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House of Project Complexity—understanding complexity in large infrastructure projects

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This paper describes our conceptualization of complexity in large infrastructure projects. Since complexity itself is an emergent concept that is hard to pin down, we focus on the relationship between various project features and properties associated with complexity such as difficulty, outcome variability and non-linearity, and (non) governability. We propose a combined structural and process-based theoretical framework for understanding contributors to complexity—the 'House of Project Complexity' (HoPC). The formulation of the HoPC draws from a rich projects literature and is developed iteratively by first applying it to two trial samples and then to the main data set of 20 detailed case studies of infrastructure projects prepared for the IMEC study. A main contribution of this work is the conceptual distinction in the HoPC between 'inherent project features', 'architectural features', and their relationship with project outcomes and emergent properties—the 'ilities.' A second contribution is the separation of 'inherent features' into the technical and institutional domains, which are then developed in parallel fashion. A third contribution is to link complexity with the concept of project architecting. The HoPC can be generally extended to projects in the extractive industries, large manufacturing projects or other industrial megaprojects.

Keywords: Complexity, infrastructure, institutions and projects, project architecture, project shaping, risk.

Introduction

Complexity is an important topic of discussion in major projects research and practice for a variety of reasons. First, the concept lies at the heart of defining what is a major project, and to what extent such projects require a different approach (Williams, 2002, Bosch-Rekveldt *et al.*, 2011). Second, complexity is important to understanding the relationship between project performance and various conditions, such as technological forwardness or the degree of coherence of a project's institutional context, and management choices such as pacing, resourcing and front-end loading (FEL), as complexity is likely to be an intervening variable (Merrow, 2011, Scott *et al.*, 2011). Finally, complexity is an object of management, since understanding a project's complexity is key to properly resourcing it, and finding ways to reduce complexity should improve performance. Large infrastructure projects (LIPs) offer a rich arena in which to model and measure complexity, since they are bounded in time and scope and yet entail a wide variety of technical and institutional considerations that are likely to be associated with complexity.

Since complexity itself is an emergent concept that is hard to pin down, we focus on the relationship between various project features and properties associated with complexity such as difficulty, outcome variability and non-linearity, and (non) governability. We propose a combined structural and process-based theoretical framework for understanding contributors to complexity—the 'House of Project Complexity' (HoPC).

Recent work on the topic of complexity in relation to large engineering projects has made advances by analytically breaking down the core concept of 'complexity' into more specific concepts. While both academics and practitioners have long possessed an intuition for the significance of complexity and its relationship with performance in complex sociotechnical systems, coping with or accommodating complexity still remains

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challenging. Current efforts in the field are focused on producing integrative frameworks that shed light not only on the structural nature of complexity but also on the process by which complexity can be actively managed. There is a clear need for a succinct representation of the concepts under the broader umbrella of complexity. Our proposed framework refines and builds on recent contributions to highlight not only the structural concepts that can be used to unpack complexity, but also the process by which key players in projects shape this structure to create favourable emergent behaviour. The juxtaposition between static structural aspects of complexity and the dynamic envelope of project uncertainties is of particular interest. We believe that both need to be reconciled in any theoretical framework.

A main contribution of our work is the conceptual distinction between project features that are inherent to project opportunities (inherent features), those that are conditional on the selection of a project concept including its governance structure and execution process (architectural features) and those that arise from the interaction of these two sets of features as the project is shaped and managed over time (emergent features). We then relate these to various high-level project outcomes and emergent properties of the LIP—the 'ilities.' A second contribution is to separate the inherent features into technical and institutional domains and to develop these two in a parallel fashion A third contribution is to connect complexity with the concept of project shaping, developed initially in Miller and Lessard (2000) and extended in Lessard and Miller (2013), and further link complexity with architecting. Architecting subsumes two process-based lenses, almost always treated separately: project shaping (the episodic process in which stakeholders make strategic moves to manage or resolve exogenous risks, uncertainties and forces acting on the project) and systems design and engineering (the process of formulating in detail the plans and instructions for making systems that can be manufactured or assembled) (Maier and Rechtin, 2009, Lessard and Miller, 2013). Project architecting is developed here as a process of 'dual domain' design—the active and intentional shaping of technical and institutional project features to result in desirable functional properties.

We use the HoPC framework to classify LIPs reflecting their complexity in both the technical and the institutional domains, and to test whether this typology helps explain variation in project performance. This typology should also be useful in benchmarking of project management choices such as pacing, resourcing and FEL, and relating them to performance. Finally, it should enable organizations managing numerous projects to better rationalize the allocation of resources and the attention given to specific aspects of project governance.

Theoretical background on project complexity and basic proposition

The concept of complexity is not new in the literature on projects and engineered systems, and many have offered frameworks for understanding complexity in large engineered projects, of which LIPs are a subset. These frameworks have matured to an extent that complexity is recognized as a broad umbrella concept, and recent literature has focused on which sub-concepts should be included, the relationships between those sub-concepts and how they could be applied in a practical sense. Most proposals for application are contingency-based approaches, following Shenhar (2001) and Burton and Obel (2004). These approaches typically focus on technical aspects of the project or its internal organization. However, a new literature argues that the institutions within which a project is embedded and interacts also should be taken into account, thereby refining or extending traditional contingency models (Scott, 2012). We trace the evolution of the concept of complexity in projects, and identify the need for a conceptual model that systematically includes and relates structural and process aspects of complexity, linked with project outcomes.

Baccarini (1996) made one of the first attempts to pin down the concept of complexity in projects and highlighted the difficulty project managers faced in coping with complexity in construction projects. He took as a given the notion that large projects in general, and construction projects per se, are *invariably* complex and that projects had increased in complexity since the Second World War. Baccarini (1996) proposed that project complexity could be defined as 'consisting of many varied interrelated parts, and operationalized in terms of *differentiation* and *interdependency*.' He also put forward the notion of types of complexity and operationalized both differentiation and interdependency in the technical and organizational domains, to emphasize how complexity in those two domains differs in nature and manifestation. Some might view this as no more than a restatement of Lawrence and Lorsch's (1967) concepts of *differentiation* and *integration*, or of the parallel concepts of *decomposition* and *integration* in technical design (Browning, 2001). We view it as an incremental contribution since it explicitly identifies different types of differentiated features and articulates how integration across these differences result in complexity, or at least in some the 'ilities' associated with complexity.

Much of the early definition of project complexity was structural, focusing on the concepts of *number* (tasks, technical specialties, departmental units, groups, components), *hierarchy* (levels or depth—of an organization or technical process) and *connectivity* (pooled, sequential or reciprocal). This conceptualization of project complexity tied many previously separate threads in the literature in system sciences, organizational theory and project management (Miller, 1959, Dewar and Hage, 1978, Mintzberg, 1979, Klir, 1985, Hall, 1987). The concepts of project *size* and *uncertainty* were identified as separate from project complexity in the early definition, but as the discussion below shows, the concept of complexity was quickly refined to include both size and uncertainty.

Williams (1999) later suggested that the idea of 'structural complexity' should be fixed as a distinguishing concept from 'complexity' in general—reserving the latter as a broader umbrella term. He offered that to the extent a project involves the design and delivery of complex product, it is the *product's* (structural) complexity that drives the *project's* (structural) complexity. While this framing reinforced the importance of structure in both the technical and organizational domains of the 'project', it further highlighted the nature of interdependencies in both domains, especially in terms of sequential relationships and reciprocal feedbacks (Thompson, 1967). Whereas both *sequentiality* (one element's output is another's input) and *reciprocity* (each element's output are others' inputs) were found to significantly affect project outcomes in studies he was involved with, Williams (1999) suggested that reciprocity particularly intensified complexity (Williams *et al.*, 1995, Ackermann *et al.*, 1997). The increase in the use of concurrent engineering practices (Lawson and Karandikar, 1994, Prasad, 1996) was identified as a possible causal factor driving the increase in reciprocity and therefore the structural complexity of projects. Structural complexity was thus articulated as a concept category under the broader umbrella concept of overall 'project complexity'.

In roughly parallel work, others discussed the relevance of the concept of uncertainty for the management of complex projects. Notable among these are Shenhar and Dvir (1996), Williams (1999) and Shenhar (2001). Shenhar and Dvir (1996) took issue with the sparse theoretical development of the project management literature. They contrasted it with the literature on innovation, which reflected a contingent approach to management of innovation for complex products or services. The particular dichotomized view—incremental versus radical innovation—suggested that organizations performing more innovative tasks (characterized by a greater degree of uncertainty) should be inherently different from those performing routine tasks or producing routine products (Abernathy and Utterback, 1978, Bart, 1988, Freeman and Soete, 1997, Burton and Obel, 2004). Invoking classical contingency theory, Shenhar and Dvir (1996) and later Shenhar (2001) suggested that a 'one-size-fits-all' approach to project management is counterproductive. They proposed a typological theory (inspired by Doty and Glick, 1994) of project management, in which project management *style* could be matched to project characteristics or *features*. Their conceptual typological model was developed using the dimensions of technological uncertainty (low, medium, high, super-high) and system scope (assembly, system, array). This model retained the structural and hierarchical connotations from the early system sciences (Boulding, 1956, Van Gigch, 1978), early design literature (Marples, 1961, Alexander, 1964), and systems architecture (Rechtin, 1992, 1999). It also linked the operationalization of hierarchy to the degree of uncertainty in complex projects. The typological model thus broadened and extended the concept of project complexity beyond Baccarini's (1996) earlier definition.

Williams picked up on Turner and Cochrane's (1993) articulation of the concept of uncertainty in terms of the degree of uncertainty in goals, and the degree of uncertainty in means. Uncertainty was used loosely to include both aleatoric and epistemic uncertainties, i.e. those stemming from a lack of knowledge. The former type—goal uncertainty—was found to result in increased feedbacks of a reciprocal nature in complex projects, through *scope* change. The latter type—*novelty* in technological means—was one of the dimensions in Shenhar and Dvir's typological model. The refined framework proposed by Williams therefore subsumed both structural complexity (number, diversity and interdependence of elements) and uncertainty (scope, novelty) (Williams, 1999, 2002), conceptualized collectively as 'overall project complexity'.

Relatively recent work on understanding the dynamic emergent behaviour of projects as complex systems has reinforced the structural nature of complexity and reciprocal interdependent relationships (Lyneis *et al.*, 2001, Williams *et al.*, 2003, Lyneis and Ford, 2007). Simon (1981) had previously defined emergent behaviour as the unpredictable consequences arising from the nonlinear interaction of the system's parts. This new body of work has improved the understanding of how complex projects behave, and linked causal factors to project outcomes through post hoc analysis using systems modelling approaches. A main learning is that project behaviour derives from 'systemic interrelated sets of factors' rather than single causal factors and that true causes of project outcomes are difficult to identify (Cooper *et al.*, 2002, Williams, 2005). Extreme behaviour was found to result from the presence of positive feedback loops in the system's structure, i.e. 'vicious cycles' and knock-on effects.

Tight time-constraints were also suggested as a feature of projects that have the potential to compound shocks or errors (Williams, 2005). When projects go off-track under a tight schedule, managerial interventions aiming to accelerate projects often further exacerbate adverse outcomes such as cost overruns or delays. Shenhar and Dvir (2004) also separately discussed the significance of *pace*—the urgency with which a project must be delivered and the consequences of failing to do so. Overall project complexity could therefore be further broadened to include not only structural complexity and uncertainty, but also their time-based interaction through pace. Shenhar and Dvir consolidated these aspects of complexity in their NCTP: Novelty, Complexity, Technology, Pace model, a more comprehensive typological model for categorizing projects (Shenhar and Dvir, 2004, Shenhar and Dvir, 2007).

While many of these recent treatments of project complexity include social or organizational dimensions, most are focused primarily on technical aspects. A parallel literature grounded in sociology, in contrast, places organizational dynamics at the core of project complexity with a focus on safety (Perrow, 1986, Vaughan, 1996). Further, Orr and Scott (2008) identify regulatory, normative and cognitive aspects of institutions as key elements of the context of projects, documenting project managers' failure to recognize them ('institutional exceptions') as key drivers of failure.

We believe that it is important to include both technical and institutional domains of complexity since both are evident in major projects, and, if anything, variations in institutional precursors to complexity contribute more to explanations of project outcomes than purely technical aspects. We also believe that it is important to allow for different structures and dynamics in the two domains.

We further believe that it is important to include aspects of organizational processes within complexity, either in terms of the dynamics of project realization or the experience of individuals 'living' the complexity of projects (Brown and Eisenhardt, 1997). Hughes (2000) was one of the first to examine the role of 'system builders' (or 'system architects'), the individuals or entities that championed complex projects and effected the formation of coalitions and processes for their realization. Cicmil and Marshall (2005) studied the concept of complexity through the lens of actuality—the lived experience of a project's participants in projects (Cicmil *et al.*, 2006). To a large extent, however, structural complexity was viewed primarily as a technical issue, and was treated separately from process aspects of complexity in projects.

Bosch-Rekveldt *et al.*'s (2011) Technical–Organizational–Environmental (T–O–E) framework is an important step in the direction of a more inclusive notion of complexity. Based on an extensive review of the literature and empirical case-study work in the process-engineering domain, the T–O–E framework includes 50 constructs. It reflects many of the structural features identified by Baccarini (1996) and Williams (2002), mostly in the Technical domain and some in the Organizational domain. Uncertainty is reflected in the form of 'risk' in all three domains, whereas contextual factors such as 'stakeholders' and project 'location' are categorized in the Environmental domain. This last category is the main extension of the T–O–E model over previous frameworks (Bosch-Rekveldt *et al.*, 2011).

While the T–O–E model was proposed as a characterization framework, it does not allow for an understanding of how various elements contribute to overall complexity as does the NCTP model or Shenhar's (2001) typological theory. A contingent approach to managing projects or structuring them on the basis of their overall complexity requires some systematic differentiation of the nature and degree of complexity along various dimensions (Burton and Obel, 2004, Levitt, 2011). Scott (2012) argues that the features or challenges presented by the normative and cultural-cognitive institutions in the project environment and a sophisticated understanding of the organizational field can better inform the contingency-based project structuring approach.

We propose a conceptual model called the HoPC that attempts to systematize both (technical and institutional) structural and process elements. First, we begin with a set of technical and institutional variables that are inherent in the project opportunity and overlay these with a set of architectural characteristics, also both technical and organizational, that are put in place as the opportunity is shaped into a defined project and ultimately executed. We then link these elements to the features of uncertainty and risk, and emergent behavioural properties of projects. Our model differs from prior frameworks, including T–O–E, in two ways: the layering approach, and the linking of elements to emergent properties. Many of the elements of our HoPC are based on concepts we reviewed in the literature, but we also identify new concepts and integrate them in two stages of exploratory analysis described in the following section.

Exploratory analysis and development of conceptual model

The initial version of our conceptual model grew out of Lessard's (2007) exploratory efforts to examine the hypothesis that projects that are complex in both the technical and institutional domains exhibit poorer performance (on average) and more varied performance outcomes. Using publicly available data on 45 major projects in the oil and gas industry, we scored each project in terms of technical ('T') and institutional ('I') characteristics associated with complexity and related them to performance.[1] Even though we labelled the 'I' dimension 'organizational' since the term institutional did not resonate in the applied context, our initial constructs in this dimension were related to the stakeholder field, e.g. number and alignment of stakeholders, and maturity and dynamics of the institutional field, rather than the specific organization of the project. We treated technical and organizational complexity as independent dimensions and performance as the dependent emergent dimension. Figure 1 depicts the basic 'House' of complexity, which we used as visual metaphor to preserve the structural connotation (Baccarini, 1996, Browning, 2001, Eppinger and Browning, 2012). Performance emerges as the 'roof' of the house.

In a further exploratory analysis, we examined the relationship between complexity and project size ($) using a different data set of 30 major projects, all from one firm in the oil and gas domain. This is of interest since it is common industry practice to use cost (materiality) as a proxy for the degree of complexity or difficulty in assigning resources and in benchmarking performance. Observations of the expected capital cost of each project were available for each project in this data set, but observations on performance were unavailable. In this iteration, we added another dimension of complexity—architectural ('A')—to denote the extent to which managerial choices in either the technical or institutional ('I', previously organizational 'O') domains appeared to have contributed to or ameliorated the project's complexity. A group of experienced project managers were then asked to score the projects along each of the T, I and A dimensions, using indicators similar to those discussed in Appendix 1. Projects were scored from 1 to 7 along each dimension with 1: benign and 7: extreme. Capital cost ($) was left as a continuous variable. A positive correlation (0.49, $p < .01$) was obtained between a multiplicative (T*I*A) scale and expected capital cost ($). As the expected capital cost increased, the subjective assessment of the relative complexity of projects also increased. When complexity (T*I*A) was regressed on capital cost, however, very little of the variation was explained (adjusted R^2 of 0.14) even though the relationship is significant with $p < .05$. Further, the outliers from this complexity/size relationship were meaningful to the analysts. This analysis confirmed our intuition that capital cost or project budget is not a good indicator of project complexity.

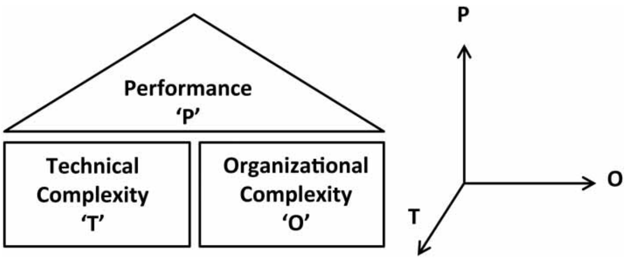

Figure 1 Initial model of the HoPC

We encountered a number of conceptual and methodological issues in this exploratory analysis. First, we found that it was not always easy to separate structural indicators of technical complexity from those of institutional complexity, especially in terms of the chosen project design. Some elements could just as easily be categorized as either 'T' or 'I'.

Second, we noted that project designers had selected project concepts and structures based on their perception of the technical and organizational features, and their understanding of project-specific risks. These choices were at a higher level of abstraction in the project, e.g. at the level of defining project scope and technology selection.

These two observations taken together led to our refined HoPC with a clear separation of inherent technical and institutional features. Further, a set of architectural features that includes both technical and institutional aspects is overlaid on inherent features, during the project concept selection and engineering design phases of projects.

Primary research method and data

Our main objective in this study is to identify the specific phenomena and features of projects that relate to our conceptualization of complexity and to test the relationship between them and project performance. Armed with the basic construct of the HoPC comprising Technical, Institutional and Architectural dimensions, we do this using a sample of LIPs that include much more detailed narratives than either of our two exploratory samples. We code case-study write-ups to not only reconcile key concepts we observed in the literature but also to identify new concepts and relationships and further develop and refine the proposed framework. We proceed in three steps, beginning with formulation of a coding protocol, followed by relational analysis and then framework development in the final step. We discuss the data and methodological details of each step in this section.

While the earlier versions of the HoPC relied on data from the oil and gas sectors, we wanted to see if the HoPC construct was useful in other large project sectors, particularly LIPs. The data comprise in-depth case studies of 20 large projects, briefly described in Appendix 2. The case studies were prepared for the IMEC Research Programme, a benchmarking study for best practices in large projects, based on interviews with key participants and questionnaires to project sponsors. The set of projects spans electric power, hydro development, roads, bridges, tunnels, urban transportation and an airport. The earliest projects in the sample were undertaken in the early 1980s. Some were completed only recently in the 2000s. Projects in the sample are located in North America, Europe and Asia.

Although the IMEC projects have been analysed extensively in Miller and Lessard (2000) and other works, and have led to a number of theoretical frameworks, the cases have not been studied in depth to gain insight into the idea of project complexity per se. For our purposes, the data can therefore be considered to be a new sample.

Based on the examination of the literature and previous work discussed above, we first formulated a coding protocol to identify key concepts in the case data signifying technical or institutional challenges, and performance outcomes (Step 1). We then used a test case to refine the coding protocol. The refined coding protocol (Step 2) was applied to a sub-sample of four cases from the same infrastructure domain (electric power). We set the remaining 15 cases aside at this stage to avoid contaminating the data. We assigned concepts to categories and refined both. We then selected and coded another four cases (transportation), at which point we felt we had reached conceptual saturation. In other words, we had identified a large set of constructs by the end of this step; some drawn from the literature, others from our two exploratory analyses and then some 'new' constructs that we observed in the case data. Finally, we used cognitive mapping as a form of example of axial coding (Step 3) to relate concept categories to each other to flesh out the HoPC framework. The main goal of the relational analysis step is to describe how the refined categories of concepts are related to each other. Axial coding is a process for reassembling data with respect to a central theme in a way that emphasizes relationships between categories. Specifically, how are project features related to project life-cycle properties and performance outcomes? We then selectively coded the 11 remaining cases in the data set to saturate both the concept categories and the relationships between them in the HoPC.

Results—the full HoPC

Conceptual maps based on detailed coding of the 20 case studies showed how concepts occurring in the cases related to each other and across categories. Figure 2 illustrates the conceptual map for the Eurotunnel (or Channel Tunnel) project from our

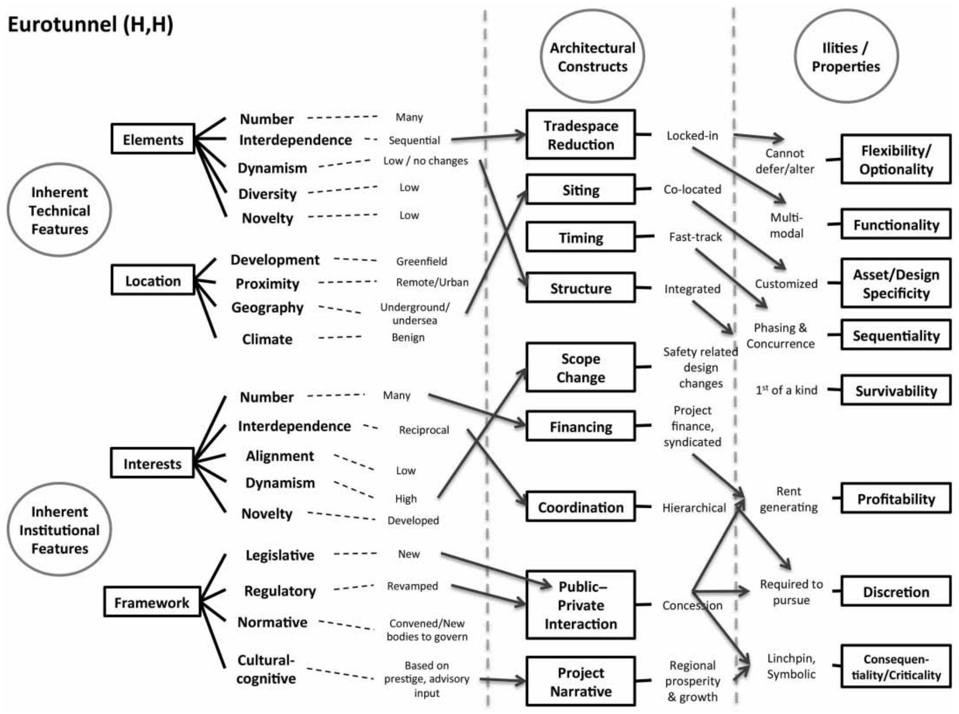

Figure 2 Concept map for the Eurotunnel project

sample. In the map, concepts about fundamental project features such as the legislative context, regulatory framework, and geological or climatic challenges appear on the left. For example, the governments of UK and France had to pass new legislation to enable the new border crossing between the two nations, which represented a major institutional undertaking. Stakeholders with disparate interests had to be aligned by revamping regulation on both sides of the Tunnel. Although the climatic conditions in the Channel were quite benign, the distance to be traversed in tunnelling presented the major technical challenge. Design choices and architectural arrangements such as the tunnel design concept and syndicated project financing appear in the middle and flow from the features on the left. Once the tunnel concept was locked in, the architectural decision to fast-track the project by concurrently tunnelling from both ends raised the logistical challenge of excavating tunnelling debris, further increasing the technical complexity of the project. The project's functional properties, and design or economic outcomes are situated on the right. These are a result of both the features on the left and constructs in the middle. Safety-related design changes late in the execution process because of changing regulations delayed the project, thereby increasing costs and decreasing its profitability.

We abstracted from concept maps to populate our refined HoPC (Figure 3). After populating the HoPC, we observed that projects could be scored using the HoPC along a number of dimensions in terms of degree of complexity. For example, we scored the Eurotunnel project as high on complexity on both its technical and institutional features as well as high in complexity in the architecture arrangements. This process was repeated for the other cases in the sample. The scoring analysis and its results are discussed later in this section, after presenting the HoPC.

The HoPC has two 'stories' and a 'roof', for a total of three layers. The bottom layer contains 'Inherent Features' in both the technical and institutional domain, which are the foundation for the structure of the project in those dimensions. The layer 'Architectural Constructs and Arrangements' rests immediately above and interacts with 'inherent features'. Architecture represents the project concepts that were actively chosen or shaped, given the inherent features. The uppermost layer or the roof of the House represents the many emergent properties or 'Ilities' of the projects in delivery that may drive project outcomes. While the layers are explained further below, Appendix 3 provides a detailed definition of the concepts with citations for the sources of definitions, and examples or indicators of the concepts.

Inherent features in the foundation of the House describe the fundamental technical and institutional nature and characteristics of the project opportunity. Such features tend to be a given, and independent of the particular project concept (or 'solution'). Inherent features are the raw material with which architecture sculpts a project opportunity into a realizable project. The sub-categories of 'Location' and 'Elements' denote technical characteristics of the project opportunity, whereas 'Framework' and 'Interests' represent

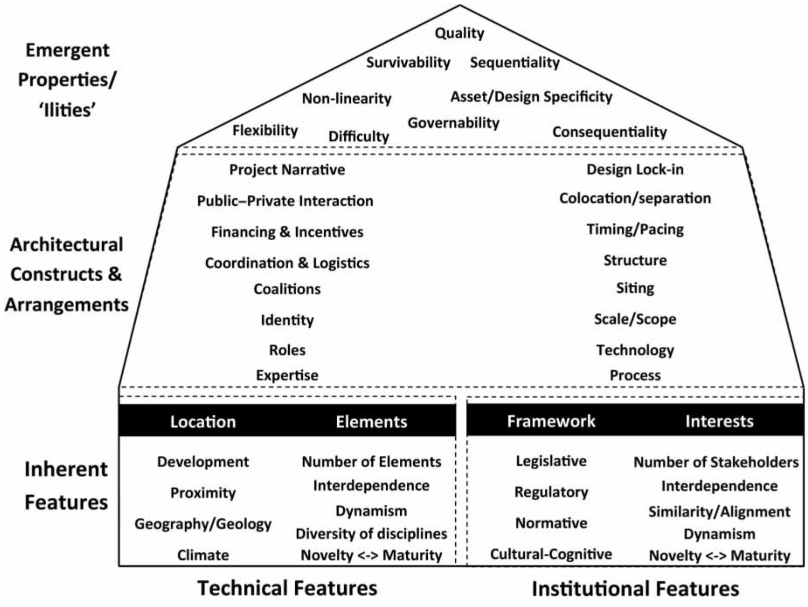

Figure 3 The full HoPC

features of an institutional nature. We applied a parallel framework for characterizing inherent features in the technical and institutional domains, such as number, interdependence, dynamism and novelty, and found it to be a good match for the data. For example, the same term interdependence resonates in both domains, representing the degree to which components or sub-systems are sequential or reciprocal in the technical execution of the project, and the degree to which institutional interests are influenced sequentially or reciprocally. In the Eurotunnel project, technical elements (sub-systems) were executed sequentially, however, the greater degree of feedback in stakeholder deliberations made the institutional interests reciprocally dependent. This parallel arrangement of concepts in the separate layer of inherent features is one of our contributions in refining the concept of complexity beyond the broader 'Environmental' umbrella category of the T–O–E framework (Bosch-Rekveldt *et al.*, 2011).

Architectural constructs and arrangements transform inherent features to realize the project. Architecture is therefore the mediating layer between features and emergent properties, since it uses the features of the project primarily as context, needs and requirements. This category contains concepts that represent the processes—both technical and institutional—by which the form, organization and logistical activities of the LIP are shaped and eventually fixed. Locking in design aspects, setting scale and scope, pacing or selecting technologies are of a more technical nature, although they have organizational aspects. Similarly, financing structures, public–private contractual arrangements, and coordination and logistics are primarily institutional/organizational in nature, with some technical implications. Architectural arrangements are therefore harder to categorize as purely technical or institutional. These concepts provide a high degree of detail and specificity as individuals or entities engage in an explicit process of project architecting, or shaping as in Lessard and Miller (2013). Architectural activities intend to achieve the project design goals or objectives and desirable performance properties for which the project was conceived.

Emergent properties, which we refer to as 'ilities', are the uppermost level of the House. These concepts broadly represent outcomes of the process of project architecting. They thus expand the understanding of project performance beyond the usual cost or schedule outcomes. The emergent properties are the result of the interdependence and interactions between various technical and institutional features of the project and the architectural constructs and arrangements that mediate these features. The qualifier emergence signifies a possible departure or deviation from the properties that project architects originally architected for or intended. Deviation is not always observed—sometimes properties are aligned with goals and needs, sometimes they are not. In essence, the HoPC is a conceptual frame that attempts to explain how and why an LIP's outcomes and properties emerge.

In our analysis, we explicitly looked for various emergent properties associated with complexity along with the usual measures of project success or failure ('on budget and schedule', but also including functionality —delivering intended technical outputs and services, and profitability—generating economic returns for the financial interests involved). As shorthand, we refer to these emergent properties as the 'ilities'—for example, non-linearity and 'recycling' (vicious cycles of re-work as in the Eurotunnel) and other extreme outcomes. The coding process also revealed some behaviours such as consequentiality (the possible reputational impact of a first-of-a-kind project as in the Bakun hydro project in Malaysia), which we did not initially expect to find. The set of 'ilities' listed here is therefore far from exhaustive and limited to the behaviours we observed in the data.

We used the fully populated and refined HoPC as a scoring device to relate complexity to performance. We coded and scored the 20 cases drawn from the IMEC study along the inherent technical and institutional dimensions as either low ('L') or high ('H') complexity. Projects could thus fall in one of four quadrants based on their inherent complexity score, as shown at the top of Table 1. We also scored each in terms of architectural complexity ('L' or 'H'). Project performance was scored as a success ('Y') if the project achieved both its stated functional design goals and articulated economic profitability objectives. If a project missed either set of goals and objectives, possibly because of episodic delays, rework, schedule extensions, budget overruns or other uncontrollable shocks that we sought to identify, the project was deemed unsuccessful. Table 1 shows the relative sorting of projects based on degree of complexity and also lists project scores along these dimensions.

Our scoring enables simple statistical analysis of the relationship between inherent complexity, architectural complexity and performance. The projects in our sample are spread quite evenly among the four quadrants of complexity in inherent features. Tests of association show that for the projects in our sample, success is associated with low inherent institutional complexity ($X^2 = 7.18$, $p < .01$), independent of inherent technical and architectural complexity. Project success is not independently associated with the two latter dimensions for our sample. This result suggests that although technical and architectural complexities matter for performance, institutional complexity matters more.[2]

Table 1 Complexity and performance scoring for the IMEC cases

Project name	Inherent (T,I) (L/H)	Architecture (L/H)	Match? (M/NM)	Success? (Y/N)
Nanko	(L,H)	H	M	Y
Orlyval	(L,H)	L	NM	N
LambtonFGD	(L,L)	L	M	Y
LambtonRehab	(L,L)	H	M	Y
WabashRepowering	(H,L)	H	M	Y
Hwy4075ETR	(L,H)	H	M	Y
SecondSevern	(H,L)	H	NM	Y
ThamesWR	(L,L)	H	M	Y
Hopewell	(H,H)	L	NM	N
MRTA	(H,H)	L	NM	N
Ankara	(L,H)	H	NM	N
Tanayong	(L,H)	L	M	Y
PortDickson	(L,L)	H	M	Y
McWilliamsRe	(H,L)	L	M	Y
Gardermoen	(H,H)	H	M	Y
Hub	(L,H)	H	M	N
Gazmont	(L,H)	H	M	Y
Bergen	(L,L)	L	M	Y
Bakun	(H,H)	H	NM	N
ChannelTunnel	(H,H)	H	NM	N

N = 20

	Institutional complexity	
	Low	High
Technical complexity		
Low	5	7
High	3	5

	Success?	
	Yes	No
Match?		
M	12	1
NM	1	6

We used dichotomous scores to simplify the analysis and limit 'judgement calls' fully recognizing that we were losing some information. Even with this limitation, the results support our intuition and findings from earlier exploratory work. While these scales could be refined further—performance scoring in particular could be unpacked and expanded—the results can be considered as strongly indicative based on the 'proof-of-concept' application of the HoPC to the small sample size of cases.

In scoring architectural complexity in our sample, we found that scores largely corresponded to the average within-project scores for T and I and added little additional information. This could reflect the fact that project architecture tends to respond to inherent technical and institutional features, but also that we did not have sufficiently fine-grained temporal data to know when particular architectural constructs were laid in for the projects. We also noted the complexity of A did not appear to be linked to performance, rather it was the alignment of A with the T and I precursors to complexity. In a number of cases, a relatively high degree of architectural complexity appeared to be justified since it was well aligned with the given T and I structure and challenges of the project. In others we found that a lesser degree of architectural complexity was disconnected from the inherent features. This led us to conclude that what mattered was 'requisite architectural complexity', a concept that seems to resonate with the systems design literature (Crawley *et al.*, 2004, Maier and Rechtin, 2009), and one that we would like to identify and code *ex ante* in future work.

In the Orlyval light-rail project on the outskirts of Paris, for example, the chosen architecture was highly simplified to push the project through, without addressing a number of the diverse interests characterizing the initial context. As a result the deliberative and benefit-capturing structures were ill-suited to align the complex constellation of interests involved in the project. The project is an economic failure, even though it is a technical and functional success. Project architects in other cases with low technical but high institutional complexity such as the Nanko Power Plant or Highway 407 Express Toll Route in Canada crafted the architectural arrangements carefully. In Nanko, the firm sponsoring the project prioritized extensive stakeholder consultations and community involvement, whose interests broadened the project's technical scope but also made it much more acceptable to the local community, creating a higher likelihood of project success. In the Highway 407 ETR project, the architecture was made more complex by inserting a value engineering stage, carefully coordinating the concurrent integrated design from the start and allocating risks differentially between the provincial authority and the private developers, enabling both a functionally and economically successful project.

The Thames Water Ring, which can be analysed as a project in two phases, is also instructive. In its first phase, it employed fairly simple functional contracts with limited information sharing. After this approach failed, it adopted a 'matrixed' integrated approach with a high degree of best practice sharing and coordination among various contractors, and moved the ownership of tunnelling machines from contractors to the authority. This was a much more complex contracting and execution architecture, but it also resulted in greater information sharing and alignment. These examples show that project architecture itself may need to be complex to moderate or mitigate inherent complexity. Of course, it would be even better if this could be accomplished through a simpler architecture.

To check if the concept of 'requisite architectural complexity' was associated with performance, we revisited the cases and assigned scores based on whether we thought the chosen architecture was a match ('M') or not a match ('NM') based on the project's inherent features. Our M/NM 'proof-of-concept' scoring is based on a subjective interpretation of data available in the case write-ups, relative to our deeper and more refined understanding of the inherent and architectural features. The rough guideline we followed to determine match was whether stakeholders had accounted for the inherent features and intentionally and consciously chosen architectural features in response. The 2 × 2 arrangement of scores is shown at the bottom of Table 1. We found that there is a higher incidence of success when the complexity of a project's architecture was judged to match the complexity of its inherent features. The probability that the project outcome is a success for architectural match is greater than for no match ($X^2 = 12.175$, $p < .001$). These results support our intuition that architecture can modify complexity in inherent project features to improve performance. While we tried to separate our coding of architectural match and performance, there is some possibility that one influenced the other. Going forward, the M/NM coding and 'requisite architectural complexity' sub-dimension would also be specified *ex ante* as part of the architectural layer, as shown in the refined HoPC (Figure 4—centre). Again, further work on this concept will necessitate the use of more deliberate scales and scoring mechanisms.

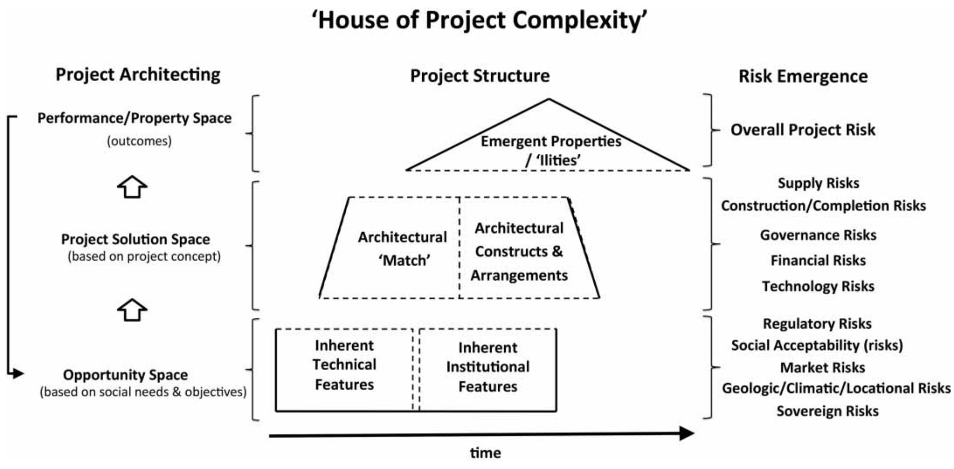

Figure 4 The refined HoPC with a temporal dimension

Insights from coding the cases in detail and exploring the concept of requisite architectural complexity helped us to map the process of project architecting and risk emergence with a temporal dimension (Figure 4). Project architecting in the left of the figure describes the high-level abstract process of first creating an infrastructure project concept to meet stakeholder needs and objectives and then taking the concept all the way to realization in a series of phases. The House in the central part of the figure is our much-refined representation of the project structure that emerges in various stages of project architecting. The right-most part of the figure denotes the risks that are realized and the outcomes that emerge as a consequence of the interaction of structural components and background uncertainties during the process of project execution.

Project architects are the subset of an LIP's stakeholders that work actively to take the project from concept to reality (Miller and Lessard, 2000, Merrow, 2011, Lessard and Miller, 2013). While stakeholders can be thought of as all the individuals and entities that are affected by a project and may even influence its development, the architects are those that actively and directly influence, control, design or manage some aspect of the LIP's progress. Project architects often work in close concert with other stakeholders to bring the LIP to fruition, but the other stakeholders do not bear the same degree of responsibility in advancing the LIP from one stage to the next. Fred Salvucci, for example, played an important architecting role in Boston's Central Artery/Tunnel ('Big Dig') project (Hughes, 2000), Just as the project's stakeholder set may evolve dynamically over a project's life, so can different individuals and entities fulfil the role of project architects. Shaping is consequently a messy and episodic process in which architects work hard to move a project from the opportunity to the outcome space through strategic moves with risk-resolution in mind.

Societal needs for infrastructure services create a project opportunity space, the starting point for the process of project architecting. The opportunity space maps onto the Inherent Project Features layer in the structural core of the HoPC. The *raison d'être* of a project concept and ultimately the project itself is to realize a subset of the opportunities present in the opportunity space in the form of a project. The process of architecting moves into the project solution space by locking in some dimensions of the opportunity space. A project concept can be executed or implemented in many ways. In design terminology, project design concepts relate combinations of form to desired functions—each detailed form–function combination can be thought of as a design solution. It maps onto 'Architectural Arrangements and Constructs' and 'Architectural Match'. The solution space is thus the collection of different form–function combinations, representing design in not only the technical domain but also in the institutional domain. The process ends with the outcomes space, when the emergent properties are observed, as indicated by the roof of the House.

Risks emerge because of the inherent technical and institutional structural drivers, the layering of architectural construct, or are unearthed during the process of architecting. The process of risk emergence is mapped in parallel to the right of the structural House in Figure 4. The discussion of risks is well developed in Miller and Lessard (2001) and Lessard and Miller (2013).

Conclusions

We have proposed the HoPC as a conceptual framework for understanding and interpreting the core concepts of complexity in LIPs. The HoPC comprises three principal components: the foundation of the house that captures the technical and institutional elements of the project opportunity that contribute to complexity, a set of technical and institutional architectural choices that are put in place as a project concept and core coalition takes form, and the set of performance outcomes or 'ilities' that emerge as the project is engineered, constructed and put into operation. This 'house' in turn can be seen as linking the process of project architecting with performance and risk emergence over the project's life.

The HoPC reconciles concepts from a rich projects literature that considers structural conditions and dynamic uncertainty, as well as project process dynamics, as contributors to overall project complexity. The HoPC also iteratively integrates these with some new concepts through two trial applications in our exploratory analyses and one 'proof-of-concept' test on the IMEC case studies.

A main contribution of our work is the conceptual distinction between project features that are inherent to project opportunities (inherent features), those that are conditional on the selection of a project concept including its governance structure and execution process (architectural features) and those that arise from the interaction of these two sets of features as the project is shaped and managed over time. We then relate these to various high-level project outcomes and emergent properties of the LIP—the 'ilities.' A second contribution is to separate the inherent features into technical and institutional domains and to develop these two in a parallel fashion. A third contribution is to connect complexity with the concept of project architecting, developed initially in Miller and Lessard (2000) and extended in Lessard and Miller (2013).

We use the HoPC framework to classify LIPs based on a project's degree of complexity in both the technical and the institutional domains, and to test whether this typology helps explain variation in project performance. We believe that the results demonstrate the validity of breaking project elements into inherent technical and institutional features, project architecture and emergent outcomes in line with the dynamic temporal nature of projects. Our empirical results should be taken as indicative rather than definitive for several reasons. First, as we document, our framing co-evolved with our coding, and while we took care to separate the two activities, we cannot rule out *ex post* bias. Further, our sample is quite small, yielding at best weak statistical support. Finally, the number of projects in our sample does not permit the creation of distinct typologies or patterns (as in Shenhar, 2001, for example) to predict which 'ilities' will manifest. The sample does, however, enable us to identify the dimensions and concepts that should be operationalized in further work. Unpacking the dimensions of architectural 'match' and performance and subsequently collecting observations along these dimensions for a larger sample may reveal meaningful project 'archetypes'. We urge others to explore these concepts and linkages in their project samples and to use the HoPC to frame their work.

We believe that the HoPC may be extended to other substantive contexts that exhibit similar properties as LIPs—extractive industries, large manufacturing projects or other industrial megaprojects and we hope that it will provide a context for further discussion, framework development and testing. Our sample includes projects such as the Eurotunnel that may be viewed as Global LIPs, projects that span geographical or institutional boundaries in some substantial manner (Scott *et al.*, 2011). Many of the projects in our set also exhibit transnational commercial arrangements among contracting firms. This work implicitly treats Global LIPs as a subset of LIPs. Further work may reveal the former as relatively more complex when viewed through the lens of the HoPC because of misalignment or greater interdependence in interests.

Several logical next steps include: (1) formalizing the elements of the HoPC through (network) matrix modelling methods such as Design Structure Matrices or Domain Mapping Matrices (Eppinger and Browning, 2012, (2) expanding the concept of interdependencies to include types, e.g. sequential, pooled or reciprocal following Thompson (1967), (3) deepening the concept of 'match' that emerges as a central element in our 'proof-of-concept' test, and (4) applying the framework to additional samples of projects to further refine it.

Notes

1. Appendix 1 contains a detailed description of our initial exploratory analysis, including the scaling method for operational indicators for both T and O complexity, descriptive statistics, ANOVA analysis and regression results for the relationship between performance and T and O complexity. The regression results supported our intuition that the interaction of technical complexity and organizational complexity had a more important effect on project project's performance than their independent individual contributions. Specifically, project performance worsened in our sample ($p < .01$) along with an increase in the dispersion of performance, as the relative overall compound (T^*O) complexity increased, with better fit than T or O individually or additive T+O.
2. We considered using qualitative comparative analysis (Rihoux and Ragin, 2009) given the small N and relatively large number of constructs in our sample, but found that the more widely used parametric analysis was adequate to demonstrate the significance of our results. In future studies with more detailed project coding, we most likely will use an alternative method.
3. It is well recognized that initially overambitious schedules are often imposed on major projects (see e.g. Priemus *et al.,* 2008), and that this schedule pressure is itself a source of complexity, introducing the potential for correlated errors between the dependent and independent variable. However, deviations from publically announced schedules are the only information available in the public record.

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Appendix 1

This section describes the first exploratory analysis of 45 projects in the oil and gas sector that led to the initial construct of the HoPC, based on Lessard (2007). Table A1 lists the projects with the Project Name (A), Location (B), Operator (C), and Completion date (D) as of the time of the study in 2007.

Table A1 List of 45 oil and gas projects used in the first exploratory study for scoring project complexity and performance

Project name (A)	Location (B)	Operator (C)	Completion date (D)	Project name (A)	Location (B)	Operator (C)	Completion date (D)
ACG, offshore	Azarbaijan (Az)	BP	Various	Mad Dog	GoM	BP	2004
Agbami	Nigeria	Chevron	2008	Malampaya	Philippines	Shell/ Chevron	Producing
Albacora Leste	Brazil	Petrobras	2008	Marlin	GoM	BP	Producing
Asgard	Norway	Statoil	Producing	Mexilhao	Brazil	Petrobras	2008
Atlantis	Gulf of Mexico (GoM)	BP	2007	Moho Bilondo	Congo	Total	2008
Blue Stream	Turkey (Tk)—Black Sea	Gazprom/ Eni	Operating	Na Kika	GoM	BP	Producing
Bonga	Nigeria	Shell	Producing	Oil sands project	Canada	Various	Various
BTC	Az, Georgia, Tk	BP	2007	Ormen Lange	Norway	Hydro/Shell	Producing
Caratinga	Brazil	Petrobras	Producing	Oryx (GTL)	Qatar	Sasoil/ Chevron	2007
Chad project	Chad	ExxonMobil	Producing	Pearl	Qatar	Shell	2010/2011
CPC	Kazakhstan to Russia	State/ Chevron	Operating	Plutonio	Angola	BP	2008
Diana Hoover	GoM	ExxonMobil	Producing	Rasgas expan.	Qatar	ExxonMobil	2001
Erha, offshore	Nigeria	ExxonMobil	Producing	Sakhalin I	Russia	ExxonMobil	Producing
Girassol	Angola	Total	Producing	Sakhalin II	Russia	Shell	2008
Gorgon	Australia	Chevron	2011	Sakhalin IV	Russia	BP/Rosneft	2010
Holstein	GoM	BP	Producing	Shah Deniz	Azarbaijan	BP	2007
In Salah	Algeria	BP	2006	Snohvit	Norway	Statoil	Late 2007
Karachaganak	Kazakhstan	Agip/KPO	Producing	South Pars	Iran	Various	Various
Kashagan	Kazakhstan	Agip-KCO	Late 2010	Tangguh	Indonesia	BP	2008
Kizomba A/B/C	Angola	ExxonMobil	Producing, 2008	Tengiz	Kazakhstan	Chevron	Producing
Kristin	Norway	Statoil	Producing	Thunderhorse	GoM	BP	2010

Note: Completion date (D) is the expected completion date at the time of the study in 2007.

Table A2 summarizes the scaling system used for determining complexity and performance scores. The degree of complexity was based on a subjective assessment of project features including reservoir geology, climate, remoteness of location, novelty of technical means (in the 'T' domain); and operatorship, host stability, host requirements and contractual relationships (in the 'O' domain). Projects were scored on a scale of 1–5 along both these independent dimensions with 1 representing the least complex or 'benign' projects and 5 representing the most complex or 'extreme' projects. Although the scores reflect the use of judgement and are subjective (they do not 'measure' complexity), they are reasonably objective when applied in a relative sense—'less' or 'more' complex, for example.

Performance was operationalized in the form of schedule delay[3] and budget overruns. Each performance indicator had three levels in the scoring scale (schedule: 1—'< one-year delay'; 2—'one- to two-year delay'; 3—'> two-year delay' and budget: 1—'<25% over budget'; 2—'25–50% over budget'; 3—'>50% over budget'). Projects deemed to perform well thus received low scores. Overall performance was determined additively, i.e. by adding the scores of the two indicators such that overall performance ranged from 2 to 6 across all projects.

Indicator scores were categorized by both overall technical complexity and overall organizational complexity. Note that the minimum technical complexity score was 3, suggesting that none of the projects in the sample could be considered technically benign. Organizational complexity scores did in fact range from 1 to 5.

The sample was then broken by 'eyeball' into two groups according to T*O, least complex and most complex. The descriptive statistics for the two groups, shown in Table A3, suggest that complexity leads to both lower (average) performance and a great dispersion of performance.

Table A3 Descriptive statistics: complexity and performance

	Least complex (*N* = 28)	Most complex (*N* = 17)
Average T score (SD)	3.54 (0.58)	4.24 (0.66)
Average O score (SD)	2.86 (0.93)	4.12 (0.70)
Average performance score (SD)	3.21 (1.50)	4.06 (1.43)

A subsequent statistical analysis of these eyeball results confirms the initial intuition. Table A4 shows descriptive statistics, ANOVA results, and correlation of each indicator with overall complexity scores using the indicators described in Table A2.

Based on the ANOVA results for technical complexity, mean scores are found to be significantly different across categories ($p < .001$) in 'Geography/Climate' and 'Novelty' and less so ($p < .01$) for 'Remoteness'. In other words, variance of scores within the category groups is significantly less than variance across category groups for these indicators. These three indicators are also positively correlated with the overall technical complexity score, as shown by both the Pearson and Spearman correlation coefficients, suggesting that the overall technical complexity score is a reasonable compound indicator. The inter-item reliability analysis (alphas ranging from 0.65 to 0.75) further supports the use of the overall technical complexity scale as a compound indicator. 'Reservoir' appears to be uncorrelated and brings down inter-item reliability, but it is retained in the compound indicator to avoid loss of information.

Under the organizational complexity categorization, mean scores of 'Host Stability', 'Host Requirements' and

Table A2 Descriptions and scales for relative scoring of complexity and performance in oil and gas projects (Lessard, 2007)

Complexity dimensions	
Technical ('T') complexity (1: low—5: high)	*Organizational ('O') complexity (1: low—5: high)*
Reservoir—does the project have particularly complicated reservoir geology, high pressure or sour gas, or more importantly a combination of these features?	**Operatorship**—are there are many shareholders, and/or decision-making must be done by a qualified majority?
Geography/climate—is the project in a particularly difficult environment, either in terms of sensitivity (endangered species, migration routes) or hostility (extreme heat or cold which make construction and operation difficult)?	**Host stability**—for example does the host government have a stable regulatory, fiscal or legal environment?
Remoteness—is the project far from existing resources?	**Host requirements**—is there a demanding production sharing agreement in place, or large local content requirements?
Novelty—does the project apply new technology or pushes existing technology beyond current experience?	**Contractual relationships**—are there are many contractors involved, with intricate relationships between them?
Performance dimension	
Schedule delays (1: good—3: poor)	*Budget overruns (1: good—3: poor)*
1—delay of less than one year	1—less than 25% over budget
2—delay of one to two years	2—between 25% and 50% over budget
3—delay of more than two years	3—more than 50% over budget

Table A4 Descriptive statistics, ANOVA and reliability analysis for scoring of technical and organizational complexity

Variables	1	2	3	4	5						
	Benign Mean (SD)	Mean (SD)	Moderate Mean (SD)	Mean (SD)	Extreme Mean (SD)	ANOVA df	F	Correlation Pearson's	Spearman's	Reliability	
Technical complexity											
Reservoir			3.69 (0.19)	3.59 (0.16)	3.86 (0.28)	2, 42	0.34	0.04	0.00	Cronbach's alpha	0.66
										Std. Cronbach's alpha	0.65
Geography/climate			3.00 (0.17)	3.36 (0.15)	4.29 (0.26)	2, 42	8.25***	0.50***	0.46**	(excluding 'Reservoir')	0.75
Remoteness			2.93 (0.25)	3.00 (0.21)	4.43 (0.38)	2, 42	6.18**	0.37*	0.29*		
Novelty			3.06 (0.14)	3.86 (0.12)	4.57 (0.21)	2, 42	19.67***	0.69***	0.72***		
Organizational complexity											
Operatorship	4.00 (0.65)	2.36 (0.20)	3.00 (0.22)	2.89 (0.15)	3.20 (0.29)	4, 40	2.79*	0.23	0.21	Cronbach's alpha	0.82
										Std. Cronbach's alpha	0.79
Host stability	1.00 (0.91)	1.27 (0.27)	2.00 (0.30)	3.10 (0.21)	3.60 (0.41)	4, 40	10.23***	0.70***	0.69***	(excluding 'Operatorship')	0.92
Host requirements	1.00 (0.92)	1.36 (0.28)	2.33 (0.31)	3.53 (0.21)	4.20 (0.41)	4, 40	13.99***	0.76***	0.75***		
Contractual relationships	1.00 (0.70)	2.00 (0.21)	2.33 (0.23)	3.90 (0.16)	4.00 (0.31)	4, 40	19.71***	0.77***	0.81***		

*$p < .05$.

**$p < .01$.

***$p < .001$.

Table A5 Three-step hierarchical regression of performance on technical, organization complexity scores ($N = 45$)

	Model 1		Model 2		Model 3		Model 4		Model 5	
	B (SE *B*)	Prob > |T|	*B* (SE *B*)	Prob > |T|	*B* (SE *B*)	Prob > |T|	*B* (SE *B*)	Prob > |T|	*B* (SE *B*)	Prob > |T|
Intercept	1.78 (1.26)	0.165	2.11** (0.74)	0.007	−0.4 (1.50)	0.79	−0.21 (1.34)	0.88	1.86** (0.63)	0.005
Technical complexity (T)	0.46 (0.33)	0.163			0.59 (0.31)	0.06				
Organization complexity (O)			0.42 (0.21)	0.051	0.49* (0.21)	0.02				
T + O							0.52** (0.19)	0.007		
T × O									0.13** (0.05)	0.007
R^2	0.04		0.08		4.03		0.16		0.16	
Adjusted R^2	0.02		0.06		4.03		0.14		0.14	
F	2.02		4.03		3.94*		7.96**		7.96**	

$^{*}p < .05$.
$^{**}p < .01$.
$^{***}p < .001$.

'Contractual Relationships' are significantly different across categories ($p < .001$). These indicators are also positively correlated with overall organizational complexity. Once again the high correlation and high alpha reliability scores (0.79–0.92) support the use of organizational complexity as a compound scale. 'Operatorship' is also retained in the compound organizational complexity indicator to avoid loss of information.

The compound scores of complexity were then regressed against performance scores to explore the relationship between complexity and performance. A three-step hierarchical regression was used, in which five models were tested (Table A5). In the first step, the independent effects of Technical Complexity (T) only, Organizational Complexity (O) only and both T and O were examined. Only the model with both T and O was found to be significant ($p < .05$). In the second step, the additive term T + O was tested and found to be significant, however, the best fit was obtained in the third step when the multiplicative interaction term T*O was tested (Model 5, $p < .01$). These results support the proposition that the interaction of project features contributing to technical complexity and organizational complexity affect a project's performance. Specifically, project performance was found to worsen in our sample as the relative overall compound (T*O) complexity increased.

Appendix 2

This section contains brief descriptions of the 20 cases in our sample, all drawn from Miller and Lessard (2000). Summaries of the detailed case write-ups for these and the rest of the cases in the IMEC study are available online: http://www.er.uqam.ca/nobel/r34670/anglais.html

Appendix 3

This section provides detailed definitions, citations and indicators/examples for the concepts populating the HoPC, as described in the fifth section. The main concept categories are Inherent Features (the bottom layer), Architectural Constructs and Arrangements (the intermediate layer) and Emergent Properties/'Ilities' (the uppermost layer, the roof of the House).

Inherent features

Inherent features are those project features or characteristics that are common to the project and precede the architectural choices in the process of project architecting or shaping. Inherent features are of four main types—Framework and Interests (in the institutional domain), and Location and Elements (in the technical domain). Table A7 defines the concepts contained in the Inherent Features category.

Architectural constructs and arrangements

This category forms the intermediate layer between the Inherent Features and the final layer consisting of Emergent Properties. Architectural constructs and arrangements are those features by which project architects shape and fix the form, organization and logistical activities of the LIP. A higher level of detail and specification is observed as compared to the inherent features.

Emergent project properties/ilities

At the uppermost level of the HoPC structure, the 'Ilities' category contains concepts that broadly represent outcomes of the process of project architecting. The emergent properties are the result of the interdependence and

Table A6 Sample of cases for developing 'HoPC': brief descriptions from Miller and Lessard (2000)

Project name	Sector	Brief description
Ankara Metro	Urban transport	A first-phase subway in Ankara, Turkey. The sponsors were SNC Lavalin, of Canada, and Gama and Guris, of Turkey. The project cost was US$650 million
Bakun	Hydro	A partly built 2400 MW hydroelectric plant in Sarawack, Malaysia. The sponsor was Ekran Berhad, a Sarawack firm. The project was stopped during the Asian financial crisis
Bergen	Power	A 50 MW repowering of an original coal-fired power plant in Ridgefield, New Jersey, to use natural gas or fuel oil. The sponsor was Public Service Electric and Gas Co. of New Jersey, and the cost was US$400 million
Channel Tunnel (Eurotunnel)	Tunnel	An undersea transport system with a tunnel about 50 km in length, linking Kent in the UK and Calais in France
Gardermoen	Airport	New airport near Oslo, Norway, sponsored by the Ministry of Transport and Communications, to be completed in 1999. Estimated cost was NOK 22.3 billion
Gazmont	Power	A small peaking power plant built at a cost of US$50 million using gas from a dump in Montreal, Canada. The sponsor was a group of firms led by Novergaz of Montreal
Hopewell	Urban transport	A partly built elevated rail-system in Bangkok, Thailand, sponsored by Hopewell Holdings of Hong Kong under a concession from State Railways of Thailand
Hub	Power	A 1300 MW oil-fired power plant located in Hub Chowki in Pakistan, costing US $1.8 billion. A Build–Operate–Transfer (BOT) project sponsored by National Power International of the UK and Xenel Industries of Saudi Arabia
Highway 407	Toll road	A toll-highway project near Toronto, built at a cost of CA $1 billion by a corporation of the Ontario government and later sold to a consortium of engineering firms and banks. Estimated cost was US$440 million
Lambton FGD	Power	A flue-gas desulphurization project to serve the Lambdon coal thermal power plant built in the mid-1990s. The sponsor was Ontario Hydro and the cost was CA $537 million
Lambton	Power	The repowering in the mid-1990s of a 2100 MW thermal power plant in Sarnia, Ontario, by Ontario Hydro at a cost of CA $410 million
McWilliams	Power	Repowering from coal to gas of a 150 MW power plant located in Gant, Alabama, at a cost of US$70 million. The sponsor was Alabama Electric Cooperative
MRTA	Urban Transport	A proposed subway system in Bangkok, Thailand, sponsored by the Metropolitan Rapid Transit Authority of Bangkok
Nanko	Power	A 1800 MW liquefied natural gas thermal power plant built in the late 1980s by Kansai Power in a residential area of Osaka Bay, Japan. The cost was Yen 260 billion
Orlyval	Urban Transport	Development of a link between Orly airport and the RER public transport near Paris, France. MATRA was the sponsor and the cost was 1.74 billion French francs
Port Dickson	Power	A 440 MW IPP thermal power project built in Malaysia in the late 1990s by a consortium led by SIME Darby, at a cost of RM 700 million
Second Severn Crossing	Bridge	A road bridge linking England and South Wales. A joint venture led by John Laing with GTM Entrepose
Tanayong	Urban Transport	An elevated rail-system in Bangkok, Thailand, sponsored by Thai and European engineering firms. The cost was US$1.65 billion
Thames Water Ring Main	Water distribution system	Water distribution system completed in the mid-1990s at a cost of US$500 million. The sponsor was Thames Water in London, England
Wabash River	Power	A 200 MW repowering of the Wabash River generating station from coal to synthetic fuel gas. The project is a joint venture between Destec Energy and PSI Energy. It is located West Terre Haute, Indiana. The cost was US$400 million

Table A7 Inherent project features in the HoPC

Category • Concept	Definition	Indicator/example
Framework		
• Legislative	The legal framework that forms a basis for decisions and actions in the infrastructure domain. Formulated by deliberation and analysis in sovereign or regional law-making bodies	Privatization, or private participation
• Regulatory	The framework of rules that instruments the intent of legislation. Made legitimate by legal sanction	Rule-setting, monitoring and sanctioning activities; markets' processes (Scott, 2012)
• Normative	The code that determines what is socially appropriate on the basis of moral beliefs; 'prescriptive, evaluative, and obligatory dimension' (Scott, 2008)	Value-based domains such as religious communities, kinship systems, status and prestige orders
• Cultural-cognitive	Shared conceptions and beliefs of a community that constitute the 'nature of social reality' through patterns of thinking feeling and acting (Geertz, 1973, Hofstede, 2005)	Epistemic systems such as religious, philosophical, intellectual and ideological (Knorr-Cetina, 1999, Scott, 2012)
Interests		
• Number of stakeholders	The number of individuals, entities or groups that can 'affect or are affected by achievement of the organization's objectives' (Freeman, 1984, Freeman *et al.*, 2007) or 'have an interest in the actions of an organization and the ability to influence it' (Savage *et al.*, 1991)	Corporations, banks, regulatory agencies, consumer groups, contractors, residents of a region
• Interdependence	The one-way or two-way flow of information, processes or materials between the stakeholders that are critical for project architecting to proceed	Contractual, informational or material interdependence; may be pooled, sequential or reciprocal (Thompson, 1967)
• Similarity/ alignment	The degree of 'likeness' among the stakeholders that allows for their categorization or treatment as a class of individual or entities	Consumer advocacy group representing many consumers
• Dynamism	The degree of change or variation in the needs, preferences and interdependent interactions between stakeholders over time that may affect their power to influence (Chinyio and Akintoye, 2008)	Investment preferences, willingness to pay
• Novelty/maturity	The extent to which organizational age, experience and precedent actions of stakeholders influence their future actions and interactions (Jawahar and McLaughlin, 2001)	Novel/birth, emergent/growth, mature, revival
• Expertise	Differentiating set of skills and knowledge possessed by firm or entity in a particular domain	Nuclear plant design, deep-sea exploration
• Legitimacy	The unique characteristics of the particular individual or entity that lends credibility to the project concept	Reputation, track record, brand
Location		
• Development	The extent to which the geographical region under consideration for a project opportunity has undergone prior infrastructure work	Greenfield, brownfield
• Proximity	The physical closeness of the geographical region to supply chain nodes or demand centres for the output of projects	Urban, suburban, rural, remote
• Geography/ geology	The difficulty of performing site-related activities such as site preparation, excavation, drilling, construction or even life-cycle operation	Deep-sea reservoir, sub-surface transport

(*Continued*)

Table A7 Continued.

Category • Concept	Definition	Indicator/example
• Climate	The extent to which weather cycles and temperature in the geographical region make project-related activities difficult	Storms, extreme temperatures, precipitation
Elements		
• Number of elements	The number of discrete artefacts, components or tasks that required to achieve intended functionality of a project concept (Miller, 1956, Dewar and Hage, 1978)	May be pooled, sequential or reciprocal (Thompson, 1967)
• Interdependence	The relationship between entities that cannot exist or operate without each other (de Weck *et al.*, 2011). The one-way or two-way flow of information, processes or materials between the elements or sub-systems that is critical for a project opportunity to be fully conceptualized or formulated	Design, surveying, construction, drilling, tunnelling
• Diversity of disciplines	The number and degree of difference between the trades/functional domains/expertise invoked by a project opportunity (Baccarini, 1996)	
• Dynamism	The degree of change or variation in the technical or functional needs over time	
• Novelty/maturity	The extent to which technological development and processes make the project opportunity technically feasible	

Table A8 Architectural constructs and arrangements in the HoPC

Category • Concept	Definition	Indicator/example
Architectural (institutional)		
• Project vision/ narrative	A deliberately crafted story that motivates the project opportunity and describes how the project concept will satisfy the social needs that justify the project opportunity	Motivated by economic development, reputation or job creation
• Public–private interaction	The explicit, often contractual, arrangement of roles and division of responsibilities between identified institutional actors in the public and private sector who participate in the project solution (Grimsey and Lewis, 2007)	Concessions, BOT, privatization
• Coalitions	The subset of stakeholders that become aligned or to advocate their interests or specific agenda (Sullivan *et al.*, 2009). Coalitions generally tend to either be supporting or opposing aspects of the project concept, and coalitions may evolve over time, i.e. their membership and position on the issues may change	Groups of firms/sponsors advocating a project
• Roles	The set of rights and obligations, or expected behaviours that various stakeholders, who are now explicitly identified, are expected to perform in the project concept	Convening, financing, designing
• Financing and incentives	The structuring of financial flows, investment and contractual incentives in the project solution (Esty, 2004a, 2004b)	Project finance, syndication, revenue collar
• Coordination and logistics	The protocol for communication and decision-making in the project solution	Lean methods, concurrent design and engineering

(*Continued*)

Table A8 Continued.

Category • Concept	Definition	Indicator/example
Architectural (technical)		
• Design lock-in	The detailed, irreversible specification of the technology paradigm, elements/components, and processes as a precursor to construction or final implementation	
• Collocation/ separation	The intentional choices regarding the geographical arrangement of technical processes and components (Joskow, 1988, Browning, 2001)	Mine-mouth coal plant, collocated utility easements
• Scale/scope	The magnitude of production output/services envisioned in the project concept and associated tasks and activities that must be completed to enable the project (Shenhar, 2001, Project Management Institute, 2004)	Sub-system, system, programme/ array
• Technology/ process	The basic technological paradigm that enables output in the project concept, and the mechanism by which the technology paradigm acts on material/information inputs to transform them to desired outputs	Thermal power, rail transport, combined cycle, pulverized coal
• Timing/pacing	The chronological sequencing of various design and logistical activities in the project solution (Williams, 2005)	Fast track, concurrent
• Structure	Aspects of the design that support scaling, operation and maintenance of the technology and process (Sosa *et al.*, 2003, Eppinger and Browning, 2012)	Modular, integral

interactions between various technical and institutional features of the project and the architectural constructs and arrangements used to mediate these features. 'Ilities' are defined as (de Weck *et al.*, 2011, pp. 187–188):

The ilities are desired properties of systems, such as flexibility or maintainability (usually but not always ending in 'ility'), that often manifest themselves after a system has been put to its initial use. These

Table A9 Emergent properties/'ilities' in the HoPC

Category	Definition	Indicator/ example
'Ilities'		
• Quality	The ability to deliver requirements at a 'high' level, as perceived by people relative to other alternatives that deliver the same requirements (de Weck *et al.*, 2011)	
• Flexibility	The ability of a system to undergo classes of change with relative ease and efficiency, especially as new requirements, needs and possibilities emerge over time (de Weck *et al.*, 2011)	
• Sequentiality	The property of a chronologic sequencing of activities and events, such that earlier activities must be completed before later ones can be begun	
• Survivability/ robustness	The ability to persevere in existence, in spite of shocks or crises to the system, or changes in environment (de Weck *et al.*, 2011)	
• Difficulty	The property of being hard to accomplish	
• Consequentiality	The extent to which failure of a system results in the loss of economic, material and or reputational resources	
• Governability	The ability to steer the system through turbulence in the institutional domain (Miller and Lessard, 2000)	
• Non-linearity	The property of a system that results in effects and impacts being disproportionate to the causes, either through amplification or attenuation (Anderson, 1999)	

properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders than are embodied in those primary functional requirements. The ilities do not include factors that are always present, including size and weight (even if these are described using a word that ends in 'ility').

The 'ilities' observed in our sample are defined in Table A9.