

Teaching and Learning CAAD and CAM in a Fluid Era

Tools and Strategies for the Analysis and Synthesis of Ill-Defined Construction Problems

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Abstract

In this paper we discuss a series of tools and strategies to support learner-centred construction education in the complexity of the era today (Bauman, 2000). By using these tools in the education of CAD and CAM in construction education at universities for the arts, design and architecture, we aim to support the student in the abstract aspects of Bloom's (1956) cognitive learning domain. In order to present a coherent spectrum of educational tools and strategies, we start with the introduction of a tool for problem-analysis. The tool is explained by applying it to the context of spatial design construction, digital design and fabrication. Then we shortly discuss the process of design-evaluation. Next we introduce three models for design-synthesis. Afterwards, an test case is used to elaborate on the different tools and strategies which are tested and evaluated.

Introduction

Students at universities for the Arts, Design and Architecture (ADA), are often confronted with complex digital systems and elaborate spatial structures during their education involving Computer Aided Architectural Design (CAAD) and Computer Aided Manufacturing (CAM). The complexity of student learning in these courses is often enhanced by the fluid character of the era of today. In this context, a fluid era is understood as a rapidly changing age that undermines all notion of durability and stability (Bauman, 2000). Accordingly, the knowledge transferred to first and second year students today, is highly likely to become obsolete by the time the student is actively involved in professional practice after graduating. Therefore a revision in teaching and learning is compulsory in order to link the end of the students' education to the start of their professional careers.

The great body of knowledge and large number of parameters and decisions to be captured in CAAD, CAM and design engineering courses can provoke a sense of discouragement to ADA-students with minimal background in making and construction, and limited abilities in abstract thinking and abstract reasoning. Generalising concepts, finding patterns and removing unnecessary details require abilities often associated with engineers and scientists (Roberts, 2009). ADA-students in the courses at universities we teach, generally have difficulty with these tasks (Vrouwe, 2013). However, learning theories indicate that when students are provided with sufficient sense of **competence** and enough **autonomy** in their work and actions, they often obtain adequate *intrinsic motivation* (Deci et al., 1991) in order to attack the tasks and challenges ahead. As opposed to being *extrinsically motivated* by earning points and diplomas, this type is driven by internal rewards like the enjoyment of making, interest in the topic and the satisfaction of making progress. Consequently, students experience abstract and difficult challenges being more meaningful and less insurmountable. Though, when these needs are not met, **non-learning** (Illeris, 2003) is likely to occur and students start to lose focus and motivation and shift their attention to digital social networks and similar distractions.

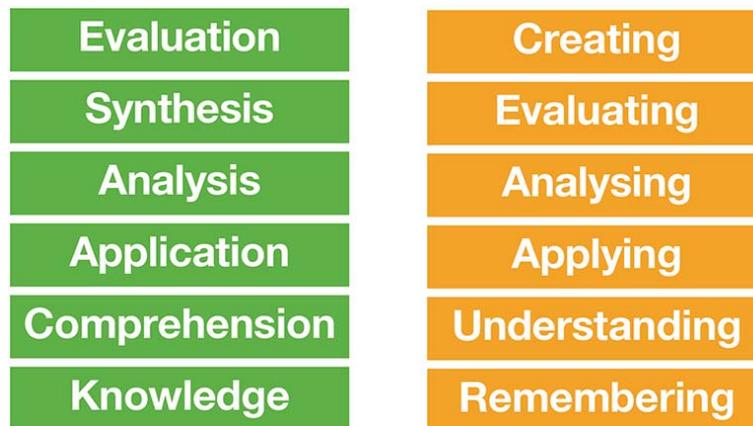


Figure 1. Bloom's Taxonomy of the Cognitive Domain. Traditional version by Bloom, Engelhart, Furst, Hil and Krathwohl, (1956) on the left side, Revised version of Krathwohl (2002) on the right side.

In order to frame the discussion on teaching and learning in this paper, Bloom's taxonomy of the cognitive domain (Bloom et al., 1956; Krathwohl, 2002) is used. The taxonomy was first introduced in 1956 and was revised in 2002. Both the taxonomy of the cognitive domain are divided into a lower and a higher level but differ in order and designation of the individual categories. When we take the revised version for example, the lower level describes the categories 'remembering', 'understanding' and 'applying'. In the higher levels we find the categories 'analysing', 'evaluating' and 'creating'.

Traditionally, engineering education aims at the assessment of student learning at the lower level of the taxonomy (Arens, Hanus, and Saliklis, 2009). By using a staff- or teacher-centred approach in education, the teacher is an active instructor by giving lectures. In turn, the student is a spectator or passive reader. In this setting, knowledge is transferred and exercises of well-defined problems are demonstrated in large classrooms during sessions of approximately one hour. Finally, during assessments and exams, students are asked to reproduce the knowledge from the course by answering questions and to demonstrate their understanding by solving slightly altered problems as demonstrated by the teacher.

In recent years, the staff-centred approach has become ineffective to a greater extent (Wagenaar, 2014). Consequently, Barr and Tagg (1995) discuss a paradigm shift from an **instruction paradigm** to a **learning paradigm**. As opposed to learning as being a spectator sport or passive activity, the new paradigm aims at active involvement of the students in structured exercises, challenging discussions, team projects, and peer critiques (Chickering, 1995). As a result of the change from the passive paradigm of spectators to an active paradigm of producers, the aim of student assessment shifts from the components in the lower level in Bloom's taxonomy of the cognitive domain to the competences in the higher level.

In order to strengthen the construction education towards the learning paradigm, and support ADA students in our classes to achieve the higher levels of the cognitive domain, we will introduce the tools and strategies that are designed by the first author as part of his doctoral research called 'Sensemaking in Construction'. First we will discuss a tool for problem-analysis and shortly explain various aspects of aspect evaluation. Then, a series of strategies for design synthesis will be presented and evaluated through tests in a workshop environment.

Tools and Strategies

As discussed in the previous section, Krathwohl (2002) describes three components in the higher level of the cognitive domain. From the lower category ‘analyse’, to the higher categories ‘evaluate’ and ‘create’, the complexity as well as the embedded cognitive processes increase. In textual description and visual representation in Krathwohl’s work, the components are presented as independent units. However, in educational practise, he emphasizes an overlap in the categories in order to provide a fluent transition of activities during courses and workshop exercises.

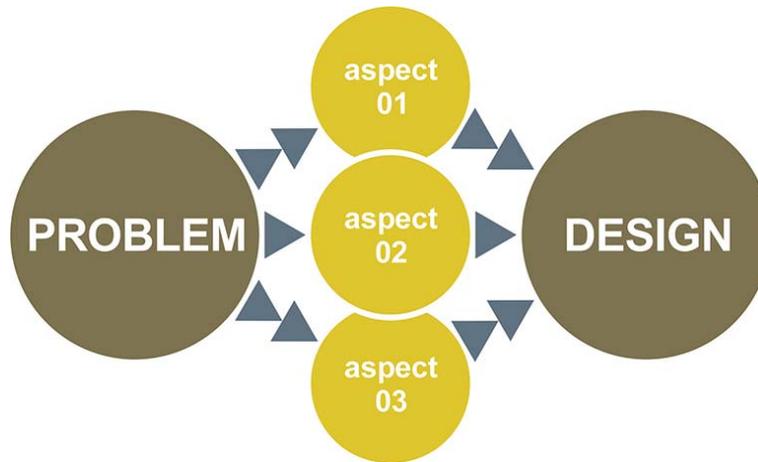


Figure 2. Operation model of the categories of the higher level of the cognitive domain.

In figure 2, we describe an operation model where the three categories of the higher level of the cognitive domain are placed in sequence. In this model we perceive an operation where a problem is taken into constituent aspects first. The nature of these aspects is highly dependent on the problem at hand. For example, in spatial design construction, aspects like ‘material’, ‘products’, ‘processes’, ‘connection’ and ‘structure system’ can be discussed. In poetry aspects like ‘cadence’, ‘form’, ‘rhyme’, ‘rhythm’ and ‘verse’ can be considered. Secondly, the aspects acquired during the first step are discussed, explored, tested and evaluated. Finally, the most satisfactory set of aspects is put together into a novel and coherent whole.

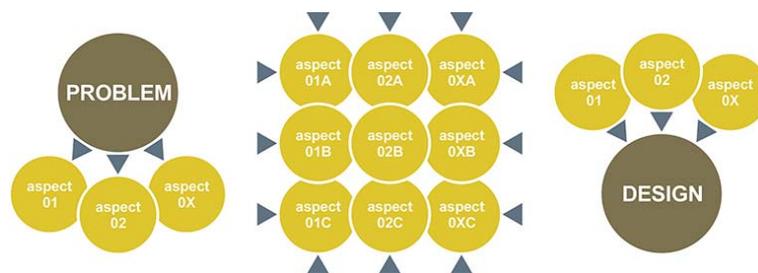


Figure 3. Problem Analysis (Image on the left side), Aspect Evaluation (Image in the middle) and Design Synthesis (Image on the right side).

In order to support the operation model as discussed in figure 2, we distinguished three components called ‘Problem-Analysis’, ‘Aspect Evaluation’ and ‘Design Synthesis’ (as presented in figure 3). For the first component of the operation model, a **problem-analysis-tools** is designed. The tool assists students in the process of subdividing complex problems into smaller constituent aspects. As a result of this division and abstraction process when analysing the problem, the aspects can be studied in a smaller, less complex context. By first

studying the aspects in small combinations of two to three items, knowledge and understanding of the matter at hand can be acquired in coordinated and structured steps.

Opposite to the independent ‘parts’ of atomistic part-whole relationships, this tool distinguishes ‘constituent aspects’ in order to preserve the holistic properties of the whole. In problem solving using part-whole relationships, parts can be solved independently from the whole as it is the case with for example complex mathematical or software problems. Constituent aspects however behave interdependent. In this case, the student is directly confronted with the multitude of aspects of the design problem at hand and the relations of one aspect to the other. Consequently, the change of one aspect may influence the decisions in another (van Merriënboer and Kirschner, 2007). To visualize these interdependent aspect properties, the aspects in figure 2 and figure 3 are positioned in an overlapping and linked sequence.

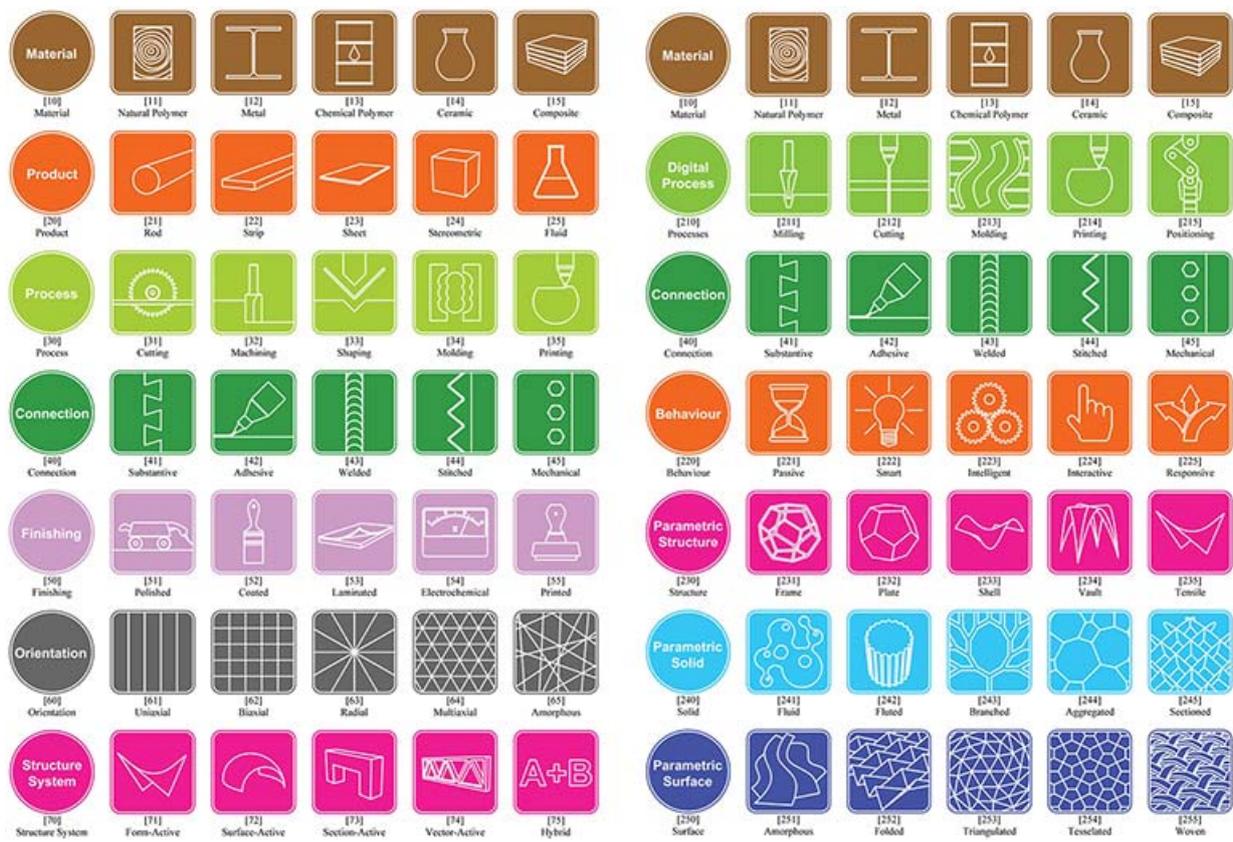


Figure 4. Problem Analysis Tools; Taxonomy for Spatial Design Construction (Image on the left side) and the Taxonomy for Digital Design and Fabrication (Image on the right side).

In order to illustrate the use of the problem analysis tool in pedagogical design workshops, two taxonomies are designed. The first taxonomy, presented on the left side in figure 4, discusses spatial design construction and is introduced during the eCAADe 2013 conference (Vrouwe and Swieten, 2013). The second taxonomy, presented on the right side of figure 4, discusses digital design and fabrication and is introduced during the eCAADe 2014 conference (Vrouwe and Pak, 2014). Both taxonomies discuss seven constituent aspects named supertypes and positioned vertically. Each of these aspects is subdivided into five subtypes, positioned horizontally.

When a student is presented with a design problem concerning spatial design construction or digital design and fabrication, the analysis process of subdividing the task into constituent

aspect (i.e. supertypes) is supported by the taxonomy presented in figure 4. By studying a combination of small sets of subtypes the student acquires adequate knowledge and understanding of the aspects discussed. These studies can range from written research and presentations to building mock-ups and prototypes (Vrouwe, 2013).

After finishing the **problem-analysis** component of the operation model, the student starts with the second component of the operation model called **aspect-evaluation**. In the universities we teach, the level of skill needed in this phase is often well developed through studio and project education. Therefore no particular tool or strategy for this component is designed in the presented research. In the evaluation-process, the aspects are reflected against an underlying concept, a predominant idea or a set of program requirements first. Then, the aspects properties are calibrated against one another. When, in this process, one aspect is changed or adapted, this may influence the choice of others. Therefore, evaluation is often described as an iterative process discussing combinations of testing alternatives.

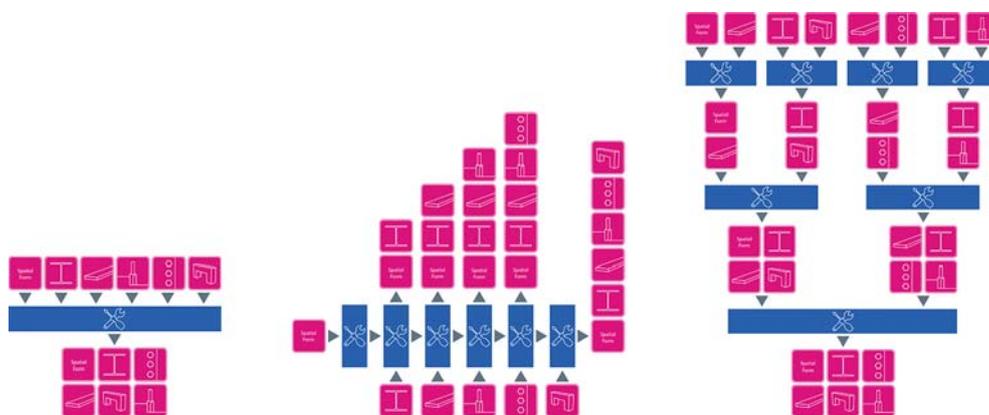


Figure 5. *Parallel-Synthesis-Strategy (Image on the left side) Linear-Synthesis-Strategy (Image in the middle) and Pairwise-Synthesis-Strategy (Image on the right side).*

The aspects, deriving from the aspect-evaluation form the basis for the final component of the operation model. For this stage a series of **design-synthesis-strategies** is designed. In this strategy ‘synthesis’, as used in the original taxonomy of the cognitive domain, is applied because of the connotation in relation to the content of the tool. By these **synthesis-strategies**, the studies of the constituent aspects are integrated into a design by a step-by-step process.

The first model discussed is the **Parallel-Synthesis-Strategy**, presented on the left side of figure 5. In this model, the student starts with a large set of constituent aspect and brings these elements to a design in a undefined and unstructured process. In practice, this synthesis process proves to be ineffective. The large number of parameters and decisions to be captured at once during these exercises are often considered as overwhelming. Accordingly, student start skipping aspects, which brings the exercise to an incomplete and incoherent design (Vrouwe, 2013).

When complex models fail in practice, most design models emphasise dismantling the exercise to a scale that is manageable by the student. However, novice learners solve simple tasks differently than complex ones (van Merriënboer, Clark and de Croock, 2002). Consequently, whatever skill is learned in a simple task, may not be useful in a more complex variant. In order to avoid this ineffective parallel-synthesis-model, whole-task experiences are

used. These experiences are based on real-live tasks and are presented as a holistic whole. By linking easy-to-difficult tasks in a coherent sequence, the complexity of the task is increased gradually without isolating exercises. Consequently, the student is likely to be provided with sufficient sense of competence and autonomy in their work and actions along the course in order to remain motivated to finish the challenges ahead (van Merriënboer and Kirschner, 2002).

In order to test different whole-task models, two models are designed. The first model is the **Linear-Synthesis-Strategy** as presented in the middle of figure 5. This strategy describes a series of iterations that are linked in a linear sequence. At first, the sequence starts with a spatial form. This form can, for instance, be a folded paper model a cardboard study or a foam miniature. Then, with each step in the sequence, an aspect of the spatial form is replaced by one of the aspects as discussed in the evaluation phase. For example, the paper model can be replaced by a cardboard model first. In this step the complexity of material thickness and decreased material flexibility is introduced. Secondly, the processing aspects are introduced. Instead of cutting with scissors or knives, different tools will be explored in order to machine rigid materials. Then, the sequence can be finished by introducing the chosen connection details, finishing processes, increasing the complexity gradually.

The second whole-task model, as presented on the right side of figure 5, is the **Pairwise-Synthesis-Strategy**. The strategy consists of multiple steps, increasing the complexity exponentially. In the first step of the strategy, a large set of aspects is studied in combinations of two. In this phase small mock ups are made combining aspects like material, product, process and finishing. With every step, the outcomes of the former step are combined in another study until all aspects are brought together into a holistic and coherent whole.

Test Case

In order to discuss the opportunities and challenges of the design-synthesis strategies as described in the previous section, an experimental test case was prepared . This study was an eight-day construction workshop assisted by CAD and CAM based on a problem-based-learning approach (Newman, 2005). In order to keep the objects of production manageable within the boundaries of table top 3D printers and laser cutters, the scale of furniture design was chosen.

The workshop was carried out by four teams of eight second-year bachelor spatial design students from Utrecht University of the Arts. Generally, the students have limited background in CAD and CAM. In the exercise, the taxonomy of digital design and fabrication was used for analysis. Furthermore, both the Linear-Synthesis-Strategy and the Pairwise-Synthesis-Strategy were used. In order to compare both the serial-synthesis-strategy and the pairwise-synthesis-strategy, two teams worked according to the one model and two teams according to the other.

All four groups designed a sleeping couch. The construction is assembled by digitally manufactured connection details. The couches are designed for use in their own living environment. By day, it is a couch. In the evening, the couch is transformed easily into a single or double bed.



Figure 6. Aspect-studies of the furniture construction workshop.

At the start of the workshop sequence, the two synthesis strategies were explained. Then, groups of eight students were chosen and divided by using the Belbin test. The Belbin Team Inventory is a personality test that measures preference for specific team roles. In the model nine team roles are described ranging from action roles to social roles and thinking roles (Gündüz, 2008). Starting from the students team roles that scored the highest in the Belbin test results, specific tasks were assigned within the team. One person of the group was assigned the role of chairwomen or chairman. Subsequently, the remaining students took on the role as manager, builders, planner or researcher.

First, the chairman and the manager discussed the assignment. Then the assignment was divided into constituent aspects by using the assigned taxonomy. Next, the planner assigned the work related to the different constituent aspects, to the different individual team members and worked out a working plan for the workshop period.

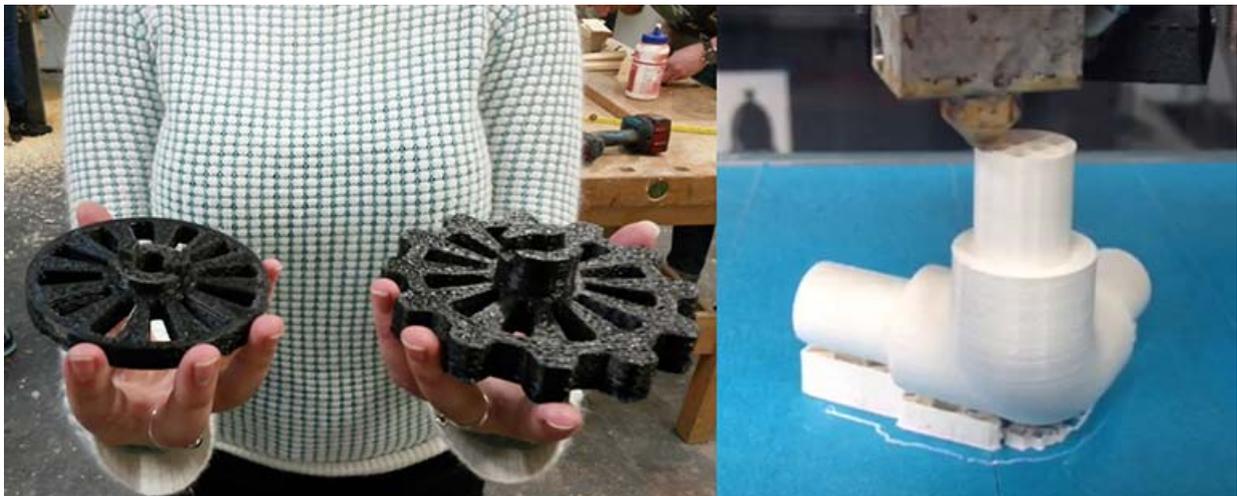


Figure 7. Digital aspect-studies of the furniture construction workshop.

Every week a reflection on the process was scheduled. In the first weeks, the chairwomen, managers and planners participated in these meetings. During the meetings, workshop progress, group dynamics and prospects were discussed. In the following weeks, researchers and builders joined the discussion. Finally, the workshop period was completed by a video presentations from each group. The videos showed a montage of all steps of the process and forms the basis for a final discussion on the process.

In order to reflect on the student experience of the use of the synthesis strategies, interviews, exhibitions, presentations and the success reflection method of Benammar et al. (2001) were used. With this method, a group-wide reflection was conducted, using a four-step process. The method started with small group discussions that resulted in the naming of success factors using pens and post-its. These success factors were words or sentences that describe aspects that add to the success of using synthesis strategies during the workshop. Then, using a series of steps, the collected success factors from each group formed a basis for group reflection and feedforward.

The grouping of the outcomes of the success reflection described four success-themes, namely, group work, materials, process and phases, and execution. In this theme qualities of the synthesis model with respect to management and collaboration were elaborated. In this series of aspects the quality of the assignment of task within the group was appreciated. By dividing the assignment into constituent aspects, clear tasks could be assigned to individual team members. As the result of the clear structure that which occurs, collaboration and communication was better supported. Furthermore, the team roles helped to accelerate the building process. Because all students were assigned with specific responsibilities, not all students were involved in reflection moments each week. Consequently, at every time of the workshop period, a group of students was active.

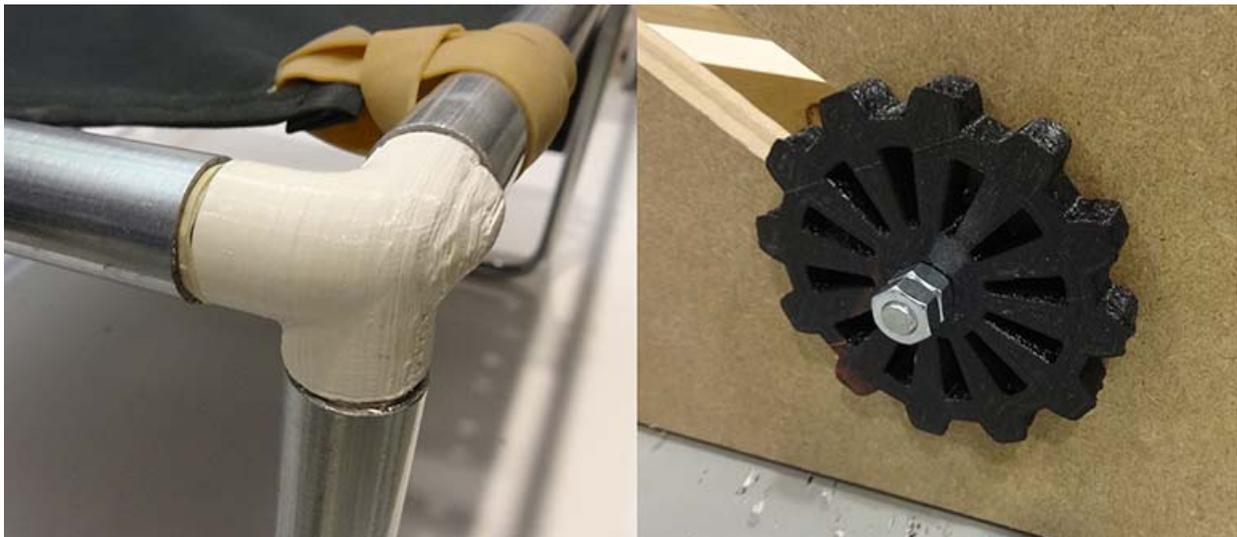


Figure 8. CAM-details of the furniture construction workshop.

In the second theme, the material qualities of the exercise was discussed. In this series of aspects, the research aspects of the exercise was valued the most. By dividing the process in smaller aspects the students describe a sense of overview of the task at hand. As a result of the small steps, described in the synthesis model, design decisions with respect to material and construction can be coordinated easily. Furthermore, the discussion of various proposals, assisted the quality of group discussion and constructive design decisions.

The third theme, was the result of workshop phasing. By making a description of workshop phases, the students experienced a clear process and a distinct working structure. Supported by the constant attention to planning and responsibility, the weekly reflection was experienced as a constructive meeting where decisions were made quickly and easily.

In the final theme, the quality of design-synthesis by hands-on learning was valued. During the exercise, the students were motivated in the learning process, by the active interaction with the constituent aspect on the one side and the collective goal on the other. Furthermore, the motivation was enhanced by the application of software and digital manufacturing processes in a world-scale object, in a limited amount of time. The short period in which the model was designed and produced provided the student with a sense of a sprinting mind-set rather than an endless process. Where in studio exercises, the conceptual phase of the design process is of the emphasised, in this exercise all phases were experienced equally. Consequently, the relativity of skill and action of specific phases and activities was experienced. Accordingly, performing a specific role in a team of multiple disciplines, provided a taste of the experience of professional practice.

Conclusions and Future Suggestions

In the case study, the presented synthesis-strategies was effective in supporting the students in the aspects of abstract thinking and abstract reasoning of problem solving in construction education supported by CAD and CAM. By subdividing a complex design task into manageable constituent aspects, the students were able to interact with the different components effectively. Results from the success reflection indicate that the use of aspect model studies supported the understanding of the studied aspect. By using a iterative process of model reflection, aspect proposals for use in the final design were understood adequately by the group members.

In interviews, students indicated that using the synthesis-strategies, they were able to bring a series of aspects to a coherent whole using the step-by-step approach in an active and playful way. This quality, provided the student with competence and autonomy in order to solve complex construction challenges. Consequently, the students gained sufficient intrinsic motivation in order to finalize the project effectively.

The competencies as described in higher level of the cognitive domain were effectively supported by the tools and strategies provided in this research. This quality was well reflected in the final exhibition of the designs. The different aspect were well analysed evaluated using a wide range of model studies. Then, the relation of one aspect to the other was studied in synthesis iterations by testing, exploring and combining.

By using visual representations of the different steps of the design, combined with the model studies, the students showed their ability to construct knowledge and understanding in the act of creation. With a shift on the emphasis on the competencies described in this level, rather than the emphasis on the transfer of abstract knowledge, the students could construct the knowledge, required in construction design exercises, during the design process.

With the shift from a teacher- to a learner-centred model, the student was introduced to **real-world** and **ill-defined problems** (Simon, 1973; Rittel and Webber, 1976). Accordingly, with a focus on the knowing-how, rather than knowing-that, the students developed competences that are less time-dependent (Wagenaar, 2014). Therefore, the students were more likely to be prepared to act in the fluidity of professional practice of today and were better to respond to real-time information and systems.

In the success reflection session, no obvious differences between the group using the linear-synthesis-strategy and the group using the parallel-synthesis-strategy were found. In future

research, the different observation and reflection tools will be used in order to compare both models more effectively. Consequently, the comparison of differences in quality of use and the quality of resulting models will be an interesting research trajectory to be followed.

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