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Competences beyond engineering: a mental model of conceptual building design

Wim Zeiler

ABSTRACT

The demand for more sustainable society leads to the necessity for reduction in quantity of materials and energy. As buildings require substantial amount of materials for construction and consume a substantial amount of energy while operational, there is a need to address and optimize both demands. The design of products like buildings has to change and lead to more sustainable solutions. Architecture has an important role to play in directing sustainable building development (Taleghani et al 2010). From the very point of conception of a sustainable building design project, it is important to bring in the specific knowledge and experience of different designers with engineering background (structural, building physics and building services consultants) as well as the architect. The increased complexity of building design inevitably calls for more design collaboration (Lee and Jeong 2012). Early collaboration of architects and engineers should provide for creation of new knowledge and solutions beyond specific scope of disciplines (Kovacic and Filzmoser 2014). New design tools and working methods are therefore needed which could help architects in the design process (Kanters et al 2012).

In order to support team design in the conceptual design phase, a design approach is proposed: Integral Design. Integral Design uses morphological charts, which are made by individual designers from different disciplines, and which are then transformed into a morphological overviews. The morphological overviews represents the interpretation of the
design brief and the connected relevant knowledge of the whole design team. Between 2001 – 2012, the approach was tested in a series of workshops in cooperation with the society of architects (BNA) and the society of consulting engineers (NLIngenieurs) in the Netherlands (Savanovic 2009, Quanjel 2013) with more than 250 experienced professionals participating. After the successful testing with professionals the design method was introduced at the university in the master program of the Faculty of Architecture in 2005 (Zeiler et al. 2009). This was further developed into workshops with students and professionals, where the effect of adding a professional to a students’ design team was also studied. It showed its effects on the number of solutions. The paper explains the theoretical framework, the experimental setting, the results and discusses the effects of using an expert within the learning process of building design. As such it illustrates the competences needed beyond engineering that are needed for conceptual building design.

METHODOLOGY

Sustainability is a crucial issue for our future and therefore the European Directive 2002/91/EC requires practitioners to provide buildings with design solutions that comply with minimum energy performance requirements, while safeguarding thermal comfort (Mazzeo et al 2008). Since the 2nd world war technology made fast progress, however not all development were a success and the necessity for improvement of design was felt. As a result people started to investigate new design methods as a way to improve the outcome of design processes (Cross 2007, Margolin 2010) which has lasted through the 1990s right up to date (Chai and Xiao 2012, Ranjan et al 2012, Gericke and Blessing 2012).

From Methodical Design towards Integral Design

In the Netherlands Methodical Design initiated by van den Kroonenberg (1974) is the most widely used design method within the mechanical engineering domain. It is a synthesis of the Anglo-American and German design schools with a strong relation to the general system theory. Using the analogy with Systems theory van den Kroonenberg (1974) thought of a design process as a chain of activities, which starts with an abstract problem and results in a solution. General systems theory was conceived by Ludwig von Bertalanffy (1951) in the 1940s to provide a systematic framework for describing general relationships in the natural and the human-made world. One approach to a supportive orderly framework is the structuring of a hierarchy of levels of complexity for basic elements in the various fields of inquiry. A hierarchy of levels can lead to a systematic approach to systems that has broad application and was formulated by Boulding (1956). Methodical Design is problem oriented method and distinguishes steps in the design process itself (Blessing 1994, Zeiler 2007). This individual oriented design method was extended into an integral design method for design teams by the intensified use of morphological charts to support design team activities in the conceptual design process (Zeiler and Savanovic 2009, Zeiler 2014). The morphological charts are formed as each designer translates the main goals of the design task into functions, which are than listed on the first vertical column of the morphological chart, see Fig. 1.

Figure 1. The two steps leading to the first column with functions/aspects to be fulfilled and sub-solutions of the morphological charts and the following two steps to make the individual morphological charts into a group’s morphological overview
After this first step, in the second step the (with the mentioned functions related) proposals can be listed on the corresponding rows. Each participant of a design team develops a morphological chart from their own specialist perspective to the design brief. These individual discipline-based morphological charts can be combined to one overall morphological overview in two steps. First, the design team discusses the different proposal for the functions in the first column of the morphological overview. In this discussion, everyone brings in the notated functions from their own individual morphological chart and possible misunderstandings can be cleared. Afterwards, the team will reach a shared understanding and interpretation of the design brief. In the next step, the design team can than add the different proposals in the rows connected to the specific functions. Based on the given design task, each design team member perceives reality due to his/her active perception, memory, knowledge and needs. The morphological charts represent the individual interpretation of reality, leading to active perception, stimulation of memory, activation of knowledge and defining of needs. Within the morphological overview these individual stimuli can be combined to those of the whole design team. As such the morphologic overview can be used by the designers to reflect on the results during the different design process stages. This illustrates how the design thinking in the team develops. The individual morphological charts of each individual designer represent their active perception, the active part of their memory, their individual knowledge as well as their interpretation of the design needs. As such everything becomes more transparent and that is one major goal to achieve. The effect of the applied Integral Design method using the morphological overview can be presented in analogy with the mental model of Badke-Schaub et al (2007) (Casakin and Badke-Schaub 2013a).

**Mental Models in Design Teams**

Researchers in several disciplines have applied the construct of mental models to understand how people perform tasks based on their knowledge, experience and expectation (Badke-Schaub et al 2007). The concept of mental models was first proposed by Craick (1943) in order to explain human behaviour coping within a complex world (Casakin and Badke-Schaub 2013c). Most research on team mental models focused on operating complex technical systems (Mohammed et al 2010) which activities mostly follow standard operations and procedures rather than design which involves inventive problem-solving. Badke-Schaub proposed a modified framework for design activities (Neuman et al 2006, Badke-Schaub et al 2007). Team Mental Models are not meant to only refer to multiple levels or sets of shared knowledge but also to a synergetic functional aggregation of the team’s mental functioning representing similarity, overlap and complementarity (Langan-Fox et al 2004). Designing typically takes part in an organizational context, with relations to clients and users and specific market situation. Thus, mental models in design teams include context knowledge that reflects on the given situation, see Fig. 2.

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**Figure 2. Mental models (Badke-Schaub et al 2007) & Figure 3. Design Team mental model Morphological Overview in analogy with the model by Badke-Schaub**

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The way team members perceive and understand reality can vary according to their background knowledge, expertise etc. which have effect on their mental models (Casakin and Badke-Schaub 2014). When team members interact with each other, they evolve and adapt their own mental models and construct a mental model shared by the team (Casakin and Badke-Schaub 2013c). Each team member has a different influence on the development of the sharedness of team mental models and can only be derived from the exchange of communication acts (Casakin and Badke-Schaub 2013b). Mental models are hypothetical constructs that normally cannot be directly measured (Neuman et al 2006) however, using the morphological charts and morphological overview as a tool of intervention from the integral design method enables to measure and to represent a mental model of the team. So by applying a design method it becomes possible to describe the design process in such a way that it could be used to illustrate the mental model of the design team in analogy with the model of Badke-Schaub (Badke-Schaub et al 2007). It shows how the mental model in teams develops. Based on the current situation, each design team member architect, structural engineer, building physics consultant and building services engineer perceives reality due to his/her active perception, memory, prior knowledge, skills, abilities and needs, see Fig. 4 and compare it with Fig. 3. Given that designers poses different knowledge, skills, expertise, and objectives, their approach to a design task varies significantly with respect to other team members. However, through exchanging views with each other, they develop gradually their own team’s representations and adapt them to build models shared by the team (Casakin and Badke-Schaub 2013a): the transformation from their individual morphological charts towards the morphological overview.

**EXPERIMENTS: THE WORKSHOPS**

After extensive experiments with different set ups for implementing the Integral Design approach, in which well over one hundred professionals participated (Savanovic 2009), it was concluded that a good way to test our design approach was a workshop setting for professionals. The above described approach was tested in a series of 5 workshops, these typically include around twenty participants and lasted for two or three days. A total of 108 designers participated in a four workshop series, in which 74% of the designers were present during all days. The average age of the participants, all members of either professional organisations BNA(architects) or NL Ingenieurs (engineering consultants) was 42 and they had on average 12 years of professional experience. This workshop model was implemented in the educational program of the Faculty of the Built Environment of the University of Technology Eindhoven and formed the basis for the master project Integral Design. In this project, students from at least 4 different disciplines (architects, structural engineers, building physics, building services and building technology) formed a design team and had to design a nearly Zero Energy Building within one semester. At the start of the project workshops were organized to teach the students the basic principle of Integral design as well as hands-on experience working with morphological charts and overviews. In the last 10 years, more than 300 students have participated in this specific master project. Each year the project is evaluated and adjustments made as needed. Also new additions or interventions in the workshops were tested. The students were split up in design teams of 4 students of different disciplines during the sessions and all students worked only once with the same students. This was to avoid a learning effect in teams as they otherwise start to know each other better. In all design settings the teams were given the same or similar design tasks as used in the research by Savanovic (2009). In session 1, 2 and 3 the participants started individually, working on the different design task and making their own morphological chart, see Fig. 7 in step 1 and step 2. At the end of the first part of each session the teams made from the morphological charts morphological overviews. The individual part of all the sessions took 20 minutes and communication between participants was discouraged when they had to make their individual morphological chart. The team parts lasted 40 minutes. The master students had an average age of 22 and no working experience. In addition, six professionals with an average of 50 years participated in session 3, one in each student team. This made it possible to observe and notice effects of the interventions: adding an experienced professional to a team of novice student designers.
**RESULTS**

The result of the session with teams of students with the participation of an experienced professional in session 3 is presented. The generated amount of functions and proposals are shown in Fig. 4.

Figure 4. The number of sub-solutions proposed in the morphological charts (MC) and morphological overview (MO) by students & professionals of the Master project integral design, compared with the results from the professionals research workshops (Savanovic 2009)

On average the student teams (2011-2015) produced in their morphological charts quite similar results compared to the professionals: slightly less functions (14.4% less: students 6.5 professionals 7.6) but slightly more sub-solutions (19% more: students 20.6 professionals 17.3) than the professional teams of the research by Savanovic (2009), see Fig. 4. The average number of sub-solutions was increased by using the morphological overview compared to the morphological charts from 20.6 to 31, an increase of 50%. The average number of mentioned functions in the morphological overview was increased from 7.6 in the morphological charts to 9.4, an increase of 23.6%. In Fig. 5 the theoretical model of the intervention in the design process is represented, as well as an example of the real MC's combined to one MO.

Figure 5. The model of the intervention and an example from a workshop (Zeiler 2013)
In the next step we looked at the effectiveness of the professionals and students in the design teams. We defined the effectiveness as the number of mentioned functions or proposals in the morphological chart of a professional, in relation to the number of functions or proposals that were notated in the morphological overview of the design team. So for example, of the 6 functions mentioned by the professional in his morphological chart, see Fig. 4, only 3 made it into the morphological overview. Of 15 mentioned proposals only 3 made it into the morphological overview, see number 1 in Fig.6. Based on these numbers the effectiveness of the professionals/students were defined in a percentage based on the number of functions/proposals mentioned by the professional/students divided by the total number of functions or proposals mentioned in the morphological overview, see Fig. 6.

Figure 6. Effectiveness of a professional and students

The professionals had a major influence on the selected functions in the morphological overview, as an average their function effectiveness was 92% higher than that of the students 0.48 compared to 0.25. In contrast, the influence of the professionals in the total amount of mentioned proposal was almost equal to that that of the students, an effectiveness of 0.36 compared to 0.34.

DISCUSSION AND CONCLUSION

How knowledge can be better coordinated, communicated and shared in teams that in many cases are heterogeneous and multi-disciplinary is a critical aspect that did not receive enough attention (Casakin and Badke-Schaub 2013c). In the past many design methodologies were developed at universities, however design methodologies find less or slow industrial applications (Birkhofer et al. 2005, Stolterman 2008, Tomiyama et al. 2009). Although student studies play an important role in design research, we in our research tried to develop a link between industrial and experimental contexts. The need for such an approach was identified by Cash et al. (2011), as it enables comparison between the behaviour of students with that of professionals when designing (Cash et al. 2012). Analyzing the different design teams a rather big spread in results, indicates that the results of a design team depends heavily on the specific combination of and interaction between the different design team members.

At the TU Eindhoven, an Integral Design method has been developed and tested in practice in cooperation with the Dutch society of Architects and society of consulting engineers and is applied at the department of architecture for the multidisciplinary Master project Integral Design. The educational setting allowed us to further investigate interventions in the design process of students. Such intervention tested to stimulate the creativity of design teams within the integral design process was the introduction of a professional to the student’s design teams during the workshop. Adding a professional to a student design team had a positive effect on the number of generated proposals and also on the amount of notated functions in the morphological overview. This indicates that the creativity of the student teams was increased by adding a professional. The morphological overview could be seen as a kind of mental model that designers construct.
representing their internal working models of the world. In this way we can explore this models and to look for new necessary competences.

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