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Implementation of Innovative Methods for the Digital Manufacturing of Architectural Models

Stefan Junk*, Philip Gawron

University of Applied Sciences Offenburg, Department of Business and Industrial Engineering, Campus Gengenbach, Klosterstr. 14, 77723 Gengenbach, Germany; stefan.junk@hs-offenburg.de

Abstract

Various methods of Digital Manufacturing (DM) have been available for the manufacturing of physical architectural models for several years. This paper highlights the advantages of 3D printing for digital manufacturing of detailed architectural models. In particular, the representation of architectural details and textures is treated. Furthermore, two new methods are being developed in order to improve the conditions for the application of digital manufacturing of architectural models. The first method makes the production of models with very detailed textures and interior rooms possible. While these architectural models allow the representation of a variety of details, they are usually rigid, i.e. not scalable in their size.

In order to allow to overcome this disadvantage this paper develops as a second method a parametrized CAAD model that allows boundary conditions to be modified and adapted while complying with the scale. The necessary parameters are defined in a multi-step process, then the relationships are described and implied. The parameters take into account the restrictions from Digital Manufacturing, but also the shape of the building and the texture. A variation of the scale or the texture of the architectural model is thus possible within a very short time. Within two case studies is demonstrated in which the developed methods are applied in order to implement detailed but also scalable architectural models.

Keywords:	CAAD; Architectural models; Additive manufacturing; Redesign; Parametrization

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1. Introduction

The implementation of digital technologies in architecture has rapidly advanced in recent years. Thus, a series of tools are available today which support all phases of the virtual development of architectural projects from the design to the construction to the realistic representation with embedded environments. To date, several technologies have been developed for the Digital Manufacturing (DM) or 3D-Printing (3DP) of architectural models based on CAAD data. A common feature of the technologies is that the physical models are created directly from the virtual 3D-Computer Aided Architectural Design CAAD-model [1].

The physical 3D-models are manufactured generatively, i.e. the models are created layer by layer by adding material. The application of these technologies for the manufacturing of architectural models provides a number of advantages over conventional technologies [2]. For example, it allows models to be created in minimum time with a greater degree of details. Furthermore, the reproduction and variation of drafts are also simplified considerably. Another advantage in addition to this implementation speed is the low costs for the systems and materials used, resulting in a considerable reduction of the model costs.

The use of DM is already established for standard models in the architectural sector. However, these applications are subject to some restrictions. Complex buildings, which have a variety of different rooms, superimposed stories, or even filigree design elements, have to be subjected to expensive pre-processing so that they can be produced as an architectural model using DM. In addition, these models have the disadvantage that they are generally only designed for only one specific scale. Thus, a scaling of the models is not possible, since their physical implementation is no longer possible due to different restrictions.

Through the collaboration of digital development processes and digital manufacturing, the advantages of the disruptive development of the two technologies can be sensibly combined and further developed in recent years. In this contribution, therefore, the requirements and restrictions in the DM of architectural models will first be explained. Two methods are then developed to overcome these obstacles today by means of a smart subdivision and parameterization. The application of this methods is demonstrated and evaluated within several case studies.

2. Literature review

About 30 years ago, the first process of digital manufacturing was developed with stereo lithography (SLA). To date, a large number of procedures has been established, all of which are characterized by the layer-by-layer design of the components and the direct implementation of CAAD using 3D printing. The methods used differ primarily in the joining technology of the layers as in the building material used. The application of the methods of digital manufacturing to implement architectural models has been investigated for several years. For example, a very comprehensive investigation of the different technologies showed that despite the still high costs, rapid prototyping through the direct manufacturing of the models can significantly influence the design [3]. However, at this time the models were often still evaluated as insufficient in size and appearance [4].

In the meantime, significantly larger DM systems are available and the costs have also decreased dramatically, mainly due to competition among the OEM of 3d printer but also 3D print service providers. For this reason, the number of additively produced components has risen sharply in recent years [5]. At present, the current range and performance of the different methods, also for the representation of architectural concepts show a wide range [6]. For that reason, a selection process using various criteria to find the best suitable method of digital manufacturing architectural models is developed [7]. The advantages of DM are particularly important when complex shapes (such as filigree supports or organic shapes) are to be created as models. Thus, it can be shown impressively how digital manufacturing can be used in the production of models with organic forms from the topology optimization of bridges [8].

In addition, the integration of DM into the design education of architects is an important approach to driving this technology forward. The use of Digital Manufacturing technologies to train students is being examined in architectural design education. The advantages when using design versions are especially emphasized in this [9]. It was shown in a comprehensive study on the impact of this new technology on the training of architects that students are more integrated into the design process and also become more creative. Additionally, they are enthusiastic about the new ways in which models and prototypes can be generated and benefit from direct feedback through the physical, and therefore "tangible", models [10]. The use of DIY kits for 3D printers can provide students with a practical insight into the technology. Students can learn how to create architectural and landscape models in a short time [11].

3. Process chain from CAAD to physical architectural model

The basis for the development of the models in CAAD are the specifications. These contain both restrictions of the geometry of the model as well as process-specific specifications, which depend on the digital manufacturing process involved. In all DM technologies, the 3D CAAD data are then imported in pre-processing and 3D Printing is prepared. A system-specific software is available for this purpose. This is followed by the actual "slicing" of the model in layers. Finally, the models must be post-processed, e.g. to remove support structures or improve the strength of the models. Since many architectural models consist of several parts, an assembly is required at the end of the process (see Figure 1).

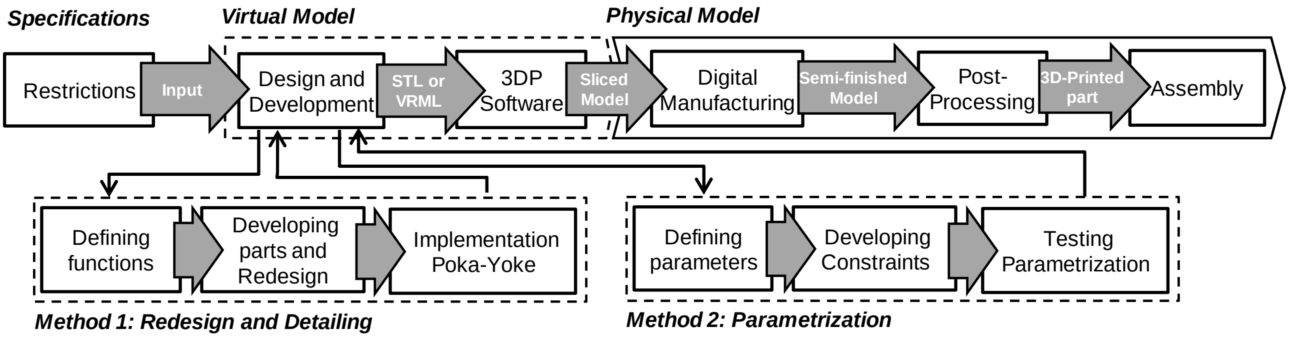

Figure 1. Process chain in DM of architectural models with two innovative methods

3.1. Digital manufacturing technology for architectural models

The Fused Layer Modelling (FDM)-technology utilises a heated nozzle where a plastic filament is inserted, molten and finally extruded. Each layer is produced through material deposition in the necessary areas. The printed object is therefore created by stacking layer onto layer. A nozzle is limited to handle one material as well as only one nozzle can actively extrude material. Dual extruders are common for most printers, thus two materials can be used in one print job (usually model and support material).

The PolyJet Modelling (PJM)-technology makes use of several print heads, each containing an array of several nozzles. As material resins (photopolymers) are used which are cured via UV-lamps after the deposition on the build platform. State of the art 3D-printers (e.g. Stratasys J750) can handle up to six materials next to the support material. There are rigid, rubber-like, transparent as well as coloured materials available, which can be mixed among each other to create application specific materials. This offers a wide colour palette as well as an adjustable hardness. The model and support materials are printed simultaneously.

In the binder jetting process (BJ) a powder mixture of plaster and polymers is used. This powder is applied by means of a roller in thin layers. Then the powder is sprayed with binder so that it bonds. Actually, the models produced in this way are monochrome white. In addition, the jet nozzles can be used to colour the models so that colourful models with textures and logos can be created. After the DM process, the excess, loose powder is removed by means of compressed air. During post processing the models still need to be infiltrated with a resin to increase the strength of the printed models and the brilliance of the colours. An additional support material is not required because the powder bed carries the models.

3.2. File formats suitable for digital manufacturing

The most common file formats are STL (Standard Tessellation Language) and VRML (Virtual Reality Modelling Language). Basically both formats can be utilised to create multi-coloured models, but there are differences and restrictions regarding the pre-processing of the files. Also native CAD-file formats can be used instead of STL, allowing to skip the STL-conversion process. The necessary pre-processing remains unaffected. To print highly detailed textures (e. g. wallpapers, floor tiles or parquet floor) the VRML-format is recommended because image file can be used. The focus of the pre-processing is the creation/ preparation of the textures using a suitable software. The textured volume is imported as a single volume. The restrictions only allow a fixed colour palette based on black, white, cyan, magenta and yellow. Other combinations including adjustable transparency or hardness are not possible.

The main focus on the pre-processing for STL-files is the separation of the original volume into several sub-volumes. Theoretically a comparable amount of detail like in the VRML-file (with its image files) could be achieved, through the separation into infinitesimal volumes. But the necessary amount of time to do this would not be justifiable, thus STL-files usually have a lower amount of detail. The sub-volumes are imported into the pre-processing soft-ware as an assembly. There are different colour- and material-combinations that can be assigned to each single sub-volume. Transparent windows as well as geometries with arbitrary hard-ness are possible. There are no restrictions regarding material properties like in the VRML-format.

STL and VRML-files have to be printed separately, for example the textured floor as VRML and an assembly of walls and windows as STL. Printing a combination/assembly of STL and VRML is not possible. After the print job the objects have to be assembled by hand.

4. Case study for redesign and detailing of an architectural model

In this case study, a detached house is chosen as an example. In order to assign different materials, it is necessary to separate the original volume into several sub-volumes and add non-existing volumes (e.g. windows). Figure 2 left shows the original volume without modifications. According to the customer's wishes and the restrictions of the PJM-technology the volume has been separated into several sub-volumes, shown in Figure 2 right. The floor was textured afterwards and therefore the VRML-format was used. Everything else was in the STL-format. During the separation the subsequent manual assembly after the print job should be kept in mind in order to prevent unnecessary iterations.

To achieve best possible results there should be further modifications in regards of the used printing method as well as the pre-processing software (see Figure 3 a to d). Experienced users with the necessary rights can modify parameters in the software in order to prevent specific functions. Regular users usually do not have the rights to access these areas in the software and therefore the following steps are based on structural approaches.

The Poka-Yoke method was originally developed in Japan and means to prevent inadvertent errors from the

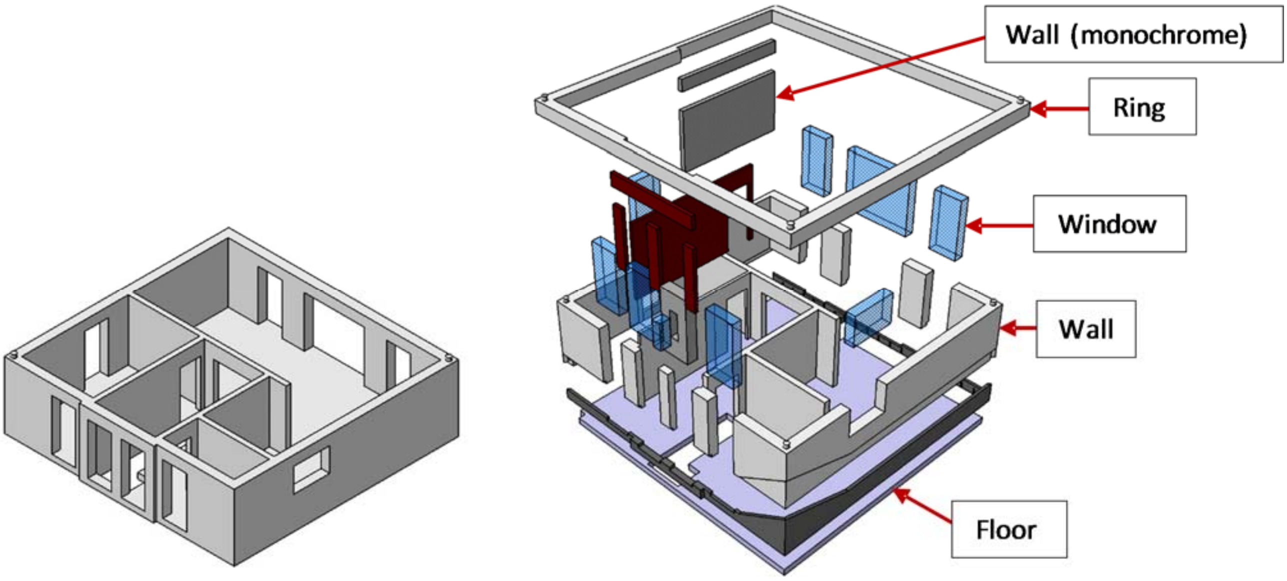

Figure 2. Separation of the ground floor (left) original volume,
(right) Redesign with separated and coloured sub-volumes (exploded view)

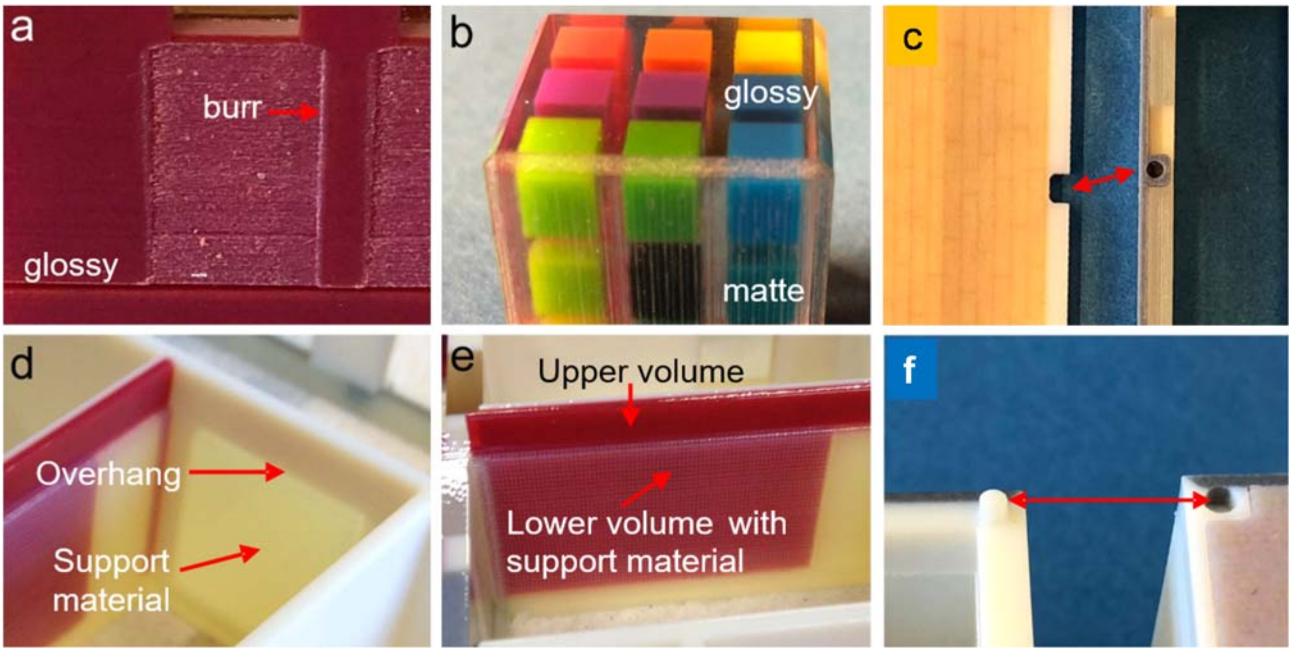

Figure 3. Details: (a) matte and glossy surface finish, (b) transparent material in matte and glossy,
(c) notch in floor plate and corresponding counterpart (d) overhangs with support material,
(e) accumulated support material, (f), pin and hole between structural levels

user [12,13]. In order to ensure a faultless assembly of the models dedicated geometries where implemented. Notches in the floor plates only allow the assembly with the corresponding structural level in the correct orientation, see Figure 3 c. Pins between the structural levels only allow one orientation, see Figure 3 f.

The assignation of colours and material properties was done in the pre - processing software GrabCAD. The majority of the windows where chosen to be transparent while a mixture of transparent and white material was assigned to single windows in order to create opal glass (see Figure 4). Due to the utilisation of the flexible material it is possible to create haptic impressions. For example, a pattern of very small cubes or pins, with flexible material assigned, can mimic the feel of a carpet.

Figure 4. Printed models: FDM (left), PolyJet modelling (right)

5. Digital manufacturing of scalable models using parametrisation

When implementing virtual CAAD data in physical models, different process steps are executed. First, the CAAD data are transferred to the data preparation software via an STL-interface. This format uses simple triangles for the representation of geometry. During pre-processing, various tests are performed. For example, is tested whether all triangles in the STL-data are correctly aligned and whether there are "holes" in the model. It is also checked whether the minimum wall thickness for 3D printing is sufficient. This can lead to the fact that a 3D printing is not possible, especially with models of very small scale. Many software packages offer automatic correction of the data in such cases. Subsequent changes, e.g. the scaling of certain areas (for example, only the wall thickness, but not of the supporting ceilings) or the cutting out of certain areas is either not possible or is only possible with great effort.

Furthermore, a return of the changed data to the CAAD system is only possible to a very limited extent since only simple geometry information is transmitted in the STL format. Because the STL format is not a native format of a professional CAAD software system, complex information, e.g. the construction history, design-features, textures or materials, can no longer be traced back to this format. The result of this data preparation is therefore a "rigid model", which can only be printed on one scale and can only be changed to a very limited extent. This is transferred as print data to the 3D printer and can then be built up layer by layer. The model of the detached house presented before in Figures 2 and 4 is an example for such a "rigid model".

To overcome the disadvantages of "rigid models" a parameterized model was developed. All the essential dimensions of the virtual model are already provided with parameters in the CAAD system so that they can be varied independently of each other. Thus, when the scale of an architectural model is changed, the outer dimensions can be scaled. However, the wall thicknesses are not scaled to the same extent in order to ensure the manufacturability by 3D printing.

A four-story university building with an integrated experimental hall is used as an example for the use of parameterized models. On the one hand, the difficulty consisted in the fact that a particularly small scale was chosen. Thus many details had to be adapted or changed [14]. In addition, a special texture of the façade was required. In this example, the wood panelling of the façade should be made visible. Also some details of the experimental hall (for example, roof construction, roof structures and visitors' balconies) should be presented despite the strong reduction. In addition, however, it should also be possible to produce the model on a larger scale without having to significantly rework the CAAD model.

Parametrization makes it possible to select specific dimensions and to vary them. This allows the details of the building to be changed according to the chosen scale, so that the requirements from 3D printing are met. In addition to the simpler feasibility, parameterization also results in cost advantages, since the parameters can be adapted to different scales within a few minutes. The change of a rigid model in the CAAD or the data preparation usually requires several hours.

6. Case study for the implementation of parametrisation: Scalable model of a university building

In practice, parameterization is carried out in series of process steps. In the context of parameterization, all necessary parameters are first selected and implemented as such in the CAAD system. It is then possible to define which parameters are to be changed during scaling. These parameters are then linked using relationships to the scale or to each other.

When the scale is changed, the parameters are automatically adjusted using the relationships. Finally, extensive tests are carried out to check whether all necessary dimensions are adapted using the relations according to the specifications. In addition, these tests are needed to detect errors in the formulation of the boundary conditions and then to rework the affected formulations.

For illustration, a multifunctional building, which has both offices and laboratories, was created using the new method. The particular challenge in this case is that a very small scale of 1: 500 should be implemented. The Binder Jetting was used as DM technology in this case study. This technology allows the manufacturing of coloured models. Due to the use of polymer gypsum as a construction material, these models are cheaper than PJM models. Furthermore, because of the powder bed additional material can be dispensed with. This also significantly reduces reworking during post processing. As a disadvantage, only the low resolution due to the higher layer thickness must be accepted here.

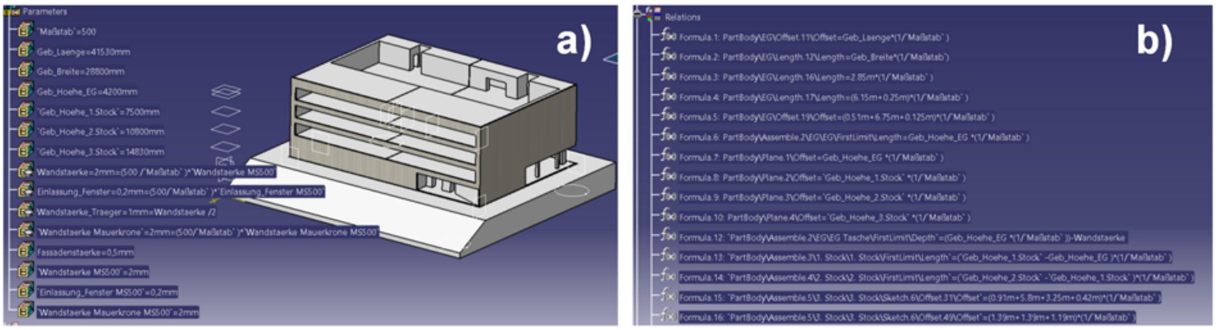

Figure 5. Screenshots from CAAD Software: CAAD model and list of parameters (a), List of boundary conditions (segment) (b)

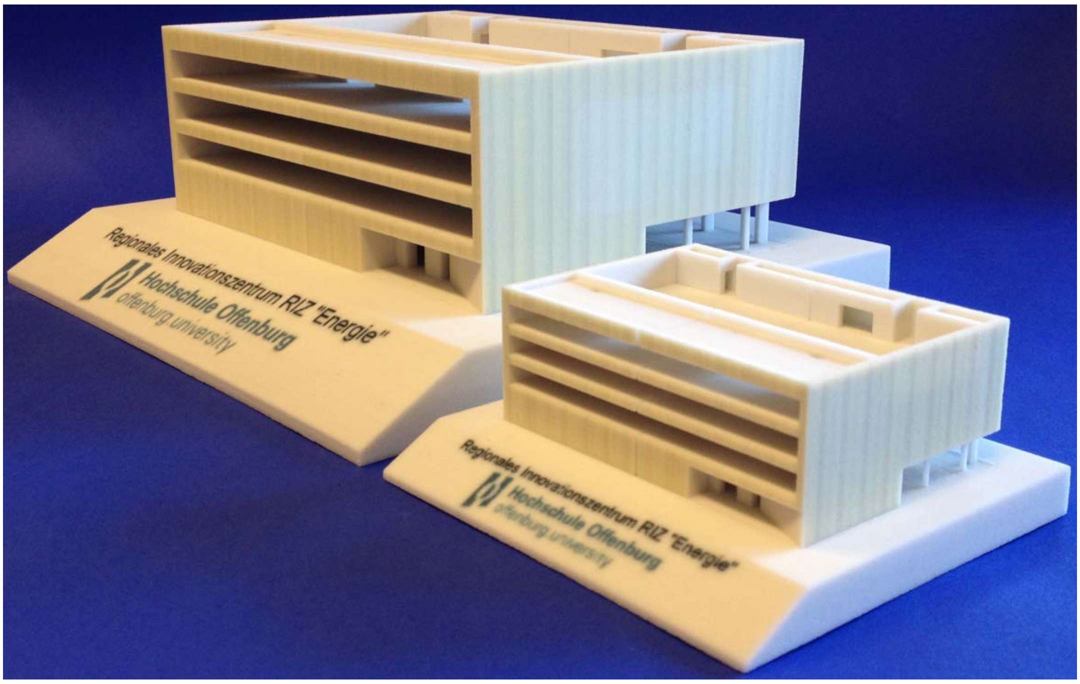

Figure 6. Parametrized architectural model in scale 1:250 (left) and scale 1:500 (right) manufactured by Binder Jetting

In this extreme case, many details cannot be represented due to the small dimensions. On the other hand, certain minimum wall thicknesses must be maintained in order to ensure the printability. The model was divided into two parts to be able to remove in the inside powder during post-processing. Due to this partition in the CAAD software (see Figure 5 a) the user of the model has the possibility to open the model and recognize the internal structure of the building. In addition, a bed plate has been developed which serves as a receptacle for both building parts.

A total of 15 independent parameters were defined during parameterization. In addition, the façade should be presented in a particularly realistic way. For this reason, as a separate sub model was developed that provides special parameters in order to be able to individually adjust the facade's texture. The total of approx. 290 relationships allow a very detailed adaptation of the CAAD model to different scales and requirements. The creation of the parameters and relationships means an extra effort of approx. 25 hours. This effort is justified, however, since the change of one of the parameters, namely the scale, adapts automatically all affected dimensions in the model, since these are connected by relationships. As an example of the application, the multifunctional university building, that is uses as regional research enter for renewable energies, is shown in Figure 6 in the two different scales 1: 500 and 1: 250. In the implementation of the architectural model, the method of binder jetting was applied, since a colour representation of the wooden texture on the façade is possible.

7. Conclusions and outlook

Today, digital manufacturing processes offer a highly developed technology to produce architectural models. Therefore, these technologies are used in many areas of the design of buildings and bridges, but also in the training of students. In order to be able to depict even larger buildings with complex internal structures, this article presents a method which allows the models to be split up. Individual floors and structures can be made visible. The assembly of the individual parts of the models is simplified by the Poka Yoke method. In a case study with a two-story nursery, consisting of 10 individual parts, the application of these methods is successfully demonstrated.

The models are usually limited to a certain scale. A simple scaling, in particular a reduction in the scale, is not possible since important criteria for the feasibility (for example, minimum wall thickness) are not met. In this contribution, therefore, a further method is developed, such as the application of a parameterization, this disadvantage can be overcome. For this purpose, a certain number of parameters are defined. All dimensions of the CAAD model that are important for digital manufacturing are then linked via relationships. Depending on the complexity of the design, a large number of relationships may be necessary. By means of a case study, it can be shown that the scaling of the architectural model can be easily implemented when this new method is applied. In both case studies an additional effort in the CAAD is necessary during the development phase of the virtual model.

In the further development of the method, the focus is on the inclusion of further DM technologies. Thus, the restrictions in various processes are quite different (e.g., support structure is necessary or not). Furthermore, the relationships must also be adapted to these restrictions. In addition, the establishment of relations should also be simplified. Today, this is still carried out experimentally today. It should be investigated to what extent the use of methods from computer science and numerical mathematics (for example, generic algorithms and data mining) may reduce the effort.

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