

THE MANAGEMENT OF REQUIREMENTS: WHAT CAUSES UNCERTAINTY IN INTEGRATED DESIGN APPROACHES?

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Abstract

Although a substantial amount of literature advocates the integrated collaborative design processes for construction projects, very little explicit knowledge exists about the impact of the integrated processes on project uncertainty. In contrast with construction site processes, which can in most cases be organized as a sequence of tasks mutually interlinked by technological interconnections, design is a highly interdependent and iterative process that needs different management approaches. To manage the complex interdependencies of design, managers need to make sense of how far-reaching the impact of addressing a particular requirement will be on project outcomes.

By using the theoretical dichotomy of wicked and tame problems, this paper conducts a study on a design and engineering mega-project to induce the shortcomings of traditional project management applied to complex design problems. This study develops a cognitive map of how a requirement propagates through the entire scope of an ill-structured design problem and contends that the traditional design management techniques do not capture the ill-structure of the design sufficiently. The paper finally develops a list of theoretical propositions and an accompanying set of practical recommendations that are based on the notion that design should be managed on the basis of distinguishing between wicked and tame parts of the problem. The study contributes to design management literature with an early normative framework for managing complex construction design.

Keywords: construction design, requirements management, systems thinking, uncertainty, sensemaking.

INTRODUCTION

During the last two decades, the Architecture, Engineering, and Construction (AEC) sector has witnessed the emergence of a number of management concepts with the sole aim of reducing the fragmentation for which the sector has traditionally been considered notorious. More specifically, the fragmentation within the industry comes not only at the traditional boundaries of architecture, engineering, and construction; it is also a matter of internal fragmentation within each of the disciplines (see, for instance, Latham 1994; Egan 1998). *Integrated project delivery* is a common methodological umbrella to cover different approaches if reducing this fragmentation to make the industry more efficient (AIA 2007). One of the most popular approaches of integrating project delivery is to use the design/build method where the contractor assumes responsibility for the entire scope of work starting with client's project requirements (e.g., Anumba and Evbuomwan 1997). The focus of this type of integration is, however, limited to constructability of the design and does not encompass integration within each of the included disciplines extensively enough. Furthermore, design/build contractors tend to be organizations specializing in construction because the total costs of construction significantly exceed those of design activities (see, for example, Eldin 1991). As a consequence, what is considered integrated at the design/build interface, as a rule, can be oftentimes considered relatively disintegrated within the boundaries of design and engineering.

The most common approach to designing complex systems is by using systems engineering reasoning, where the total system is subdivided into hierarchies of subsystems (NASA 1995). The main assumption of systems engineering is that by managing the parts, one is also managing the whole. Indeed, the only way to manage a project of any scope is by using a subdivision-based reasoning and organizing the dependent units into separate tasks to be assigned to different project teams for execution. However, the resulting interdependency is a source of great complexity that needs to be addressed in the subsequent execution of the project. This complexity underlies every project decision in the form of uncertainty that accompanies project decisions. The essential problem is, therefore, to identify such interdependencies between parts of the design, which will enable the process to be organized as a set of independent tasks and tasks that need continuous process-level integration (see, for example, Thompson 2003).

This paper is an attempt of early inductive theorizing to present the interdependence and complexity in construction design. The main aim of the paper is to argue that organizational integration at the level of processes, not contracts, is the key characteristic of integrated delivery approaches. To accomplish its aim, the paper begins with a theoretical overview of design management concepts and techniques in the AEC context. After the theoretical overview, the paper continues with presenting a case study of an integrated engineering design from which it extracts a series of issues in the form of a cognitive map. From the case study findings, the paper finally induces a set of theoretical propositions and practical recommendations.

BACKGROUND THEORY

Designing a new product (or artifact) with an engineering content is normally defined as the activity of producing information about the system that embodies the functions necessary for fulfilling the set of requirements set forth by the client (e.g., Pahl et al. 1996; Cross and Knovel 2000). In the case of facility design, these requirements need to be mutually negotiated between the stakeholders and the project coalition (Winch 2010). This significantly complicates the design decision-making process as interests of the client, the stakeholders, and the project coalition diverge. Additionally, the elicitation of requirements for the designed system is a tremendously challenging task because the requirements are often changing through time. For all these reasons, the process of facility design is *ill-structured*.

The dichotomy between the *ill-structured* or *wicked* problems in contrast to *well-structured* or *tame* problems was first introduced by Rittel and Webber (1973) who argued that design problems are impossible to define and therefore no optimization in the traditional mathematical sense is possible for such problems. Some of the most obvious differences between tame and wicked problems are that the former are describable and determinate, whilst the in the latter, problem definition incorporates solution and only indeterminate solutions can be achieved (see, for instance, Winch 2010)

Wickedness and ill-structure have, to date, remained considered the fundamental property of design. In a more recent discussion about the subject, Coyne (2005) corroborates evidence for the ill-structured nature of design and extends the debate by stating that:

“Wickedness is the norm. It is tame formulations of professional analysis that stand out as a deviation.”

In contrast with the theoretical discussions about design, most known techniques used in design are by and large deterministic in that they disregard the wickedness of the design problem. Some of the most famous of such methods in the AEC sector include the likes of: *Quality Function Deployment, Design Structure Matrix, and Process Models* (e.g., Austin et al. 2000; Ahmed et al. 2003; Tzortzopoulos et al. 2005). In Coyne’s terms, all of these methods are tame formulations of the wicked problem and, therefore, have a limited value.

To come up with more realistic representations of the wicked problem and to develop better methods for managing it, first the traditional positivist paradigm of “the rational man” needs to be replaced with an interpretive paradigm that acknowledges the subjective and relative nature of decision-making (Simon 1955). Following this cognitive concept, contemporary scholars in construction project management (Winch and Maytorena 2009) contend that decision making in such highly-uncertain conditions, as the ones that appear in design, can be classified more reliably as *sensemaking* under bounded rationality than as rational economizing as advocated by hierarchical breakdown structures from traditional project management literature. Sensemaking is the process of retrospectively assigning meaning to past events and thereby shaping the organizational context for present and future events (Weick et al. 2009).

Using the cognitive concept of sensemaking, we will argue, is a step forward towards describing the decision making process in complex problems of integrated construction design.

RESEARCH DESIGN

To learn more about interdependencies in the complex design project, we chose to conduct a retrospective study because the decisions that affected the project events can only be evaluated *ex post*. The traditional project setting for decision making relies on management procedures that only deal with identifiable contingencies, thus, they belong into the realm of tame problem solving and hard systems thinking. The project normally deals with uncertainty only through risk management procedures that are, again, limited in their predictive potential. We, therefore, chose to trace the processes resulting from decisions in a fast-paced and complex design-build railway engineering project. In a retrospective process-tracing setting, we hoped to encapsulate the uncertainty that would have not been possible to address with ongoing project events.

There are several additional reasons why we chose a large contractor-led design and build engineering project for analyzing interdependency in construction design. Firstly, most design and build projects are characterized with a relatively fast pace with a possibility of overlapping design with construction. Due to the pace of such projects, many design activities are planned in parallel rather than sequentially, which causes additional fragmentation and complexity of the design process. Secondly, because design and build contracts are undertaken relatively early and they are based only on the clients' requirements; there is an inherent uncertainty concerning the scope of the project. The deliverable dates, however, often do not change in such projects, which calls for a robust organization that is capable to adapt to sudden changes in scope and still deliver the job on time. Thirdly, the geometry and size of the constructed facility, along with the multidisciplinary contributions, accentuates the importance of design integration across numerous project interfaces. All these project properties highlight the need for tracing the interdependence in the design system to reduce consequences of uncertainty. Finally, since we wanted to make generalizations from this study at the project level, we chose a project that we believe makes a suitable unit of analysis for an exploratory study.

During a one-week stay in the project offices, the first author used extensively interviewed five representatives of the owner's project management and the contractor engineering organization using ethnographic techniques (Spradley 1979). For the purpose of this study, only accounts by the contractor's engineering organization were further analyzed, thus setting the level of analysis to the contractor's system sensemaking. The aim of the data collection by interviews was to uncover the managerial sensemaking process retrospectively, by having all the relevant data after the project had finished (Weick et al. 2009; Winch and Maytorena 2009). In contrast with the process maps as the result of the ongoing project, here our aim was to develop a cognitive map of the traced processes according to the managers' sensemaking and, finally, induce conclusions of theoretical validity from the single-case study (Eisenhardt 1989; Yin 2003).

Apart from fixing the interview framework to issues in the design management processes, the interviews were open-ended, allowing the subcategories of the topic to naturally emerge during the one-hour long interview interactions with each informant. This unstructured interview setting enabled us to better understand the scope of the complex inter-organizational arrangements in the supply chain and their influence on design. We triangulated the data obtained from the interviews with relevant internal project documentation (project reports, schedules, organizational diagrams, etc.) and with publicly available material from press coverage of this public-funded project. After having analyzed the data from open-ended ethnographic interviews and project documentation,

we then carried out two follow-up telephone interviews that were structured around several topics identified in the initial research session. The aim of the follow up interviews was to get more in-depth information about specific instances of design issues. Following the open ended and structured interview sessions, we tried to induce theory by tracing the processes of how the project design was unfolding in an attempt to establish causal relationships between the events and their consequences occurring in the project (George and Bennett 2005). We finally coded the structured follow-up interviews with all instances of unforeseen uncertainty cause by complex interdependence.

CASE CONTEXT

The case project involved extending a section of a rapid transit urban railway system and incorporating it into the suburban rail system of a congested European metropolitan area. The scope of works comprised partial extension of tracks, replacement of track and signaling equipment, construction of four new stations and refurbishment of five old stations. The project was particularly demanding in civil works as 3.5 km of track is on viaduct and another 3 km is in tunnel. Besides the construction of a new section, the complete section needed to be upgraded to meet the national mainline standards. The design and construction were completed in two and a half years and the schedule itself consisted of roughly 16000 design and construction activities.

The public agency project owner undertook the contract under a contractor-led design and build scheme. The main reason for choosing this delivery method was that the project owner expected a single point of responsibility to better integrate the design, construction, and operation stages of the project. An additional reason for choosing a fast track delivery approach was the political significance of the completion date (public opening). Therefore, owner-perceived advantages of a fast-track delivery method were the integration and collaboration between project contributors. The core project organization included the public agency owner and the contractor. Because the owner organization did not have substantial experience in railway construction, they appointed a project management organization to manage the project on their behalf. Concurrently, the contractor's organization mobilized an engineering department for the project with the aim of coordinating design and construction. The project also had three major external stakeholders, being representatives of the urban and the suburban rail systems as well as the operating company. The former two had the role of ensuring that the newly built section complied with the existing standards of both networks and the latter had the role to ensure that the delivered facility complied with their train operating procedures.

The design scope was organized in disciplinary *work packages* and geographic *design areas*. The disciplinary work packages comprised civil design, structures, buildings and services, mechanical and electrical systems in buildings, and design of accompanying rail systems (Fig 1). Each work package was further broken down into *design areas* defined as “geographical groups of neighboring work packages or a logical system comprising a number of subsystem work packages”. Because of its fragmentation, the project developed an *Interface Management Plan* to identify and manage issues that would occur between work packages, design areas and organizations in the design supply chain. As the design evolved, the identified project interfaces were planned to be translated into requirements for each of the design contributors.

The flow of the design was planned as a two stage process: conceptual design and detailed design for the owner’s construction approval. The project further fragmented the design process along those stages because the project management organization was supposed to produce the conceptual design work packages and design areas for the contractor’s design team. The transfer of knowledge and assumptions made in the conceptual design stage would be transferred to the contractor’s engineering organization before the detailed design production. During the detailed design production the lead designer and the contractor’s engineering organization needed to ensure coordination via interdisciplinary design review meetings as the principal method of design integration.

The contractor had a web-based collaboration system in place to manage the requirements across different project levels. The high-level requirements would emerge from any of the project stakeholders, the contract, or other obligations with respect to technical standards and legislation. The contractor would then translate those high-level requirements into system-level requirements with such attributes as object type, work package, design area, and contract (see Fig 1). This structure should have ensured traceability of the requirements between the design team level and the project owner.

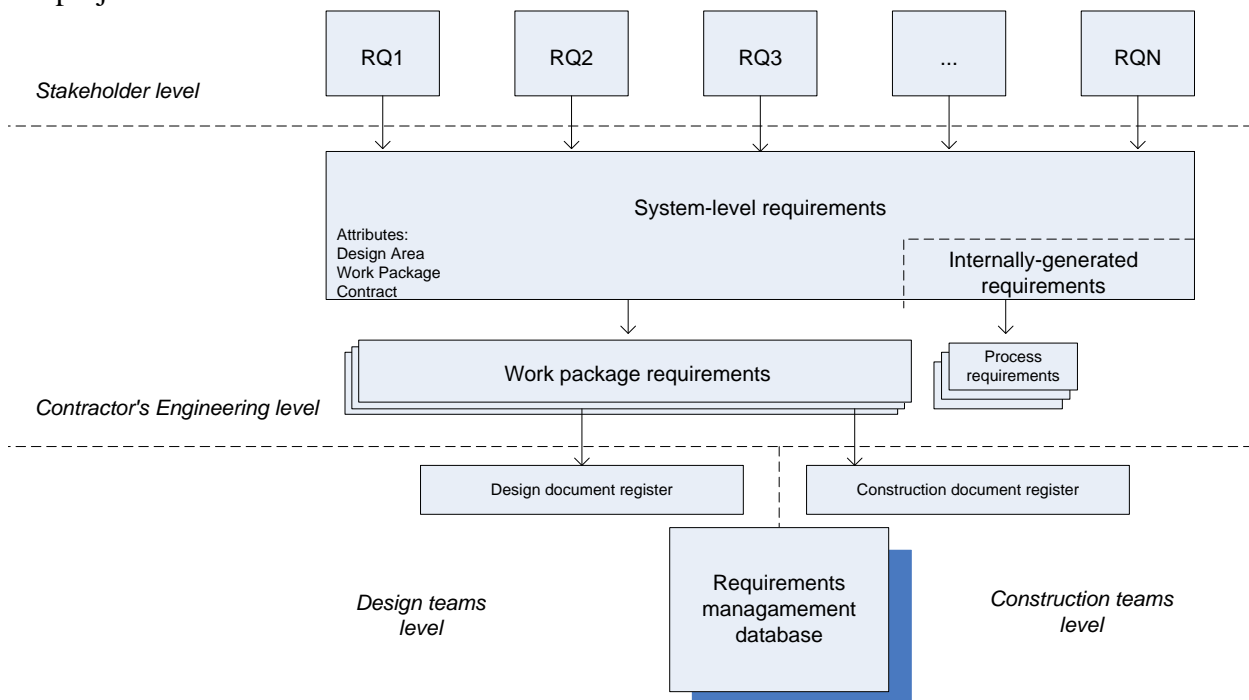


Figure 1: Hierarchical structure of the requirements management system

DISCUSSION OF THE FINDINGS

In reconstructing the design management story from the perspective of the contractor’s engineering organization, we immediately noticed the complexity that resulted from interdependence between the design tasks. This complexity was not included in the project management procedures that only described the hierarchical decomposition of project structure. Therefore, at the outset of the project, the design process was structured in an overly simplified way that did not predict well the implications of changes on the entire design process. We

continue with a more detailed description of how the above introduced seemingly small project requirements played out a significant role in the project. Figure 2 below depicts the traced process of a situation, in which a seemingly simple requirement amplifies and propagates through the project due to complex interdependence and sensitive dependence on initial conditions in a wicked problem-solving context.

The traced process begins with two requirements simultaneously being introduced by the client and internally within the project team. The client's requirement was that design team provides a possibility for subsequent installation of an external escalator in one of the stations. The passive provision for an external escalator, however, required that additional power be supplied to the stations and, in turn, the entire section. More power meant that thicker cables had to be arranged for its supply. Thicker cables meant a higher volt-drop and, consequently, further increased the demand for power in an interdependent loop that caused a substantial amount of the power systems to be redesigned for this sole purpose. Redesigning the power systems caused a requirement for additional space to accommodate the newly designed systems. This space, however, was not available neither in the station that had already been designed by that time (and, in other instances, also built), nor in the form of land along the tracks. Therefore, additional land had to be acquired to run the cables along the section, and the buildings had to be redesigned with the new space requirements. It caused another iteration loop in the building design that led to subsequent design integration problems due to geographically-distributed organization of the design process that was the main designer's choice.

Roughly at the same time, a second requirement emerged that needed to be implemented. It related to fire-safety as a consequence of implementing the fire-safety regulation into the design. The implementation of this requirement, in turn, caused an even greater demand for power and, consequently, more land to be acquired to run the additional cables along the tracks. When combined, the total amount of power that was now required for the section became so large that not even the local power supplier was capable of supplying it. Therefore, it wasn't until very late into the design process that the design team and the project owner decided that implementing one of the requirements is not possible and that it had to be relinquished.

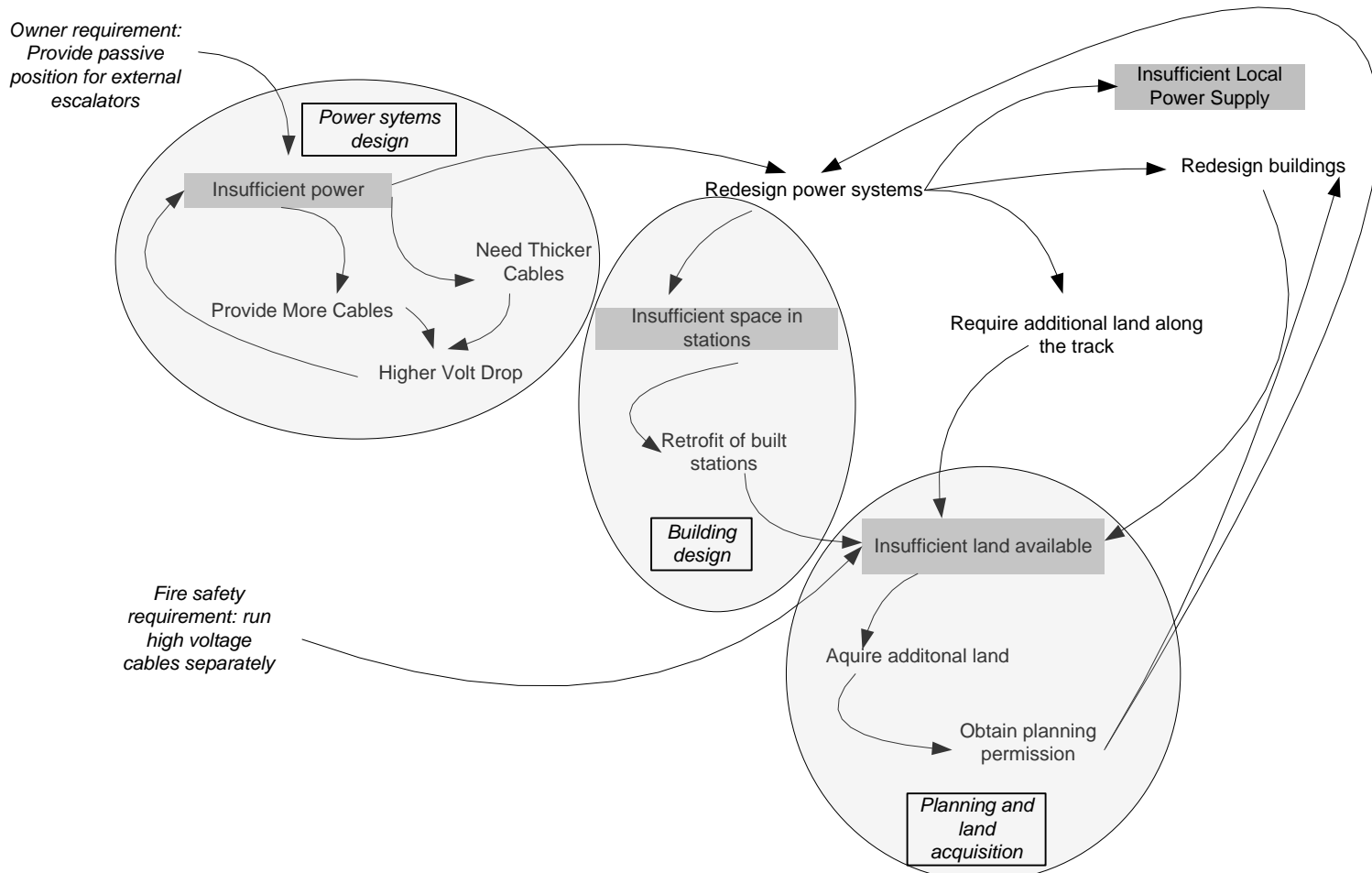


Figure 2: The process-tracing map of sensemaking in complex interdependence of infrastructure design.

This example demonstrates that requirements, however insignificant they may have seemed at the time when their implementation was decided upon, cause significant consequences for the project. In the case of insufficient local power supply, these difficulties were insurmountable and resulted with rejection of the requirement. The subdivision of the project linked requirements to discrete and abstract entities such as work packages, design areas, and contracts. In practice, however, parts of the system have not proven to be manageable in discrete pieces. Instead, they acted as an interconnected system of events that needs to be analyzed in the cause-effect context.

Having such a project representation would have facilitated managers' understanding of intricate interdependencies between the tasks captured within the design subsystems. The cognitive process-tracing map shows three distinct design subsystems: power systems, buildings, and planning with land acquisition. Besides the overall design iteration loop, these design subsystems performed additional iteration loops within themselves. The subdivision logic that was employed in the project did not follow these loops. Suboptimal design decomposition exacerbated fragmentation of the overall design scope with the result of unforeseen delays and costs on the project resulting from rework and problems with design integration.

PROPOSITIONS AND RECCOMENDATIONS

Based on combination of the above introduced theory and the findings from the traced process in the case study, we induce several theoretical propositions. From them, we derive the corresponding practical recommendations for managing complex engineering projects.

Proposition I: A wicked problem is characterized by reciprocal interdependence between its constituent parts.

Although it may seem tautological, this theoretical proposition argues that wicked parts of the design are also ones that are reciprocally interdependent. Their main characteristic is that a change in any one part of the system will cause changes on all the other parts of the system. As originally argued by Thompson (2003), such tasks need to be managed by the process of mutual adjustment instead of by standards and plans.

Recommendation 1.1: Differentiate the wicked from the tame parts of the design process.

Before starting to organize the design process, design managers should try to analyze the design problem and divide it into a group of tasks that result in a concept solution and a group of tasks that result in a detailed elaboration of the design concept. The former will form the wicked group and the latter, the tame group of tasks. This will be the first step towards the decomposition and management process.

Recommendation 1.2: Define success and failure criteria for the wicked group of tasks.

Since solving a wicked problem is a cognitive process of socially constructing project information, the key issue is to negotiate the goals of the project and metrics of success. Aligning the stakeholders' interests into a congruent set of project criteria will help lead the design process and reduce organizational friction between members of the project coalition.

Recommendation 1.3: Include buffer time in the project schedule.

Based on the level of complexity of the project, rework is likely to occur. Due to reciprocal interdependency in engineering design, deterministic planning is not likely to yield accurate forecasts. Including a substantial buffer time in schedules will help initially address the emergent complexity of the wicked tasks.

Recommendation 1.4: Be prepared to reiterate the entire process when new requirements arise.

Due to reciprocal interdependencies that are characteristic for design, there is high possibility of iteration to implement a requirement into the overall design. Given that any design problem is by definition wicked, taming it is only possible with limited results. Depending on how well the internal design interdependencies are assumed, managers can try to predict the impact of a requirement on the project. In certain cases, iterative loops of rework can become so frequent that project teams need significant mutual trust to avoid the failure of the project due to what Weick (1993) calls the collapse of sensemaking. In such instances, subcontracting or geographically distributing work across different offices is not advisable.

Proposition II: The better the organizational design follows the combination of tame and wicked tasks within the overall design scope, the lower the resulting fragmentation of the process.

Recommendation 2.1: Develop work breakdown structures based on the level of interdependence between the packages.

Although it is the basis of every project management system, work breakdown structures based on simple hierarchies of dependency are not sufficient to subdivide a complex design problem. Such problems should be subdivided based on interdependencies between the systems that often go beyond the classical space-discipline logic and also include relations with, for instance, external stakeholders or the overall need for communication between members of design teams.

Recommendation 2.2: Only subcontract tame tasks.

When decomposing the overall scope, it is important to create such design modules that are relatively independent of each other so that the amount of communication between the modules is reduced. The most obvious way of weakening the interdependence between the modules is overdesigning to account for possible future changes. Therefore, only tasks that are identified as tame are appropriate for subcontracting to third parties.

Recommendation 2.3: Wicked tasks should be integrated at the process level.

Although the advantages of contractually-integrated project approaches clearly exist, such approaches do not guarantee integration at the design process level. In fact, when contractors take responsibility for the entire project delivery, there is a realistic possibility of introducing an additional level of subcontracting that can be difficult to integrate into the project. Therefore, a design task that is identified as wicked should be executed by a collocated and socially-coherent

design team. Although team collocation is not the sufficient condition for efficient team performance, the authors' experience indicates that mutual adaptation, which is necessary for executing reciprocally interdependent wicked tasks, is most likely to occur in a collocated social context.

CONCLUSIONS

This study presented an early stage of inductive theorizing about the design complexity. This theorizing developed a cognitive map based on making sense of how requirements impact the overall design. This cognitive map of sensemaking indicates that reciprocal interdependency causes a requirement to amplify and propagate within the boundaries of the integrated project, thus making the problem wicked and ill-structured. The study further developed a list of theoretical propositions coupled with practical recommendations that managers should use to reduce the unforeseen uncertainty on their future projects. These recommendations advocate the need to distinguish tame from wicked parts in the design scope and accommodate the decomposition and integration strategies to the corresponding characteristics of interdependency.

The results of this study contribute to theory on several levels. The sensemaking example of design complexity, we believe, unifies two prevalent high-level approaches of construction project management: the objectivist school of systems engineering (see, for instance, Walker 2007) and the cognitive view of information processing (see, for instance, Winch 2010). More specifically, we believe that the results of this study also contribute to the toolbox of integrated project delivery (AIA 2007) and concurrent engineering (Anumba and Evbuomwan 1997) with a normative set of recommendations that can be used for organizing the integrated delivery process. Finally, we believe that the results of this study complement the standard construction design management toolbox (e.g., Austin et al. 2000; Kagioglou et al. 2000; Ahmed et al. 2003) with a view on the ill-structured problems than can complement the existing methods.

We are aware of several limitations of this study that future studies should address. Namely, generalizations drawn from a single-case study are not at the level of a particular population, but at the level of replicating causal relationships for the given sensemaking context. Gaining insight at the level of particular project characteristics would require a larger sample and a different approach. Methodologically, a continuation of this study should extend this descriptive and qualitative theorizing into further normative and predictive models. We are also aware of the need to extend the normative decision making framework based on its applicability to different procurement routes and organization structures in the construction design field. Moreover, this paper advocates neither the integrated design-build nor the traditional design-bid-build contractual arrangements. It solely attempts to offer a way of thinking in ill-structured problem solving that can occur in either of the contractual approaches. Integration, therefore, is a process-level, not contract-level concept. Finally, this paper does not attempt to give answers to aspects of the project that are beyond the decision-makers' comprehension (i.e. wicked aspects). It aims to bring about awareness of the existence of unforeseen problems and the need for their ad-hoc resolution. This is, we believe, the main practical idea from this study.

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