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Integral design: the next step after Integrated design between engineering and architecture

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Abstract: In the present day design is understood as a highly complex process that requires the support of multidisciplinary design teams. Therefore a supportive design approach has been developed: Integral Design. Integral Design combines an engineering design method with an innovation strategy, to support innovative integrated design between engineering and architecture. The innovative Concept-Knowledge theory by Hatchuel and Weil is used in combination with the Integral Design method. Morphological Overviews, which are produced by combining mono disciplinary Morphological Charts, provide a tool to structure and to give an overview of the communication and information exchange between design team members, while C-K theory supplies the theoretical framework for the reflection on the Integral Design. The resulting synthesis between architectural concept and engineering functionality is as such a good example of a next step after integrated design.

Key words: creative architectural management, integral design, C-K theory

1. INTRODUCTION

The design of buildings is complex and to avoid risks the building industry is traditional in their approach to the design process and innovation is rare. In modern history, design of buildings is largely seen as an individual’s creative act. This is certainly the case for the conceptual design phase, where the architect is traditionally the one that lays down the vision of the whole building. Moreover, “the belief that a single designer should be in control of all levels of environmental form” [Habraken 2005, p.89] was even seen as a professional ideal. As a result the built environment uses 40% of all our energy for conditioning the buildings. This results in a major contribution to the emissions that increase the effect of global warming. Building designs thus need to provide solutions for increasingly complex programs of requirements, especially related to sustainability issues ranging from flexible use to energy saving measures while maintaining and even increasing comfort level of users. Therefore building design involves many designers/experts from different disciplines.

Sustainability is a real-world problem and as such cannot be solved by any one discipline alone it requires multiple disciplines with a shared theoretical understanding and an agreed interpretation of knowledge according [Dykes et al 2009]. However, just putting people with diverse perspectives and from different disciplines in the same room is no guarantee that effective boundary-spanning collaboration will occur [Joyce et al 2010].

As complexity and scale of design processes of buildings increase, traditional approaches may no longer suffice [van Aken 2005]. Through the creation of knowledge based on diverse skills, experience and information exchange, the quality of design process and the creative performance of design teams improve [Badke-Schaub et al 2010]. Due to the cognitive diversity among team members
in terms of knowledge and skills there is a broader access to information and knowledge, creating more and different insights in to the current design task and its problem field [Badke-Schaub et al 2010].

Synergy between the different disciplines involved in the design process is necessary to attain the best innovative and sustainable designs. It no longer suffices to just merely solve the problems which arise at the level of detailing on the borderlines of disciplines. New approaches are needed to bridge the gap between the worlds of theory and practice in building industry and which looks at designing as a process in which the concepts of function, behavior and shape of artifacts play a central role [Vermaas & Dorst 2007]. Such integral design approach can eventually lead to an integral process, team and method – all the required conditions for innovation of the end product; the building [Seppänen et al 2007].

The main body of the paper starts (Section 2) with the development of the Integral Design (ID) method: a design method to merge the different perspective of all designers and engineers involved in the design process. The core of this method is the use of a process model to divide the design process in different phases and levels of abstraction. This makes it possible to focus on different design phases and to develop specific tools to support the process within such a phase. The tool used for the conceptual design phase is coming from the mechanical engineering domain: morphological charts. By combining morphological charts of each individual building design discipline, a morphological overview is created. This morphological overview represents the interpretation of the design task and the design knowledge within the design team related to the design task. As such this leads to a representation of the problem and solution space. The main aim of the ID-method approach is to improve conceptual design (the process level) in order to increase the potential for creation of innovative integral design concepts [the product level].

In section 3 the Concept-Knowledge (C-K) theory of Hatchuel and Weil is introduced to further enhance stimulation of innovative concepts. Further the relation between the morphological overviews and the C-K theory is explained to reach knowledge transfer and knowledge creation, both essential elements for innovation. To test the derived design method workshops for professionals in building design practice, architects and engineers, were held which are described in section 3. In section 4 the results are presented of the application of the ID-method within the workshops. A short reflection is given in section 5 on the developed ID-method use to stimulate innovation in building industry compared to another method, the KCP workshops. In section 6 a new set-up for Integral design workshops is presented which was tested in the 2011 Master project Integral Design with students and professionals. Finally in section 7 there is a discussion followed by some conclusions in section 8 about the added value of the presented approach for innovation and knowledge transfer/creation in the Dutch building industry

2. METHODOLOGY: INTEGRAL DESIGN METHOD

In the early sixties due to problems with the quality of products and projects people started to investigate new design methods as a way to improve the outcome of design processes. The origins of new design methods in the 1960s were based on the application of ‘scientific’ methods derived from operational research methods and management decision-making techniques in the 1950s [Cross 2007]. In the 1980s engineering design methodology of the systematic variety developed strongly and it was a period of substantial revival and consolidation of design research. Since then there was a period of expansion through the 1990s right up to day: design as a coherent discipline of study was definitely established in its own right [Cross 2007]. Still there is no clear picture [Horváth 2004, Bayazit 2004]

Methodical Design as developed by van den Kroonenberg [Blessing 1994] was chosen as a starting point, as it is based on Systems theory and a synthesis of the German and Anglo-American design models of the mid seventies [Zeiler and Savanovic 2009] and as such has exceptional characteristics [Blessing 1994]. Starting from the prescriptive model of Methodical design a method, Integral Design, was developed to articulate the relationship between the role of a designer as descriptor or observer within the design team and to reflect on the process [Savanovic 2009]. The Integral design method, though based on methodical design, is an extended design method; the cycle [define/analyze, generate/synthesize, evaluate/select, implement/shape] forms an integral part in the sequence of design activities that take place, see Fig. 1.

Figure 1. Four-step pattern of Integral Design

A distinguishing feature of Integral Design is the intensive use of morphological charts to support design activities in the design process. The morphological chart is formed by decomposing the main goal of the design task into functions and aspects, which are listed on the first vertical column of the chart, with related subsolutions listed on corresponding rows. The functions and aspects are derived from the program of demands. Possible solution principles for each function or aspect are then listed on the horizontal rows. The use of morphological charts within the integral design method supports step 1 and step 2 of the integral design method’s four step pattern, see Fig. 2. The morphological charts made by each individual designer can be combined into a [team] morphological overview, see Fig. 2, after discussion on and the selection of functions and aspects considered important for the specific design.

Figure 2. Building the morphological overview; Step 1; The Morphological overviews show the agreed functions and aspects of the different morphological charts. Step 2: The Morphological Overview with the agreed on sub solutions from the separate morphological charts.

The advantage of this approach is that the discussion begins after the preparation of the individual morphological charts. As each designer uses his own interpretation and representation, in relation with his specific discipline based knowledge and experience, this gives an overview of different
interpretations of the design brief resulting in a domain specific morphological chart from each design team member. Importantly, this encourages and allows engineering based disciplines to think and act in a more ‘designerly’ way than is common in the traditional design approach. In sum, this approach allows a greater freedom of mind of the individual designers and results in more creativity in interpretation of the design problem and generation of subsolutions from the different disciplines. Such a morphologic overview can be used by the designers to reflect on the results during the different design process stages.

2.1 Applying C-K theory to the conceptual Integral design phase

Design is process existing knowledge and information about the actual needs of the client forms the basis to work from. If solutions based on existing knowledge are not adequate, the needs have to be transformed into new unknown concepts. As such a distinction can be made between the known (knowledge) and the unknown (concepts). This distinction determines the core propositions of C-K theory [Hatchuel and Weil 2007]. C-K theory defines design as the interplay between two interdependent spaces having different structures and logics: the space of concepts C and the space of knowledge K. Within this research, in the case of a multidisciplinary building design team, space K represents all explicit representations of a design team’s knowledge [Hatchuel and Weil 2002]. From here, two types of synthesis are possible: either the representations are combined, using the $K \rightarrow K$ operator, or are transformed, using the $K \rightarrow C$ operator. Adding new properties ($K \rightarrow C$) to a concept, the set is partitioned into subsets, see par example C1 in Fig. 3; subtracting properties includes the set in a set that it contains [Shai et al 2009], see par example Co in Fig. 4. After partitioning or inclusion, concepts may still remain concepts ($C \rightarrow C$), or can lead to creation of new propositions in $K$ ($C \rightarrow K$), see par example the Ck to Kk conjunction in Fig. 3. A design solution is given by a concept Ck which after a transformation, from the unknown to the known, becomes a true proposition in $K$, see Fig. 3. The other branches of C are concept expansions which do not reach a proposition that belongs to K [Hatchuel and Weil 2007].

![Figure 3. The C-K design square (Hatchuel et al 2009).](image-url)
2.2 Integral Design as tool to elucidate C-K in the conceptual design phase

Morphological charts and overviews are used to generate, define and record design aspects/functions and sub solutions. Within the Integral Design approach, after the first step of generating discipline specific morphological charts and discussing the results as a team, the individual charts are combined into one morphological overview containing all of the useful sub solutions from the individual team members. The next step is for the team to take the knowledge and ideas from the overview and translate them into a proposed design solution. This step can take two forms: either the design team combining known sub solutions into RE-designs (K-K) or the design team starts transforming object-design-knowledge into new concepts (K-C). The Integral Design model combined with the C-K theory enables the focus on the distinction between redesign (K-K transformation leading to RE) and integral design concept generation (K-C transformations leading to ID-concepts). To illustrate this an example is presented in Fig. 4, where after step 2 there is a transformation of known sub solutions or from a specific aspect or function to a new concept of function (Y) or to a new concept as possible sub solution (IDx). The elements IDx6, IDy1 and IDy2 represent conceptual sub solutions as a result of the concept generation K-C, see Fig. 4. This distinction is crucial to generate creative solutions to the highly complex contemporary design problems that society faces. In this research the main area of interest lies in the conceptual phase of the design process. Here, the focus is on K-K and K-C relations. Nonetheless, C-K theory also offers value in subsequent building design stages, where it can be used to focus on C-C and C-K relations. In essence, in the current research ID-concepts are seen as essential for the creation of new, innovative building designs, which increase the possibility to ultimately realise sustainable building solutions. Perhaps more importantly, ID-concepts represent the potential for the definition of new object design knowledge, which can then be exploited to solve future design problems in the building design domain.

Figure 4. The ID-method steps according to the C-K theory operators
Looking at the design process the knowledge of the individual designers is represented as a morphological chart and which makes it possible to project these ‘knowledge boxes’ into the space of $C$. Meaning that all that lies outside these Morphological Chart boxes are unknown concepts for the individual design team members, see Fig. 5. After the discussion in the group about the relevance of different functions and aspects in relation to the design task, a selection is made from the morphological charts and put into the morphological overview, see Fig. 5.

Now the knowledge of the design team relevant to the design task is put in the MO box. Through interaction between the different designers with each their own disciplinary background sometimes an interaction and inspiration occurs which leads to the formulation of new aspects or functions, added to the MO box, leading to concepts, new additional possible subsolutions, added, see Fig. 6.

Figure 5. Morphological charts representing initial knowledge $K$, Morphological Overview representing the initial relevant team’s design knowledge and the thinking outside of the box.

Figure 6. The expansion from the team knowledge within the morphological overview by $K$-$C$ transformations: thinking out of the box.
So by using the morphological overview the design team has a overview of the interpretations and possible solutions by each discipline, which can lead to synergy between the different disciplines as well that it forms the starting point of going from the known to the unknown word of concepts.

3. FIRST EXPERIMENTS

The Integral Design approach has been tested in a series of 5 workshops, typically including around twenty participants and lasting for two or three days. A total of 107 designers participated in the workshop series. Here only a brief selection of all the results is given. More results and information are presented by Savanovic [2009]. From the analysis of the workshops it could be concluded that the number of functions and aspects considered as well as the number of subsolutions offered, was significantly increased by applying the Integral design method with its Morphological Overview. A good example of this increase can be seen from the results from session 1 (without morphological carts and overview) compared with the results of session 4 (with use of morphological charts and overview), see Fig. 7. The comparison of design setting 1 and 2 presents the effect of starting with all the different designers from the start.

![Figure 7. The four different design sessions and a comparison of the results](image)

This led to a decrease of the number of aspects and subsolutions, indicating a less effective design process. This is inline with literature about brainstorm experiments [Nystad et al 2003], were they also found out that by just bringing together more designers the productivity does not increase compared with the results from individual sessions. The team has to have a kind of guidance, in our case the Integral design method.

4. EXPERIMENTS WITH A NEW SET-UP FOR STUDENT WORKSHOPS INTEGRAL DESIGN

The results of Savanovic 2009 showed that the amount of overall integral concepts generated in the workshops was rather low. Therefore we looked for possible ways to stimulate the design team to expand their morphological overview with concepts. In the next stage of the research the use of so called C-constructs, some times called C-projectors, of the KCP-method by Hatchuel and Weil was
investigated to stimulate the creation of new concepts in the Integral Design workshops. The KCP workshops were held in different companies in France and more recently in Volvo in Sweden [Elmqvist en Segrestin 2008, 2009]. The intended effect of the C-projectors is the expansion of the solution space in C, after which, by means of research and evaluation, is the expansion of space K, via the transformation of C-K. Applying C-projectors to the Integral Design approach enables to expand the knowledge domain, to expand the design task related morphological overview. This could be used to further stimulate connections between space C and space K. From these new connections it may be possible to derive new concepts. These C-constructs are domain strange concepts, which are used as a source of inspiration for further research to make a connection between the existing domain knowledge in space K, and so determine the possibility of concepts resulting from these new connections. After this evaluation these concepts become part of K, allowing the C-K transformation to take place.

To test the application of C-constructs, workshops were used within the masterproject Integral design (MIO). In this multidisciplinary master project students from the faculty of Architecture Building and Planning with different disciplines background (architects, structural engineers, building physics, building services and building technology) have to design together a building which always has to become a net zero energy (NZE) building. This year the task was to design a sixty stories NZE building for a specific location in Rotterdam. The workshops started with an afternoon setting consisting of two sessions and followed the next morning by another two sessions. The focus of the workshops was to learn the students the use of morphological charts and morphological overviews. This was done by giving starting with a lecture about the Integral Design method and its specific application of morphological charts and morphological overviews as design tools. The students were divided in design teams in such a way that to avoid a learning effect during session 1, 2 and 3 all students worked only once with the same students. In session 1, 2 and 3 the participants started individual working on the different design task and made their own morphological chart, see Fig.8.

![Figure 8. Workshops MIO project, four different set ups with different team configurations](image)

After this first part of each session the teams put together the morphological charts to make a morphological overview as a team. The individual part of the sessions 1, 2 and 3 took 20 minutes and the team part lasted 40 minutes. In the first individual part of the sessions there was no communication between the participants. In session 1 the teams existed of an architectural student and an engineering
student, all together 15 teams. In session 2 the teams existed of two architectural students and two engineering students, in this way there were formed 8 teams.

In session 3 the students were again rearranged now in teams of 5 or 6 students. In addition each student design team was strengthened by an expert who joined the design team. After session 3 a lecture was given about C-K theory and the possible application of C-constructs. After which the design team continued in session 4 with the design assignment of session 3 and tried to generate concepts with the help of some C-constructs that were given to them.

In design setting 1 and 2 the teams were given the same design task as used in the Integral design research by Savanovic [2009]. The 3th design setting for students teams with an expert was to propose a conceptual design for a 60 stories net zero energy (NZE) apartment building on a specific location. The design teams were formed based on the actual teams of the Master project Integral design (MIO-project). Besides 2 or 3 engineering design disciples present in the design teams they had 2 or 3 architectural students. This meant that 5 or 6 students formed a design team. In addition each student team was strengthened by an professional expert. The members of the design teams started individual, making the morphological charts and after that worked together to make the morphological overview.

In the 4th design setting, students with an expert worked on the same assignment from session 3, the Net Zero Energy apartment building but the task was now to try to use the C-constructs as a stimulus to come to new ideas. Starting point for this session were the results of the 3th design session, the morphological overview of the design team. The teams stayed the same compilation as in session 3. The focus of the 4th assignment was on the expansion of the design team’s knowledge box, their Morphological Overview, so to stimulate thinking out of the box by applying C-constructs to make the step from existing knowledge to the unknown world of concepts. C-constructs were presented to the design teams and had to try to use these to stimulate their conceptual thinking process.

5. RESULTS WORKSHOPS INTEGRAL DESIGN

The participants of the workshops were master students of the faculty of architecture, building and planning and had an average age of 22 and no working experience. During the sessions 1 and 2 29 students participated and in session 3 and 4 27 students participated. In session 3 and 4 six professionals participated, in each student design team one, which were on average 50 years old and had around 25 years experience. The number of functions and sub solutions mentioned by the designers in their morphological charts were counted and are represented in Fig. 9. The same was done for the sub solutions mentioned by the design teams in their morphological overviews, see Fig. 9. This makes it possible to compare the results between the average number of functions and subsolutions mentioned in morphological charts and morphological overviews for all three different design sessions. Although the design tasks were different for all three sessions they were seen as a stable factor, since from former research it was found that the complexity of these design task were quite simular and no significant effect on the results as such [Savanovic 2009]. In all sessions combining morphological charts into a morphological overview leads to an on average increase of the number of functions and solutions as mentioned by the design teams, Fig. 9.
Overall there is an increase of the number of solutions mentioned in the morphological overview after session one compared to session two (on average 24.5 compared to 27.3), which could be an indication that the students learned to improve the process of combining the individual morphological charts into the team’s morphological overview. There is only a rather small difference between the students making the morphological charts in session 3 (MC3Stu) compared to that by the professionals (MC3Pro), which is quite remarkable. Quite remarkable is also the small effect of adding a professional to the students teams in session 3, MO3 (7.8 functions and 30 solutions), compared to the outcome of session 2, MO2 (7.1 functions and 27.3 solutions), however still there is an increase of 10% overall.

The first part of design assignment 1, 2 and 3 were the same for all designers, they all had to make his or her morphological chart based on their individual interpretation of the program of requirements and their individual knowledge relevant to the design task. After this first step the teams formation for the different assignments were changed from teams of two (session 1) to teams of four (session 2) and teams of five or six (session 3). From Fig.10 a is shows that there is no real significant difference in the average outcome of the morphological charts in the different sessions of the workshops. The professionals are a little more focussed on the functions (on average 7) as compared to students (on average 5.6) and as a result generate less sub solutions. Professionals must have much more knowledge about possible solutions than the students, thus you would expect that they generated more solutions.
To focus more on the effect of the application of C-constructs as used in the 4th session of the workshops, the outcome of the average number of functions and solutions, mentioned in the morphological overview, were compared as a percentage of the average numbers of the morphological charts, see Fig. 10 b. Compared to the morphological overview of session 3 there is a significant increase in additional mentioned functions (+61.5%) as well as an increase in proposed solutions (+42.3%). Remarkable is the increase of the average number of additional functions generated by the interpretation of the C-constructs, which than can lead to new ideas for possible solutions. This shows that there is happening thinking out of the box, as the morphological overview of session 3 represents the knowledge of the design team that was inside the box.

6. DISCUSSION

Building design changes when the other building designers such as building services engineers, structural engineers and building physics engineers join the architect in the conceptual design phase. To analyse the building design process the distinction was made between the solution space of the known (K) and the possible solutions in in unknown, concepts (C) which have an undetermined status (either true or not), in analogy with the C-K theory of Hatchuel and Weil [2009]. This distinction between concepts and knowledge by Hatchuel and Weil [Le Masson et al 2007, Hatchuel et al 2008] is similar to the model for conceptual design by Jansson [1991], were the conceptual design process is described as movement between two spaces: configurations space and concept space. Hereby differs the concept space from the configuration space, in that the elements it contains are ideas, relationships, or other abstractions, which may later become the basis for elements in configuration space. C-K theory defines design as the interplay between two interdependent spaces having different structures and logics. This process generates the co-expansion of two spaces, space of concepts C and space of knowledge K. Since C-K theory defines a piece of knowledge as a “proposition with a logical status for the designer or the person receiving the design” [Hatchuel and Weil 2002].

Innovation is fundamental to the survival and advancement of society [Joyce et al 2010]. Collaborations that cross disciplinary boundaries are essential to innovation and the occurrence of boundary spanning, where ideas from one domain, discipline or functional area are importet into another [Joyce et al. 2010], in a way that solves new problems or presents new solutions [Burt 2004].

The size and specialization of modern professionals makes finding the right conceptual bridge between domains difficult for any one individual to solve the complexity on his own. Therefore, collaboration is required [Joyce et al 2010] for innovation to let experts recognize the analogous qualities of ideas from distant conceptual realms, identify ways they can be usefully connected and work to realize them [Burt 2004]. The Integral design method with its use of morphological overviews in combination with the C-K theoretical focus on concept generation is an important step to reach true collaborative building design.

The combining of the mono-disciplinary morphological charts into a design team’s morphological overview leads to a new approach for the support of knowledge transfer and knowledge creation. This is similar to the developed KCP [Knowledge Concepts Proposal]-workshops, derived from the C-K (Concept-Knowledge) theoretical framework in collaborative exploration in France at Ecole des Mines de Paris by Hatchuel and Weil [Elmquist and Segreslin 2009]. These KCP-workshops aim at structuring collaborative exploration of an innovation field. The results are a structured set of innovative concepts for further development [Hatchuel and Weil 2009]. The KCP-workshops were used in a number of innovative projects with industrial partners such as RATP [the French company operating the Paris subway], Thalès and Renault. The KCP workshops involve a series of three meetings [Elmquist and Segreslin 2009]: one for knowledge sharing (phase K), one for the conceptual
exploration (phase C) and one to structure the proposal (phase P). The KCP-workshop aims at structuring the exploration of a set of innovative concepts and offers a framework in which to collectively address the tasks. More information can be found in [Hatchuel et al. 2009].

There are similarities between the ID-method workshops and the KCP-workshops. In the KCP-workshops there is a strong influence by the organizers as they generate and structure the first concepts from which the connection with the existing domain knowledge is initiated. The integral design workshops C-constructs are presented to the participants to stimulate concept generation.

7. CONCLUSIONS

With the use of morphological overview of the Integral design method and the C-K theory to focus on specific transformations par example from knowledge to concepts or from concepts to knowledge is it possible to make the conceptual design phase more transparent. As such the proposed model will also have implications for new kinds of interactions between stakeholders and the design team. No longer does the conceptual design phase have to be a closed black box for client and project manager during the design process which means that they can intervene if they think it is necessary. This improves the quality and productivity of the architectural design process.

8. REFERENCES

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