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BUILDING A RESILIENT AND INTEGRATED URBAN INFRASTRUCTURAL SYSTEM THROUGH A NEAR ZERO AGENDA

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ABSTRACT

Climate change is considered as one of grand challenges to the discipline of project management and engineering. Yet, our research community is slow in addressing it. Designing near zero energy districts is proposed as one of major solutions, which requires a systems design of integrated infrastructure systems at the level of urban district and calls for a new form of organizing. This paper attempts to address this challenge by proposing an approach that involves two parts: design strategy and design process. Design strategy is defined by re-conceptualizing infrastructure networks in the context of cities while design process is derived through unpacking design activities in related disciplines and drew on literature of design thinking. This model was then experimented in a large scale, collaborative research project that brought together two disciplines—urban design and engineering—to collectively design for a site of 2.7 km^2 in Shanghai. The paper discusses benefits and challenges facing the design strategy and multi-disciplinary design process and identifies opportunities of advancements.

KEYWORDS: Grand Challenges, Urban Infrastructure, Energy Performance, Urban Design

INTRODUCTION

Climate change is considered as one of major challenges to the discipline of project management and engineering and yet our research community is slow in addressing it (Taylor, Chinowsky, and Sakhrani, 2014; Ferraro, Etzion, and Gehman, 2015). Climate change has multifaceted, multi-level impacts on the built environment, which amounts to great challenge to our discipline in terms of managing the cumulative effects of issues beyond the level of a single project. Near zero energy design of districts or cities with low carbon emission is proposed as one of major solutions tackling climate change. It requires a systems design of integrated infrastructure systems at the level of urban district and managing energy performance of initiatives at the level of program or city. Therefore, it is fundamentally an organizational and managerial issue because it propels a large array of actors from distinct domains into collaboration (Ferraro, Etzion, & Gehman, 2015).

We attempt to address this issue by proposing an approach for designing integrated infrastructure systems for near zero energy districts. Our goal is to ensure that the approach addresses organizational and managerial challenges inherent in tackling complex, ill-defined design problems like near zero energy urban design. At the same time, the proposed approach needs to move beyond the theoretical level to serve the actual needs in practice by translating research findings into solutions (Tsui, 2013). Therefore, two components are essential: a design

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strategy that connects the performance of district physical and geographical forms and that of infrastructure systems, as well as a design process that organizes design activities of urban design and engineering design.

Design Strategy: Re-conceptualizing urban infrastructure systems

The approach conceptualizes infrastructure networks (e.g., power grids, water supply, and wastewater treatment) as constituent systems of cities, in which a city's resilience capacity is built (Novotny, Ahern, and Brown, 2010, ch. 3). Well-functioning infrastructure systems directly support the security, economy, health, and quality of people's daily lives. They must be planned, designed, delivered, and operated as a system integrated with other interdependent systems such as economic development initiatives and ecologic systems (ASCE, 2009). At the same time, exploring the synergies of multiple urban infrastructure systems through the lens of urban planning and design potentially maximize the improvement of energy performance.

There is also time dimension in near zero energy district design, which reflects the concept of resilience. To maintain long-term performance of low carbon emission of a district, the infrastructure systems need to be resilient, which entails two critical attributes: (1) reliability and efficiency and (2) adaptability and flexibility (McDaniels, Chang, Cole, Mikawoz, and Longstaff, 2008). The first attribute emphasizes the stability and predictability of functions and services provided by infrastructure systems even under extreme or unforeseen conditions. The second attribute is about continuous adaptation to conditions that unfold and evolve over the long lifecycle of an infrastructure system or a city (Albers and Hayes, 2003).

In other words, the design strategy of near zero urban infrastructure systems needs to take into account the interrelationship between infrastructure systems and their surrounding physical and social networks, which is often designed separately by engineers and urban designers. Obviously, conventional approaches of developing infrastructure systems over fragmented, uncertain, and stochastic processes are inadequate in building resilience capability (Pandit et al., 2015). Our design strategy needs to develop an understanding of critical interactions and interdependencies between infrastructure systems and how they are shaping and shaped by their surrounding urban compositions (ASCE, 2009; Novotny et al., 2010).

Design process: Organizing design activities in the domain of engineering and urban design

Engineering design decomposes complex systems with a paradigm of reductionism (Pandit et al., 2015), viewing complex systems as composed of layers of interacting sub-systems or components (Simon, 1962). Designing complex engineering systems thus involves the determination of sub-systems, their interdependent variables, and how these variables interact (Steward, 1981). Typical engineering design is deterministic design that aims to improve reliability and predictability. Deterministic design is analysis-based design process in which functional requirements are clearly identified, approaches of achieving the requirements are relatively well defined (e.g., power can be generated from hydropower, solar, or wind), and system modules and components (e.g., solar panels or wind turbines) are rigorously developed and tested. A loosely coupled system with a high level of modularity improves resilience because external impacts may be localized within sub-systems (Sanchez & Mahoney, 1996).

On the other hand, urban designers also see complex systems as hierarchical (e.g., neighborhood contains houses and house contains rooms) (Habraken,1987). However, the design problems they are tackling are ill-defined and value laden (Dorst, 2006). Design rules, building typologies, and constraints are inferred from concepts, policies, or observations of cities rather than derived from clearly defined by specified functional requirements or defined through scientific analysis and mathematical rules. Urban design emphasizes capacity instead of function. The capacity of “what we produce on one level to hold configurations on a lower level” expresses the function of a space, which is explored by trying out a variety of arrangements of objects appropriate for the intended use (Habraken, 1987: 13). Capacity deals directly with physical objects and thus can be studied and tested locally at different levels such as the capacity of an office floor to hold walls and furniture and the capacity of a neighborhood to hold households. In addition, urban design deals with spatial properties that emerge from societies and cultures, which encapsulate social artifacts connected through patterns of social life. Even when determining land uses and functions, urban designers draw from norms and regulations governing territorial structure and division between public and private space in a society. Apparently, although urban designers, similar to engineers, are also working with artifacts and geographic elements, the emergent properties they strive to achieve are significantly context dependent.

Drawing on theoretical concepts and empirical studies from literature of project management and design thinking (Alberts & Hayes, 2003; Arias, Eden, Fischer, Gorman, & Scharff, 2000; Brown, 2008; Levitt, 2011), a co-design process is developed to organize design activities of the two distinct disciplines. The process comprises three highly interdependent phases—Inspiration, Ideation, and Implementation—in which three critical coordination mechanisms are embedded: shared goals, collaborative principles, and sense-making tools (Yoo, Boland, & Lyytinen, 2006). Specifically, **inspiration** is a collective sense-making process (Arias, Eden, Fischer, Gorman, & Scharff, 2000) in which actors collectively identify and define problems that motivates project efforts. **Ideation** contains iterative cycles of generating concepts, frameworks, and scenarios of solutions followed by rapid prototyping, testing and refining. The process allows multiple ideas to be communicated, discussed, analyzed, tested, evaluated, which eventually results in an agreed solution (Nussbaum, 2004). Finally, **Implementation** integrates all required specialized knowledge to realize the selected solution and put the final product to use. But more importantly, design does not stop here (Brown, 2005). This phase links design to the feedback from actual performance of real-world projects, which instantiates continuous adaptation and improvement.

METHODOLOGY

Experimental Setting

The proposed approach was tested in an experimental project that aims to identify interconnectedness between integrated energy systems and their surrounding urban forms through the process of designing energy resilient urban systems at the scale of urban district. The experimental research project is named “Near Zero Energy District” (hereafter nZED). It is a collective effort of three laboratories with different research capabilities: Disney Research China (DRC) focusing on integrated urban infrastructure systems, Sino-U.S. Eco Urban Lab (EUL) of

Georgia Institute of Technology (GT) and Tongji University (Tongji) focusing on eco-urban design and planning, and Applied Energy Innovation Institute (AEii) focusing on advanced energy technologies and innovations. Due to the constraint of time and actual conditions of the project, only the first two phases were experimented.

The three laboratories initiated nZED in May 2015 and decided to develop a prototype of integrated urban energy system design through a transdisciplinary studio. In the studio, students and faculty members from the School of Architecture and Urban planning and the School of Civil and Environmental Engineering at GT in the U.S. and the College of Architecture and Urban Planning of Tongji in China, and research scientists of DRC collectively designed for a site of 2.7 km^2 in Shanghai. The site is a green field right next to Shanghai Disneyland, which allows us to use available data of site conditions to explore more possibilities of achieving near-zero energy goals without constraints of existing buildings and infrastructure systems. The process is illustrated in Figure 1.

Figure 1 Process of the experimental project nZED

Process

Inspiration: We organized four workshops discussing design process, goals, tools, research questions in the domains of urban design and engineering design, and four smaller group co-working sessions identifying specific, major design variables of the two disciplines. We developed a list of vocabularies based on confusion arising in discussion. For instance, both designers and engineers need to clarify and define their key vocabularies such as "system", "performance", "model" and "design"…etc. in the list. We discussed and documented the agreed goals, co-design process, common toolbox and research questions. However, the design interfaces of the disciplines, how these variables potentially interact, and how the common tools in individual discipline relate to each other remain unclear in lengthy discussions.

Ideation: We decided to elicit internalized, implicit knowledge from participants of different disciplines through collectively designing for an actual site of 2.7 km^2 in Shanghai. Shanghai local government supported this initiative, providing us site information and introducing us to one of the planners in charge of the site's planning who kindly answered our questions and led us to site visit.

The design was taking place through a course of international joint urban design studio at GT in Atlanta and Tongji in Shanghai. We added three components based on the design strategy and Ideation activities:

1. "Toy problem" was developed to explore and understand the effects of urban form design (Lynch & Rodwin, 1958). "Toy problem" is a simplified, well-defined problem through which the relationship between a limited number of variables (e.g., urban forms and energy-cost performance) can be explored and tested. This approach is common in the engineering field but rarely practiced in the urban design field.
2. Inputs and knowledge about energy and water engineering design were provided at early stage when students just began to design for the site. The energy engineering design component was provided by DRC and the water engineering component was provided by a group of six students and a faculty member from the School of Civil and Environmental Engineering School of GT.
3. Systematic iteration was added to observe how the relationship between variables identified in toy problems could help design evaluation and inform systematic design improvements. Design iteration aims to integrate knowledge and solutions from different perspectives/disciplines in order to innovate. It is a process commonly emphasized in design literature (Brown, 2008; Dym, Agogino, Eris, Frey, & Leifer, 2005; Gero & Kannengiesser, 2004; Habraken, 1987). However, in practice, it is often undifferentiated with design development and design changes. Systematic iteration is uncommon when designers face time and resource constraints in real world projects. Unfortunately, it is also uncommon in design courses where students only need to complete one design for satisfying course requirements.

Due to the different time of school terms between GT and Tongji, we had to give lectures separately to students at GT and students at Tongji. After that, students only had one week physically working together (week 11, see Figure 2). Figure 2 presents the specific process.

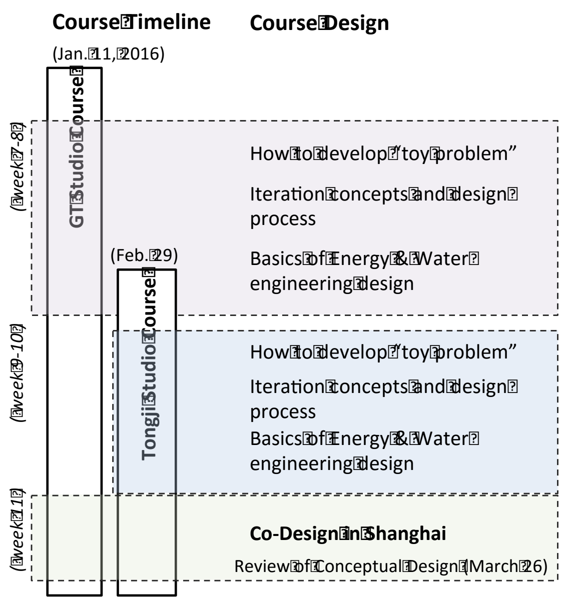

Figure 2 Studio process

Both authors participated and provided lectures to all students. The first author took note of events prepared and participated with DRC research team and discussed with the team after the events. These notes are main data of analysis for this study. Over the course of the experimental project, the first author repeatedly read the workshop and meeting notes, summarized what have known and what remained unknown in a living document, an execution plan, which was shared with research group for feedback and discussion. It helped develop experimental process and capture the evolution of design framework.

LEARNING FROM THE NZED MEETINGS AND STUDIO

Challenges of cross-disciplinary communication

The core members of the three labs quickly reached an agreement on the significance of the nZED research and the urgent need for an integrated design at the district level. We agreed that our goal of this research is to understand (1) how we design for a near zero energy district and (2) how to evaluate our design.

A discussion within the engineering group organized by DRC went very effectively. The approach reflected engineering design paradigm: modularization and measuring interdependencies.

1) Develop "Design Modules" of different systems (specifically, urban form, energy, water, eco-system/microclimate, and transportation)

   a) Make explicit (a) design inputs/outputs, (b) design variables/parameters (c) design steps/methodologies, and (d) design rules and constraints of each system design;

   b) Develop performance objectives, measurements, metrics used to evaluate technologies,

c) Develop a database of technologies, design components, cost models, maps of input-output for each system;

2) Define and test interfaces and relationships of different systems;

3) Develop methodology, principles, procedure of integrated design (roadmap that indicates interfaces among all different systems);

Figure 2 presents the note of this discussion and system diagrams generated based on the concepts and approach of modularization.

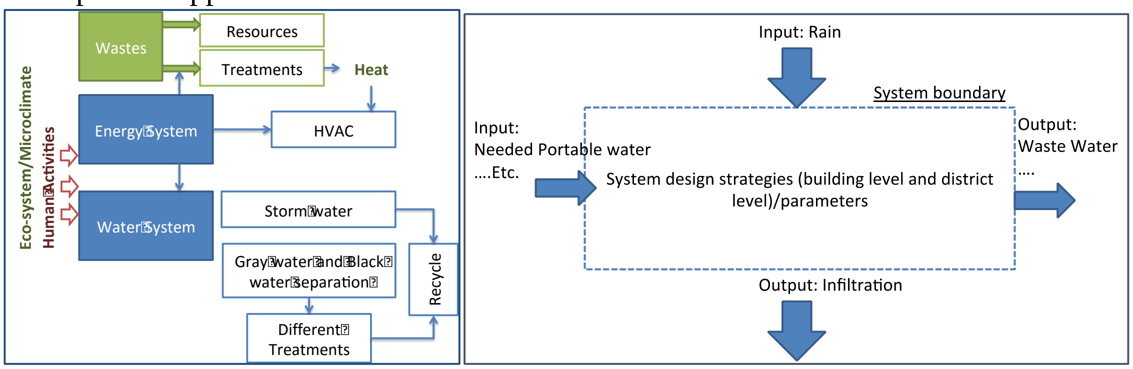

Figure 3 Diagrams of engineering system design

However, the discussion across distinct disciplines was challenging and required more time than expected, a situation termed as “shareability constraint” (Weick, 2004: 42). Both the urban design group and engineering group introduced their design processes and approaches through presentations and demonstration of computational modeling tools, but we could not fully understand each other.

The engineering group asked the urban design group (from meeting notes):

“What do you mean by modeling?”

“What are the major variables and constraints in your design?”

“What are the assumptions, input-output of your modeling tools?”

But the urban designers tended to think of design as a creative process and rarely thought of design in terms of variables, assumptions and constraints. The urban design group talked about spatial arrangements in terms of patterns, typologies, and forms instead of formula and equations like engineers normally do. Figure 3 presents graphs through which a member from the urban design group explained the key parameters of their design with spatial representations and approximate values of the parameters derived from on existing cities.

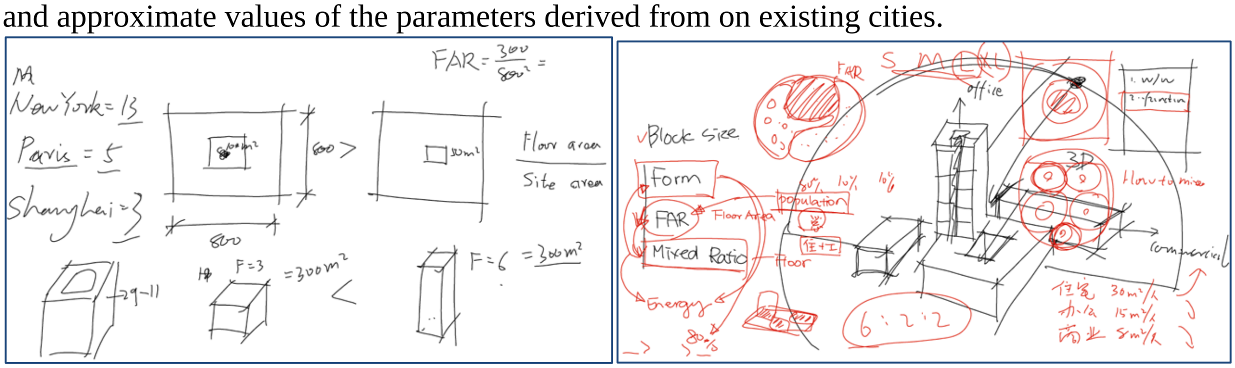

Figure 4 Discussion of key variables in urban design

A small breakthrough took place in January 2016 among a core group of researchers who have multi-disciplinary research and training background with a mixed combination of architecture, engineering, and urban design. This was an example of how cross-domain knowledge supported cross-disciplinary collaboration (Bruns, 2013).

They adopted the approach of multi-objective design optimization (MDO) (Best, Flager, & Lepech, 2015) in developing a toy problem. The toy problem was developed through about 5.5 hours of recursive exploration and discussions of objectives, measurements of objectives, variables/parameters, interdependencies, and design workflow/logics supported by examples of shared interests (low energy buildings and districts) and shared understanding (cities like Shanghai, New York, and Paris).

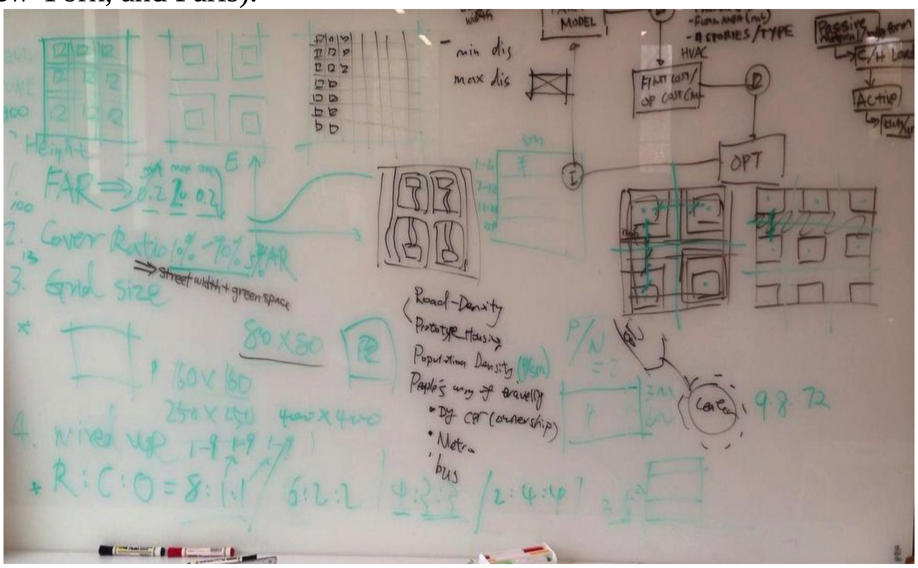

Figure 5 A toy problem developed collectively by researchers across disciplines

The core group taught each other their key domain concepts and design steps. Two researchers who were familiar with MDO helped translate the knowledge into MDO language. The group came to realize that there are two types of parameters in urban design: spatial parameters (e.g., building depth, cover ratio, window/wall ration etc.) and attribute parameters (e.g., building materials, energy technologies and MEP systems, etc.). Attribute parameters such as energy systems within buildings are often determined in modeling tools by selecting among built-in options, which are directly related to estimated demand of energy and water. For engineering system designers, these options have physical, functional, economical, environmental and spatial implications. The newly gained knowledge directs us to explore more attribute parameters in urban form design that we can unpack through energy-saving design with advanced technologies, materials, or approaches such as passive systems. Both DRC and EUL thus developed their design frameworks. The first framework illustrates identified opportunities for integration, while the second one provides a performance-based, urban design, computational model for a procedure of phases from Preliminary (data presentation), Pre-processing (baseline performance before design), Design, Post-processing (performance after design) to impact assessment (evaluation of "better" design).

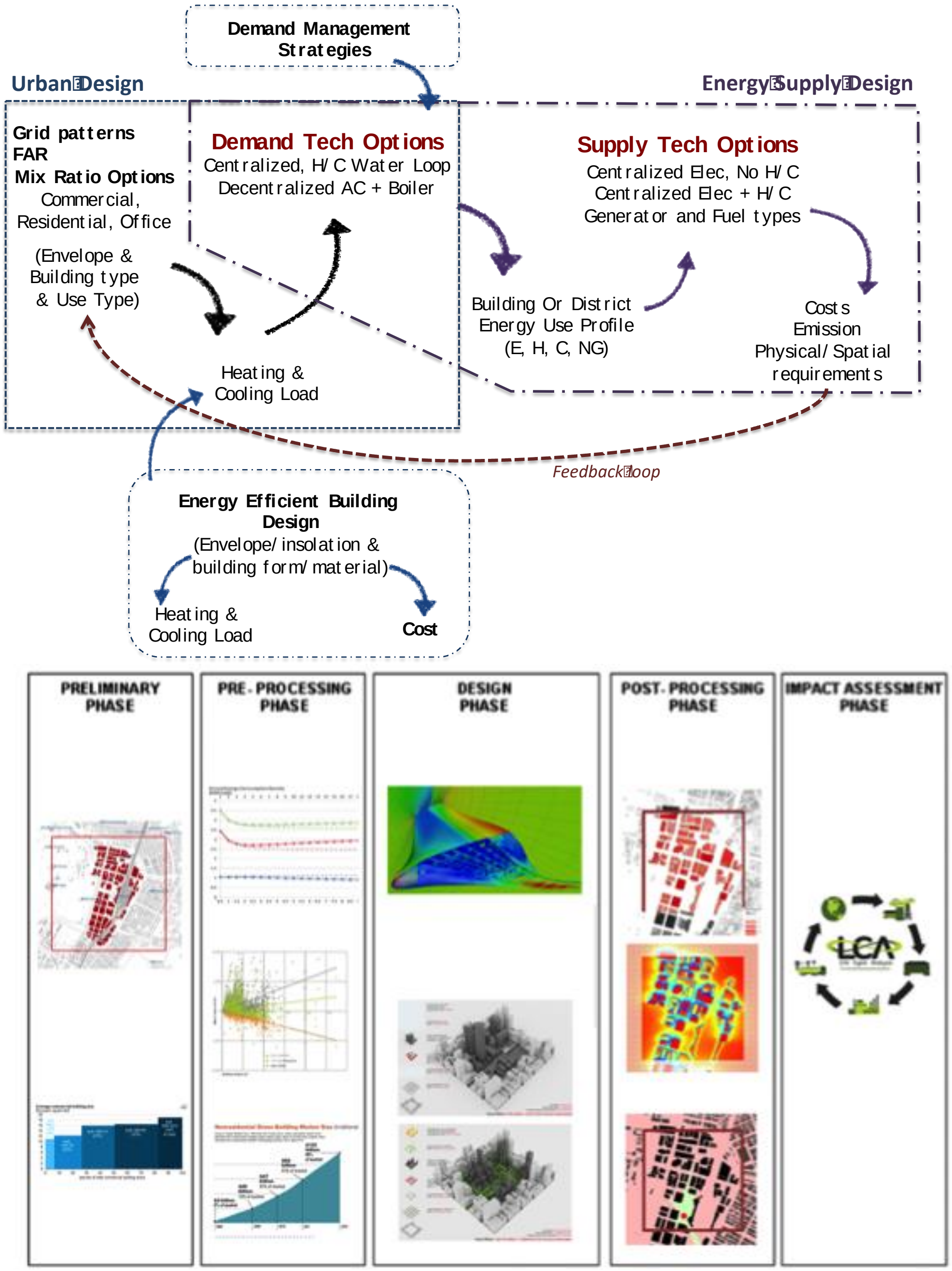

Figure 6 The evolving framework of integrated design for nZED by DRC and Urban design computational model by EUL (revised from Manfren, Caputo, & Costa, 2011).

Challenges of multi-disciplinary design process

Challenge 1: how to link design values, performance, and toy-problem components?

Urban design group adopted an engineering design approach, testing relationships between urban morphology and energy performance and solar energy potential, mixed land use and energy consumption, etc. However, in the face of real site information, it was unclear how to initiate the design with the knowledge they gained from toy problems and how the toy problem components played a role in a design. For engineers who are used to have clear design logics and principles, testing design components is part of the design. However, when urban designers began to define their design issues against site contexts with value statements like livable, attractive, and healthy districts, and social economic goals like employments and capacity for residents, the logics and principles generated from the toy problem components became disconnected. Obviously, these energy performance based design principles could not help define the properties of desirable and livable districts. This leads to the challenge 2.

Challenge 2: what are desirable as a district in this location? Design for future or design based on existing models?

Even faculty members from GT had different ideas about how to do urban design: What generates design alternatives? Should the district design layout be developed based on other urban form models that existed elsewhere, e.g. urban grids based on current Shanghai city or other well-known examples such as Savannah or Manhattan, or is it possible to generate the district urban form design from the principles derived from toy problems? The urban design group learned about the site context from the survey map, zoning, government requirements, and came up with problem definitions of all kinds. Although near zero energy was a clear design objective, but it was far from enough to characterize a district and capture possible and desirable futures. The actual urban design process was quickly turned to interpretations of situation and scenario-generation.

Challenge 3: falling back to conventional design paradigms:

The engineering groups did not participate in the discussion regarding the features and properties of the future city district, including how people will experience the place, what kinds of populations will be accommodated and attracted by this district. They only asked for population so that they could estimate water and energy demands for their design. But the urban design group needed to complete the design to come up with an estimated population. For the engineering groups, they could assume a number for population and began their design process with a set of clearly defined variables and system components such as available technologies and functions. They did not see the necessity of developing future scenarios for this site together with urban designers. They did their design separately and with their conventional approaches. The segregation in their conceptual design could be seen in Figure 7.

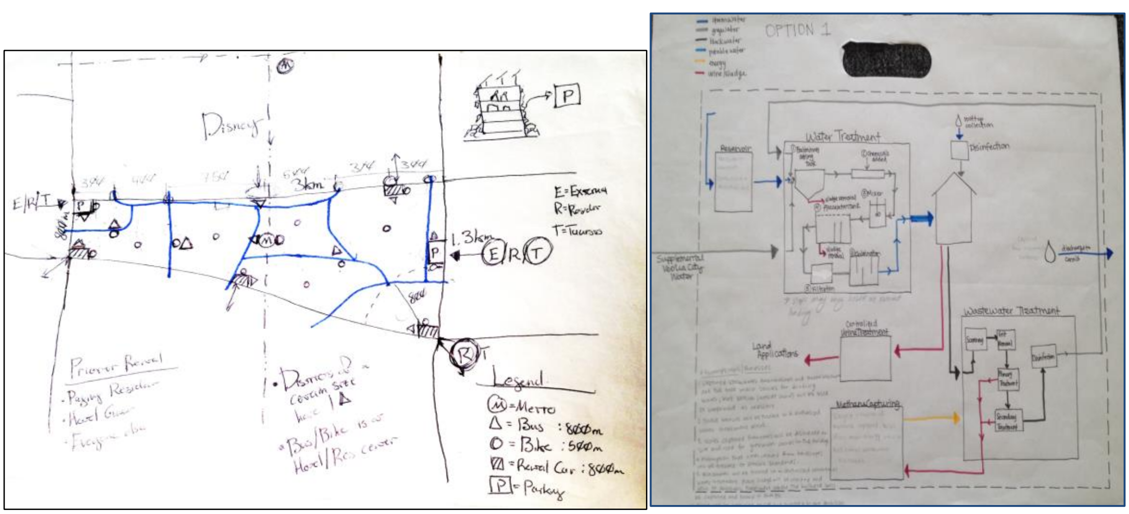

Figure 7 Representations of design of urban design group and water engineering design group during the conceptual design.

Challenge 4: Difficulties of iteration and identifying feedback loop in the classroom setting:

Normally, urban design studio would produce two to three alternative design scenarios and compare them against predetermined dimensions. Often, the limitation of time and course requirements only allows students to produce one round of design as the maximum.

When DRC researchers introduced the process of iteration (as defined in our design process component), it was novel to both instructors and students from GT and Tongji of the studio. Iteration process in the studio aimed to connect urban design and engineering design through the feedback loops identified in the course of collaborative design. The fact that the urban design group and engineering group worked away from each other did not necessarily affect iteration. Each discipline needed time working on their design, which requires a high degree of specialized expertise and knowledge (Bruns, 2013). However, if the time of collaboration and coordination was minimized to the degree that the two groups were not aware of each other's design parameters and considerations, they would be unable to identify connections between their designs, not to mention providing feedback.

Limited time of the studio was obvious one of critical constraints. Students needed to acquire specialized knowledge in their own domain and learn about design before they could start their own design. They did not even spend sufficient time for the readings of their own domain and the survey of the actual site (only spent about one hour on the site). It was very difficult for them to spend additional time learning about design from other disciplines. In addition, students just tried to complete one design by the end of the joint studio. There was no collaboration among student groups of different disciplines after they came up with the concept design.

DISCUSSION AND CONCLUSION

This paper documents the experiment of a proposed approach for designing near zero energy districts through the research project "nZED". The proposed approach is derived from existing literature and the experiment reveals critical elements required for tackling challenges like climate change. The experiment generates insights that are critical to the translation of research findings into solutions for grand challenges.

Although there exists different understandings in vocabularies, concepts, tools, models, research questions, and key assumptions of design between the discipline of urban design and engineering, we have recognized opportunities to bring together people from both academic and industries in these disciplines through common challenges embodied by an experimental project. At this stage, after multiple discussions and the experiment of design studio, we have gained new knowledge that informs next step.

First, the experiment brought us attention to the intertwined relationship of domain knowledge and design process in tackling complex challenges. Process design at the implementation level needs to be informed by domain knowledge and practices in order for collaboration and integration to happen. At the same time, generating new knowledge from cross-disciplinary interactions requires a deliberate and well-facilitated process in place.

In our experiment we began with a design strategy that informed us potential linkages between urban infrastructure systems and urban forms and a design process informed us how to foster collaborative design. Both of the two components are necessary for giving participants a sense of direction and motivating their commitment to a lengthy solution-searching process. More importantly, both of the design strategy and design process are far from a plan to be implemented. Once we began to talk across disciplines and clarify definitions of our terminologies, we found that none of us had a clear picture of how to move from hypothesized “potential linkages” to real collaborative design. The design practices and common tools of our two disciplines are very different. And we needed new knowledge to inform us next steps.

This leads to our second important finding: the knowledge was generated through experimentation, boundary spanner (Williams, 2002), and collaboration effort. Initially, our conversations did not produce any insights or synergies with techniques of workshops and brainstorming sessions. Collaboration did not naturally occur when a group of experts who agreed with the goal and meaning of the research project sat together. Our breakthrough happened when a small group of core members adopted the approach of “toy problem” as experimentation in which they intensively discussed how each discipline designed. At the same time, they used the approach of MDO as a way of establishing a common language where knowledge from different disciplines can be translated, communicated and then integrated.

The collaboration efforts are worthy special attention. The core group members put great efforts to collaborate. They all had an appreciation of the interdependencies between urban forms and infrastructure systems, as well as learning experiences in relevant knowledge domains. They asked different questions and answered questions patiently in order to understand design logics and practices in different domains and then proposed potential solutions according to their newly gained understanding. They were boundary spanners (Williams, 2002) who collaborated. As Bruns (2013) observed, collaboration should be clearly differentiated from coordination in the context of innovation. Collaboration leads to the generation of new knowledge and change of practices but coordination does not. In our experiment, it was apparent that, discussions or brainstorming techniques promoted knowledge sharing but did not lead to collaboration. Eventually, the core group members, not all participants, were able to uncover assumptions embedded in design practices in urban design and engineering, and consciously made design decisions taking into account social-economic contexts, or, attend to “critical reflexiveness that acknowledges the constitutive nature of their activities” (Orlikowski, 2004: 92).

Third, design knowledge and practices comprise multiple intertwined dimensions. It includes knowledge of design procedures, behaviors, thinking logics, and design components including their physical objects, attributes and constraints as well as how to evaluate the design outcome (Dym et al., 2005; Gero & Kannengiesser, 2004). We have learned from the studio that knowledge as well as computational skills needed is likely to be distributed among multiple experts rather than one or two experts. This endeavor needs to be a larger scale cross-disciplinary collaboration. Most challenging part of the collaboration is that we need to preserve different specialized expertise and logics in the integrated solution. For instance, the design subject of the project was near zero energy district, which was a familiar goal for engineering design and urban design students tried to learn about energy performance. At some point we found that urban design still needs to consider critical attributes like quality of life, livability, connectivity, resilience, in order to produce a desirable design, which engineering students rarely thought about. How to preserve differences in the integrated solution will be an area of our next exploration.

In sum, the approach proposed in the study provides a useful starting point to initiate multi-disciplinary collaboration for tackling complex challenges. However, it is through the small-scale experiments and the effective exchange of domain knowledge, important knowledge gaps are uncovered and the feasible and promising next steps unfold. As Ferraro, Etzion, and Gehman (2015) suggest, grand challenges are complex, uncertain, and evaluative and therefore, three strategies—participatory architecture, multifocal inscription, and distributed experimentation are critical in tackling these challenges.

The inextricable relationship between domain knowledge and process deserves research community's attention. Global trends including growing population, environmental degradation and climate change are expected to drive significant shift of demand and consumption patterns, and wide applications of new technologies such as pervasive computing and electrical cars, which, in turn, further shape our ways of living, working, and communicating. Engineers need to change their design paradigm, considering how engineering systems contribute to the properties of a desirable and livable future city (Graedel & Allenby, 2010), exploring the synergistic effects of infrastructure systems taking into account their social-economic environments (Pandit et al., 2015).

We thus argue that a new integrated design paradigm, a situated design perspective (Gero & Kannengiesser, 2004), should allow a iterative interpretation of a changing world to lead design exploration rather than merely search of design options. In other words, engineers need to interpret and define problems in light of the future cities they want to create together with urban designers and architects. Currently, engineering research and organization research are conducted by different groups of researchers. To explore practical organizational and managerial solutions for tackling grand challenges, collaboration between research communities are urgently needed.

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