Large Scale 3D Printing of Complex Geometric Shapes in Construction

Jochen Teizer[1], Alexander Blickle[1], Tobias King[2], Olaf Leitzbach[3] and Daniel Guenther[2]

[1] Ed. Züblin AG, Stuttgart, Germany
[2] voxeljet AG, Friedberg, Germany
[3] MEVA Schalungs-Systeme GmbH, Haiterbach, Germany

Abstract –

3D printing, also known as additive manufacturing, has become an established technology in many industry sectors for the fabrication of three-dimensional (3D) objects. The layered production of scaled prototypes and smaller series typically use automated computer controlled systems that rely on a-priori designed digital 3D models. General principles for 3D modeling, printing, and finishing exist utilizing the cutting, melting, or softening of paper, polymer, or metal materials.

While advantages and limitations of the 3D printing processes require careful review for its final application, the construction industry itself has adopted industrial applications successfully in many examples where, for example, consecutive layers of concrete are combined into a desired structure or form. One of construction's key challenges though is its need for large scale 3D printing of complex geometric shapes on projects where construction time, cost, and quality are the predominant and determining success criteria. While complexity and scale of the planned structure become available at finer detail during the architectural design process, final fabrication of large scale geometric shapes often fails because of constructability issues.

This article introduces conventional construction methods for building large scale and complex geometric structures using on purpose built, automated and robotic 3D printing machines. It therefore contributes the missing link between demanding architectural design that otherwise could only be built at large cost. Commonly known advantages and limitations of existing 3D printing processes, including modeling, printing, and finishing principles are reviewed. Significance of resolution, speed, and quality of materials in 3D printing are explained. Results to an implementation of complex formwork in a major capital construction project are shown. Preliminary benefits and limitations from the perspective of a construction company explain what it takes to advance 3D printing to a field-ready construction method.

Keywords –

3D printing, additive manufacturing, concrete formwork, contour crafting, machine automation and robotics, modularization.

1 Introduction

Three-dimensional printing has been the focus of attention in the media at present and a subject that arouses great expectations. Why then, is this technology, which is often seen superior to conventional methods, so little used in the realm of construction?

One of the roots of additive manufacturing lies in a MIT patent from Sachs et al. from 1989. It describes "a process for making a component comprising the steps of (1) depositing a layer of a powder material in a confined region; (2) applying a further material to one or more selected regions of said layer of powder material which will cause said layer of powder material to become bonded [..]; (3) repeating steps (1) and (2) [..]; (4) removing unbounded powder material [..]".

As a digital means of fabrication, 3D printing offers many advantages. Computer control of the manufacturing sequence affords latitude and shorter production times, often just a matter of days from design to the finished object. Analogue forms of production, in contrast, frequently involve a lot of stages and take much longer. 3D printing is found in many realms of work – in mechanical engineering, in metal pouring, medical technology, research and development, design and education. In architecture, the technology reveals its advantages especially in the creation of 3D building models. Construction companies, however, have yet to develop a strong business case for implementing the technology and its overlaying processes in practice.

2 Background

2.1 Principles of 3D printing

The fundamental principle of 3D printing is that a three-dimensional volume is reduced in the computer to a series of 2D layers. What are initially virtual layers are then built up into a real object, each successive layer being individually worked; for example, by means of laser rays. The process is a generative or additive. The principle is implemented by machines in a number of different forms.

2.1.1 Stereolithography (SLA)

Stereolitography (SLA), for example, is based on a process in which a platform is repeatedly lowered in a bath of synthetic resin (see Figure 1). The very thin layers formed in this way are hardened by exposure to ultraviolet (UV) laser rays. Projecting parts have to be supported, and after hardening, the resin is smoothed. This step is repeated until the construction object is complete. The elements themselves are strong and transparent and have a good resolution. Mainly polymerhybrid resins are used. In part, these contain ceramic additives and have a strength known of 2k cast resins. The largest machines have a capacity of up to two cubic meters. This process is, therefore, particularly suited to the creation of architectural models.

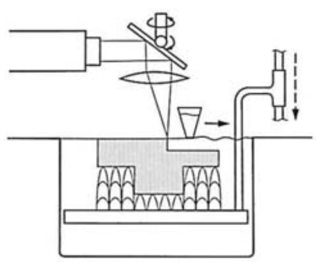

Figure 1. Diagrammatic depiction of the Stereolithography 3D printing system [3]

2.1.2 Selective Laser Sintering (SLS)

Another process is selective laser sintering (SLS). Powder is poured in a thin layer on to a platform, which is moved in a steel container or “box” (see Figure 2). The material is shaped in a series of layers that are fused together by means of a laser ray.

The individual steps are again repeated until the building component is complete as a powder block. After the units have cooled, they are cleaned of loose powder. Overall, the SLS process can lead to a high degree of resolution and excellent strength. The surface quality – often an important criterion for a construction company to get its work approved and paid – will depend on the material used. Normally, particles of medium grain (ca. 50 µm) are used, creating a porous, but not coarse, finish. Metals, such as aluminum, rust-free steel and titanium can be processed, as well as plastics – polyamide mainly. In view of the thermomanagement of the machines, elements not much larger than an eighth of a cubic meter in size are produced.

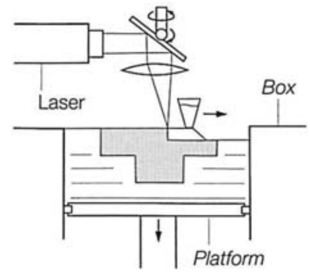

Figure 2. Selective laser sintering (SLS) [3]

2.1.3 Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM) is a process by which plastifiable building material is extruded through a usually heated nozzle (see Figure 3). The latter is moved in relation to the construction platform.

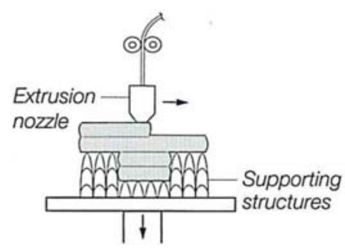

Figure 3. Selective laser sintering (SLS) [3]

The shape of the element is defined in outline and the enclosed area is then filled. Different kinds of material can be used with this method such as plastic, wax, concrete paste or ceramic paste. A variation of this system is known as “contour crafting” [1], whereby an adjustable outer rim prevents the material from flowing out unimpeded. The rim consists of parallel slabs or strips that can be turned about the nozzle. In this way, for example, rapid- hardening vertical concrete wall elements can be formed [2]. This process allows resolution of only low detail. For bigger volumes, very large nozzles are required [3]. Although constructing spaces of more than 10 m^3 becomes available, a major current limitation is the precision in which large and likely free-swinging nozzles form the material. Construction industry experts claim the final surface quality, for example of concrete walls, to be required to be within millimeters to find acceptance by the client.

2.1.4 3D printing with inkjets

3D printing with inkjets is closely related to superficial printing on paper. In contrast to the techniques described earlier, inkjet print heads, usually with several thousand nozzles, are not drawn along a contour line, but across the construction area (see Figure 4).

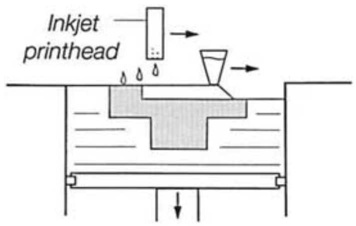

Figure 4. 3D printing with inkjets [3]

The liquid is hardened after leaving the head; for example, through a polymerization process stimulated by a hardener previously mixed into the powder. With non-powder-based applications, the supporting structure and the construction element are printed with different materials – similar to FDM techniques. With powder-based processes, various ground materials can be applied over a large area while the print head selectively prints binder onto the surface where the parts are to be produced and subsequently bonds this area. The process is repeated until the object is complete. Powder-based methods are limited by the grain size of the material, which cannot be reduced at will. The strength of these products is generally low, but it can be increased subsequently by incorporating 2K synthetic resin. The spatial volume of the largest production machine at present is 8 m^3 [3]. An example of its PolyPor system with binder-based on acrylics (a mixture of binder monomers and chemical activator in the powder [4]) is shown in Figure 5.

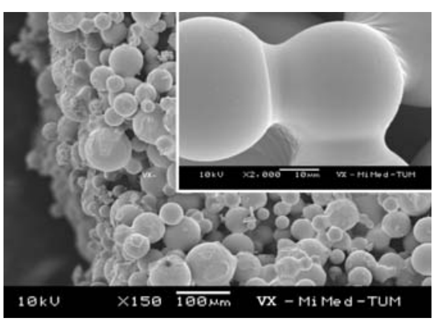

Figure 5. Binding mixture of particle materials [5]

2.2 Cost of 3D printing

The overall costs of 3D printing include the machines, materials, and labor. The latter occurs mainly at the extraction stage. SLA and SLS are the most expensive 3D printing processes to date, with costs of more than €30,000 per m^3. Powder-based 3D printing with sand costs about €3,000 per m^3, and the FDM process, depending on the type of material, costs less than €2,000 per m^3.

2.3 Direct and indirect use of 3D printing

A distinction is made between the direct use of 3D printed units and the indirect manufacturing of elements by means of 3D printed tools. Many architects, for example, already employ models of buildings created with 3D printing machines for presentation purposes. A special feature of powder-based 3D printing is the use of color (see Figure 6). Obstacles to a wider application in the design process are the high costs and the lack of easy data preparation.

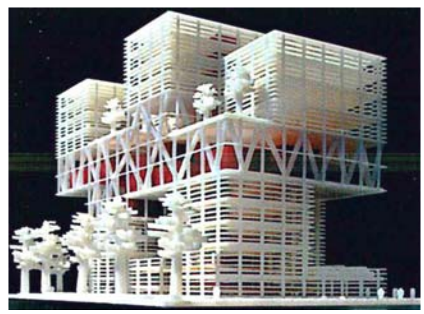

Figure 6. Color-printed building model [Rietveld Architects, New York]

2.4 Techniques in construction applications

Several individual cases exist where engineers applied 3D printing in practice. A few are briefly highlighted. A manufacturing technique known as the "D-shape" process developed by the Italian engineer Enrico Dini and first presented in 2009 used an inorganic liquid solidifying agent that is poured into the powder mix. Part of a large pavilion created by these means is shown in Figure 7.

Figure 7. 3D printed architectural object from powder mixture with inorganic solidifying agent

The Chinese company Winsun is developing whole buildings by means of 3D printing. With a technique similar to contour crafting, wall elements are manufactured that are from extruded prismatic bodies; i.e. there is no change to their cross-sectional form over their full height. The rather simple form of the elements created in this way can be assembled using conventional hoisting techniques. They then form constructional components for use in buildings ranging at present from single-family houses (see Figure 8) to a multi-story (5) housing block.

Figure 8. House assembled from printed basic elements, manufactured by Winsun

As an alternative to direct production, indirect processes use forms that have been created as tools. For example, sand forms are already being printed in large numbers for applications with cast metal. They can also be used for mineral castings and concrete. As with metal castings, the mould is usually unfit for use after a single pouring, but the advantage of this system is the possibility of inserting reinforcement in the mold prior to casting. Figure 9 shows a concrete column form for a washbasin cast in two halves. Similar processes have been used to produce sculptures in ultra-high-performance concrete (UHPC) or free-form façade elements.

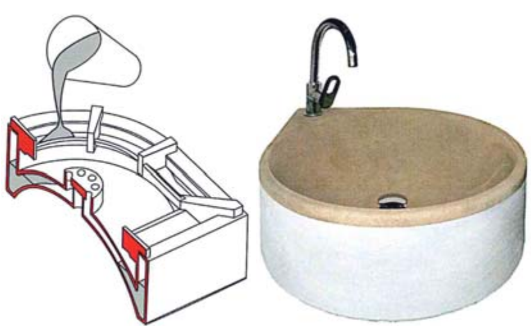

Figure 9. Cast-concrete washbasin: diagrammatic depiction of the casting process in 3D printed form (left); finished washbasin with tap fitting (right) [3]

2.5 Ongoing research activities

A lot of current research is focused on the materials used. Efforts are being made to exploit the properties of UHPC in powder-based 3D printing techniques. Investigations [3] have led, for example, to a cement-based material that, after final treatment, possesses a closed, weatherproof surface with great fire resistance. An example of a screen wall with dimensions of roughly 5 x 2 m is shown in Figure 10). Its strength, however, is not comparable with normal concrete, and it is subsequently not suitable for load-bearing elements.

Figure 10. Directly printed building component consisting of cement-bonded material; design: Wieland Schmidt [3]

Many investigations are also concerned with integrating other construction elements in what are essentially monolithic components, things like reinforcement, conduits and cables. The 3D Print Canal House project in the Netherlands is another example. It investigates the use of printing techniques in the realm of architecture. In this project, a large FDM machine has been installed in a container. A synthetic material is used (or externally called “bio-plastic”) which is worked in a container close to the working site (see Figure 11). After being printed, the elements can be directly assembled. Alternatively, hollow forms filled with concrete can be used for load-bearing purposes.

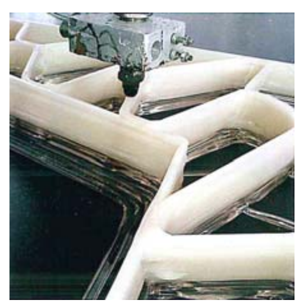

Figure 11. Fused deposition modeling process: 3D Print Canal House; DUS architects, Amsterdam [3]

A further example of printing entire houses is the work of the group 3M-FutureLab about Peter Ebner. An extremely compact "micro-home", developed as a student project, was printed out to full scale as a demonstration object. It was produced in two half-shells as a sand model (see Figure 12). This home offers the bare minimum for living with just a few square meters and a height of approximately 3 m.

Figure 12. "Micro-home" printed as sand model; design: Peter Ebner and 3M Future Lab [3]

In mechanical engineering, 3D printing techniques are well established. In construction, however, 3D printing is not commonly encountered despite its many potential benefits it may yield for the society at large. The largest construction components are created at present by extrusion methods, but their monolithic character makes it difficult to incorporate other components such as reinforcement, insulation and many more items. With the use of sintering techniques, it is possible to produce entire building elements, but high costs often prevent a wider application.

Since transformation of well-known industry best practices can and usually take a long time, gradual rather than immediate change is expected to happen in the construction industry. New approaches that are likely to enrich existing construction methods, such as pouring concrete in 3D printed forms, offer an alternative to conventional formwork. Soon they might be incorporated as established technique. The many different techniques and materials used in 3D printing demonstrate that there is a great potential for it use in construction and that the method offers new design scope. For these reasons, research was started to investigate 3D printing in construction in greater detail.

3 Methods

3.1 Team building and setting goals

The companies Ed. Züblin AG (a large construction company belonging to STRABAG SE), voxeljet AG (a manufacturer of 3D printing machines and supplier of large scale 3D print elements), and MEVA Formwork Systems (expertise in formwork systems) teamed up to investigate the understanding and potential of 3D printing in the construction of complex-shaped geometric concrete elements. Ed. Züblin AG's research and development team was in the lead role of the project.

3.2 Work steps

After aligning the project team and setting the goals, the following main work tasks were agreed upon and executed. First, in order to improve any of the existing design, planning and work processes, they had to be analyzed in great detail for potential return on investment (ROI). Building information modeling (BIM) processes were about to be integrated, i.e. the use of digital 3D design techniques that 3D printing machines can read and automatically use in the fabrication process. Second, the team allowed itself the time to understand any market potential and to ensure technical feasibility. Third, digital design began based on a priori known architectural drawings. Tests on smaller scale (reason: small investment and risk) were to demonstrate the feasibility of the selected approach. Meanwhile, choosing a test site for the final field trial fitting the criteria set at the beginning of the project (i.e., answering one of the main research question: where does 3D printing make most sense, economically as well as from construction methods and quality viewpoints?) was selected. Repeating the earlier process of creating a digital 3D design put heavy focus on any potential constructability issue. Second to last, the elements were printed and prepared for the final field trial. The steps can be summarized:

1. Understanding conventional and desired construction processes
2. Survey of market potential and technical feasibility
3. Digital design processes and 3D design generation
4. Test printing of small scale 3D prototypes
5. Selecting a test site and finalizing digital design
6. 3D printing of elements
7. Infiltration of printed elements
8. Final large scale implementation and tests on realistic construction project (in progress)

Some tasks, due to their nature, overlapped with others and were schedule to occur simultaneously. Since 3D printing has yet to become a standardized construction method, all elements included in the preliminary tests and the final field trial, were supposed not to be of the final structure. They were solely built for testing purposes and soon afterwards archived or demolished. Due to the nature of being a research project, some of the work steps are still in progress.

3.3 3D printing technology and process

This project used the voxeljet AG VX4000 3D printing machine (see Figure 13) to produce the sand molds for the elements. The machine's space requirement is 25 x 12 meters and a height of 4.5 m. As a standalone factory, it is one of the largest industrial facilities of its kind. Fabricating one piece at a time, it produces elements of up to 8 m^3 (4,000 x 2,000 x 1,000 mm) using a fully automated layer building process. Depending on size and shape, 3D prints can last several dozen hours (15 mm/h build speed at 600 dpi print resolution), while each piece typically weighs hundreds of kilograms or much more. The process selected for 3D printing is explained in Figure 14.

Figure 13. 3D printing machine VX 4000 [3]

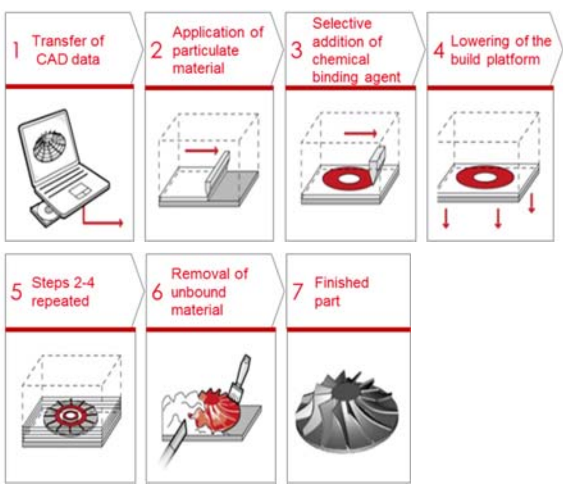

Figure 14. Powder-based 3D printing process [3]

The standard for data exchange is .STL (Standard Tesselation Language (STL), which uses oriented surfaces that are represented by triangles. Their composition is: header (Type (ASCII, binary), name, number of triangles (4 bytes)) and data ((3 vectors of 3 points each (4 Bytes), 1 normal vector). STL allows the identification of sectional planes that are running through all triangles. Since in 3D printing only cut lines are saved (2 points per line) it makes data exchange efficient. The creation of the jetting dataset is based on: real-time conditions while printing (allowing some flexibility), movement data and printing data. Casual events are replenishment of print head and powder and the preparation of data.

4 Experiments and results

Two experiments were performed: printing (1) small scale 3D elements for early feedback on the design, including material tests and (2) large scale 3D elements to determine constructability, including reusability of formwork system elements. First, however, the wider business scope for 3D printing on a large scale capital-intensive construction project is introduced.

4.1 "Stuttgart 21" main central station

The requirements that were set for 3D printing originated from a realistic construction project, called "Stuttgart 21". The heyday of railway stations in the 19th century saw great halls for train terminals in many European cities. Typically, stations were erected outside the historic city center, which soon grew around them, turning the tracks into a hindrance to urban development. This is especially true for the city of Stuttgart in southwest Germany. The existing station is a terminus and difficult to link to the growing European high-speed rail network. New tunnels and an underground station are being built. The most striking impression of the new subterranean station will be its brightness and visual openness, which combines aesthetic with security advantages. It will have an attractive special white and light-weight concrete structure subjected only to compressive loads with minimal construction thickness. The thickness of the optimized shell structure, i.e. of the complex parabolic concrete columns, was reduced to one hundredth of the span, resulting in the use of much less material for construction (see Figure 15).

Figure 15. "Stuttgart 21" main station with parabolic concrete column [ingenhoven architects, Düsseldorf]

These reasons required the reuse of formwork and the prefabrication of modular components which facilitate efficient construction [5,6]. It made it very attractive for exploring the potential of 3D printing.

Figure 15. Isometric view on main station model

4.2 Small scale testing

The research method foresaw to experiment initially with small scale test models first. A simplified 3D model of the column was generated and divided into two sand mold segments. These later were joined to function as a formwork system. Aside from developing the general 3D printing process for formwork purposes (see Figure 14), the experiment allowed practical experiences with handling and hardening the sand mold with epoxy resin, pouring the concrete into the molds, and removing the formwork. The success of generating the structure can be seen in the center of Figure 16.

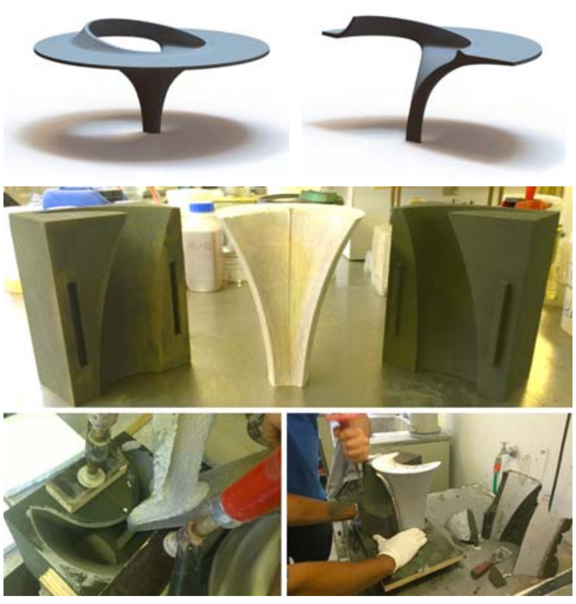

Figure 16. Conceptual 3D model of the parabolic concrete column (top left and cross-sectional cut top right side), printed sand molds (middle image on the left and right side), pouring concrete and removing formwork (bottom image left and right side, respectively) and finished element (center of the middle image)

4.3 Large scale testing

The large scale test involved detailed element and formwork design as well as construability planning (see one segment in Figure 17) of one parabolic concrete column in the main station. Due to the original size of the concrete model, any of the supporting scaffolding was not modeled before the 3D printing process.

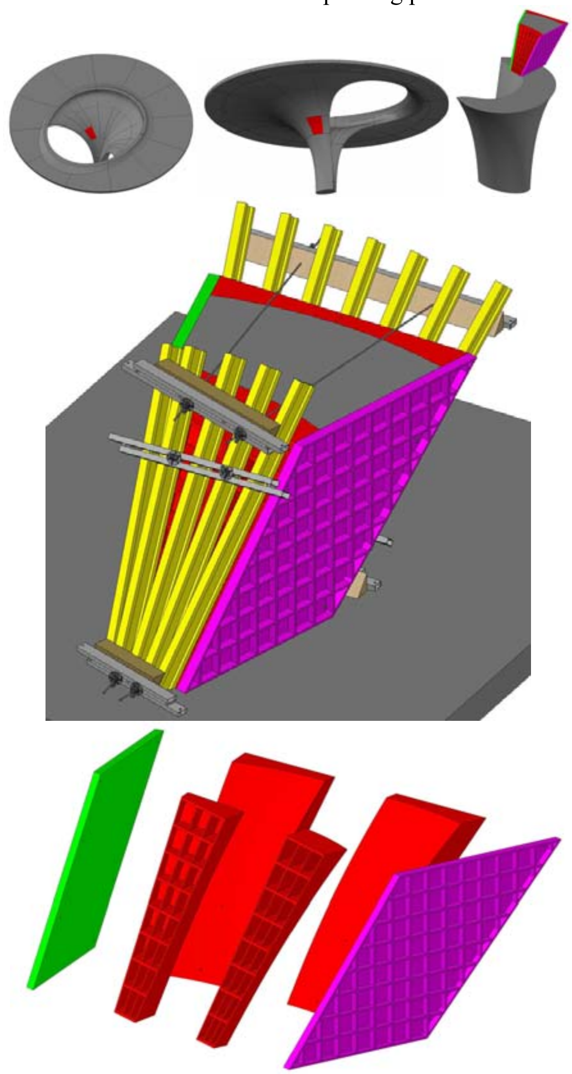

Figure 17. Detailed model (top image), detailed formwork model (middle) and extracted formwork elements due for 3D printing (bottom) [MEVA Schalungs-Systeme GmbH]

The elements were further arranged and optimized for efficient 3D printing in the VX4000 (see Figure 18). The expected total weight of all four elements was about 840 kg. The 3D printing lasted about 1 day. The task thereafter was to harden the material with epoxy resin which took also about 1 work day (see Figure 19). A final task was to erect the 3D printed formwork elements and to pour a layer of concrete. This has yet to be done at the construction site, but has been tested in indoor laboratory-like settings with smaller 3D printed elements already (see Figure 20). As the resulting concrete structure shows, the desired complex geometric shape was successfully built. Structural and further quality performance tests, which have been done for the small scale experiment, have still to be conducted to meet the client's and any regulative demands. Furthermore, efficient processes to repeat the process for all concrete column elements need to be investigated in future work.

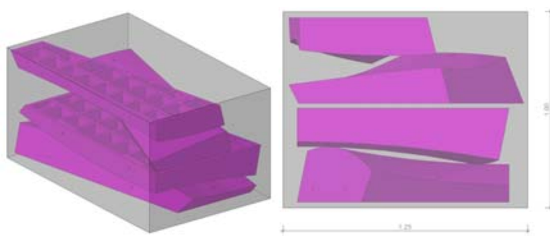

Figure 18. Efficient 3D printing: isometric (left image) and front views (right image) [MEVA Schalungs-Systeme GmbH]

Figure 19. Manual application of epoxy resin on the surfaces of the 3D-printed elements

Figure 20. Concrete after removal of 3D printed formwork elements [3]

5 Discussion and Conclusions

Additive manufacturing offers new opportunities in the production and in particular in the fabrication of highly individualized and repetitive modules. It is likely to impact the entire construction supply chain. The current awareness of 3D printing in the media also helps bringing it into a spotlight where construction companies start exploring alternative construction methods. Therefore, the current interest in investing in research and development is growing, albeit many issues remain that demand intelligent solutions. Many of them relate to structural and quality issues (i.e. material properties and finishes) and some, of which many are of high relevance to construction companies, relate to constructability issues.

The presented research gives a brief overview in additive manufacturing and provides a realistic scenario when a construction company investigates alternative construction methods. Examples of small and large scale 3D printing of complex shaped concrete formwork elements demonstrate the successfully developed process along this avenue that likely is transformative.

To achieve the latter, several tasks have to happen before such processes, incl. the application of 3D printing technologies, begin changing the business. They have to be cost efficient and need to follow standardized procedures. For the technology itself it will be important to rely on open data formats, process-oriented design and constructability planning, and flexible material characteristics that yield highest quality work and reduce waste [6] (e.g., rework).

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