Morphology in conceptual building design

Citation for published version (APA):

DOI:
10.1016/j.techfore.2017.06.012

Document status and date:
Published: 01/01/2018

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Download date: 28. May. 2021
Morphology in conceptual building design

‘WE CANNOT PREDICT THE FUTURE, BUT WE CAN INVENT IT’

- DENNIS GABOR

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Abstract
As the effects of the environmental damaging of our environment becomes more clear there is a social change towards sustainability which effects technology development and makes forecasting more difficult. This calls for a holistic integrated design approach with the involvement of the various design experts from different domains to form multidisciplinary design teams right from the conceptual design phase of buildings. To support these teams, a supportive design method based on the use of morphological charts and a morphological overview was developed in cooperation with the Dutch professional organizations of architects and consulting engineers. This tools aids architects and engineers with their new role in the conceptual design phase as it enables effective exchange of each discipline’s perspective on the design task as well as structuring the available domain knowledge. After this proof of principle the method was applied in the master program of the Faculty of the Built Environment of the Technical University Eindhoven in their Master project Integral Design.

The design support tool is part of multidisciplinary master’s program at the Technical University Eindhoven in which students partly work together with experienced professionals. The outcome shows that the design support tool facilitates significant increase in the number of possible solutions generated by design teams and it demonstrates that the morphological charts and morphological overview can be used as analyses tools for evaluating the impact of different interventions during the conceptual phase of the building design process.

In this paper, in addition to a detailed discussion of the design support tool, also the use of the tools to determine the effectiveness of individual designers is illustrated. Furthermore, the impact of various interventions is investigated, such as the adding of an experienced professional to a student’s design team and the use of C-constructs based on the Concept-Knowledge theory of Hatchel and Weil to further stimulate the generation of sub-solutions. By all the interventions the morphological charts and morphological overview were used to measure the quantitate effects of the interventions in conceptual building design.

Keywords integral design; morphological chart; morphological overview; C-K theory, C-constructs

1.0 Introduction
People need buildings to protect them against the environmental conditions to be able to work and live. Building Services make it possible to provide comfort and an acceptable indoor Air Quality for building occupants. However, with 40% of the energy use within the developed world and 36% of the CO₂ emissions the built environment is one of the most important areas for sustainable development [BPIE 2014]. The European Union and its Member States have a large number of on-going policy initiatives directly aimed at supporting of sustainability of the built environment. Future building regulations will require nearly Zero Energy Buildings in Europe. The increased complexity of building design [van der Linden et al 2016] inevitably calls for more design collaboration [Lee and Jeong 2012, Hakkinen et al 2015], and the early collaboration of architects and engineers can facilitate the creation of new knowledge and solutions beyond the specific scope of each individual discipline [Kovacic and Fitzmoser 2014]. According to the Royal Institute of British Architects (RIBA) president Jane Duncan, architects, engineers and builders must collaborate [CIBSE 2016]. This needed collaboration might however not be very easy to achieve during the early stages of the design. There is therefore the need for a design support tool to facilitate interaction and information exchange between the various design team members as they come up with viable alternatives to be considered by all design team members [Zeiler 2016].

In section 2, details of the developed design method are presented. The methodology is described in section 3 as well as the different interventions to improve the design process and descriptions of the experiments for testing the method and interventions with professionals and with students are provided. In section 4, the results of the different experiments are provided, in section 5 the analysis of the results followed with a discussion of the results in section 6. Finally in section 7 provides the conclusions about the added value of the design method as a support tool and research tool as well as some remaining needs for further research and developments in relation to the morphological aspects of the developed design method.
2.0 Integral design

Due to problems resulting from the lack of quality of products and projects, in the early 1960’s researchers and practitioners began to investigate new design methods as a way to improve the outcome of design processes [Cross 2007]. Since then, there has been a period of expansion through the 1990’s right up to the present day [Chai and Xiao 2012, Le Masson et al 2012]. However, there is still no clear picture of the essence of the design process [Horvath 2004, Bayazit 2004, Almefelt 2005, Atkinson & Oppenheimer 2016], and many models of designing exist [Wynn and Clarkson 2005, Pahl et al 2006, Howard et al 2008, Tomiyama et al 2009]. Moreover, many of the design methodologies were developed at universities, and are rarely applied in industrial applications [Birkhofer et al 2005, Stolterman 2008, Gericke and Blessing 2012, Dorst 2016]. In 1999, the professional Dutch organization for architects and consulting engineers together with the University of Technology Delft and the Building Services Society started a research to develop an Integral design method to improve the conceptual building design process. Since 2003 this research has continued at the University of Technology Eindhoven and led to a design method based on intensive use of morphological charts. After studying different design methods, it was decided to use Methodical Design by van den Kroonenberg [van den Kroonenberg 1988, Zeiler and Savanovic 2009] and its outcome was evaluated in a situation as close as possible to practice amongst professionals, see section 3. The design method has a distinctive feature, the step pattern of activities (generating, synthesizing, selecting and shaping), that occurs within the design process, see Fig. 1.

Figure 1. The four-step pattern of Integral Design.

This method was expanded to a multi-disciplinary design method, Integral Design, through the intensified use of morphological charts developed by Zwicky [Zwicky & Wilson 1967]. Specifically, the use of a morphological overview built from the individual design team member’s morphological charts. Morphological charts were derived from the General Morphological analysis, based on the pioneer work by Zwicky [1948a]. General Morphological analysis was developed as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes, its history and some applications is given by Ritchey [2010]. Zwicky [1948b] gives a clear description of the morphological method; “The morphological method essentially is nothing more than an orderly way of looking at things. The only innovation which we propose is to carry morphological thinking to a degree of generality not commonly realized. Our aim is to achieve a schematic perspective over all of the possible solutions of a given large-scale problem. Naturally not all of the solutions which we are thus led to visualize can be carried out individually in all detail. Because of unavoidable limitations on time and means a choice must obviously be made, and preference must be given to some specific solutions. With the general perspective achieved, this choice will however be more rational and organic than it would be if one engaged haphazardly in work on this or that solution of a given problem”.

Morphological charts originate from the n-dimensional morphological box [Zwicky and Wilson 1967]. The two-dimensional form of the Zwicky’s box is usually referred to as ‘morphological charts’ [Jones 1992, p.292]. The typical individual designers’ use of morphological charts requires all important design functions to be defined and possible solutions for each function to be listed, resulting in the framing of solution space. However, because instead for ‘straightforward’ problem-solving the main use is for exploration of ‘new’ concepts.

It was Norris [1963] who first introduced the application of the morphological approach into the domain of engineering design methods. The use of morphological charts also has definite advantages for communication and – notably – for group work [Ritchey 2004].

A morphological chart is a kind of matrix with columns and rows which contain the aspects and functions to be fulfilled, see Fig. 2 step and the possible solutions connected to them, see Fig. 2 step . These functions and aspects are derived from the program of demands. In principle, overall solutions can be created by combining various sub-solutions to form a complete system solution combination [Ölunder et al 2008]. Morphological chart structures the solution space and encourage creativity. Morphological charts are essentially tools for information processing, it is not confined to technical problems but can also be used in the development of management systems and in other fields [Pahl et al 2006].

Design processes can be improved through improving three types of process communication [Senescu et al 2013, Senescu and Haymaker 2013]: understanding, sharing and collaboration. The use of the morphological charts and morphological overview is an excellent way to improve the design process communication procedure. It makes it possible to record information about the solutions for the relevant functions and aids the cognitive process of understanding, sharing and collaboration [Ritchey 2010].
In the first step of the integral design method, the individual designer has to make a list of what he thinks are the most important functions that has to be fulfilled based on the design brief. This is derived from their own specialist perspective. The morphological charts are formed as each designer translates the main goals of the design task, derived from the program of demands, into functions and aspects and is then put into the first column of the morphological chart, see Fig 3 step 1. In the second step of the process, the designers add the possible part solutions to the related rows of the functions/aspects of the first column. 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 definition of needs. These individual morphological charts can be combined by the design team to form one morphological overview, see Fig. 3 step 2.

The morphological overview of an integral design team process is generated by combining in two steps the different morphological charts made by each discipline. First, in step three functions and aspects are discussed and then the team decides which functions and aspects will be placed in the morphological overview. Then, after this, in step 4 all participants of the design team can contribute their solutions for these functions and aspects by filling in the rows within the morphological overview. Putting the morphological charts together enables ‘the individual perspectives from each discipline to be put on the table’, which in turn highlights the implications of design choices for each discipline. This approach supports and stimulates the discussion on and the selection of functions and aspects of importance for the specific design task.

Important is the keeping of a phase individual of individual creativity during the morphological chart. From the works of Paulus et al [2012], Korde and Paulus 2017 on group creativity and the works on fixation by Jansson [1991], Smith [1995], Finke and Ward et al [1999] underline the issue of fixation and they show how group creativity tend to augment fixation. Design fixation is a phenomenon that negatively impacts design outcomes, especially when it occurs during the ideation stage, the conceptual phase of a design process [Moreno et al 2015].
Most people are likely to encounter obstacles during idea generation [Smith et al 1995, Cassotti et al 2016]. So therefor it is important to have the individual morphological chart, to have first individual creativity then collective. This in line with the work of Girotra et al [2009] where they found that groups where individuals first work alone and then work together (the hybrid process) are able to generate more ideas, to generate better ideas compared to teams that rely purely on group work.

By structuring design (activities) with morphological overviews as the basis for reflection on the design results, stimulates communication between design team members and helps the understanding within design teams. It stimulates collaboration as it makes it easier to come forward with new design propositions. Through visualizing the contributions morphological overviews stimulate the understanding of the different perspectives among design team members.

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. Although morphological charts are based on Zwicky’s ‘totality research box’, morphological analysis is not meant to be imposed on architects as an objective and rational engineering method. Especially the input of ‘soft’ aspects adds a new dimension to the strict engineering’s 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. Rather, it’s neutral and hands-on characteristics are seen as appropriate to accommodate multidisciplinary building design teams [Savanovic 2009].

Generally speaking, design thinking is a creative process based around the transformation of needs into solutions. In this process existing knowledge and information about the actual needs of the principle forms the basis to work from. This often has to be transformed into new unknown concepts if solutions based on existing knowledge are not adequate than it is necessary to develop from the known the unknown. As such the distinction can be made between the known (Knowledge) and the unknown (Concepts) this distinction determine the core propositions of C-K theory [Hatchuel and Weil 2007]. Also important is that the cognitive effect of C-K theory which could help overcome fixations [Agogue et al 2014].

2.1 C-K theory and Morphology

The main aim of our integral design approach is to support design teams. Supporting design teams could improve conceptual design collaboration in order to stimulate the creation of new design proposals. As such, we analysed the effect of applying design theory and design tools to increase creativity within multi-disciplinary design teams. Similar to the research by Le Masson et al. [Le Masson et al 2011], we examined how to influence the interplay between creativity issues and design theory. Design is to process existing knowledge and information about the actual needs of the client to come to yet unknown solutions, 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 space K represents all explicit representations of a design team’s knowledge [Hatchuel and Weil 2002], see Fig 4. If we apply C-K theory to the transformation of the morphological charts into the morphological overview than we can distinct the steps within the C-K design square [Hatchuel and Weil 2007].

![Figure 4. The C-K design square [Hatchuel and Weil 2007].](image)

From the representation of knowledge K within the morphological charts, two types of synthesis are possible. Either the representations know to all team members, see f1-3 in Fig. 5, are combined into the morphological overview using the K→K operator, or are transformed, using the K→C operator, as they are partly unknown to some of the design team members. This way part of the morphological chart set C is partitioned into subsets for partly unknown solutions, for example f4&5 in Fig. 5 [Shai et al 2009]. After the partitioning concepts may still remain concepts [C→C], or can after explanation and discussion ultimately lead to the creation of propositions in
K [C→K], see in Fig. 5. Also based on some misunderstandings between team members new design sub-solution are formed from a concept C, for example f6 in Fig. 5, which after a transformation by sketching or discussion changes from the unknown to the known and thus becomes a true proposition in K. This transformation can done by validation and evaluation. Also from the discussion and sketches new functions/aspects or sub solutions arise, also a kind of C-K transformations. However, some elements might remain unclear, see for example the ? in Fig. 5 and are as such elements of C-C transformation, without further transformation to K. The Integral Design approach with its use of the morphological overview combined with the transformation between space C and space K, leads to the schematic of Fig. 6.

Figure 5. Morphological representation of the transformation process

Figure 6. Morphological representation of the transformation process within the four operators of C-K theory Hatchuel and Weil (2003)

To stimulate the creativity of design teams further we looked at the effect of the use of the so called C-constructs, sometimes called C-projectors, of the KCP (Knowledge Concepts Proposition) [Elmqquist and Segrestin 2009]. The C-construct is an active K→C operator. These C-constructs can be domain strange concepts, which can be used as a source of inspiration. The C-construct stimulates the subconscious of the designers and as a result they come forward with new concepts. These concepts can then, after evaluation of the possibility of concepts, result in new solutions. This use of C-constructs [Elmqquist and Segrestin 2009] within the integral design method was tested in our Integral Design workshops [Zeiler 2012]. The application of C-constructs enables to expand the knowledge domain, which was formed by the design task related morphological overview by stimulation of new transformation between space K and space C.
3.0 Methodology

Researchers in several disciplines have applied the construct of mental models to understand how designers perform tasks based on their knowledge, experience and expectation [Badke-Schaub et al 2007]. Mental models are often seen as critical indicators of team success [Kennedy and McComb 2010].

Figure 7 depicts McComb’s [2007] three-phase convergence process framework indicating a directional mental model convergence process with feedback loops [Kennedy & McComb 2010]. First, the team members orient themselves by capturing information pertinent to the task. Second, the team members differentiate among the information gathered to discover similarities, differences or irrationalities in their individual approaches. Third, the information becomes integrated into the team members’ views: the individuals’ internal representations of the design task from an individual perspective changes into a team perspective [Kennedy & McComb 2010].

Research on the relationship between design and the creation of knowledge is a relatively recent phenomenon [Heylighen et al. 2009], especially in architecture designers tended knowledge as a hindrance to unfettered creativity. So maybe it is hard for them to admit that knowledge and structure really helps the process. The analysis of the workshop series we organized in the past years showed that morphological overviews actually can provide this knowledge. This has eventually lead us to the idea that morphological overviews, besides being introduced as a tool for integral design process could also be used as a research tool for observation of the design process itself to look which steps and actions were explicit made.

Unfortunately in the conceptual phase of the design it is not possible to accurately evaluate the quality of the mentioned functions/aspects or sub–solution. Only a quantitative analysis is possible by counting the number of mentioned functions/aspects and sub solutions. The number of functions and sub-solutions mentioned by the designers in their morphological charts and the design team’s morphological overview were counted, for an example see Fig. 8.
| Morphological Chart Designer 1 | 11 | 38 |
| Morphological Chart Designer 2 | 11 | 25 |
| Morphological Chart Designer 3 | 10 | 41 |
| Morphological Chart Designer 4 | 10 | 27 |
| Morphological Overview Design Team | 13 | 54 |

Figure 8. An example of the transformation of the individual morphological charts into a morphological overview, indicate the functions/aspects in the morphological overview and where they came from.

3.1 Experiments
Since the year 2000 we, together with the Royal society of architects (BNA), the Association of Consulting Engineers (NLI) and the Society of Building Services Engineers, organized a series of
workshops in the Netherlands. More than two hundred professionals, with at least 12 years’ experience, from different professional organisations voluntarily participated in these workshops. After extensively experimenting with different setups for the workshop, a 2-day workshop setting was selected [Savanovic 2009]. The two days’ workshop was organised as part of a professional training program for architects and consulting engineers (structural engineers, building services engineers and building physics engineers). Since 2005 the structure of the workshop for professionals was applied in the educational “Multidisciplinary master design project” at the TU Eindhoven, department of the Built Environment. Besides the professional setting, in the educational setting at University well over 400 students participated in lectures and workshops about the developed design method. Having a tested framework for introducing the design method allowed us to investigate the effects of different interventions as well as the analysis of several aspects, such as the effectiveness of different designers or the effect of communication in words or sketches [Zeiler 2014]. Here only the latest series of workshops since 2011 will be described focusing on the effects of specific interventions: adding a professional to a student’s team and the use of C-constructs. Figure 9 shows the structure of the workshop sessions with the different interventions.

![Figure 9. Structure sessions of the workshop Integral Design](image)

### 3.2 Workshops for professionals & students

The integral design workshops were the start-up workshop of our multidisciplinary masters’ project. Students from architecture, building physics, building services, building technology and structural engineering was offered the opportunity to participate. Each year there was an average 6 teams consisting of 4 disciplines: architecture, structure, building physics and building services. Students performed similar design assignments, as in the workshops for professionals [Savanovic 2009]. All the assignments of the different sessions were related to aspects of nearly Zero Energy Buildings (nZEB) and had a similar level of complexity which made the results comparable. The whole project took 14 weeks. The average age of the students was 23 and they had no professional experience. In total 142 students participated in the first session of the workshop doing an exercise with morphological charts and the morphological overview.

### 3.3 Intervention: adding a professional to a student’s design team

After the student session, six professionals with about 25 years’ professional experience and having an average age of 50 years participated in session 3, see Fig. 9 and 10. In total, 132 students and 34 professionals participated.
in these workshops series since 2011.

Figure 10. (1) Building the morphological overview; the MO contains the chosen functions and aspects, the individual interpretations from the different MC’s. (2) The MO with the accepted sub solutions, the individual knowledge from the separate MC’s

3.4 C-K theory experiments: intervention with C-constructs
In 2011, 2012 and 2014, experiments with the use of C-constructs were performed. In these experiments 68 students and 17 professionals participated. First in the session with the professionals, the design teams made their morphological overviews, after which a lecture was given about C-K theory and the possible application of C-constructs. The design team continued with the design assignment and tried to generate concepts with the help of some examples of C-constructs that were given to them. The starting point for this session was the morphological overviews of the former design session. The focus of this intervention was on applying C-constructs to make the step from existing knowledge to the unknown world of concept and generation of new alternatives, see Fig. 11.

The number of functions and proposals mentioned by the designers in their morphological overviews makes it possible to compare the outcomes for all different team’s configurations and different workshop sessions. From the used forms we counted the number of functions and sub-solutions in the morphological overview as well as the additional functions and sub-solutions mentioned after the introduction of the C-constructs. The focus of the new assignment was on the application of C-constructs in making the step from existing knowledge to concepts stimulating K-C transformations.

4.0 Results

4.1 From Morphological Chart towards Morphological Overview
A Central element of the Integral Design process is the use of morphological charts by individual designers which were combined into one morphological overview by the design team. Figure 12 gives the results
of the individual morphological charts of the students and Fig. 13 gives the results of the morphological overview of the students’ teams both from 2011-2017. The average number of mentioned functions/aspects in the morphological chart rises from 6.5 to 8.2 mentioned functions/aspects in the morphological charts, an increase of 26%. The average number of mentioned sub-solutions in the morphological chart rises from 20.1 to 31.4 mentioned sub-solutions in the morphological charts, an increase of 56%.

Figure 12. Results students’ workshops Integral Design 2011-2017 first session Morphological Overview, see Fig. 9.

Figure 13. Results students’ workshops Integral Design 2011-2017 second session Morphological Overview, see Fig. 9

4.2 The effect of adding a professional to a student’s team
On average, the student teams (2011-2017) produced in their morphological charts, see Fig. 14 quite similar results compared to the professionals, see Fig. 15: slightly less functions (12% less: students’ average 6.6 professionals’ average 7.5) but slightly more sub-solutions (16% more: students 21.3 professionals 18.4). The results of the Morphological Overview are given in Fig. 16.

Figure 14. The number of functions/aspects or sub-solutions proposed in the Morphological Charts by students in the third session of the Master project integral design (MIO) 2011-2017, see Fig. 9.
4.3 The effect of C-constructs

On average, the teams produced after the intervention with the C-projectors in their morphological overview more functions/aspects from 9.6 to 13.2 (38%) and more sub-solutions: 32.9 to 46.4 (41% more), see Fig. 17.

5.0 Analysis

Using morphological charts during a conceptual design phase is not new, but adding the morphological overview after a team discussion makes it a new design approach. Results show that the group interaction is of great importance during the conceptual design phase and has a clear positive effect on the number of functions and aspects discussed as well as on the number of generated part solutions. This was found by the original research with professionals as well as in the educational setting with students. Given the number of involved design teams in the latest series of workshops, around 34 teams with around 132 participants, there is a sound quantitative basis to draw conclusions from the results. However, there are quite big difference to the effects on the process due to the different characteristics of the individual designers as well as the teams. This although the students all had the same basic educational background from the faculty of the Built Environment on master level and the professionals were selected on at least 12 years of experience.
5.1 From Morphological Charts towards Morphological Overview

An unpaired two-sample t-test was used to assess if the number of formulated functions and solutions differ significantly between the individuals’ Morphological Charts and teams’ Morphological Overviews, see Fig. 18. The average number of functions formulated by the individuals (6.45 ± 2.05) is significantly (p < 0.01) lower than that of the teams (8.24 ± 2.41). The individuals formulated 1.0 - 2.6 (95% confidence interval) functions less than the teams.

The average number of solutions formulated by the individuals (20.08 ± 9.05) is significantly (p < 0.01) lower than that of the teams (31.38 ± 11.82). The individuals formulated 7.8 – 14.8 (95% confidence interval) solutions less than the teams.

Figure 18. Number of functions and number of solutions formulated by individuals compared to teams (based on data from the years 2011 to 2017).

5.2 The effect of adding a professional to a student’s team

An unpaired two-sample t-test was used to assess if the number of formulated functions and solutions differ significantly between the non-professionals and professionals, see Fig. 19. The average number of functions formulated by the non-professionals (6.6 ± 2.03) is significantly (p < 0.05) lower than that of the professionals (7.50 ± 2.06). The non-professionals formulated 0.2 – 1.7 (95% confidence interval) functions less than the professionals.

The average number of solutions formulated by the non-professionals (21.30 ± 9.26) is not significantly (p = 0.09) different compared with the professionals (18.35 ± 8.44).

Figure 19. Number of functions and solutions formulated by non-professionals compared to professionals (based on data from the years 2011 to 2017).

An unpaired two-sample t-test was used to assess if the number of formulated functions and solutions differ significantly between the individuals and teams, see Fig. 20. The average number of functions formulated by the individuals (6.6 ± 2.0) is significantly (p < 0.01) lower than that of the teams (9.5 ± 2.4). The individuals formulated 2.1 – 3.7 (95% confidence interval) functions less than the teams.

The average number of solutions formulated by the individuals (21.3 ± 9.3) is significantly (p < 0.01) lower than that of the teams (32.7 ± 9.7). The individuals formulated 7.9 – 14.9 (95% confidence interval) solutions less than the teams.
Figure 20. Number of functions formulated by individuals compared to teams (based on data from the years 2011 to 2017).

5.3 The effect of C-constructs

The effect of the C-constructs is in all teams positive for the number of sub-solutions, see Fig. 21, however for 3 teams there is no change in the number of functions/aspects. Still also in these cases there is an increase in the number of mentioned sub-solutions in the Morphological Overview. So the effect is positive in all teams.

Figure 21. Percentage of change in the numbers of the functions/aspects (and sub-solutions included in the Morphological Overview after the intervention with the C-projectors

6.0 Discussion

Although workshops are not a real experiment as there are no controls like in a real experiment we have some arguments to choose this approach. The workshop setting of a team in the conceptual phase of design is a common situation in Dutch practice, when the integral design approach is applied meaning normally that from the beginning all design team members start together. Schön (1987) has proposed a practicum as a means to ‘test’ design(ing). Where a practicum is “a virtual world, relatively free of the pressures, distractions, and risks of the real one, to which, nevertheless, it refers (Schön 1987, p.37)” A practicum can assess a design method and the degree to which it fits human cognitive and psychological attributes (Frey and Dym 2006). Crucial is the simulation of the ‘typical’ design situation. A workshop can be seen as a specific kind of practicum. It is a self-evident way of working for designers that occurs both in practice as during their education. As such a workshop provides a suitable environment for testing the design approach. Workshops make it possible to gather a large number of students and professionals in a relatively short time, repetition of the same assignment and comparison of different design teams and their results. Fortunately the researchers were involved in the design of a multi-functional nearly Zero Energy Building in the Netherlands and could organize in December 2014 as workshop in a real project setting. This enabled us to compare the results of this workshop with those of the professional teams from the research of Savanovic [2009] as well as with the results of the session 4 of the MIO workshops at the University in which students and professionals cooperated. As shows from Fig. 22 the results are quite similar, which shows that the use of the workshops is a good way of representing the design process in practice.
The advantage of our approach, which uses individual morphological charts transformable by the design team into a morphological overview, is that the design team’s discussion begins after the preparation of the individual morphological charts. This allows each designer to develop his own interpretation and representation, in relation to his specific discipline based knowledge and experience. This interpretation can then be combined with the interpretations by the other designers into a morphological overview. The different interpretations of the design brief result in a team specific morphological overview based on the morphological charts from each design team member. In summary, this approach results in more functions and aspects generated through the individual interpretation of the design problem as well as the generation of more sub solutions from the different disciplines.

6.1 The effect of adding a professional to a student’s team
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 has not yet received enough attention (Casakin and Badke-Schaub 2013). Traditionally, a design method is developed at a university where it is tested on students and then implemented in practice. In this research, that was changed; the testing was done as close to practice as possible with professionals and then implemented at the university. 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).

6.2 The effect of C-projectors
As stated by Le Masson et al. (2007) there is an interplay that links creativity and design theory. That interplay leads to new ways of managing design, new ways of managing knowledge, processes and organizations for design activities. In our case we used the framework of integral design in combination with C-K theory to stimulate creativity within multi-disciplinary building design teams. In all situations (18 teams and participants 78) there was a positive effect of the application of the C-constructs. However, to be sure about the effect, we should in future also want to do the experiment in a kind of double blinded procedure. So for example, allow 3 teams work with the C-constructs and give the other teams the same time to work on the extension of the morphological overview without any new input or tools.

6.3 Quantitative analysis
Using the morphological charts and morphological overview as analysis tools allowed us to present the outcome of the group interaction in large numbers, something that would not be possible when using say protocol studies. In the earlier research by Savanovic (2009) all session were videotaped, some participants were interviewed and surveys directly after the workshops and after a period of six months were held. As our focus was on the stimulation of the generation of possible sub-solutions and less on what actually happened in that interaction it was decide not to use additional analysis methods.

As the sub-solutions mentioned in the Morphological Overview have to be agreed on by all design team members before they become actually part of it, this might indicate a higher quality level of those sub-solutions compared to one mentioned in the Morphological Charts and not included in the Morphological Overview. Still in the conceptual design phase it is not possible to accurately evaluate the quality of a proposed sub-solution. The activation of design team member’s knowledge through a priming manipulation such as the use of a
morphological overview or interventions like the use of C-projectors, leads to the generation of more sub-solutions. However, there is an uncertain relation between quantity and quality. The most parsimonious interpretation of the quantity-quality relation is chance [Rietzschel et al 2007]: each generated idea has an equal probability of being a good idea. Therefore, according to the laws of chance, the number of good ideas produced should increase in dependency of the total number of ideas produced [Rietzschel et al. 2007]. Still there is no simple linear relation between total productivity and the number of good ideas. An alternative view is proposed by Rietzschel [2007], which states that creative idea generation is enhanced by deep exploration of relevant domain knowledge, and that generating more ideas within a particular subcategory of the overall problem should be associated with a higher originality of those. This view fits to the application of Morphological Charts as an overview of the specific domain knowledge. The degree to which individual designers undertake deep exploration of a particular function or aspects from out their domain is a mechanism to stimulate the process and to focus on quality. That would mean an important step to added value of the combination of design & creativity in the building design process.

7.0 Conclusion

A new design approach, Integral Design, was developed to support all the disciplines involved in the building design process by structuring the communication and solution generation process in steps and structuring the information flow about the tasks and solutions of the other disciplines. The method forms a design within the design process and enables a structured approach even in the conceptual design phase. All the steps in the process become transparent and can be analysed and learned from to further improve the design team’s process. The use of morphological charts and morphological overview enables to open up important parts of the team’s mental model, so that the team can reflect on their collaboration process to further improve it. Results showed that Integral Design was a good way of showing the knowledge and influence of each design discipline/member. The main lessons from the paper are that Integral Design with its use of morphological overview stimulates collaboration and exchange of ideas and perspectives between architects and engineers and helps them with their communication. It is a good method for supporting the education of a new generation of architects and engineers, who each have new roles in the highly complex tasks of designing sustainable cost effective nearly Zero Energy Buildings.

The educational setting allowed us to further investigate interventions in the design process of students and professionals. The results of three interventions were presented:

1. stimulate the creativity of design teams by applying the integral design method with its use of morphological overview
2. introduction of a professional to the student’s design teams during the workshop
3. use of C-constructs to further stimulate the generation of alternatives

All presented interventions had a positive effect on the number of proposed sub-solutions and also on the amount of functions and aspects considered in the conceptual phase of the design process. This indicates that the effectiveness and productivity of design teams can large improved by adding structure to the process as well as add experience to the design team. Making the design process steps transparent enables easier exchange of information. This will also improve team members understanding of each other’s tasks and results in better communication and combined efforts to further generate more part solutions. This way students, architects and engineers will be better prepared for their future professional collaborative role in sustainable development by means of integral design approach. The role of the morphological charts and morphological overview is essential in structuring the process as well as it enables analysing the conceptual design process in more detail. As such is it a valuable approach to invent the necessary new more sustainable solutions for the future.

Our research is focussed on the conceptual design phase. However, as the sub solutions are put forward in the conceptual design phase, there is no possibility to make a statement about the quality of the mentioned proposals. In this face there is often not enough information, this being gathered during the design process. Therefore, we only included qualitative results in relation to the effect of the interventions that we made to the design process. The only thing about quality might be that the more functions are mentioned the broader the analysis of the design brief might be done. For example in the case of the application of the C-constructs there is clearly a positive effect, as there was an increase in the average number of mentioned functions.

The results of individual design teams can show large differences, depending on all kinds of aspects relating to personality, social capabilities, attitude etc. of the individuals within the teams. Therefore, we selected students from our University who all had similar educational background and experience, as well as were about the same age. Nonetheless there is still a big difference in the manner people are able to express, discuss and share their thoughts in design sessions. It would be interesting to research more diverse design teams.

The method has been part of the professional education program of the Dutch Society of Architects in 2005-2009. Quite remarkable is that one of the participating architects became a true propagator of the method and uses it in all his projects, gives lectures and publishes about it [Goossen 2013, 2017]. The method is being taught
since 2005 at the Faculty of the Built Environment of the TU Eindhoven. It forms the main part of a Dutch educational design book for students in higher education, published in 2015 and of which have been sold around 1,000 copies a year and of which this year also an English version was published [Zeiler 2017]. So in the Dutch educational system the Integral design method with its specific use of Morphology found its place. However, given the relative small number of professionals which participated in the workshops and the students now working in industry, it will take quite a while before the morphological approach in conceptual building design will be diffused into general architectural practice.

Acknowledgements
This research was done in cooperation with the Dutch engineering consulting companies: Deerns, Smits van Burgst, Valstar Simonis, RHDHV and Nieman. The project was financially supported by the professional organisations UNETO-VNI and OTIB as well as the foundations WOI and PIT. The earlier research which formed the basis was supported by the Dutch Society of Architects BNA, the Dutch Society for Consulting Engineers ONRI-NL and the Dutch Society for Building Services Engineers TVVL.

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