

# From Concept to Reality: Digital Systems in Architectural Design and Fabrication

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One of the challenges for today's architectural designers is the establishment of continuous digital processes between design and fabrication. To achieve this, designers need to acquire knowledge about the production and the methods and tools involved. Two case studies organized at the Norwegian University of Science and Technology (NTNU) on digital timber fabrication investigate the new field of collaboration between architectural designers and fabricators. The studies demonstrate the design potential of acquiring insights into the fabricators' software and digital production machinery and reflect contemporary fabrication technology in formal expression. We identified two different approaches to formal exploration that we defined as "sophistication of the detail" and "variation of the element".

## I. INTRODUCTION

The potential to design whatever non-regular shape imaginable with the aid of modern CAD systems has successfully entered the realm of architecture and the curriculum of architecture schools. Rapid prototyping equipment like 3D printers is becoming more and more common and allows the materialization of such designs on a model scale. But the 1:1 realization is too often just handed over to specialists, assuming that fabrication methods in full-scale architecture follow the same principles as model making. To really bridge the gap between design and fabrication, it is necessary to acquire knowledge about the real building process and the methods and tools involved. We will argue that this will not only lead to a smoother and more successful building process, but also to an enhanced quality in design itself.

The frictionless exchange of data is today a major concern in the AEC industry at large, as epitomized by the efforts of the International Alliance for Interoperability and the building SMART initiative. The optimization of the digital data exchange from design to production is a part of this larger picture but also with its particular challenges. Although we today may ‘print’ the model of a building digitally as in rapid prototyping, there is still some major obstacles before we can send design data directly to a producer and expect a flawless result just as imagined in the designer’s mind (or computer). A central issue here is the material that is intended to be used in the final structure. Already in the project development phase, the designer must be aware of the fact that the production machinery is constructed so as to handle materials with specific characteristics. In consequence, the design must be materially oriented from the outset.

### I.1. The Digital Chain

The concept of the “digital chain” or “file-to-factory” processes has been explored by researchers and also in several teaching projects during the last few years [1–3]. There are also several research and teaching projects in full scale based on a digital production chain [4–8]. However, in these cases practical requirements for a long life-cycle such as rain drainage, structural needs, user safety, and other legal building standards have rarely been considered. Our projects may be regarded as a contribution to the line of 1:1 experiments realized through a digital chain, but with a strong emphasis on the practical requirements of a structure that is intended as permanent.

### I.2. Timber Structures and CNC Fabrication

This article focuses on design and production of timber structures. It will argue that it is not only the digital tools used during the design phase that determine the architectural outcome of a design process. The result of the design process may be interesting in itself. However, if the designer intends

to see the project realized as a close approximation to the design as possible, the limitations given by the CNC production machinery and indeed the material itself must be taken into consideration even in the early design phase. Since the beginning of industrialization, timber construction has been the standard material for prefabricated housing. Because of this background, between the nineteenth and twentieth centuries the technical development of timber production chains and machines was more advanced than any other in the building industry. Today, timber manufacturing infrastructure has changed significantly from inflexible mass production tools to an excellent level of flexible CNC-machines. Producers are relying largely on digital processes to control their computer-aided tools, but are using this potential mostly for customizing industrial processes in prefabricated housing. CAM software and CNC tools in timber construction differ from other applications in the building industry. While routers, lathes and mills were well introduced in machine engineering before they were used in building construction, CNC machines for timber construction were specifically developed for their trade and therefore match the requirements of the building industry, such as the large scale of the prefabricated panels, specific tolerances, low budgets, and high processing speed.

The most widely used CNC machinery in the timber building industry are machines that prepare components such as beams for subsequent assembly into larger elements or panels. In general this type of CNC machinery is termed “beam processors”. In our projects we have worked with two types of CNC machines, both made by the German company Hundegger Maschinenbau GmbH [9]. Hundegger calls the simplest of their beam processors – the SpeedCut SCI machine – “an automatic cutting machine”. It was developed mainly for the rapid and precise cutting and the processing (milling, drilling, marking, and lettering) of simple wooden constructional components. The tools operate in four axes. The larger Hundegger K2 and K3 may be either 4-axis or 5-axis machines, defined by Hundegger as “fully automated joinery machines”. These machines make the same operations as the SCI.

While the timber building industry’s beam processors are mainly used for mass-production, our projects, on the other hand, aimed to study the use of the same machines in the context of mass-customization so that each building component may be different but without affecting the efficiency of planning and production. The projects aimed to demonstrate the design potential of the beam processors taking the production capacities of the machines beyond their normal use and to show how contemporary fabrication technology can be reflected in design. The aim was to demonstrate for architectural practices the design possibilities when working with the production technology in mind using the capabilities of digital fabrication technology consciously in the design process. Timber construction holds a large share of the Norwegian building market, especially in housing projects, but there are hardly any architects involved in

the design. Thus it was considered an important outcome of the projects that architectural practices should become aware of the industry's possibilities for realizing new concepts in architectural design.

► Figure 1. The Hundegger Speed Cut SCI CNC machine used by Kjeldstad Sagbruk & Høvleri AS to produce the nearly 700 timber components for the Ringve Botanical Garden Viewing Platform, one of our case studies. All components were automatically labeled with the machine's ink lettering unit. Without this numbering system it would not have been possible to assemble the structure.



## 2. CASE STUDIES

The two case studies presented here are the results of a research, development and innovation project in the years 2006 - 2007 at the Faculty of Architecture of the Norwegian University of Science and Technology (NTNU). The project was funded by the Norwegian government's industrial development organization, Innovation Norway. Innovation Norway promotes nationwide industrial development profitable to both the business economy and Norway's national economy.

The series of case studies is called 1-2-TRE, aimed to study how digital fabrication technologies and off-site production may enhance timber construction in Norway. The numbers (1, 2) refer to the digital content of the project while the word "tre" refers to wood, which is the building material that the project focused on. However, the word "tre" has two different meanings in the Norwegian language. Firstly, "tre" means the number three; secondly "tre" means wood. Thus, read in Norwegian, the name will be as in English "one-two-three", as well as "one-two-wood".

### 2.1. Project Realization

The framework for the case studies was two courses for graduate students in the fall terms of 2006 and 2007, organized as full semester courses. In each of the courses we aimed to identify a client for the project and also to build a structure that was intended to be permanent and not as a kind of temporary installation. For the two case studies presented in this article we cooperated with several wood fabricators. These companies had acquired beam processors in order to make their production of standard pre-cut components for roof trusses and pre-cut components for framed timber wall panels more efficient. In other words, their aim was mass-production with increased speed and cost-efficiency in comparison with manual production.

The first course in the fall semester of 2006, called I-2-TRE:6, designed and built a permanent walk-in Camera Obscura in the center of Trondheim city for the “Trondheim Science Center”, an institution established by the university with the purpose of informing the public about principles and advances in science and technology. The structure of the Camera Obscura consists of four gluelam sill beams and four gluelam top beams with rather complicated cuts to accommodate the 16 wall planks of each of the four walls. Each of these wall planks has different geometry.

For the course in the fall term of 2007, called I-2-TRE:7, the management of the University’s botanical garden at Ringve invited us to build a combined viewing and access platform to a small natural woodland that is part of the botanical garden. Their vision was to have a structure that would become a permanent installation for the benefit of the garden’s visitors. The platform should have two purposes. First, it should lead visitors into the woodland, and, second, it should give the visitors an opportunity to look into the tree crowns. The structure based on a concrete and steel foundation consists of more than 700 components, all with different geometry.

The two courses had three main purposes. These were to give the students knowledge of and experience in (1) the use of wood as a building



◀ Figure 2. The Trondheim Camera Obscura completed in December 2006. Photo: Øystein Hermstad, Norsk Fotofagskole.

material, (2), the use of digital technologies for the planning and production of timber structures, and (3) the legal and practical requirements concerning the building of a permanent structure in full scale at a fixed site. Thus, one might say that the digital content is a part of a larger whole. Although this article focuses on the digital content, it is also necessary for the understanding of the case studies to keep in mind that during the two courses the students designed, fabricated, and constructed on site the two buildings during a relatively short period of time. The building phase in both case studies was remarkably smooth and was without incidents. No doubt this was due to the high degree of prefabrication and the file-to-factory process.

► Figure 3. The Ringve Botanical Garden viewing platform in Trondheim completed in December 2007 by students of the NTNU “I-2-TRE:7” course. The timber used for the project is heartwood of larch of local origin donated to the project by the municipal forest authority of Trondheim city. Photo: Pasi Aalto.



### 3. DESIGN DEVELOPMENT OF THE PROJECTS

#### 3.1. Concept Finding and Refinement

In order to find the design for the Camera Obscura and the Ringve Botanical garden Viewing Platform we organized an architectural competition between teams with three students in each team. Design explorations were done conventionally in various 3D design tools, such as Form-Z, Sketchup, 3D Studio Max, and Rhinoceros, as well as 2D tools (mainly Archicad and Autocad). In addition, the students also used to a large extent sketching and the building of physical desktop models in various scales.

We find the use of several different computer programs important for design exploration and evaluation. Using different programs gives different insights, contributing to the design process in a positive way. Different techniques for digital modeling lead to different models in which various problems may be highlighted or hidden. When working with physical models it is important to vary materials, scale, and level of precision in order to explore a design fully. We observed that the same logic also applies to the digital model.

The students also had access to and had been trained to use the I-2-TRE:lab's three-axis router, a Datron M8 machine. Although they were encouraged to use the machine for prototyping, it was used to a very limited extent. It is difficult to conclude if a more extensive use of the machine could have given another result or other insights to the design challenge. However, we have not made a particular study in our case studies as to the extent a digitally produced model would have benefited the design itself or the students' understanding of the production process of the components for the final structure. Other researchers, for instance Lawrence Sass, have, on the other hand, integrated the use of digital prototyping into 1:1 projects [2].

## 3.2. Digital and Analogue Tools in Early Phases

The use of digital tools in the early phases of the design process has been a topic of discussion for more than a decade. Dokonal and Knight have studied architectural practices to see if the simultaneous use of digital and



◀ Figure 4. During the concept development phase the students used mostly analogue tools such as sketching and building of physical models, but also simple 3D modeling tools, such as Sketchup.

analogue design tools, such as sketching and physical desktop models, may be a question of the architect's age. They reflect on the future possibilities for more extensive use of digital tools in the early phases of design development. They ask if the use will increase or maybe completely make the analogue methods redundant when new generations of architects who have used the computer as a design tool from the outset take over the architectural scene [11].

From the results of our case studies we observed that this might not necessarily be a question of either or, but rather both and. As, on the one hand, the use of different digital models gives different insights and perspectives to the design, and, on the other hand, the varying scale and materials of physical models also offers the same possibilities for the architect to enrich and develop the design, it would be a pity if the latter should be abandoned from the design field. Digital modeling and physical models are from the experience of our two case studies to be considered as mutually enriching for the design development.

## 3.3. The Fabrication Model

The technological backbone, so to speak, of our case studies were the CAD/CAM software Cadwork coupled with the Hundegger beam processors. [10] First, from the students' perspective, Cadwork turned out to be easily learnable but highly effective and therefore especially suitable



for large groups such as semester courses. With comparatively small efforts, the students learned how to prepare the machine data for a highly developed industrial CNC-machine. Second, from the timber industry's perspective, the pair Cadwork / Hundegger is of high practical relevance through its wide application in the industry, providing us with ideal conditions for cooperation. The CAD/CAM pair Cadwork/Hundegger was chosen as well by Neumann within his research at the University of British Columbia in Vancouver [7–8].

The periphery around this backbone was rather flexible: In the concept phase, any means of design from manual sketching to 3D-CAD software was implemented. The interface to Cadwork was not crucial, as all the detailing was drawn directly with the timber software as a 3-dimensional model with timber specific attributes such as fiber direction and joints.

It was not our intention to teach the student the use of a specific computer program. The reason for using Cadwork was simply that it has an adequate export function to the production machinery almost as easy to use as a printer. It was rather an underlying intention that the students should learn to identify what program suits a specific need, making them more capable of finding the most appropriate tool for a given task.

The Cadwork model for production was treated as an isolated file, managed by just a few of the students being responsible for the editing and to keeping it updated with the rest of the project work. For design exploration in 3D, Cadwork was in this case not an ideal tool, as it was both faster and more intuitive for the students to work in other programs. Many design decisions can be explored with a simpler model as long as modeling speed and flexibility are important factors. However, modeling in Cadwork is vital for production but also for the design, as many potential problems were identified and solved because of the precision and level of detail in the Cadwork model.

We could not have managed to bring the Cadwork model into production if we had not had the competent advice and input from the timber engineers working for our cooperating fabrication companies. We realized that collaboration is crucial for success and that the human interfaces between the various participants in a collaboration project are as significant as the digital interfaces.

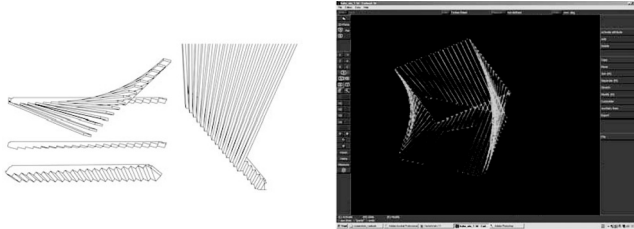
In this respect, Cadwork is a CAM software, used to translate the geometry designed in a CAD system into the production data needed to control the fabrication. Since some constructive problems only become visible after the additional information needed for fabrication is added, the CAM system is an important part of the prefabrication process. The crucial point in regard of the digital production chain is the interface between the CAD and the CAM model, which up to now still requires a lot of manual interaction.

Construction of the lens housing for the Camera Obscura was done almost exclusively in 2D because its metal parts were to be manually built in one of the mechanical workshops at the university. The craftspersons

required precise 2D construction drawings. This gives an example of how production technology and method influence the design process and the use of appropriate digital tools for each purpose.

### 3.4. Structural Evaluation

The structures were evaluated with the structural software Robot Millennium [12]. The French company Robobat is one of software developers cooperating closely with Cadwork for optimizing the IFC



◀ Figure 5. Left: The sill beams and wall planks of the Camera Obscura. Right: Cadwork screenshot of the walls.)

(Industry Foundation Classes) interface. However, as the structural engineer imported our IFC-model, it turned out that the volumes of the structural members had been split up into their b-rep surface elements and could not be recognized as a structural member. An import via CBS-Pro, another Robobat product, solved the problem for most members.

## 4. PRODUCTION

We had a rather steep learning curve during the fabrication phase of the first case study, the Camera Obscura. As we were going into production it became evident that our communication with the producer had not been adequate. This was mainly due to the fact that we had at that time not acquired the simulation module of the machine software. If this had been the case we would have discovered the problems we under heavy time pressure had to solve. Then, all processes could have been simulated in the studio and possible flaws could have been corrected before we were entering into production.

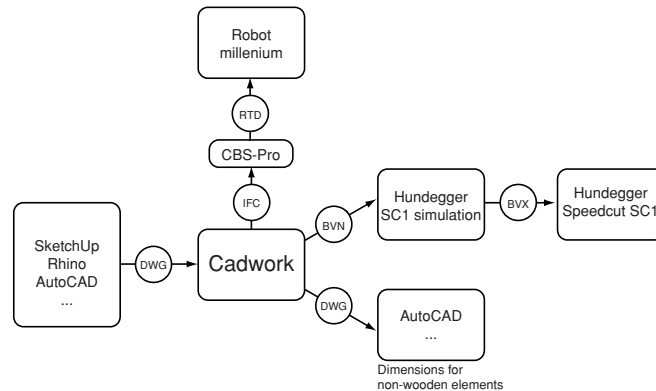
The first problem was related to the wall planks. These were to be made of standard strength sorted spruce (*Picea abies*) of the dimension 48mm x 198mm and 4 meters long. The challenge here was to model and produce an intricate cut being different on each plank and going from zero to several centimeters in order to allow the fastening of the internal horizontal wall planks.

The second problem was more severe: the tools of the Hundegger SpeedCut machine operate in four axes. We realized as we went into production that it would not be possible to produce the complicated cuts in the sill and top beams on this machine. For the purpose we would need a 5-

axis machine like the Hundegger K2. Luckily, another producer of timber components in a neighboring village of our main producer kindly agreed to help us out and produce the parts on their Hundegger K2.

Here we realized the next problem in the production. The custom made gluelam beams we had ordered for the project were too short

► Figure 6. Overview of the digital chain with standard software solutions.



because of the many cuts along the line of each beam. This left no clamping area for the machine. Therefore, the beams should have been one meter longer than the beams we had at our hands. However, the timber engineers at the producer's workshop managed to find a way around the problem, but some of the cuts had to be made manually by the students after the machine production was finished.

After having underestimated the joinery machine's constraints in the Camera Obscura project, we tested the Cadwork model for the Viewing Platform from the very beginning in the simulation module of the machine software to ensure their technical feasibility.

#### 4.1. Sophistication vs. Variation

While technically only a few details in the course concept had changed, the ways we used the given technology differed significantly in the Camera Obscura project and the Viewing Platform project. The Camera Obscura project focused on the characteristics of the automated joinery machine's CNC tools. Our formal exploitation could be called a "sophistication of the detail". We designed the building elements as complex as possible, such as the wall planks with their shifted cut and especially the sill and top beams. Those latter elements were very laborious, even for digital fabrication. The fabricator's engineers used two days of work to prepare the fabrication. The fabrication time itself of a single sill beam was time-consuming on the Hundegger K2, in addition to the problems mentioned above, namely that we had to finish them manually because we forgot to respect an area for



◀ Figure 7. The Camera Obscura project. Left: The cut along the wall planks. Right: Assembly of the sill beams on concrete foundations.

clamping the beam. While the single element was complicated, the total number of different elements was only 8.

The Ringve Botanical Garden Viewing Platform followed a very different approach that might be called a “variation of the element”. While a single element was quite simple and optimized to the joinery machine’s normal use, we achieved the formal intention by adding lots of elements in which we gradually varied some properties. To be able to identify those elements on the construction site, we labeled them with the Hundegger’s implemented ink lettering system.

From the perspective of fabrication, the difference between the two approaches was absolutely surprising. Although consisting of approximately 70 components, the digital fabrication of the Camera Obscura had taken several days. In contrast, the approximately 700 components of the Viewing Platform were fabricated within 5 hours. On average, an element was manufactured within 25 seconds. Comparing both approaches with manual fabrication, we can safely conclude that without the digital chain from the 3D model to the production software, the project could not have been realized within the given timeframe.

## 5. COMPARATIVE STUDIES

Only a few of the “file-to-factory” projects mentioned in the introduction are dealing with timber construction. However, we refer below to three projects that are quite comparable to our case studies in their general design-build approach, and, in particular, in their use of digital tools from project to production.

### 5.1. Projects at the University of British Columbia, Vancouver

At the School of Architecture and Landscape Architecture at the University of British Columbia (UBC), Oliver Neumann and partners have realized two projects that well illustrate the logic of project development in the digital age with a view to creating buildings in the real world and in cooperation with professional fabricators [7–8]. The Outdoor Theatre Roof Structure at

the UBC Malcolm Knapp Research Forest explores technical, spatial, and cultural aspects of CNC wood fabrication. The Maramata Roof Project explores CNC wood fabrication technologies for the design, fabrication, and construction of a small roof structure for farm use.

In the theatre roof project timber construction CAD/CAM software from Dietrich's was used. This software has the same characteristics and capabilities as the Cadwork package. It also has interfaces to the most widely used CNC production machinery, including the Hundegger machines. In the case of the theatre roof project a Hundegger K2 was used for the production. From the published documentation it seems as if also in this case, as in our case studies, the digital model in the CAD/CAM software was built directly in the software itself without any export from the digital applications that had been used in the design development.

In the Naramata Roof Project the team developed the design using Rhinoceros 3-D modeling software and, in addition, they used physical model studies, a design approach which closely assembles the approach in our case studies. As timber CAD/CAM software they used Cadwork in this case. Again they used Hundegger K2 for the production.

According to the published documentation "digital models were imported into Cadwork wood fabrication software". The details of this import are not described in the documentation. [7]

This approach which uses direct data import to the fabrication software represents significant advantages, since few architects have access to timber fabrication software in their daily practice. If data from design software that is common for architects to use can be exported directly to the timber fabrication software without loss of significant information, this is a great step forward in the world of timber construction. On the other hand, it was crucial for the success of the project also in this case that the architects had direct access to and used the timber fabrication software for the final detailing and for production preparation.

Neumann emphasizes the need for architects to understand their role as collaborators in a larger context in order to successfully realize their designs. They need to consider equally material resources, production, design, and assembly processes in order to achieve effective design solutions [7].

## 5.2. Project at the Royal Academy of Fine Art, Copenhagen

In a study of timberwork joints in complex geometries for the wooden façade of a multistoried parking house, the researchers wished to explore links between design intent, the formal and spatial expression, and the realization process [13]. The concept was developed using the associative and parametric modeling system Generative Components. An iterative process was used where the researchers developed the design with custom-made tools within the software and then explored the result by building physical

models. After the feedback they gained from the physical model, the tools were altered to meet the design intent, and a refined model was developed in the software. Whereas the first series of physical models was made on a 2D laser cutter, a 1:1 mockup proved the possibility to realize the concept's design intent in relation to the production.

For the final adjustment of the structure's joints and detailing and for production preparation the researchers used a third kind of timber CAD/CAM software, the HSB Cad system. This fabrication software has the same capabilities as those mentioned earlier in this article (Cadwork and Dietrich's). The custom-made parametric model within Bentley's Generative Components software was set up in a way that allowed the produced data to be used within the CAD/CAM software. Again, this is a most crucial point when architects wish to fully explore the design possibilities in timber fabrication technology. However, it is important to bear in mind that the success of the project also in this case was that the researchers had access to fabrication software so that they themselves could control the final detailing and fixing of joints and prepare the final production data. This is especially important as the CNC machinery in this case was used to its limits, which had to be discovered and implemented within the parametric model in order to generate the fabrication data.

## 6. CONCLUSION

In the introduction we asserted that to really bridge the gap between design and fabrication, it is necessary to acquire knowledge about the real building process and the methods and tools involved. Further, we assumed that such a comprehensive understanding of building would not only lead to a smoother and more successful building process, but also to an enhanced quality in design itself.

In our case studies as well as the projects referred to in the preceding section of this article all the significant components of the final structure were produced with beam processors or automatic joinery machinery at fabrication facilities. Our projects compared to those of the University of British Columbia and the Royal Academy of Arts in Copenhagen differed somewhat in the use of digital tools in the design phase and the export of data to the CAD/CAM fabrication software. This is a point that would require further investigation in order to achieve an optimized process.

### 6.1. The Digital and the Human Interface

A common denominator in our two case studies as well as those comparable projects referred to above, is that the designers worked directly with the CAD/CAM fabrication software in order to finalize the detailing of their design. A further common characteristic is that the projects were collaborative projects including architectural designers, structural designers, and fabricators. In such a collaborative environment the interfaces become

the focal point. The term “interface” has in this context two meanings: firstly, it relates to digital interfaces, e.g. between an architect’s digital model and a producer’s CAM software; secondly the term must be considered in a figurative sense as the information exchange and communication between the parties in a building project. The implications of this dual understanding of the term interface is central to achieving success in an architectural design project in the digital age where the aim is to create a frictionless exchange of data from design to production in order to realize a design intent.

The new field of collaboration between architectural designers and fabricators may offer the architects increased design potential and open a new business segment for the producers as well as offering the client a better product in terms of both architectural quality and price.

## 6.2. Design Feedback from the Machine’s Specifications

Today, many producers of timber-based components for the building industry include advanced CNC machines such as automatic joinery machines in their production lines. Most of these companies have acquired the machines in order to automate and make more efficient their daily production of fairly simple components such as roof trusses and panels. However, the case studies presented in this article have demonstrated that the same machines are also capable of making more sophisticated components to realize new and daring architectural concepts. The projects have taken the machines’ production capacities beyond their normal use as optimized mass production machines. The central points as shown in the projects presented here is the need for the architectural designer to have insight into and be able to use the fabricator’s CAD/CAM software in order to optimize the detailed design of components, such as joints.

## 6.3. Educational Value

Our case studies also demonstrate the challenges when introducing the design-fabricate-build paradigm into the curriculum of architectural schools. When the main aim of a project is to design, produce, and build a permanent structure in 1:1 for a client, and the sponsoring of a large part of the project has to be handled by the students, it is very challenging to keep a focus on the study of the digital chain. During long periods of the course, the focus will inevitably be on the architectural quality of the finished product and the handling of all the necessary practicalities in order to realize the project. These “external” aspects, particularly the focus on the cultural or architectural aspects may take the focus away from the digital challenges.

We conclude that it is important for student to see the possibilities of design realized and reflected in fabrication technology to realize complex shapes. We do believe that the knowledge of building should be the core of

an architect's education. Today, students are thrilled by digital technologies, both in design and fabrication. By superimposing those digital technologies with the often very dry reality of building, the construction site turns into something contemporary and fascinating.

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