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Preface

The aim of this last volume of the CIB World Building Congress (WBC), 2016 *Intelligent built environment for life*, is to explore the various needs of modern construction and offer new ways and techniques to address them. In recent years, stakeholder expectations have led to political, social and economic pressure on the construction industry. Modern buildings are expected to be innovative, sustainable, resilient to hazards and other risks as well as being easy to manage. In addition, clients expect to be part of the decision process to ensure their needs are met and often tied to legal bonds with professionals, a situation that can generate conflicts.

More than 200 authors have contributed to the 98 papers included in this volume. The vast majority of this research work is led by academics (70 papers) who discuss problems from a theoretical background and suggest solutions; whilst the remaining is led by industry researchers (28 papers) who provide an insight on real life through case studies. The present research work is led by researchers in 28 countries representing east and west, north and south of the globe. We hope that product and service enhancement will result from our sharing of information and collective experience.

Papers were classified into seven areas, including:

- Procurement, finance and conflicts (10 papers);
- Stakeholder involvement and satisfaction (12 papers);
- Innovative design and construction (17 papers);
- Risk mitigation, resilience and health and safety (13 papers);
- Sustainable construction (15 papers);
- Building information modelling (BIM) (16 papers); and
- Facilities management (15 papers).

Many lessons could be learned from each area and each research paper. However, one of the key lessons to be learned from this body of international research outputs is the need to better integrate design, construction and post-occupancy management in a construction lifecycle specifically with advancement of technology and availability of BIM tools. The second key lesson is the increasing acknowledgment of resilience and sustainability as a major part of modern construction.

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Application of the Domain Theory to Warehouse Concept Development: A Case Study

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Abstract

The need to manage and coordinate design has been recognized in different industries, including construction. However, teams need to have a shared language, which requires a design framework or in other words ontology, providing a terminology, principles and methods. Systems thinking approaches have been used in variety of design ontologies, here we have focused on the Domain Theory (DT). The purpose of this work is to understand how a common design framework aids the design inquiry and management. For that the DT is outlined, its implications to construction are reviewed and a case study as a main method is carried out to illustrate the effectiveness of this design theory for practice. The DT provided the common framework for studying end users, their needs and requirements based on their business operations. Also, the DT supported the design team in understanding the purpose of verification and validation. Results indicate that the common theory reinforced focusing on key parameters, issues and design requirements. However, outcomes also illustrate that system approaches tend to be resource intensive, requiring a more thorough analysis up-front.

Keywords: Domain Theory, design domains, technical activities, organs, structure

1. Introduction

The need to manage and coordinate design has been recognized for some time in industrial product (artefact) development (Farr, 1966), mechanical engineering (Andreasen, 1980), architecture (Emmitt, 2010) and also in engineering design for construction (Ballard and Koskela, 1998). The main reason for these developments is the division/disintegration of master builder into dedicated disciplines as the body of engineering design knowledge and expectations to efficacy have rapidly increased throughout the last three centuries (Kranakis, 1997, Reed, 2009). This has increased the complexity of construction projects and thus, the need for more thorough cooperation, coordination and management of engineering design processes thorough effective communication (Kleinsmann, 2006).

For the latter, design teams need a common language, such as a Domain Theory (DT) (Andreasen et al., 2014). Andreasen (2011) defined 'domains' as a set of dedicated views onto a product:

activities, organs and parts. These are used as the skeleton of a procedure for the product development/design. Domains consist of entities; e.g. the activity domain is determined by the user's application of the product, which together with the user experience and usability, to satisfy the initially unsatisfied need. Thus, the DT is an ontology, a common modelling framework, providing the viewpoints and vocabulary to represent the knowledge needed in product development.

An explicit and common modelling language allows transforming mental models into explicit models that can be shared among designers (Erden et al., 2008). Defining the domains, entities and the types of relationships can serve the purpose of developing a theoretical and conceptual model for engineering design coordination and management. Moreover, a consistent ontology supports the development of computing technologies and helps avoiding mistakes due to the neglect of some domains (Gielingh, 1990).

The aim of this research is to understand how formal design framework aids the design inquiry and management. More particularly, here we review the Domain Theory and its implications into practice (Andreasen et al., 2014, Howard and Andreasen, 2013). In the first part of this paper, a theoretical framework of DT is outlined; in the second part, the implications to construction industry are summarized; and finally, a case study, informed by the DT, is compiled to illustrate the importance of design theories.

2. Methods

The purpose of this study is to understand the implications of a common design framework (Domain Theory) to design practice. Thus, this research aims to answer to the following questions: How does the common design framework aid the conceptualization of design solution from users' perspective? What implications does the framework have on design team and process? For that a qualitative case study method is used to acquire context-dependent knowledge (Fellows and Liu, 2009). The lead author of this article participated in the development of new warehouse concept for small and medium sized businesses dealing with wholesale, retails sales, services or combination of these. This work focuses on the early stages of design and processes for developing a new concept for warehousing.

3. Engineering Design Terms and Frameworks

Across industries, several design researchers have tried to propose a unified definition for engineering design. Here, we start with the definition proposed by Evbuomwan et al. (1996):

> "The process of establishing requirements based on human needs, transforming them into performance specification and functions, which are then mapped and converted (subject to constraints) into design solutions (using creativity, scientific principles and technical knowledge) that can be economically manufactured and produced."

This definition succinctly illustrates the subject and the content of engineering design and three aspects are clearly visible. First, designers work on a variety of aspects during design process:

needs (voice of the customer), performance requirements (required, expected and actual behavior), functional descriptions, structural descriptions, and production/manufacturing processes. Secondly, engineering design can be viewed as a process, using different modes of reasoning, including regressive vs. deductive (backward and forward), decomposition vs. composition (breaking down and putting together) and transformation (transferring problems between abstract and particular) (Koskela et al., 2014). Thirdly, design is between thought and object (Bucciarelli, 2002), aligning three aspects of facilities, including user needs and requirements, design solutions and production processes.

3.1 Domain Theory

Several engineering design frameworks have been developed based on the systems thinking approach, such as the DT by Andreasen et al. (2014). DT consists of several models and concepts for understanding and researching design practices. The basic domains in DT include: technical activity, organ and part (structure). Andreasen et al. (2015) define the technical activity as the user's application of the product (use functions) for fulfilling the unsatisfied need. A use function is an activity of the user to utilize the product for performing certain action. Chen et al. (2015) define a need as a subjective desire of a person to change a problematic conceptual environment into a desirable one. The organ domain is the set of functions, the means of a product, displaying a mode of action (realization of function) and its behavior (properties). Part domain consists of components as an elementary material system, making-up an organ, realizing the organ's mode of action by the part's physical states and interactions. Thus, an artefact is defined by its structure, describing the anatomy of components, properties and relationships.

Properties of the systems and components are divided into two categories, describing the product structural characteristics (form, material, dimensions and surfaces) and behavior (derived from structural characteristics) (Andreasen et al., 2014). Characteristics are a class of properties of an object that define the means by which the object's behavioral properties are realized (Albers and Wintergerst, 2014). The behavior reveals when product is deployed by the user(s) in its context for use purpose and processes. In engineering design literature, behavior is characterized by successive states, including manifestations and value of the properties of the system in response to its environment and the received stimuli (Albers and Wintergerst, 2014).

When a product is deployed it contributes to the transformation of operands such as material, energy, information and/or biological objects. The properties of use functions in relation to the operands are described by their input and output states; the necessary effects from the operators, their nature, their state and how they lead into contact with the operands; and the active environment (Andreasen et al., 2014). The organs are based upon physical, chemical or biological phenomena. When stimuli act on the organ in its context, it delivers an effect. In other words, organs are also called *wirk* functions (Hubka and Eder, 1996, Albers and Wintergerst, 2014), which is a statement about what the product does when in operation (Howard and Andreasen, 2013).

Also the structure and its components are active and interact with each other through their assembly interfaces (Howard and Andreasen, 2013). Components are related to the *wirk* functions, which are based on natural (physical, chemical and biological) phenomena. A part interfaces with other parts and its surroundings, creating the effects of the part. Therefore, the DT defines the domains, its entities and relationships to describe the practice of engineering design.

Andreasen et al. (2015) have also described the engineering design process as a progression throughout the domains in DT. They define the engineering design process as a causal chain: user need > use activity result > determination of use activity > determination of the product's effects and functions > determination of organs and organ structure > determination of parts and part structure. However, in practice, design is not a linear process from needs to structure, it is rather a top-down and bottom-up approach simultaneously (March, 1984), meaning that problem and solution are coevolving throughout the design process.

3.2 Summary of the Domain Theory

The DT, initially developed based on the Hubka's Theory of Technical Systems, distinguishes between use functions (e.g. write text) and *wirk* functions (e.g. deposition of graphite onto the paper by means of pressure and friction) (Howard and Andreasen, 2013). This shows that designers do not only designate a product's behavior or mode of action but also the use activity of the end user. Secondly, the DT differentiates two types of properties, static structural characteristics as means for realizing the objectives and behavior (state variables) corresponding to the stimuli and changes in the environment. Thirdly, design is a process, moving from the need to the description of a structure (part domain) for delivering the expected effects (behaviors). Thus, design is a modelling process for establishing the network of connections between entities in different domains through the expected behaviors to be actualized.

4. Conceptualization of an Engineering Design Framework for Construction

Essentially, buildings are designed to facilitate users' personal or business operations. Space as the functional unit facilitates the satisfaction of user needs. In this work we consider the activity, organ and part domains of DT as a common denominator for design processes and disciplines. In following sections, the content of these domains are discussed in detail.

4.1 Activity Domain: Deployment of Facilities for Value Creation

As in the theory of domains (Andreasen et al., 2015) or proposed by Pennanen (2004), the first domain to be considered is the user process domain. This is an activity-based approach for decomposing client processes (personal or business) into user activities/sub-activities and their properties that realize the client's goals and thus are value-adding. For example, in office building the activity 'meetings' can have these properties: type of an meeting, types of participants, number of participants and usage of equipment (projectors, tables, chairs etc.). Currently, this tends to be considered only informally in the design process (Pikas et al., 2015). Thus, in the activity domain, use functions are defined as interaction with the artefact.

4.2 Organ Domain: Space as a Functional Unit

The user activities, their nature and resource requirements become the basis for defining the environment and its facility centric functional organs to be decomposed into sub-functions. This is typically articulated in the project brief, including information about the area (unit of area per room/person), dimensions (e.g. ceiling height), indoor climate (e.g. temperature, air exchange type and volume, air movement speed, cooling, heating and control of indoor climate), acoustics, lighting, electricity, water supply, sewage and use of equipment. It describes the facility consisting of functional spaces and its sub-functions, some required as resource for activity and others determined by the design decisions (Pennanen et al., 2005).

However, the articulation of spaces in the project brief is a complex activity, where form and use function of the building play the main role in determining how spaces should function, laid out and utilized. Required spaces affect many different aspects of the building, including its form, layout, utilization and spatial planning (Mayouf et al., 2014). Moreover, in a building program, expected behaviors of functions and structures are determined (e.g. air exchange rate). Thus, the completed building program, even though still subject to changes in later stages, is the basis for engineering design process. Koga (2010) defined functional decomposition as value engineering in Integrated Project Delivery, or in other words functional analysis.

4.3 Part Domain: Linking Functional Requirements to Structural Description

Design theoreticians have considered this as the kernel of the design process (Andreasen et al., 2015, Suh, 1998, Kroes, 2002). In schematic design, architect analyses the user needs and translates these into functional requirements (spaces and its sub-functions) and expected behaviors (temperature level to be maintained) as a basis for design conceptualization, and syntheses of the form based on selected technologies and materials required for meeting the client needs. The form defines the internal and external spaces, a composition plan for the totality and the details (relationships), social and economic issues, and a framework for human interactions (Andreasen et al., 2014). According to Hubka and Eder (1996), form can be interpreted and modelled as geometry. Other main structural characteristics include the materials, technologies and dimensions, determined to meet the expected behaviors of the structure. The outcome is the design concept describing the system architecture and its division (structure, HVAC, MEP etc.). Each system consists of a number of components designated during the embodiment of functions and expected behaviors, and its configurations and connections (Ullman, 2009). Particularly, it is the selection of components and their physical characteristics that determine the actual behavior of a system and the best fit with the requirements of the project brief. For example, the architect can link a ventilation unit to the requirement of minimum air exchange rate in a space.

5. Case Study for Illustrating the Implications of Domain Theory

In this section, a case study is compiled to illustrate the importance of domains and their entities; particularly, how the design ontology informs the design process. One of the largest Estonian companies, in the field of logistics parks and warehousing services, is looking for new opportunities for expanding their business services. Until now they have focused on large logistics parks, but they are planning to start providing warehousing services to small and medium sized vendors, service providers and trade companies. They were interested in developing a new warehouse concept that can be detailed for a specific parcel. In this sense, it can be compared to product development in industrial engineering. In the following, a short summary of the results and key findings are given.

5.1 Design Development Process

Largely, the design development process was divided into three steps: I observation of existing solutions and user needs; II design conceptualization; and III product concept development. In the first step all similar existing facilities were mapped in and around Tallinn, Estonia, and ten existing facilities were selected by the project team for closer study. Then the team, including client representatives, the architect, the design project manager and the lead author of this article, paid a visit to these ten facilities during a period of two and a half days. The result of this was 20 page report, summarizing the problems, existing solutions, main users, use activities and user needs/requirements. In the second stage, the report developed in the first stage, became the basis for conceptualizing the product and articulating the design task. The team avoided compiling heavy documentation, instead through several iterations a two page design concept paper was compiled as a basis for schematic design. The third step, product concept development took place over many weeks in an iterative manner. The architect proposed concepts, which were discussed within the project team. The final outcome was the concept for modular and flexible combined warehouse, office and service spaces.

5.2 Observation of Existing Solutions and User Needs – Activity Domain

As a part of a activity domain, ten sites were visited and users were questioned regarding solutions and their satisfaction. The following are the main observations:

- **Complex nature of the client:** All observed companies were importing goods and depending on the type of a product, these companies were either doing wholesale, retail and/or provided product related services (e.g. a tire shop), determining which kind of functional spaces were needed. Overall the following target client categories were identified: wholesale, retail sales, product related services or combination of these.
- **Typical spatial layout:**
    - Average space area per company was 317 m^2, including either storage, office and show rooms or combination of these. However, the distribution of spatial area

varied remarkably, and excluding one very small company from the sample, the average area increased to 568 m^2.
    - There was no correlation between the number of people working in the company and storage and/or show room area.
    - The average office area per person was 14 m^2. However, most of the tenants indicated that it was too much and more storage space was required. It was concluded that around 10m^2 of space per person in the office would be around the optimal solution.
    - Show rooms must be flexible and situated on the first floor, meaning companies who want can use it as a show room and others as an office space or service space.
- **Limitations of building form, layout and solutions:**
    - Offices spaces were designed throughout the whole building depth on different floors. The problem was that companies who had storage spaces on both sides of office spaces had difficulty moving goods between these two, they had to either transport the goods through office space or from outside. The latter is a problem in winter.
    - Several solutions had storage space through three floors, resulting in heights around 9-10 m. For workers responsible for storing goods this was a bad solution as it complicated the process of stowing goods.
    - Poor layout of office spaces as people working in these indicated that they did not have space for resting, eating or meetings.
    - Thresholds between show rooms and storage spaces hindered transporting goods.
    - The shelves were too long hindering the entrance and exiting through the transportation doors.
    - Also, several companies indicated that the transportation doors for transporting goods in and out from storage space were disproportional, either too high or wide.
    - Lights and ventilation ducts were crisscrossed with roof trusses.
- **Technical solutions:**
    - Observed buildings were made of precast concrete or steel structures, including sandwich panels, steel or concrete structural frames.
    - For heating and cooling mainly electricity based systems were used, e.g. air to air heat pumps.
    - Five buildings out of ten had skylights either in office or storage sections as the storage buildings can be relatively deep.

5.3 Design Conceptualization – Organ Domain

The observations within activity domain became the basis for articulating the goal and requirements. The main goal was to develop: “Modular, flexible, spatially optimal, cost and energy efficient combined production, service, storage and office building for small and medium sized wholesale, retail or service companies.” Table 1 defines the value structure for the project, defining the category, expected performance and constraints.

Table 1. Summary of concept categories and expected performance.

Nr	Category	Expected Performance
Suitability		
1	Modular spaces	Space range per module: 200-600 m^2
2	Flexible storage and show room spaces for expansion	Movable internal walls and flexible building services
3	Effective form, spatial layout and stowing of goods	• Office spaces shall be along the front exterior wall of building • Storage spaces shall have optimal paths for the movement of equipment and transportation of goods • Office spaces must have small kitchenette and toilet on first and second floors • The width of the corridor shall be designed based on maneuvering radius of forklifts with lifting capacity of ≤ 1.5 tons. Expected width between shelves ≥ 3.2 m • For the maximization of storage spaces the optimal spacing of shelves shall have two or three corridors • Office space ≅ 10 m^2 per person • Size of the transportation doors: ≥ 2.8m height and ≥3 m width • Clean height of storage space under trusses: 6m (clean height for stowing is 4.5 m)
Aesthetics		
5	Comfortable working conditions	Well-lit working spaces and aesthetical materials
Sustainability		
6	Energy efficient	Cost effective energy efficiency solutions: minimum requirement is B-class (consider renewable energy)
7	Indoor climate control	Users have possibility to control indoor climate, heating, cooling, ventilation and lighting
Durability		
8	Optimized structures and details	Cost optimized solutions of structures and details
9	Optimal maintenance costs	Highly enduring materials and maximum lifespan (50 years for structures)
Construction Cost		
10	Construction cost	≤ 400 €/m^2 (target cost)

The overall preferred layout for the business activities is that goods are transported from behind and clients enter from front. The functional decomposition depends on the business function or main activities, which here were divided into four categories: **wholesale**, **retail sales**, **product related services** or **combination of these.** These categories became the basis for spatial decomposition as follows:

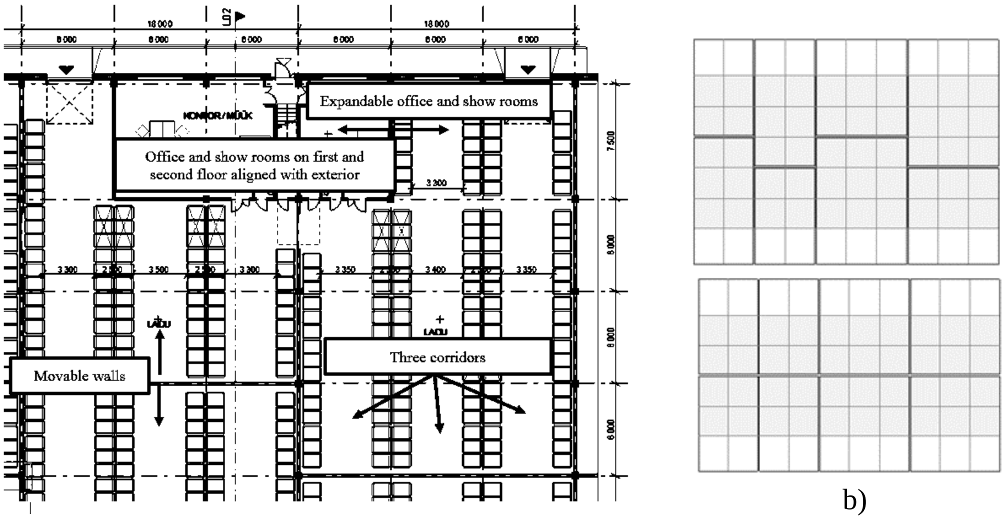
- **Office spaces**: must be aesthetical, comfortable, functional and well lit. Companies want to provide good working conditions to workers. The office spaces must have good layout, providing enough workspaces, kitchenette and toilet. Typically, companies with total space around 400 – 600 m^2 also need small meeting room.
- **Show rooms**: Not all companies need this type of space, those who need have varying requirements in terms of size. Thus, first floor offices spaces must be flexible, either be used as a show room, reception space for clients or as an office space.
- **Service areas**: Companies, who need service spaces, must have rooms two floors high. Some companies who provide services also provide shower and dressing room for workers.
- **Storage spaces:** In general goods can be divided into two groups: small and large by size. Thus, larger goods are moved with forklifts and smaller ones by hand. Companies need enough space between shelves to manoeuver with forklifts. Regarding the indoor climate, few companies had products that required controlled indoor temperature and humidity levels.

5.4 Product Concept Development – Part Domain

In this stage, architect prepared the first draft based on the selected concept, linking functional requirements to physical characteristics. The overall concept was a modular warehouse for different user needs. Modules were defined as rectangles in varying sizes, which were combined in different ways to form a whole building. However, the whole size of the building will depend on a specific site, zoning requirements and design requirements by the local government. The driving concept for the architect was “organized chaos”. A model was prepared in Graphisoft ArchiCAD to facilitate the conversation between the architect and the client. The starting point for the architect was the storage space with two or three corridors between shelves and with the size of the columns, initially 300 x 350 mm.

The second aspect that the architect had in mind was modularity, the proposed main module being 6 m x 6 m. However, the first module, including office spaces and show rooms, was 7.5m deep. The architect also had to consider the other constraints, such as transportation door width and height. For example, based on the size of transportation doors, the first floor windows were chosen to be of the same size. During this iterative process several layouts were proposed and in each iteration, the architect focused on a specific aspect. After a few iterations, the structural, HVAC and electrical engineers were involved, performing the basic calculations to verify the architect’s assumptions and proposed conceptual solutions for different systems. For example, the columns were changed to 400 x 400 mm due to the fire safety considerations.

The biggest challenge was to find appropriate solutions for flexible spaces, which was considered as an important innovation and a primary goal of the project. As shown in Figure 1, the end walls of each section are movable. The same is with the office and show rooms, however, these can be expanded only to right and left in respect to the front and back of building. Flexibility was required considering how to build lighting systems and building services in the way that these would accommodate the changes in the layout of the building. Therefore, the meters for measuring the energy consumption were designed to be placed to the beginning of every rentable section of the facility. Lighting systems were connected through outlets, in case of moving walls the connections can be moved as well from one outlet to the other. For same reason of flexibility, the floors for second floor were planned to be built of standardized prefabricated wooden frame panels and the interior walls of sandwich panels that can be easily assembled or disassembled.



b)

a)

Figure 1. Combined storage, office, service and show rooms building: a) flexibility of spaces enabled by movable walls; and b) two examples of modules and composition.

At the end of the product development stage, one Estonian contractor was involved to validate the solutions from the perspective of buildability, and to make an early cost estimation. The model was used for quantity take-off and making buildability assessments. The target cost was set to 400 €/m^2, the contractor estimated 413 €/m^2. However, the team also figured that cost can be reduced by more detailed design and elaboration of technical solutions.

Furthermore, the client used the produced concept to validate the business model on the market. They used layouts and BIM based renderings to compile a fictive advertisement. Altogether, project got around 20 views on the website and three persons called and asked for more details. Although the interest could be considered low, it was also understood that organizations who are looking for new spaces are interested in facilities, which are already existing. The client confirmed the proposed product concept, and now the first project has been initiated.

6. Discussion

The case study, guided by the application of the DT, indicated the importance of a common design framework as a means for effective communication. Case study clearly indicates the content of the different stages: I stage as a part of activity domain was focused on observing existing solutions and user needs; II stage as a part of organ domain was for design conceptualization; and III stage as a part domain focused on the materialization of product concept. All involved parties agreed on the usefulness of common domains, entities and relationships. Furthermore, a clear articulation of project value structure, in terms of targets and constraints, facilitated the iterative design process. However, as the design team was busy with understanding the DT, the focus was not on design management, thus, causing the concept development to take three months more than was initially planned. Thus, this can also be considered as the main limitation of this research. In the future projects, design management aspects must be considered, including the implementation of Last Planner System and/or Scrum (from Agile Management) to plan, execute and control the design process by defining the information flows through pull mechanism. The other reason why this is particularly important is that currently the architect still tended to make many assumptions, instead of involving downstream engineers immediately to concept development. Thus, in the near future, the plan is to implement the cell layout for project design team, to facilitate real time communication and reduce the response time for request for information. The team also noticed that systematic approaches tend to be resource intensive, which currently is not a typical practice for the early stages of design. Thus, approaches such as Axiomatic Design theory, could be used to stage the design process by focusing on a key functional requirements and design parameters in each stage.

7. Conclusions

In this article, the DT and its implications for construction were studied through a case study. Answers for two questions were sought: How does the common design framework aid the conceptualization of a design solution from users' perspective? What implications does the framework have on design team and process? As for the first question, the DT provided the common language for the design team, a mental model for the design concept development. This means that the DT provided the common framework and reinforced focusing on key parameters, issues and design requirements. For the second question, the DT supported the design team in understanding the purpose of verification and validation. An example of verification was the involvement of structural and building services' engineers in the early stages of design, doing design review. However, the limitation of this case study was that the design focused solely on familiarizing with the DT, but not on the design management. The result was that the concept development took several months longer than was initially planned. Thus, in the future research, control methods must be implemented to maintain the schedule and avoid the architect's assumptions by using a pull mechanism.

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