated problems] we learnt in Yorkshire were not repeated on the job site. We took all of our systems and our system integration in an interface test facility so that from an IT perspective we designed things simply, that could be enhanced in the first few years of operation, but that we didn't import any of the IT risks to site through that important period of configuration management and interface testing."*
Design preparation and interface compliance	*"I built a thing called the interface test center. For any electronic system to be installed in the terminal it had to prove all its dependences and interfaces offsite in the test center before it was allowed to be installed in site. So that way rework and misconfiguration and misbuilds were dramatically reduced. So this technique of taking work off the site extended well beyond just prefabricating some large steel plant."*

Table 2: Key elements for managing complexity and interdependence in T5

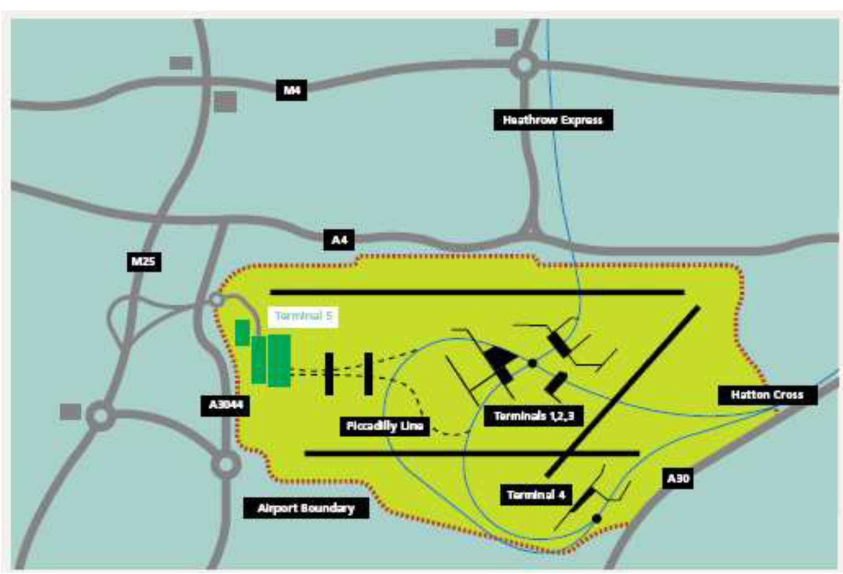

Figure 1: Geographical location of T5 terminal (highlighted in dark green on left hand side)

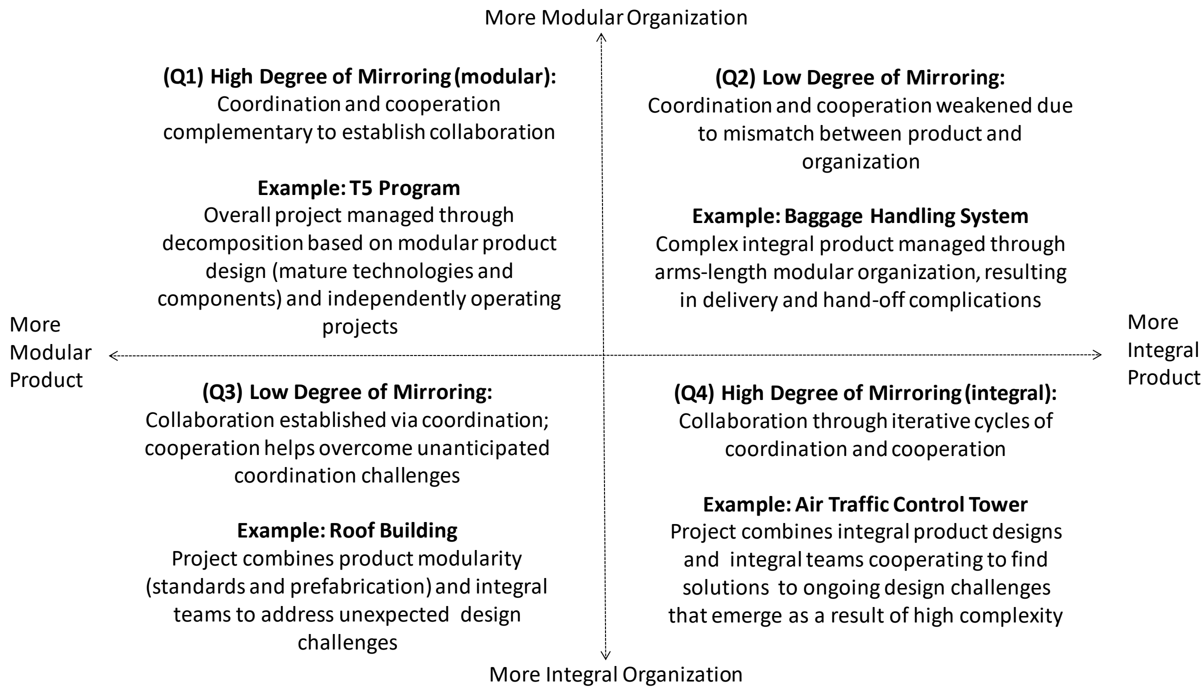

Figure 2: Collaboration and product and organizational mirroring in T5

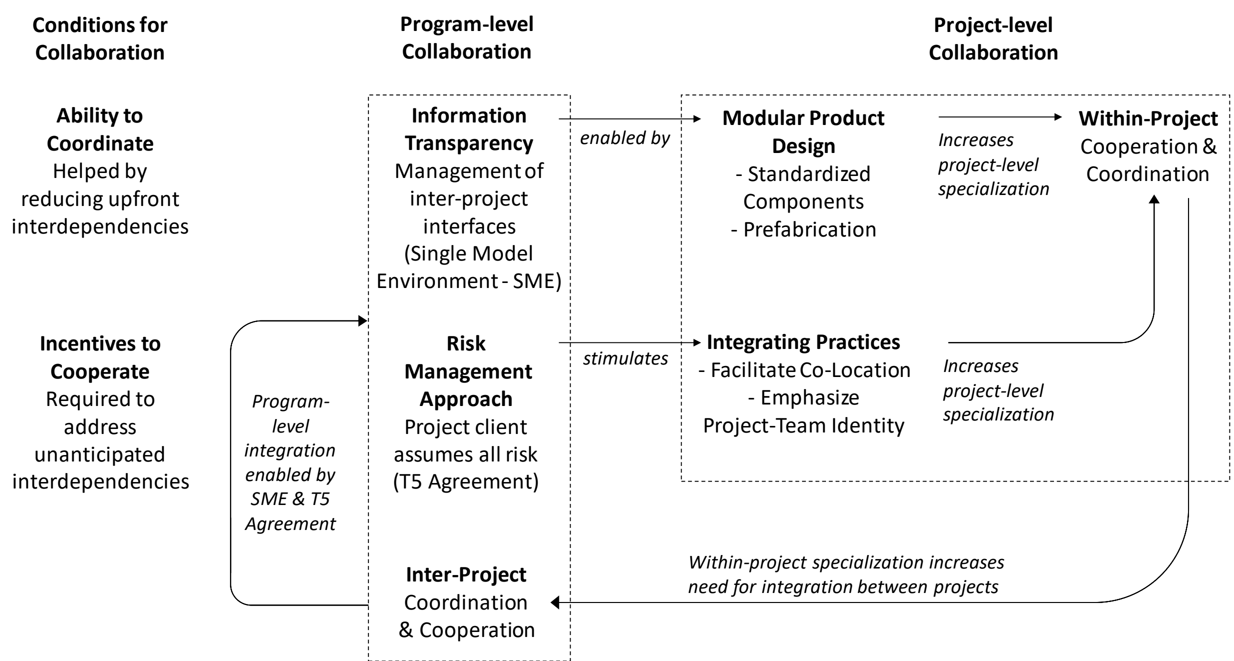

Figure 3: Managing coordination and cooperation in complex collaborations