A Direct Interaction Approach to Identify Real Options "In" Large-Scale Infrastructure Systems

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Abstract

There is a universe of real options opportunities for infrastructure development that are not fully considered in real options analysis literature. These are known as real options "in" infrastructures systems. They are design components embedded early on "in" the system design process – i.e. prior to fielding and operations – to enable time-to-build, scale alteration, product switching, and many other real options difficult to classify through a discrete set of categories suggested by Trigeorgis (1996). Real options "in" system require technical and engineering knowledge. This differs from real options "on" system focusing on managerial flexibility (e.g. investment deferral, abandonment, growth). Several example case studies show real options "in" system offer significant economic value improvement compared to a baseline inflexible design, ranging between 20% and 80%. Because real options "in" systems are numerous and different from one infrastructure to another, there is a need for analytical tools to guide the engineering effort for valuable opportunities. This paper illustrates some of the research issues involved in developing this field productively. It suggests a potential approach based on direct interactions, discussions, and close work with designers to enable real option opportunities "in" infrastructure systems.

1 Introduction

Trigeorgis (1996) presents six categories of real options relevant to the infrastructure design industry. They are options 1) to defer investment and wait favorable market conditions to commit capital, 2) of time-to-build, involving staged asset deployment over time, 3) to alter operating scale, in the sense of expanding or contracting output production capacity, 4) to abandon a project with the possibility of reselling the physical asset at salvage value, 5) to switch production output and/or input, and 6) to grow by providing future opportunities, such as by investing in R&D.

These categories can be further divided as real options "in" and "on" system, as suggested by Wang and de Neufville (2005). A real option "in" a system is a class of real option that requires in depth technical knowledge of the infrastructure design components (see examples below). It differs from a real option

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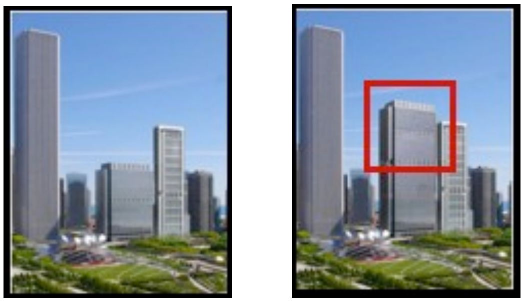
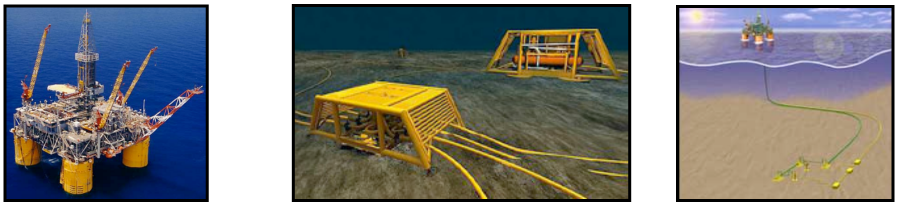
"on" the system that provides managerial flexibility without necessarily requiring technical inputs from engineers. From the categories developed by Trigeorgis (1996), investment deferral, abandonment, and growth options can be categorized as real options "on" systems as they do not require in depth engineering knowledge of the infrastructure design.

A time-to-build real option, as well as an option to alter operating scale and switch output and/or input can be associated to real options "in" infrastructure systems. They consider the technology explicitly to enable the flexibility. For example, designers can provide the real option to stage deployment of a satellite constellation by designing "in" each satellite the capability to change orbital configuration (de Weck et al., 2004). Guma (2008) and Pearson and Wittels (2008) describe the design of an office building in downtown Chicago to enable phased vertical expansion to accommodate growing needs in office space (Figure 1). The design involves careful design of elevator shafts, columns and footings to enable expansion. The real option to alter operating scale is acquired in a tension leg platform (see Figure 2) by designing more slots to enable addition of more direct vertical access wells if more oil is discovered than originally expected (Babajide, 2007). This real option is also acquired by designing the capability to connect more sub sea tiebacks – a device connected on the ocean floor to spread further the number of reachable wells – to the platform as more oil is discovered (Lin, 2009). The real option to switch condos into office space (or vice-versa) needs to be explicitly considered in the early design phase of a major real estate development project. Many other examples of real options "in" infrastructure system can be found in the literature (see http://ardent.mit.edu/real_options/Common_course_materials/papers.html for a sample).



(a) (b)

Figure 1: Example vertical expansion of an office building in downtown Chicago (Guma, 2008). The initial phase (a) was designed carefully to accommodate vertical expansion in the subsequent development phase (b).



(a) (b) (c)

Figure 2: Example tension leg platform (a) for offshore oil exploration, sub sea tiebacks (b), and how the two are connected to extract oil from oceanic ground (c). (Sources: http://www.offshore-technology.com, http://msnmoney.brand.edgar-online.com, http://www.w-industries.com).

The real options literature typically assumes that the technology enabling flexibility is available. It develops analytical tools to find its financial value using variants of the Black-Scholes formula (Black and Scholes, 1973), binomial lattice (Arnold and Crack, 2003; Cox et al., 1979) and/or Monte Carlo simulation (de Neufville et al., 2006). Identifying physical design and technical mechanisms enabling real options is however as important as the valuation aspect. For one, identifying the appropriate technology and design components can help determine the acquisition cost of a given real option. This cost can be compared to the value of flexibility to make the best investment decision.

Considering the valuation aspect only does not provide the necessary tools to identify the most valuable real options opportunities “in” infrastructure systems. This is an important issue for designing such options. If the acquisition cost is higher than the real option value, it may not be worth designing the flexibility. This may be the case for instance in systems displaying significant economies of scale. If economies of scale are strong, it may be advantageous to build a big facility upfront and not phase the deployment of the physical assets.

Another issue is that there are many more examples of real options “in” the system that cannot be associated to the time-to-build, scale alteration, and switching options described by Trigeorgis (1996). In fact, the type of real options “in” systems that designers can implement is intractably large. It can be daunting to assign them to a discrete set of categories. For example, switching from natural to mechanical ventilation in a building (Greden, 2005) cannot be clearly ascribed to a switching real option as defined by Trigeorgis (1996) because it is not the final revenue generating output (i.e. rental space) that is changed. In offshore oil platform design where thousands of design variables are involved, Kalligeros (2006) shows that so many sources of flexibility exist that one needs a Design Structure Matrix (DSM) – a square matrix where the rows and columns list all design components in the system, with entries describing the relationship between design components – to look thoroughly at all potential real options “in” the system. Other examples support this view in the car manufacturing (Suh, 2005), complex sensor design (Giffin et al., 2007), and miniature aero vehicle industries (Wilds, 2008).

This body of work shows that identifying valuable real options “in” a system is not an easy task. It needs to be addressed in the early conceptual design phase along with valuation. Currently, analytical tools to identify these options are based on a variant of the DSM method (Bartolomei, 2007; Kalligeros, 2006; Mikaelian et al., 2008; Suh, 2005). Such approaches provide a good conceptual framework to identify interesting areas to embed real options “in” systems. They are however very difficult to use mainly because of the effort and resources required to build and analyze a DSM (Browning, 2001) – they typically have hundreds of rows and columns, with tens of thousands of entries determined by interviewing designers. Other issues limit their use, as explained in Section 3.2.

This provides an opportunity for developing a new approach to identify interesting real options opportunities “in” infrastructure systems addressing limitations of existing DSM-based methods. There is also a need for valuation tools to investigate the large number of design configurations under a wide range of uncertain future scenarios. The next section presents and motivates these research needs.

2 Why Are Real Options “In” Systems Not Widespread?

The prologue leads to the interesting question: “Why experienced designers with significant knowledge and expertise in infrastructure design do not systematically design real options “in” their system?” It is clear designers realize the importance of uncertainty and how it affects the economic value of infrastructure systems. For various reasons however – some hypothesized below – they often simplify such considerations to one (or very few) deterministic scenario and optimize their design to this particular manifestation of uncertainty. If reality departs from this projection – which is most often the case (Savage, 2000) – the system ends up quickly in a suboptimal configuration. Therefore, although a few real estate case studies show designers indeed consider flexibility (Guma, 2008; Harder, 2008; Pearson and Wittels, 2008), designing real options “in” systems is currently not part of widespread systems engineering practice (de Weck, 2007).

The authors offer possible answers to the question above based on long-term interactions and experience with designers in aerospace (de Weck et al., 2004), airport (de Neufville and Odoni, 2003), car manufacturing (Suh, 2005; Yang, 2009), mining (Cardin et al., 2008), oil (Hassan and de Neufville, 2006; Kalligeros, 2006; Lin, 2009), and real estate infrastructure design industries (Guma, 2008; Pearson and Wittels, 2008):

1. Designers operate within institutional, possibly cultural, engineering “silos” and do not consider how other system components might affect the overall economic value of the system. Dong (2002) shows in the car manufacturing industry how system-level knowledge required to think about real options “in” systems in the early design phase is not very well documented across

different systems discipline. It took Lin (2009) about a year of close collaboration with oil platform engineers to consider sub sea tiebacks as a valuable real option. This is not because designers did not know or think the real option would be valuable, rather they were not actively engaged in discussions with sub-surface engineers to consider this design component.

2. Designers think they adequately consider risk when they subject design to a range of uncertainties through sensitivity analysis after an initial design is crafted. This approach however does not consider uncertainties in the early conceptual phase prior to more detailed design analysis. It does not recognize the power of real options "in" systems to adjust to changing future conditions, and its potential to increase economic value.
3. Engineering focuses on detailed (exact or high-fidelity) models. Such models are computationally heavy and cannot be used to explore many design configurations including flexibility and managerial decision rules under a wide range of uncertain scenarios.

The conclusion from the above two sections is that finding and justifying financially the right kinds of real options to embed "in" infrastructure systems is not trivial. In order to develop an approach that is effective, three elements emerge. These are needs to:

1. Break through barriers imposed by engineering "silos" and facilitate better system-level communication, documentation, and knowledge. This need is not new; there is ongoing research in organizational behavior to address such design issues (Avnet, 2008; Dong, 2002; Stagney, 2003).
2. Educate engineers to consider uncertainty and flexibility in the early design phase, which departs from the traditional engineering paradigm.
3. Define mid-fidelity, less detailed, and quicker analytical models to explore and value economically the universe of possible design configurations under uncertainty.

3 How to Identify Real Options "In" Infrastructure Systems?

This section introduces case study examples to motivate a new research direction that aims at developing a new approach to identify real options "in" infrastructures. The approach investigated relies on direct interactions with designers, meaning close collaboration and discussions focusing on the identification of valuable real options opportunities. This operates under the assumption that designers have *latent* knowledge about these opportunities based on experience and expertise with the system. The goal is to access this knowledge and facilitate their realization in a more systematic way. A more detailed review of existing approaches follows to highlight their benefits and limitations, and further justify the need for more research.

3.1 Motivating Examples

Three doctoral dissertations provide motivation for developing a new approach to identify interesting real options opportunities “in” systems (Kalligeros, 2006; Lin, 2009; Wang, 2005). Wang (2005) first proposed a screening model (Jacoby and Loucks, 1974) to identify such opportunities “in” a hydroelectric dam infrastructure development in China, under electricity price and reservoir uncertainty. A screening model is a computerized, mid fidelity model of the system replicating the economic response surface of a more detailed, high fidelity one (Figure 3). The model incorporates analytical elements to replicate the revenue and cost generating streams of design alternatives under a wide range of simulated exogenous conditions (e.g. electricity market price and demand, water reserves and flow). It enables quick exploration and validation of the universe of design possibilities. From these, the most valuable flexible design configurations can be selected and compared to an initial design not incorporating the real options.

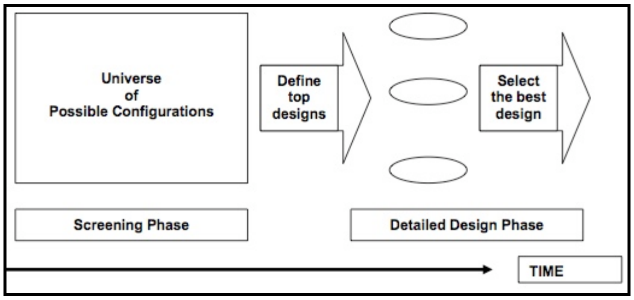


Figure 3: Conceptual representation of a screening model to explore the universe of possible design configurations quicker than with a high-fidelity model of the system (de Neufville et al., 2008).

Wang (2005) suggested screening model because current real options valuation methods (e.g. Black-Scholes formula, binomial lattice) are not well suited for detailed technical analysis of engineering components. Many economic assumptions underlying these methods do not apply in an engineering context (e.g. path independence, arbitrage-enforced pricing) (Wang and de Neufville, 2005). Screening models enable relative rank ordering of design alternatives, and do not focus on finding economically rigorous value. One issue however is that designers have to choose *a priori* the set of flexible design configurations to explore and embed in the model. No guidance is provided on how to do this, which is left to designers’ judgment.

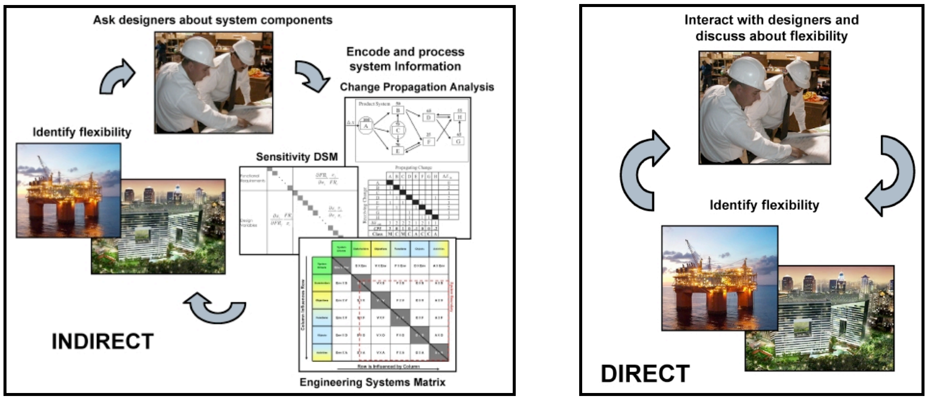
Kalligeros (2006) and Lin (2009) explored the question of identifying real options opportunities “in” an offshore oil platform infrastructure system at a major oil company under oil reserve, market price, and technological uncertainty. Kalligeros (2006) built a DSM by interviewing designers, and looked at the sensitivity of design variables – or the degree to which other variables change as a result of changing design or functional requirements – to identify areas to embed real options. Kalligeros recommended that sensitive variables should be designed flexibly to lower the future cost of switching between different platform configurations. This would ease adaptation to changing market and environmental conditions. One issue with this approach is that it implicitly sets the DSM system boundary to the oil platform. Any real option residing outside the DSM boundary, like the sub sea tieback identified by Lin (2009) and described above, is ignored.

Lin (2009) showed that working closely with the same design team as Kalligeros could lead to the identification of a major real option "in" the system, without relying on detailed DSM analysis. He showed that the flexibility to expand production capacity by connecting more sub sea tiebacks as needed improves the expected economic value of the system by up to 78% compared to an initial design without the real option. The interesting fact is that Lin's research team had no notion about the sub sea tieback flexibility because it was focusing early analytical efforts, as with Kalligeros, on the platform. The realization came about by serendipity, because the research team kept talking about flexibility with the design team. This process took nearly a year of close work, which suggests that a more systematic way to engage discussions with designers could have led to the sub sea tieback flexibility faster.

The case studies provide four lessons motivating the development of a systematic approach based on direct interactions with designers to identify real options "in" infrastructures. First, Wang's work (2005) suggests that a screening model is appropriate to explore possible design configurations, but does not provide guidance on the choice of real options to incorporate in the model. The model encompasses and represents the flexibility and managerial decision rules chosen *a priori* by designers. Therefore there is a need for guidance on how to choose these real options opportunities. Second, Kalligeros' work (2006) demonstrates that focusing the analytical effort on DSM may divert from potentially interesting sources of flexibility – even "low-hanging fruits" like sub sea tiebacks discovered by Lin's team. This outlines some of the limitations of existing DSM-based methods to identify real options "in" the system, and the need for additional tools to explore possibilities. Third, Lin's experience (2009) shows that knowledge about sub sea tieback flexibility was latent within the oil platform design team, in support for our original hypothesis. Designers knew the real option could be profitable economically, and eventually through extensive discussions recognized its relevance to the design of the platform – a connection they had not made before being exposed to the notion of flexibility "in" design. Fourth, all the above suggests that developing a more systematic way to engage discussions with designers about flexibility can help identify interesting real options faster, thus contributing quicker to economic value improvement.

3.2 Existing Approaches to Identify Real Options “In” Systems

As Figure 4 shows, there are currently two broad categories of analytical tools to identify real options “in” large-scale infrastructures. They are called *indirect* (generally DSM-based) and *direct interaction* approaches. Indirect approaches inquire designers about the system itself, the design variables, how they are connected, and not directly about potential sources of flexibility. This information is “encoded” in details in a DSM, and processed to identify interesting real option opportunities. Examples of processing algorithms are Change Propagation Analysis (CPA) (Suh, 2005), sensitivity DSM (sDSM) (Kalligeros, 2006), and Engineering System Matrix (ESM) (Bartolomei, 2007). Ongoing work by Mikaelian et al. (2008) also suggests extending the DSM boundary to the enterprise view to provide more opportunities from a management perspective. The processing algorithms essentially look for design variables that propagate more change to other design components than they receive as a result of changing initial design and/or functional requirements. They are potential real options because designing such components with flexibility can lower the switching cost when the system configuration needs to be changed.



(a) (b)

Figure 4: Conceptual representation of (a) indirect (DSM-based) and (b) direct interaction approaches to identify real options “in” large-scale infrastructures systems (Sources: Bartolomei, 2007; Kalligeros, 2006; Suh and de Weck, 2007; http://www.cs2designgroup.com, http://www.orchardscotts.com.sg/, http://www.smh.com.au, http://national.nsbe.org).

The benefit of indirect approaches is that they are widely researched. They encourage designers to consider all modules of the system to get good system-level knowledge and representation (Dong, 2002). This requires gathering information from various design experts (e.g. for an oil platform this can be sub surface reservoir engineers, and platform engineers). Such detailed analysis is useful to identify unsuspected areas for embedding real options as demonstrated by Wilds (2008). The main limitation of indirect approaches is that getting data for DSM construction and analysis is tedious and time-consuming

(Browning, 2001). As demonstrated by Kalligeros' case study, focusing on details might miss potential real options lying outside the DSM boundary. There are also several issues related to data reliability. For example, detailed system-level data may not be available due to confidentiality (Mikaelian, 2008) and/or reliable because designers are not sure about the exact relationship between design components (as experienced by Kalligeros, 2006). Building a DSM requires good training in qualitative research methods to avoid biasing questions and answers from designers (Bartolomei, 2007), which is often not part of typical engineering education. Also, system-level documentation required to build a DSM in the early design phase is often not well documented, as Dong demonstrates (2002). Therefore, data reliability issues imply the possibility for unreliable results when applying any of the DSM processing algorithms like CPA, sDSM, or ESM.

Direct interaction approaches on the other hand involve discussions and interactions with designers directly about real options opportunities – as opposed to asking about the system components first as in indirect approaches. They try to tap in designers' knowledge about real options opportunities prior to more detailed DSM analysis, or even without it. The main benefit from direct interaction approaches is to get at potential areas to embed real options faster because it does not require DSM construction and analysis. This also addresses the data reliability limitation explained above and stemming from DSM construction. They provide a higher-level, less detailed, perspective on the system to consider real options. This addresses another limitation of indirect approaches, as it does not confine the system analysis to any given DSM boundary. They also enable discovery of opportunities that can be agreed upon directly by the system owner and operators. A limitation of direct interaction approaches is that they are currently not well structured as demonstrated by the long time taken by Lin's team to access the sub sea tieback real option. There is no strategy or systematic approach to engage designers and discuss about interesting sources of flexibility. Another issue is that it might be difficult to access and work with high-level designers that can influence design decisions related to real options implementation.

In summary, there is a gap in the literature to identify interesting real options opportunities "in" infrastructure systems. Indirect DSM-based approaches provide a good conceptual framework for detailed system analysis, but are limited for reasons explained above. Direct interaction approaches seem to address some of these limitations, but need to be developed to be more systematic. The proposed research aims at addressing this gap.

4 Proposed Methodology and Upcoming Work

The following two-parts research methodology is suggested to develop a more systematic direct interaction approach. The research addresses the three barriers outlined in Section 2, and some limitations of existing DSM-based approaches. In part 1, the idea is to develop the approach through qualitative interviews, thus relying on insights and experience from designers in the oil, automotive, and real estate infrastructure industries – domains can be extended depending on research resources available. Interview candidates have several years of experience in engineering design and/or management. They have been or are currently involved with design of flexible infrastructure systems, through a collaborative research project or within industry. Interviews are conducted to learn how uncertainty is treated and dealt with at their firm, how flexibility is incorporated in the design process, and what recommendations can be made on the most efficient tools to stimulate discussions about uncertainty and flexibility "in" design. All interviews are recorded digitally and transcribed word for word. A coding procedure (Strauss and Corbin, 1990) is used to analyze interview transcripts. Coding is a well-proven social science method to analyze qualitative data systematically and reduce bias to a minimum from both interviewer and interviewee. The analysis extracts emerging and recurrent concepts in interview transcripts, and organizes concepts into abstract categories. The direct interaction approach is created from these more abstract categories. In other words, what is learned from designers is organized and "packaged" into a more systematic direct approach incorporating their knowledge, experience, and recommendations to the best extent possible. This is done using the best available social science research methodology.

Part 2 consists of testing the direct interaction approach working with a design team on a real-world infrastructure design problem. The goal is to determine whether the approach helps eliciting valuable real options opportunities "in" the system. The plan is to develop a screening model and evaluate possible design configurations from an economic standpoint using Monte Carlo simulation, similar to Lin's work (2009). The economic value of the new design incorporating the real option(s) – if any is/are found – is compared to the baseline design value without the real option(s). Several case study opportunities exist in the energy, oil, and real estate sectors.

5 Conclusion

This paper highlights the fact that a vast number of real option opportunities "in" infrastructure systems exist and have not been much explored in current real options literature. These can bring significant economic value improvement, as demonstrated by several infrastructure case studies. Because real options opportunities "in" systems are not easy to identify and value financially, there is a need for more research to develop tools that guide the engineering effort towards valuable opportunities. Existing methods to identify opportunities based on DSM provide a good conceptual framework but are limited. There is potential for developing a new approach relying on direct interaction with designers (i.e. explicitly accessing latent knowledge about real option opportunities based on their expertise and experience with the system). Also, because real options "in" system require in depth technical evaluation of possible design configurations, screening model is suggested as an economic valuation tool to find the most valuable real option opportunities. Current real option valuation tools based on Black-Scholes and lattice analysis are not well suited for deeper analysis of system design configurations for various reasons

(Wang and de Neufville, 2005). A research methodology is suggested to develop the direct interaction approach based on experienced designers' inputs. The approach is to be tested by working closely with a design team on a real-world infrastructure case study and by developing a screening model, which will determine whether the approach is helpful in eliciting valuable real options opportunities "in" the system.

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