Knowledge Engineering and Management for Integral Design based on C-K Theory

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ABSTRACT

This paper presents a theoretical approach for collaborative engineering design management. The goal is to integrate design and engineering knowledge in the conceptual phase of building design in a structured and transparent process steps. Based on an Integral Design process model, morphological overviews are used as a tool to implement C-K (Concept-Knowledge) theory, to look into knowledge creation and knowledge exchange within building design teams.

The project was done in close cooperation with the professional architectural and consulting engineering societies with in the building design field. The workshops set-up, used to implement and to test the approach, are presented. More than over hundred experienced professionals participated in the workshops. The workshops have become part of the permanent professional training program of one of the Dutch architectural professional society.

Keywords: integral design, morphological overviews, C-K theory, workshops

1. INTRODUCTION

During the last years within the building industry demands to comfort and energy consumption became more and more strict. As a result the gap became clear between the traditional architectural artistic design and the exact engineering approach based on facts and calculations. As complexity and scale of design processes in architecture and in building services engineering increase, as well as the demands on these processes with respect to costs, throughput time and quality, traditional approaches to organize and plan these processes may no longer suffice (van Aken 2003).

The architectural design process is complex and has only an overal structure. The designer starts from an ill-defined problem and through different steps and stages progress has to be made up to a blueprint for a solution. The conceptual design stage is especially vague. It often starts with rough initial ideas about the situation in which the building has to be placed and rough initial ideas about the function that the building should have (Aliakseyeu 2003). As the design proceeds, more information and detail are developed. Though there is little information at the early stages of design nearly all the important decisions have to be made at this time. There is an influence/information contradiction (den Hartog 2003), or design process paradox (Ullman 1992).

Designers in practice have produced many successful designs, most of them by developing their own method, even if they have not done so explicitly (van den Kroonenberg 1978). However, traditional design approaches in many cases may fail to solve new and highly complex design problems which need input from a large number of disciplines. The search for new design methods can be helped with the use of design methodology. Design methodology includes the study of how designers work and think, the establishment of appropriate structures for the design process, the development and application of new design methods, techniques and procedures, and reflection on the nature and extent of design knowledge and its applications to design problems (Cross 2001).

In 2004 a research project started using Integral Design methodology as a model for structuring knowledge of building design team members. Especially Morphological Overviews to visualize solution alternatives play a central role. The basis of this theoretical approach the C-K (Concept-Knowledge) theory (Hatchuel & Weil 2002), in which concepts and knowledge are distinguished.. Combination can only lead to redesign (RE), while in literature much referred designer's 'creative leap' is needed for integral concepts (ID). This is a major step in understanding how to work with morphological overviews, and needs a 'designerly' (Cross 2001) attitude. This is a start of the Integration of Design and Engineering knowledge, which is made transparent and manageable by using morphological overviews and application of C-K theory.

2. METHODOLOGY

Integral design

During the early 1970s a prescriptive design model was developed in the Netherlands to teach design to mechanical engineering students at the University of Twente. Called the methodical design model, it was based on a combination of insight from the German (Kesselring, Hansen, Roth, Rodenacker , Pahl and Beitz) and the Anglo-American design schools (Asimov, Matousek, Krick). This design model was chosen because; " it is one of the few models that explicitly distinguishes between stages and activities, and the only model that emphasises the recurrent execution of the process on every level of complexity (Blessing 1993, p.1398)". This in the Netherlands familiar model within the domain of mechanical engineering (Blessing 1994) was extended by us to get an integral design method. A distinctive feature of the integral design method is a four-step pattern of activities (generating, synthesizing, selecting and shaping, see figure 1), that occurs on each level of abstraction with the design process, that together forms the Integral Design matrix. During the design process, and depending on the focus of the designer, functions and aspects exist at the different levels of abstraction. Morphology provides a structure to give an overview of the functions and aspects considered and the alternative solutions.

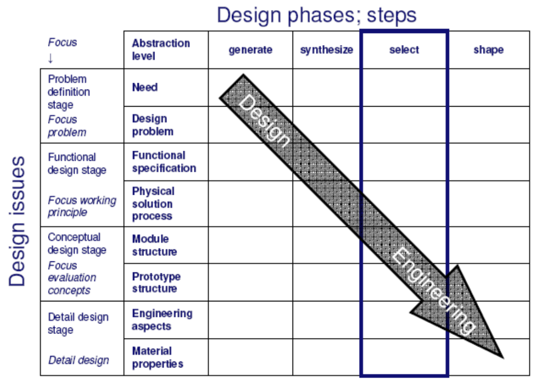


Figure 1: *Integral design matrix*

Morphological overview

Morphology was developed by Fritz Zwicky in 1947 (Norris 1963). Morphology provides a structure to give an overview of the considered functions and aspects and their solution alternatives. The functions and aspects are derived from the program of demands which defines the outcome of the design process. In the morphological chart functions or aspects has to fulfill are listed in a column. The possible solutions are listed in a row, see Figure 2.

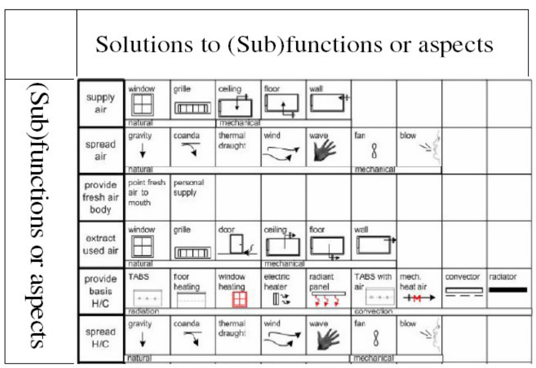


Figure 2: *An example of a morphological chart*

By using morphological charts each discipline can look if all necessary functions and aspects are listed. All the design team members now have the challenge to come up with their interpretation and possible solutions to the design task. As every designer sees the results immediately in the morphological chart, they can discuss aspects which are not clear to them. Immediately the reflection in action on the design process is initiated if the designers make the morphological chart together.

Using the morphological charts made by each individual designer, we can combine them to a morphological overview, see figure 5. The advantage of this approach is that the discussion comes 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. This allows a greater freedom of mind of the individual designers and results in more creativity in interpretation of the design problem and generation of part solutions from the different disciplines. The whole process is done in two steps first the functions and aspects are discussed and then the possible related solutions see figures 3 and 4.

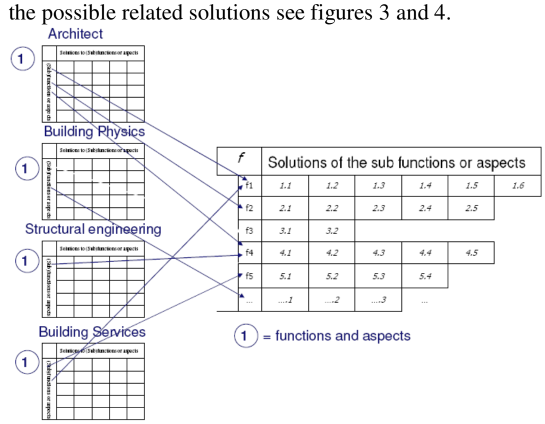


Figure 3: *Building the morphological overview; Step 1; The Morphological overviews show the agreed functions and aspects (1) of the different morphological charts.*

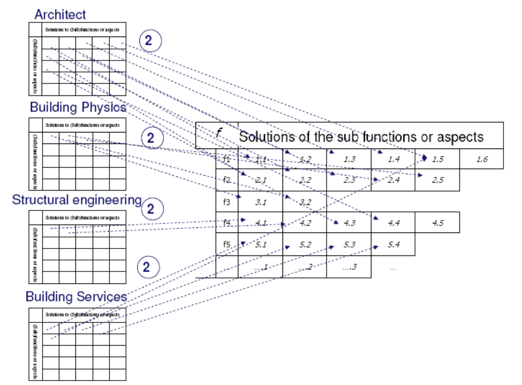


Figure 4: *Building the morphological overview; Step 2: The Morphological Overview with the agreed on sub solutions (2) from the separate morphological charts*

After selection and discussion, elements of the different morphological charts, are put into one overall overview: the morphological overview. Such a morphologic overview can be used by the designers to reflect on the results during the different design process stages. Using morphological charts as a tool and to transform it into a morphological overview, others' contributions activate individual interpretation, the reflection of a designer, based on which he or she can make the decision to also make an explicit contribution.

Especially morphological charts to visualize solution alternatives play a central role. A morphological overview is generated; see figure 5, by combining the different morphological charts made by each discipline after discussion on and the selection of functions and aspects of importance for the specific design. Such a morphologic overview can be used by the designers to reflect on the results during the different design process stages. Although the use of functional description and morphological charts is common practice in mechanical engineering design, they are rarely used in a multi-disciplinary way besides engineering. Especially the input of 'soft' aspects adds a new dimension to the strict functional approach of traditional morphological chart. The morphological overview makes it possible to change from "Form follows Function " (Sullivan 1896) to a new way of conceptualizing design as a professional practice in which design is making sense of things (Krippendorf 2006): hard and soft things.

C-K (Concept – Knowledge) theory

The theoretical background on how design knowledge can be transformed into integral design concepts is found in "C-K theory" (Hatchuel and Weil 2003): the C-K stands for concept-knowledge relation. The C-K theory defines design as the interplay between two interdependent spaces having different structures and logics, a process generating co-expansion of two spaces, space of concepts C and space of knowledge K. The structures of these two spaces determines the core propositions of C-K theory (Hatchuel and Weil 2007);

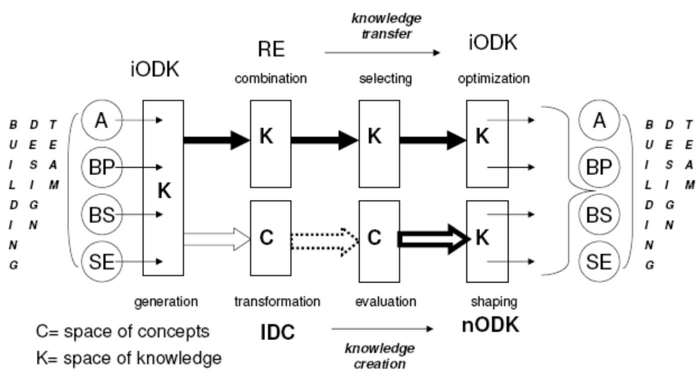
- Knowledge. A piece of knowledge is a proposition with a logical status for the designer or the person receiving the design. A set of knowledge is therefore a set of propositions, all of which have a logical status (Hatchuel and Weil 2002).

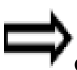
- Concept. A concept is a notion or proposition without a logical status: it is impossible to say that a concept, for instance an "oblong living room", is true, false, uncertain or undecidable. A concept is not "knowledge" (Hatchuel and Weil 2002).

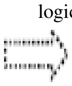
- Space K. Contains all established (true) propositions (the available knowledge, existing solutions).

- Space C. Contains "concepts" which are undecidable propositions in K (nor true nor false in K) about some partially unknown set of objects called a C-set.

A design concept is a proposition that can not be logically valued in K. Concepts are candidates to be transformed into propositions of K, but are not themselves elements of K (properties of K can however be incorporated into concepts). If a proposition is true in K, it would mean that it already exists and all is known that is needed about it (including its feasibility). Design would then immediately stop. There is no design if there are no concepts. Without the distinction between the expansions of C and K, design disappears or is reduced to mere computation or optimization. The transformations within and between the concept and knowledge spaces are accomplished by the application of four operators, see figure 5 (Hatcheul, Le Masson and Weil, 2004).



 C→K, concept→knowledge: This operator seeks for properties in K that could be added or subtracted to reach propositions with a logical status; it creates conjunctions which could be accepted as "finished" designs

 K→C, knowledge→concept: this operator adds or subtracts properties from k to concepts in C

 C→C, concept→concept: this operator is at least the classical rules in set theory that control partition or inclusions

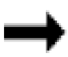
 K→K, knowledge→knowledge: this operator is at least the classical rules of logic and propositional calculus that allow a knowledge space to have a self-expansion (proving new theorems).

Figure 5: *C-K Design process scheme*

The last two operators are internal to the concept and knowledge spaces, and are not particularly relevant to the expansion of both. The first two operators cross the Concept-Knowledge domain boundary, and are significant in the sense that they reflect a change in the logical status of the propositions under consideration by the designer (from no logical status to true or false, and vice versa). Within the integral approach the space K is defined by the initial design knowledge that participants bring into the design team. (Sub)solutions are seen as 'chunks' of "object design knowledge" (Van Aken, 2005), which is mainly discipline based. Since the object of design is used as the reference, this knowledge is further specified as initial object design knowledge (Figure 3). Only explicitly presented / communicated object design knowledge within a design team is considered and the focus is on how this explicit object design knowledge is transformed / integrated within a multi-disciplinary design team setting.

The relation to the design square of Hatchuel and Weil (2003), which consists of four types of transformations that take place within and between the concept and knowledge spaces, and the integral design process is explained step by step in the following section.

Functions are 'design team subjective', meaning that all individual proposals must be agreed by others. Interpretation as an step is only possible after objective definition of design criteria and leads to determination of the functions to fulfill and the aspects to deal with. Morphological overviews show the initially available explicit knowledge within a design team, iODK see figure 6.

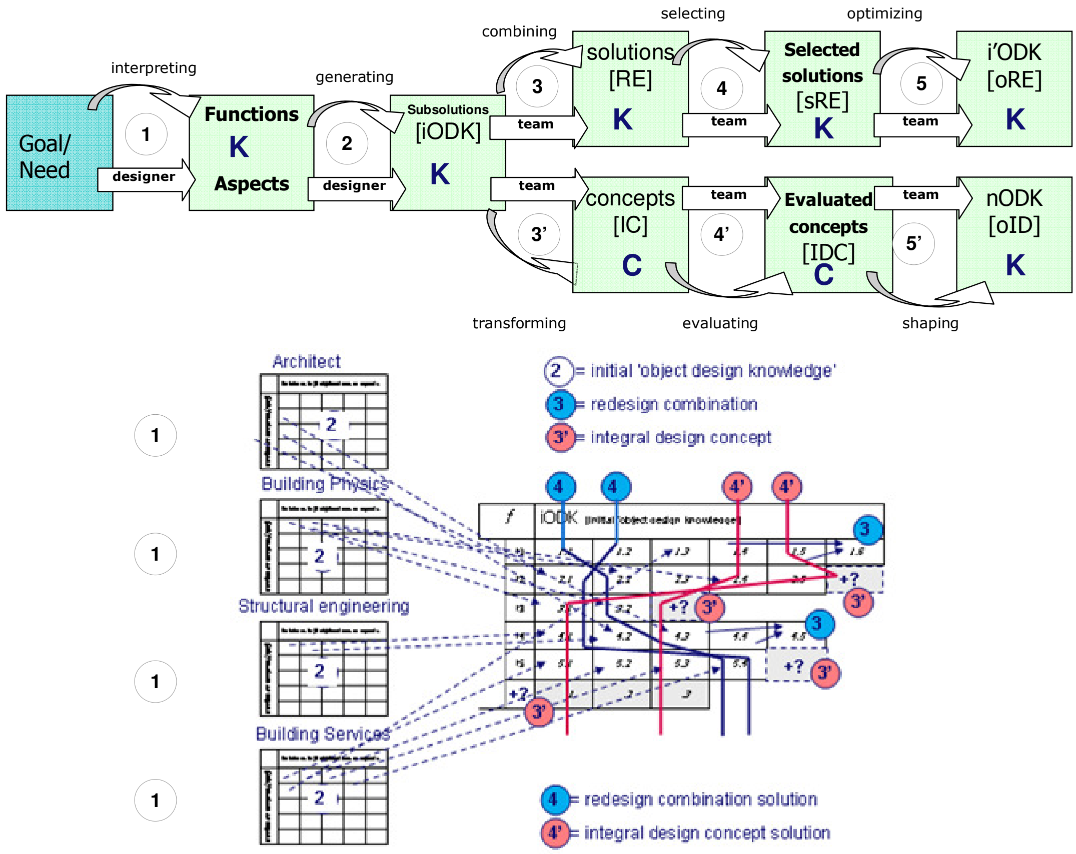


Figure 6: *C-K Design process scheme combined with Integral Design process representation*

Making object design knowledge explicit enables designers to use it for the creation of design concepts. These concepts are either integral (ID) or just plain combinations (RE). It is important to understand that integration of initially presented discipline based design object knowledge with implicit knowledge is something different than plain combination of sub-results. Combination can only lead to redesign (RE), while concept integration involves transformation of design knowledge. Contrary to redesign, the connections design team (members) make between sub-solutions in order to produce ID-concepts are subjective and design task context dependent.

Concepts acquired by only combining (sub) solutions are regarded as redesigns. Although a given combination might take all relevant aspects (defined by design team itself) into account, it doesn't represent an integral solution. See step 3 - combining [activities] in figure 6. Working out specific functions / solutions on a lower abstraction levels, optimize chosen redesigns will gradually lead to detailed solutions (shaping phase).These are optimized i'ODK, see step 4 in figure 6.

Concepts acquired through transformation of iODK into ID, see step 3' in figure 6, are regarded as integral concepts. This is a result of so-called designer's 'creative leap', triggered by (aspects of) presented (sub) solutions and their possible connections. Implicit knowledge is regarded as the other catalyst. Through evaluation of ID-concepts, new object design knowledge emerges (C-K theory) since iODK is not sufficient for explanation. This nODK represents potential for creation of innovative design solutions. See figure 6 step 4' - evaluating [activities].

The focus is on the possibility of expanding the concept space with integral design concepts (step 3'- Figure 6, ID), in order to produce potential for creation of new object design knowledge (step 5'- Figure 6, nODK). From a standpoint that a concept not being true or false (within space K), the design process aims to transform this concept and will necessarily transform K (Hatchuel and Weil 2003). At the end of the process of generation and integration of concepts, transformation of existing object design knowledge within the design team into integral design concepts takes place, offering design team members the possibility to acquire new insights.

During the processes of generation and integration of concepts, transformation of the within design team existing object design knowledge into integral design concepts takes place, offering design team members the possibility to acquire new knowledge. It is important to stress that integration of initially presented discipline-based-design-object-knowledge is something different to the plain combination of (sub) solutions. Whereas combination can only lead to redesign (RE), concept integration involves transformation of not only explicite design knowledge but also implicite design knowledge. Using morphological overviews as the integral design tool, the realisation of the potential for the creation of new object design knowledge through the integration of discipline based explicit object design knowledge into integral design concepts is aided. These integral design concepts are not merely a variation or combination of existing solutions but have some completely new element or characteristic (see the *?* symbol in Figure 7). This is the result of an implicit concept that arises by means of an often autonomic creative mental process by one of the design team members. Also this could be the result of reflection on the design task, new information or new stimuli from out side the team. So this is where possible formal matimatical based mechanism for the expansion from the space K to space C of the C-K theory of Hatchuel and Weil, can be applied within the Morphological Overview approach.

3. RESULTS

The above described approach has been tested in a series of 5 workshops, typically including around twenty participants and lasting for two or three days. More information about these workshops series can be found in (Zeiler et al. 2005, Savanovic and Zeiler 2007, Zeiler and Savanovic). The average age of the participants, all either architect or consulting engineer was 42 and they had on average 12 years of professional experience. Directly at the end of the workshop the participants were asked to fill in a questionnaire in which questions were asked about the importance of the use of morphological overviews within the design process and about the concept of the workshops themselves. The participants were asked to fill a questionnaire and had to rate the answers, see table 1.

Table 1*: Overview results questionnaires participants workshop series*

	series 1	*series 2*	*series 3*	*series 4*	*series 5*
Number participants	20	20	22	27	18
Returned questionnaires	*88%*	*96%*	*98%*	*96%*	*97%*
MO increases relevant alternatives (1-10)	6,2	7,3	5,7	7,8	7,9
MO improves insight other disciplines (1-10)	7,4	7,4	5,6	7,7	8,5
MO positive effect design process (1-10)	7,0	7,4	4,7	7,7	7,7
MO positive effect final design (1-10)	6,6	6,2	4,5	7,2	7,5

It shows from the results of the questionnaires that the participants of the workshops thought the use of morphological overviews of value to the communication and the increase of relevant alternatives within the design process.

4. DISCUSSION

At this point it is good to define the differences between integrated design and integral design more explicite; within integrated design two or more disciplines are combined in order to become more effective, within integral design all disciplines necessary and important are threated as part of, or contained within the whole building design approach. So within integrated design the focus is on combining different disciplines, were as in integral design the focus is on the whole building approach and the therefore needed different disciplines. To put it in another way, within integrated design the architectural discipline and other disciplines start separately and often in different design phases and are later made to fit, were as within integral design all necessary design disciplines start together right from the conceptual design. Integral design concepts are only possible by starting together of the different design disciplines and uniting various viewpoints of the different design disciplines involved. In order to achieve not only integration, but true synergy, between all disciplines a single designer has to 'force' himself or herself to consider different discipline based viewpoints while designing. Even if a designer has the ability to deploy most of these viewpoints, he or she usually does not have enough specialist knowledge to assess all of them in depth. For this reason it is assumed that a multi-discipline design team view on design is a better way of pursuing building design synergy than a mono-disciplinary individual designer view on design. The main concern in architectural management should be the conceptual design phase, since decisions made in this phase largely determine what can and cannot be done in the further building design stages. The focus should be on creating conditions in which different design disciplines within a design team will have the opportunity to, first of all, introduce their object design knowledge (Van Aken 2005), and subsequently to integrate it into design concepts. Emphasis on involvement of the various design disciplines forms the starting point for integral building design process organization.

We focus on possibility of (integral) design concepts producing new (design) knowledge. At the end of process of generation and integration of concepts, transformation of existing object design knowledge within design team into new (integral) object design knowledge takes place. Design team members acquire new insights in this 'learning by doing' approach. In our case K is object design knowledge that participants bring into design team. Structured introduction of this knowledge enables designers/participants to transform it into design concepts. In the workshops the Integral Design approach with its morphological overviews proved to be supportive to the experienced building design professionals.

The morphologic overviews within the integral design method can not only be used within the design team to integrate design and engineering knowledge, but can also used to improve the communication with the client. Through visualization of contributions within a design team, morphological overviews can show how (integral) design concepts are emerging within design teams, see figure 7. By structuring design (activities) and communication between design team members, morphological overviews form the basis for reflection on the design results; both by the design team members themselves and in discussion with external stakeholders such as the project manager and representatives of the client. Through the application of the integral design method each step within the design process becomes transparent, which makes it possible to reflect on all design steps. Potentially this makes it easier for design managers to manage these design steps within the conceptual design phase.

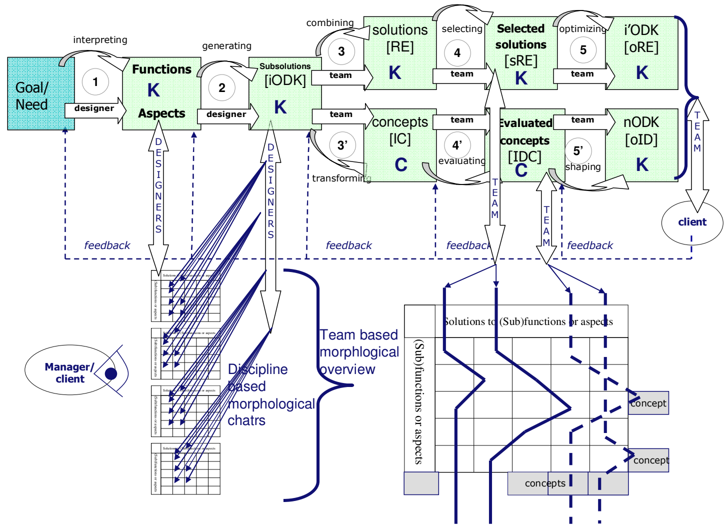


Figure 7: The morphologic overview of the combined morphological charts for the feedback to the project manager/ client in the conceptual design phase.

5. CONCLUSION

New approaches in architectural management are needed which look at conceptual designing as a knowledge development process that needs to be supported with appropriate tools. This article provides an insight into how morphological overviews can be used as a design support tool within the integral design method and based on the C-K-theory (Hatchuel & Weil 2002). Through visualization of contributions within a design team, morphological overviews can show how (integral) design concepts are emerging within design teams. The application of the integral design method makes each step within the design process more transparent, which enables to reflect on the design process steps. Potentially this makes it easier for project managers to manage these design steps.

6. ACKNOWLEDGEMENT

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