New Methods for the Rapid Prototyping of Architectural Models

Production of detailed models with 3D printing

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Abstract. *Various Rapid Prototyping methods have been available for the production of physical architectural models for a few years. This paper highlights in particular the advantages of 3D printing for the production of detailed architectural models. In addition, the current challenges for the creation and transfer of data are explained. Furthermore, new methods are being developed in order to improve both the technical and economic boundary conditions for the application of 3DP. This makes the production of models with very detailed interior rooms possible. The internal details are made visible by dividing the complex overall model into individual models connected by means of an innovative plug-in system. Finally, two case studies are shown in which the developed methods are applied in order to implement detailed architectural models. Additional information about manufacturing time and costs of the architectural models in the two case studies is given.*
Keywords. *Architectural model, CAAD, Rapid Prototyping, 3D printing, architectural detail.*

INTRODUCTION

Various Rapid Prototyping (RP) respectively Additive Manufacturing (AM) technologies, which enable the direct implementation of 3D drafts in models, have already been available for a few years. Today the most popular technologies among these are 3D-Printing 3DP with plaster powder and Fused Layer Modelling FLM with plastic filament. A common feature of these technologies is that the models are created directly from the 3D-CAAD-data.

The physical 3D models are manufactured generatively, i.e. the models are created layer by layer by adding material (hence the name Additive Manufacturing). The application of these Rapid Prototyping technologies for the production of architectural models provides a number of advantages over the conventional model production. For example, it allows models to be created in minimum time with a greater degree of details. Furthermore, the reproduction and variation of drafts and models 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. However, there are cur-

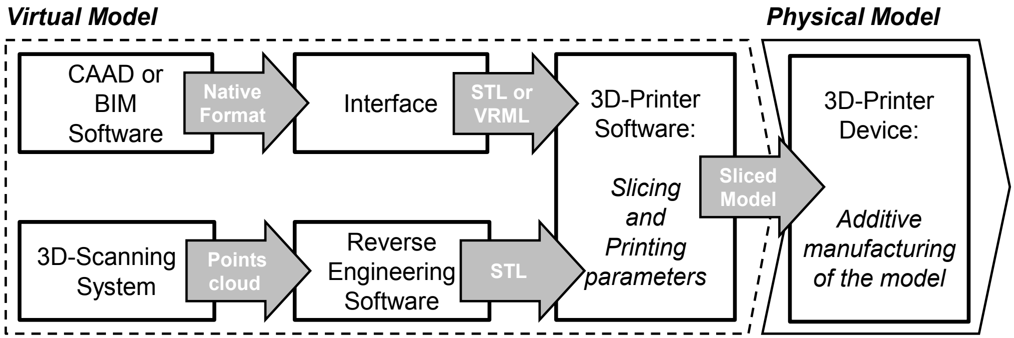

Figure 1
Data transfer from CAAD-Software or 3D-Scanning System to 3D-Printer.

rently still problems with regard to the data transfer and the preparation of the models for 3D printing, which stand in the way of further expansion of this technology (Sullivan, 2012). These problems are highlighted and dealt with in this paper.

CURRENT CHALLENGES FOR THE PROCESSING OF 3D DATA TRANSFER FOR RAPID PROTOTYPING

With all Rapid Prototyping respectively Additive Manufacturing technologies, the 3D-CAAD data are imported first and the Rapid Prototyping prepared as part of pre-processing. System-specific software is available for this purpose. The actual construction of the model in layers then takes place in a Rapid Prototyping device. Finally, the model has to be post-processed, e.g. in order to remove supporting structures or improve the stability of the model.

The 3D-CAAD data may come from different sources. On the one hand, 3D data created by means of a commercial 3D-CAAD or BIM system are usually already available for new projects. But, on the other hand, only 2D drawings are often available for existing buildings. No plans are often available for historical or even archaeological buildings. 3D scanners are often used nowadays in these cases in order to register the contours of the exterior façades and interior rooms.

The different data sources must be prepared in such a manner to allow them to be processed by the RP technologies as shown in Figure 1. In concrete terms, this means that the 3D-CAAD data have to be converted from the original file formats into a format that can be read in by the RP systems. Data based on CAAD are usually complete and consistent. However, there are still some problems with regard to the interfaces from the CAAD or BIM system to the RP software. RP devices only accept a neutral format, notably STL or VRML, but no native formats from individual commercial CAAD system manufacturers.

The simple data format STL only reproduces the surfaces of 3D objects. In doing so, the 3D object is approached with triangles, allowing the degree of detail and hence the data volume usually to be set. However, this format does not provide information on the colour or texture of surfaces, with the effect that monochrome models are created. The advantage of VRML format is the opportunity to reproduce surfaces but also coloured textures.

With data based on 3D scanners, there are usually no problems with regard to the data format, since Reverse Engineering Software often uses the STL format themselves. However, the same problem occurs time and again that the data records of point clouds by the 3D-Scanning systems are incomplete, since the scanners, which use optical sensors, find it difficult to register areas in which no light is reflected. These “shaded” areas, such as grooves and recesses, re-appear as “holes” in the data record and have to be removed with complex software operations by the use of a Reverse Engineering Software.

SPECIAL DEMANDS ON DATA FOR RAPID PROTOTYPING

Besides the data format already described, it still has to be checked whether the data are suitable for Rapid Prototyping in preparation for the construction process when processing the CAAD data. This includes, in particular, checking whether the model has a sufficient wall thickness. With a model at a scale of 1:100 or 1:200 or even smaller, it may be the case that the wall thickness of the masonry in the model does not meet the minimum requirements of the Rapid Prototyping system. It should also be checked which details are not able to be reproduced in the model.

For example, details, such as windows or banisters, are often so delicate that they are unable to be reproduced in sufficient quality by the Rapid Prototyping system, since they could break off due to their weight and fineness. Especially openings in the outer shell, such as window surfaces, skylights and doors, must be observed in particular in this respect. They are often displayed in closed condition in order to show only the exterior facade of a building. Any insights in the building or lines of sight through the building are lost in this process.

TECHNICAL AND ECONOMIC BOUNDARY CONDITIONS OF 3D PRINTING FOR THE PRODUCTION OF ARCHITECTURAL MODELS

3D printing with polymer-plaster is used and further developed in this contribution in order to overcome the previously described disadvantages for the data creation and detailing of the models. This RP technology provides several process-related advantages:

- Due to the simple printing technology, which can be compared to an ink-jet printer, the acquisition of the printer incurs only low costs, resulting, in turn, only in low hourly machine rates.
- The materials (polymer plaster, binding agent, ink and infiltrate) used is relatively inexpensive.
- Coloured models with textures and lettering are easy to produce with ink cartridges.
- Interior structures can be easily exposed with compressed air.

The economic advantages of 3D printing include the following:

- In contrast to numerous RP technologies, with this technology no additional supporting structures which have to be subsequently removed are required. In other words, only the material required to create the model is consumed. As a result, the technology goes easy on resources and is therefore sustainable (Junk and Côté, 2012).
- Overall the costs for 3D printing of models with this technology are nowadays about € 0.40/ccm. Furthermore, at approx. 23 mm/h, the construction time for a model is also relatively short (ZCorporation, 2009).

3D printing is particularly suitable for application in the field of architecture, since it is the only Rapid Prototyping technology that can be used to create coloured models. Furthermore, the model can be transferred in STL format. Since no colour information is transferred in this way, the components have to be "dyed" in the software of the 3D printer.

The second available option is the transfer in VRML format. In this case the colour information is transferred in addition to the geometry. Furthermore, additional textures, such as logos and writings, can be read in and applied in the 3D printer software.

NEW METHODS FOR THE PRODUCTION OF DETAILED ARCHITECTURAL MODELS

In order to extend the application options of 3D printing to the production of architectural models, a method has been developed to divide the buildings into individual areas. This allows very detailed models to be created, which also enable interior insights. To assemble the individual models easily without mixing them up, the Poka Joke method is also applied.

At first the building is divided into individual areas in the CAAD system. In the event of a single-family house, these sections are preferably the cel-

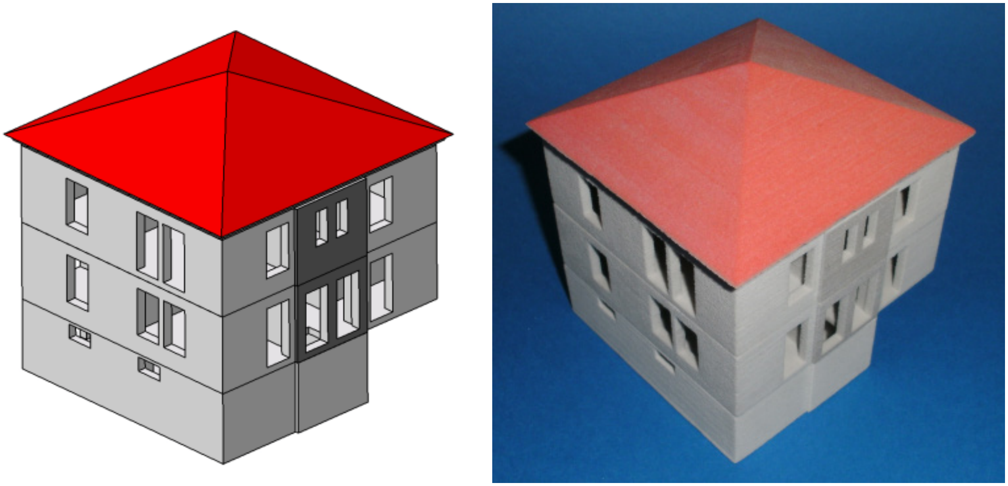

Figure 2
CAAD-Model of Single family house (left) and physical model (right), Scale 1:100.

lar, floors, the roof and adjoining buildings. Industrial buildings can be divided according to their functions, e.g. office and workshop areas, adjoining buildings, supply facilities. This gives the model a structure and allows the individual models to be designed in detail. The design usually comprises the reproduction of flooring and exterior walls. Furthermore, supporting interior walls and non-supporting lightweight walls can be reproduced. The function of the individual walls can be depicted by different wall thicknesses in the models. Interior staircases as well as pillars and supports are also reproduced.

Further details, such as windows and door openings as well as gates and skylights of industrial buildings can be integrated in the model. This allows the room layout to be recognised. Since the models are set up floor by floor and are open at the top, it is possible for the architect and customer to discuss and assess the design.

The individual models are equipped with connection elements to make it easier to handle them. They are simple plug-in connections which allow the overall model to be quickly assembled or disassembled. The Poka Yoke method is used for this purpose, i.e. the plug-in connections are positioned in such a way that there is only one way of connecting the individual models (Santos et al., 2006). This prevents the individual models from being assembled in the wrong combination. It also reduces the risk of damage due to incorrect assembly considerably.

CASE STUDY 1: SINGLE-FAMILY HOUSE

A single-family house as shown in Figure 2 was 3D-printed in this case study. The building was divided into the individual models: cellar, two living floors, roof and adjoining building.

Each floor was created with a floor plate and side walls. Furthermore, the interior walls and all openings (windows and doors) were reproduced. As needed, the functions of the rooms could be applied in the form of writings to the floor plate to provide the constructor with a better understanding. Also details like the grey painting of the oriel at the façade in the front could be demonstrated.

Since the model was created at a scale of 1:100, the interior and also exterior walls could also be reduced to the scale without falling short of the minimum requirements of the 3D printing system (see Figure 3). The individual model parts are joined by means of plug-in connections. This allows the roof and the individual floors to be raised in order to observe and assess the underlying areas. Lines of sight

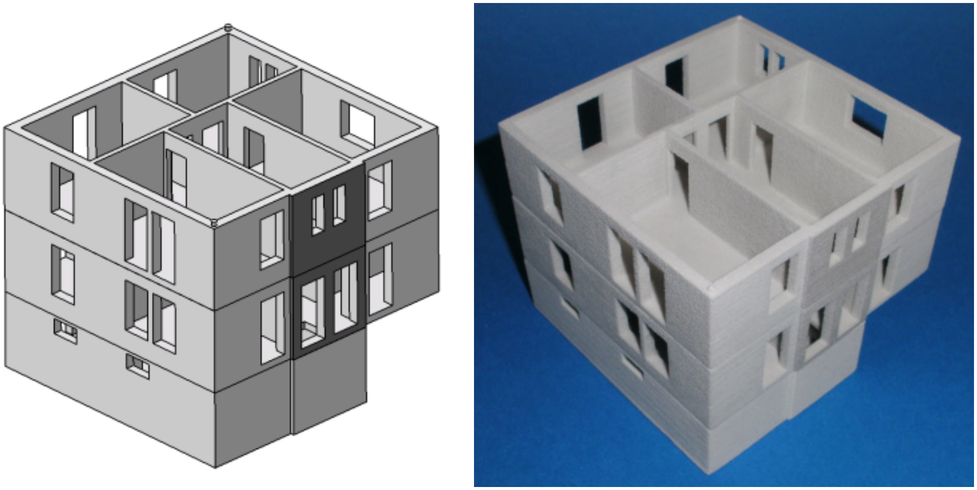

Figure 3
View on internal structures in CAAD (left) and in physical model (right), Scale 1:100.

can be seen in the building due to the open design of the building.

CASE STUDY 2: INDUSTRIAL BUILDING

The 3D printing of an industrial building is implemented in the second case study as demonstrated in Figure 4. It is used as a test centre for persons and motor vehicles. It consists of a cellar, several test halls and an office building with common rooms. The building is initially divided into storage, test, office and social function areas. However, these areas are so large that some of them need to be divided even further into floors in order to illustrate all necessary details to the constructor.

The scale 1:200 was applied to this model to allow even the largest individual model (cellar) to fit into the construction space of the 3D printer (204 mm x 253 mm x 204 mm, LxWxH). In this case, the wall thickness of the interior and exterior walls had to be adjusted (i.e. enlarged) in order to adhere to the minimum wall thickness of the 3D printer and, in this way, create a stable, durable model. As shown by the view onto the internal structure of the building in Figure 5 this distorted the scale to a certain degree, since the lengths and heights of the building are true-to-scale, but not the wall thickness.

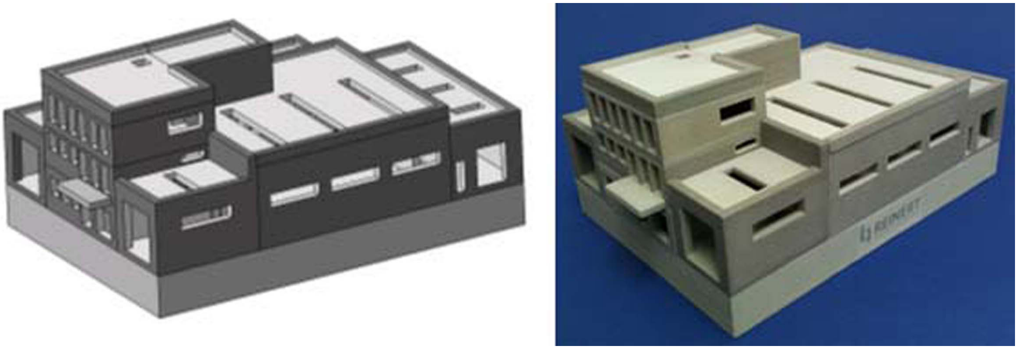

Figure 4
CAAD-Model (left) and physical model of complete industrial building (right), Scale 1:200.

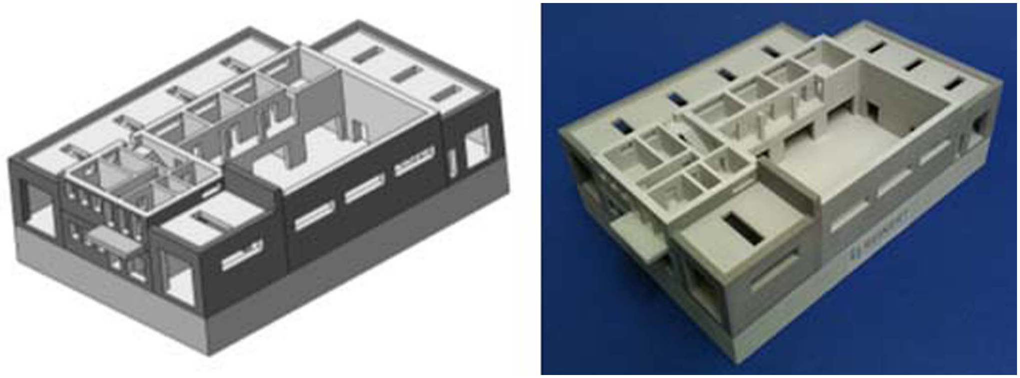

Figure 5
CAAD-Model (left) and physical model of industrial building without roof for view onto internal details (right), Scale 1:200.

The cellar, which covers all areas, serves as the basis for the overall model. The individual models are plugged onto the cellar either entirely or floor by floor. The office and common areas are particularly challenging, since they comprise numerous details.

COMPARISON OF THE MANUFACTURING TIME AND COSTS

The manufacturing times and also the costs for the two case studies are specified in Table 1. The manufacturing time is based on the actual construction time for the model and the time required for post-processing, which consists of cleaning the model to remove residual powder and the subsequent infiltration with resin. The total manufacturing time for the single-family house is considerably shorter than that for the industrial building due to the lower construction volume, the lower number of individual parts and the lower complexity of the geometry.

The single-family house is completed within a working day and can be printed, for example, overnight. In contrast, printing and reworking the industrial building is expected to take 1.5 working days, although, in this case too, printing can be performed overnight to accelerate the availability of the model. In addition it takes in both case studies some hours to maintain the preparation of the data because only 2D-drawings are available.

When comparing the manufacturing costs, a distinction must be made between material and machine costs. The material costs consist of the costs for the polymer plaster powder and binding agent used during the production phase. The costs for ink are negligible in these examples. The material costs also include the costs for the resin used during post-processing for the infiltration and hence the increase of the strength of the models. The machine costs are based on different boundary conditions (e.g. acquisition costs, service life, depreciation, interest) used to calculate the hourly machine rate. The personnel costs are not included in this calculation, since, by experience, they vary considerably.

In the both case studies the material costs of the industrial building are more than the double of the costs of the single-family-house. The machine costs of the industrial building are almost the triple of the

Manufacturing time	**Single-family House, Scale 1:100**	**Industrial Building, Scale 1:200**
Manufacturing (3D-Printing)	3 h, 2min	8h, 30 min
Post-processing (Cleaning, Infiltration)	2 h	2h, 30min
Total manufacturing time	**5h, 2 min**	**11h**

Table 1
Comparison of manufacturing time of single-family house and industrial building.

costs of the single-family house because the geometric complexity of the model. The total manufacturing costs are currently significantly higher than the literature value (ZCorporation, 2009) due to the annual price increases for materials since the publication date.

SUMMARY

The current challenges for the implementation of architectural models by means of 3D printing are illustrated in this paper. They include, in particular, the data transfer and the adaptation of data to meet the requirements of the 3D printing system. It has been demonstrated that 3D printing has a number of technical and also economic advantages in comparison to other additive manufacturing technologies.

The methods introduced for the division of the building into individual models allow numerous details to be reproduced in the exterior as well as interior. These individual models can be joined to form complex overall models using the Poka-Yoke method. Both case studies were able to show how to implement these methods successfully for a single-family house and also for a complex industrial building. The comparison of the manufacturing time and costs gives a reliable basis for the calculation of future projects.

OUTLOOK

To simplify the data exchange in future, interfaces are to be developed which simply the creation of STL data considerably. Furthermore, the printer software should be extended to make it easier to detect weak points, such as insufficient wall thicknesses, and enable the weak points to be eliminated quickly. Assistance in the division of the building into appropriate individual models would also be helpful.

For further examinations, there are plans to investigate the usage of other Additive Manufacturing technologies, such as Fused Layer Modelling FLM. This technology usually enables models of higher strength to be produced in comparison to 3DP, since plastic filament (ABS) is used as building material. However, a restriction here is that only single-coloured models can be produced. The application of multi-material printing (e.g. Multi Jet-Modelling MJM) could also be examined in order to visualise further details. This could result in a more realistic reproduction in particular of transparent details. In addition a higher accuracy of the modes is expected due to the smaller layer thickness that as used by this technology.

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