Conference Paper

# Scaled Physical Prototyping of Construction Processes Using 3D Printing

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**Abstract**

3D printing and Building Information Modelling (BIM) are two technologies that have become increasingly popular and changed a wide variety of applications in a significant manner. 3D printing enables the design, prototyping and manufacture of items that were previously impossible or infeasible to do. Similarly, BIM is changing the way building and civil infrastructure projects are conceived, designed, delivered and maintained with a push towards a digital, wholly collaborative construction environment.

This paper examines how 3D printing and BIM can be used in a complimentary manner to help visualise and communicate important aspects of a project to the relevant stakeholders and personnel involved. By using the BIM model that has been developed for a specific project and segmenting key components of this model we can then use 3D printers to create a scaled model of the job and educate the concerned parties in the construction methodology, main risk areas, and ongoing concerns for maintenance and end-of-life deconstruction.

**Keywords:** Construction, prototyping, BIM, 3D printing, architectural model

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## 1 Introduction

Scaled models have been produced for construction projects in the past (Reed 2011), however, these have only focused on the finished product and are incredibly time consuming to create. BIM programs can create virtual representations of the specific project with tools such as walkthroughs, fly-overs and simulated driving, there is still value in creating physical prototypes of the proposed design to ensure all possible sources of risk, error and undue complexity have been eliminated (Azhar, Khalfan & Maqsood 2012). Utilising 3D printing means the scaled model of the particular project can be created with an increased level of accuracy, relatively easily and can be modified to reflect changes to the design, as required.

Drawing on inspiration from manufacturing and product development processes: products are never launched into mass production prior to creating a working prototype (Heusala 2001). However, in the Architecture, Engineering and Construction (AEC) industry the physical prototyping step is skipped. This is largely due to the impracticality and nonsensical nature of creating a full-scale model; hence, creating a scaled model that is functionally correct and dimensionally accurate is an appropriate compromise.

This will enhance the design review and error checking process whereby the key stakeholders, principal designers, constructors and end users can be involved in open forums that critically analyse the physical prototype of a construction project and translate any improvements into the project BIM model and ultimately ensure a fit-for-purpose final artefact. As a result, all personnel involved in the project will better understand the scope of works, the sequencing of key activities and potential construction issues.

The case study that has been selected for this paper is the Deakin University Centre for Advanced Design in Engineering Training (CADET). Creating a physical, scaled-down model of this project, using 3D printing, will assist in retrospectively examining the project lessons learnt and efficiencies.

# 2 Prototyping from BIM

## 2.1 CADET

Deakin University has recently completed construction on the $55 million Centre for Advanced Design in Engineering Training (CADET) and moved a large portion of the administration and teaching staff for the School of Science, Engineering and Built Environment (SEBE) into this building. The CADET building also contains a number of teaching laboratories containing advanced equipment relating to rapid prototyping, virtual reality and computer-aided manufacturing (CAM). Similarly, the CADET facility is used for teaching undergraduate and postgraduate students at Deakin University.

Construction on the CADET building commenced in 2013 and was completed in 2015. Construction of CADET utilised a number of local contractors and suppliers. During construction CADET utilised Building Information Modelling (BIM).

The CADET building was selected for this case study as it was managed in-house by the Capital Projects team at Deakin University. As a result, we had access to a large package of information from the construction phase that would have been difficult to obtain if we were using a project from industry.

## 2.2 CADET digital design data

The majority of the BIM design package for CADET was completed using Autodesk Revit. For commercial construction projects of this nature this is a fairly common program to use (Asojo 2012). However, for the CADET project all of the following sub-contractors also provided design packages in Revit for coordination into the overall model. A BIM manager was appointed for this project with a separate base model created for each of the following disciplines:

- Architectural

- Audio – Visual
- Electrical
- Fire Protection
- Hydraulics
- Landscape
- Mechanical
- Structural

Each of these separate design models was then compiled into a model of the entire project. As a result, it becomes quite evident that the compiled model contains a significant amount of data and can become very detailed and intricate. This makes extracting information for physical prototyping via 3D printing a fairly laborious exercise.

Due to the native format that design data was produced for the particular purpose of construction and later for validating 'as-built' locations of actual components, the process of extracting information for printing required some manipulation and was not as simple as selecting the entire model and pressing print, as discussed later in this paper. Manipulation of data included using an STL exporter from Revit for geometry only or processing the original model through a number of other programs (Showcase then VRED Pro) to enable exporting of VRML files to include colour and texture. In particular, the overall goal of simulating construction sequences and processes using physical models quickly evaporated upon further analysis and investigation of the available data.

## 2.3 Physical Prototyping

The equipment selected for prototyping for this exercise was the Projet CJP 660 Pro by 3DSystems. Although there were a number of benefits to using this piece of equipment there was also a number of limitations as a result of the actual equipment selected, as discussed below.

This machine has a bed size of 254 mm × 381 mm × 203 mm (3D Systems 2016), hence, it is suitable for our application as this is quite a large bed size and is capable of printing large objects. This is particularly relevant for civil construction as the models and objects of interest are usually quite large, therefore, minimising the extent of scaling required is advantageous.

This printer is also capable of using the full CMYK colour palette to provide surface colours closely resembling the actual designed objects.

This printer uses the VisiJet PXL core material which largely consists of Calcium Sulphate Hemihydrate (3D Systems 2016), commonly known as 'Plaster of Paris' in a dry powder form which then has a binder added to it with colour, if required, to form a solid object. The standard layer thickness is 0.1mm (3D Systems 2016).

#### 2.3.1 Projet 660 Positives

The approach taken in this paper is slightly different to other works in this field of study. The piece of equipment chosen is part of the reason this study is out of the ordinary:

- Economical – The core material for this printer is relatively inexpensive when compared to other 3D printing materials;
- Colours – The CMYK colour palette is incredibly useful for replicating real-world objects;
- Large bed size – By comparison to other available 3D printers, the bed size of this printer is very large, therefore, we can reduce the severity of object scaling;
- Fast print rate and functional software that accepts a variety of file types.

#### 2.3.2 Projet 660 Negatives

In contrast, this piece of equipment has some limitations, as listed below:

- Intensive Post-processing – The printed object must be cleaned of all the excess core material which can be done by vacuuming or blowing compressed air (this functionality is built-in to the printer). Once the excess core is removed, the printed object may be sprayed with an Epsom salt solution to dissolve the remaining core material and dehydrate the printed part. Following this the part shall then be bathed or brushed with an epoxy product to increase the strength of the finished item as well as improve the appearance;
- Weak Material – prior to coating with epoxy, the printed objects are quite fragile, as a result they are susceptible to warping or breaking during handling. This also limits the objects that can be printed (i.e. wall thicknesses) and the amount of scaling that can be applied to full-size models and still obtain an acceptable print;
- Preparation of models for printing – the civil infrastructure and building design process is not yet focused on maximising the integrity of the model for printing, therefore, there are large restrictions on the number of objects that can be natively printed from standard designs without significant re-design or manipulation to make them print-ready. This is amplified when using the plaster printer as additional care must be taken to design models appropriate to the available process and material (Gibson, Rosen & Stucker 2010).

**Figure** 1: CADET ENTRY COLUMN (I) ACTUAL OBJECT (II) SCREEN GRAB FROM 3D VIEWER (III) PRINTED ITEM.

# 3 Results

Although the models available from the design of the CADET building were not in the ideal format for directly printing, there were some elements that were able to be extracted and printed to examine the physical representation of the object. The two main objects that were printed, from the entire building model are the steel column from the entry and a set of reinforced concrete stairs, as discussed below.

## 3.1 Steel column from the entry of CADET

Printing this object was promising as the colours and textures from the construction model (or digital design) in Revit/VRED Pro was able to be transferred to the printing software and reflected in the actual object (Zhang 2014). Further exploration in this area could be conducted with regards to shadow mapping for proposed construction in the planning phase, as discussed in more detail later on.

Two iterations of this object were printed. The first object was printed at a scale of 1: 40 and no colour was included, hence, the object was printed with just the core material (white). The second object was printed at a scale of 1:30 and the colour and shadow mapping from the digital design file was reflected in the printed item. However, another limitation that has been identified using this material is the sensitivity to sunlight. The printed item immediately after printing showed a more vibrant shade of orange that closely resembled the digital design, however, with exposure to ambient light this colour has faded (as evident from Figure 1 (iii) above). Monitoring of ambient environmental conditions is one method of reducing the impact of this.

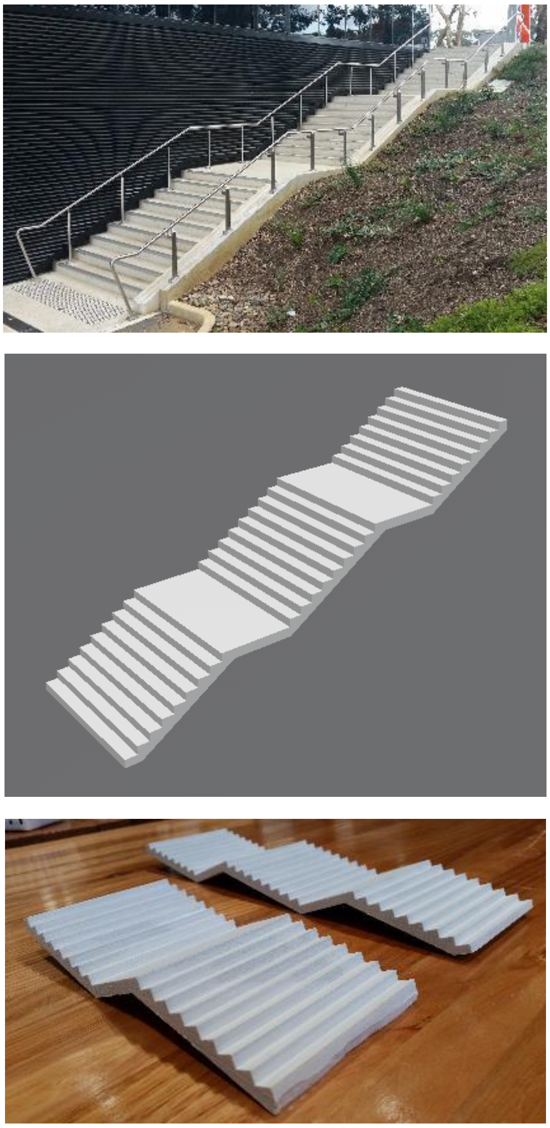

**Figure** 2: CADET REINFORCED CONCRETE STAIRCASE (I) ACTUAL ITEM CONSTRUCTED (II) OBJECT IN 3D VIEWER (III) TWO ITERATIONS OF PRINTED ITEM.

## 3.2 Reinforced concrete stairs from CADET

Like the steel column discussed in the previous section, two iterations of the reinforced concrete staircase outside the CADET building were printed. Both of these items were printed at the same scale of 1:30 and both were exported from VRED Pro in VRML format to include the colour from the original model.

As can be seen in Figure 2 (iii) the item closest to the camera is much shorter than the second iteration. It is also evident from this figure that the edge of the print closest to the bottom of the image is fractured and is not as-expected from a high quality printed object. Care must be taken using this printing technique due to plaster-based materials.

**Figure** 3: RUBBER RING JOINT (RRJ) REINFORCED CONCRETE PIPES (RCP).

Both items have been printed with minimal manipulation of objects, colours or textures from the original Revit model, therefore, emphasizing that this process can be incorporated into a project with minimal inconvenience and provide an added level of realism.

### 3.3 Other civil construction applications

The main point of difference in the data presented in this paper, when compared to existing architectural models created using 3D printing, is that we are focusing on the use of this technology to model construction operations and inform all stakeholders of the project.

Following on from the examples presented above, the use of this process has been explored with reference to precast reinforced concrete objects with promising results.

Modelling of Rubber Ring Joint (RRJ) steel Reinforced Concrete Pipes (RCP) is shown below, in Figure 3, at two scales. The larger of the objects shown is printed at a scale of 1: 10 while the smaller item is printed at a scale of 1:40.

These items were modelled using Autocad Civil3D, which is a program commonly used within industry for the design of civil infrastructure (Murad & Houston 2015), and then exported to the printing software. Some of the important observations from these prints included the influence of wall thickness on the strength of the printed object, this is evident in Figure 3 for the item at 1:40 scale which has warped due to the wall thickness being too thin, and the resolution of the models, evident in Figure 3 with the clearly evident faces of the models rather than being smooth continuous faces. These factors will be considered in greater detail for future prints and refinement of the process.

## 4 Summary and Conclusion

The main items that were achieved in this body of work are listed below:

- Successfully printed scaled objects from a design for an actual project that resemble the real-world objects;
- Developed a workflow that enables repeatability and promotes the use of such technology.

## 4.1 Limitations

Some of the limitations of the field of study discussed in this paper are listed below:

- Selection of equipment – the plaster printer that was used has limitations, hence, models and designs need to be constructed in a manner that considers these;
- Industry practice for digital design – BIM is not widely used (Pretti & Vieira 2016), only limited numbers of objects can be taken directly for 3D printing in native form without manipulation and remodelling for the purpose of printing;
- Scaling issues – building models have a number of small/thin items, such as handrails, windows, structural steel sections, that do not scale very well and become too weak when printed using the plaster printer.

## 4.2 Areas for future work

In the future, we hope to explore the following areas of research:

- Focus on bulk earthworks planning and emphasise the various addition and subtraction of volumes that occurs during civil construction projects;
- Analyse how the physical properties of prototype civil models can assist in making design decisions on actual projects;
- Segment a civil construction project into critical activities and demonstrate this sequence using 3d printed models;
- Use of physical 3d printed models for engineering education.

# References

3D Systems, 2016, Colorjet Printers Spec Sheet, pp. 1–2.

A. O. Asojo, An instructional design for building information modeling (BIM) and revit in interior design curriculum, *Art, Design and Communication in Higher Education*, **11**, no. 2, 143–154, (2012), 10.1386/adch.11.2.143˙1.

S. Azhar, M. Khalfan, and T. Maqsood, Building information modeling (BIM): Now and beyond, *Australasian Journal of Construction Economics and Building*, **12**, no. 4, 15–28, (2012), 10.5130/ajceb.v12i4.3032.

I. Gibson, D. W. Rosen, and B. Stucker, Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing, in *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, Springer, US, (2010).

H. H. Heusala, Management of innovation and new product development - Theory and a case study, in *Change Management and the New Industrial Revolution (IEMC'01)*, Albany, NY, 157–160, (2001).

M. M. Murad, and B. L. Houston, 'Influence of integrating GPS and civil 3D in engineering technology courses', in *2015 122nd ASEE Annual Conference and Exposition*, vol. 122nd ASEE Annual Conference and Exposition: Making Value for Society, (2015).

S. M. Pretti, and D. R. Vieira, Implementation of a BIM solution in a small construction company, *Journal of Modern Project Management*, **3**, no. 3, 88–95, (2016).

A. M. Reed, '3D printing in the architectural-engineering-construction market', in *RAPID 2011 and 3D Imaging Conferences and Exposition*, Minneapolis, MN, vol. TP11PUB21, pp. 1–7, (2011).

Y. Zhang, *On VRML virtual scene modeling analysis*, Xi'an, 10226680 (ISSN); 9783037859391 (ISBN), Conference Paper, https://www.scopus.com/inward/record.uri?eid=2-s2.0-84891606846&partnerID=40&md5=be8f1fb88192ec604e7c1fd25f7cb394, (2014).