Collaborative 3D Modelling and Printing: What You See Is Not Directly What You Get

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Abstract. *The aim of this collaborative 3D printing workshop is to define the production specifications, the teaching-learning pedagogical strategy aspects to help architecture students acquire: the basic competences of building representation, the pre and post processing of printing procedures (printing materials, paint, epoxy, accessories, etc...), defining the missing functions in BIM and Architectural Modelling software and determining the benefits of enhancing them for better 3D prototyping productivity. Two teams (A and B) adopted specific working scenarios based on real world printing jobs. Team A worked on an in-house scenario and Team B on an outsourcing scenario. Tasks successfully completed showed: the wide range of prototypes that could be produced in an architectural studio and the need for a collaborative network to organize the knowledge and good practices developed by research teams (professional or academic) involved in developing rapid prototyping for architecture. This knowledge network could be a discussion forum and a development partnership of 3D printing manufacturers and CAD/BIM software developers.*
Keywords. *Rapid prototyping; collaborative 3d modelling; knowledge bases; software design.*

Introduction

3D rapid prototyping printing devices promise to enhance the design and production activities in architectural studios. The drop in price of rapid prototyping technologies and the development of a new generation of desktop 3D printing machines is raising the demand for proficient 3D modellers and rapid prototyping specialists. Managing these technologies will open new job opportunities for young architects and designers. Despite excellent expectations, there are many lessons to be learned and competences to be acquired. The integration of these technologies in BIM and Architectural modelling software is still in its infancy, model making is still a manual activity and paper documents the basic methodology used in building construction. Geometric modelling tools with parametric functions that allow the printing of 3D models at different scales in full colour whilst adapting it to the machine's restrictions without the need to retouch the developed work are not available.

The rapid prototyping integration in common practice apparently seems easy and straightforward when first tests are performed with optimized demo files. Problems arise when in-house models are tested. Initial tests reveal serious problems not encountered in rendering and animation development. Tests are needed to evaluate modelling and prototype production activities; many modelling and file exchange procedures are not compatible with 3D prototyping.

Learning by doing and building a repository of good practices on rapid prototyping is needed. Architectural prototyping development methodology is still in its infancy. For the time being trial and error is the only alternative for acquiring the basic skills. Although some users consider them similar, our experience showed that 3D modelling for rapid prototyping and 3D modelling for rendering and animation procedures and strategies are totally different.

The 3D printing process is not a one man job; it's a collaborative task with at least two or more persons involved. Simple modelling/3D printing tasks require 2 persons: a 3D designer in charge of the modelling and a 3D printing technician who assumes the responsibility of checking the 3D information, repairing some printing components, organizing the output process and assuming the post processing tasks. Both persons have the same goal: to produce a successful 3D prototype.

Complex printing tasks, such as huge scale projects or urban models, require a modelling/prototyping team with each team member taking on a portion of the work. Creating a seamless integrated prototype requires coordination and mutual support, which goes beyond formal aspects like technology standards, modelling tools, compatible file formats, colour and texture standards (RGB). Integration is the key issue, without it the whole task could fail.

Collaborative workshop organization scenario

The collaborative architectural rapid prototyping workshop is a joint effort initiated by two research teams (Teams A and B). Team A is from the Hochschule Bochum, in Germany and Team B from the Escuela Superior de Arquitectura y Tecnologia, Camilo Jose Cela University, Madrid, Spain. Both teams are under the supervision of university lecturers and developed by a two independent groups of undergraduate students. Team members agreed to avoid idealized research conditions and develop several challenges of real world architectural studio scenarios. The real world scenarios will provide realistic feedback that could be shared and amplified by the contribution of other researchers and design professionals. Real world scenarios will help software and 3D prototyping equipment developers address the real needs of users.

The working scenario design

The Two teams designed two hypothetical scenarios with an architectural studio as the main setting. Both shared the same objective, exploring 3D rapid prototyping implementation and evaluating its potential in architectural education and future architectural practice.

The first scenario describes an architectural design studio whose partners decided to introduce an in-house 3D rapid prototyping machine to be used as an aid to day to day design activity and for possible commissions from their clients to build scale models for presentation purposes. Preliminary studies showed that outsourcing is expensive and slow; fast feedback of design proposals was critical.

The second scenario represents a design studio collaborating with an international design firm that owns an in-house 3D prototyping department. The studio's team is trying to use the acquired knowledge to take on a new challenge to accept the commission of using 3D prototyping to build a scale model of a project under development. Several factors led to the choice of rapid prototyping: design complexity, delivery date and cost. Studio members would develop the 3D digital prototype and a specialized service bureau would take on the prototyping job.

Team configurations

Team A assumed the role of the architectural studio that had recently bought an in-house 3D printing device and experimented with the potential of this technology. The recent acquisition of a Zcorp 650 rapid prototyping machine made them the ideal candidate. Team A would be responsible for evaluating the transition strategies and production workflow transformations for when this technology would be integrated into the day to day studio activities. Demo samples bundled with the prototyping machines usually produce a false sensation: when team members begin testing their own work they discover that implementation is not as easy as expected. The integration process should be programmed in phases to avoid workflow interruption. The same situation should be taken into consideration when such technologies are introduced into educational institutions to avoid excessive demand and work delays.

Team B assumed the role of an Architectural Studio which would outsource the 3D printing job to a rapid prototyping service bureau. Team B members made an intensive study of the local service bureaus available in their region and country. Using generic samples they asked these service bureaus for prototyping costs, including post processing and shipping. Several printing technologies were evaluated along with the service bureaus' standards for file transfer and processing. Legal aspects about the confidentiality of shared data were also analyzed. Model development was adapted to the selected prototyping technology and service bureau standards. Cost and delivery weren't the main criteria in the choice of service bureau. Other aspects were taken into consideration such as: the 3D prototyping available in their facilities, experience in this field and ease of communication between team members and technical staff. Team B added to its role that of the off shore partner. The goal was to test good practices in other conditions, and check that they are feasible. The following Table (Table 1) describes the major aspects of the two working scenarios, team observations and analysed issues.

What you see is not directly what you get

Every 3D prototyping activity is new challenge for the design team, aspects such as complexity of the model, size and level of detail are always different in each case. This situation retains its uniqueness throughout the whole life cycle of the prototype. Constant changes and modifications are required, exchange of information is not straightforward and printing file formats are primitive (only supporting one colour). Even if the final geometric model seems correct when displayed in the printing software preview interface, the final output seems different.

To build a good prototype, many tools are needed; the modelling activity is complex, in some cases the modelling process has to be repeated several times before obtaining a satisfactory result. No special routines are available for automate scale adjustments and detail simplification. The complexity of the 3D prototype increases when colour printing is required. BIM and many modelling applications don't export coloured prototypes directly to 3D printing devices. The 3D information translation process uses generic 3D files, and its consecutive interpretation by several applications with non standard import/export filters, increases the printing processes and produces an incremental number of errors during the translation operations. 3D prototypes should be checked constantly to ensure the correct translation of the data when needed. Sometimes workarounds are needed, and these may be supported by an application (slicing complex or huge models into smaller components) or using unconventional file formats to produce 3D outputs (WRML file format to produce colour 3D printing).

The post processing activities are also critical. All the 3D prototyping technologies require post processing of the output results and each available technology in the market has its cleaning (removing support or powder) and finishing processes (painting and using of bond materials). Some of these

Scenario / Team Analysed issues	IN-HOUSE / COLLABORATIVE TEAM A + TEAM B	OUTSOURCING TEAM B
Rapid prototyping know-how acquisition method-ology	- Trial and Error, good practices. - Web search. - Team collaboration. - Previous experience. - Manufacturer's assessment.	- Trial and error, good practices. - Web search. - Service bureau standards. - Hire assessment and training. - Previous experience.
Motivation	Relaxed, error tolerance. - Low cost reduces pressure. - Teams mutual support. - Exchange of good practices	Stressful, mistakes are expensive. - Cost & delivery dates increase pressure. - Limited external support.
Prototype development process	- Choose modelling strategy, Generic, BIM or R P. - Progressively develop in-house modelling standards. - Build/test in-house samples. - Test critical components. - Repeat failed RP work. - Approve post processing. - Evaluate finished work. - Present finished work.	Choose modelling strategy, Generic, BIM or RP. - Use service bureau modelling recommenda-tions and standards. - Build/Pay test samples of critical components. - Print rapid prototype. - Repeat unapproved work. - Approve post processing. - Present finished work.
Communication channels	Phone, e-mail, skype meetings, face to face meetings	Phone, e-mail, skype meetings, face to face meetings
Tested applications	- AutoCAD, Sketchup, Rhino, Revit, 3D stu-dio, Archicad. - Prototyping software not tested.	- AutoCAD, Sketchup, Rhino, Revit, 3D studio Max, Rapid. - Prototyping software tested.
Tested 3D file formats	Dwg, skp, 3dm, 3ds, pla,	Dwg, skp, 3ds, max, 3dm
Tested exchange formats	- Stl (good for one colour prints) - Zcp (native zcorp file) - 3ds and WRL (colour prints)	- Stl (good for one colour prints) - Zcp (native zcorp file) - 3ds and WRL (colour prints)
Quality control protocols	- Critical dimensions defined by in-house available technology. - Geometry export and translation tested. Failures detected. - Model integrity checked in printing software. - Errors repaired. - Printing job programmed. - Model sliced if bigger than printing de-vice tray. - Integrity is checked.	- Critical dimensions defined by Service bureau standards. - Geometry export and translation tested. Fail-ures detected. - Model integrity checked in printing software. - Errors repaired. - Service bureau quality control, if errors de-tected, Client is notified. - Slicing Model at extra cost. - Job delayed if repairs require remodelling.
One colour prints special features	- Straightforward. - Errors are due to modelling. - Fast Model export and printing. - Low cost.	- Straightforward. - Modelling errors delay jobs. - Fast Model export and printing. - Moderate Cost.
Colour prints special features	- Increase execution time. - Colour selection is critical. - Colour is not supported by many RP ex-port formats. - Requires additional programs. - Textures are difficult to create.	- Increases cost and execution. - Colour selection is critical. - Requires additional programs. - Time consuming and expensive if given to service bureau. - Textures are difficult to create.

Table 1
Major characteristics of the working scenarios, based on Teams' observations

Post processing and Finishing	- Working models don't require it. - Final finishing for exhibitions models. - Professional quality finishing requires training and equipment. - Presentation box is required. - Transportation cost is critical.	- Final finishing determines cost and quality. - Execution time is longer even when one service bureau assumes all tasks. It increases if work is outsourced to several. - Presentation box is required. - Transportation cost is critical.
Feedback and decisions making	- Fast, decisions are taken by in-house team. - Slow, if decisions are taken by partnered teams. - Very slow, if teams don't agree on standards, model quality or finishing details.	- Fast, decisions are taken by in-house team. - Slow, if decisions are taken by partner teams. - Very slow, if decisions depend on service bureau staff response.
Cost and budget estimation	- 3D prototyping Machine. - Printing materials. - Maintenance fees. - Energy. - Consumables. - Technician or student salary. - Shipping and handling.	- Prototyping (technology and post processing dependent). - Model repair (extra cost if time and knowledge are critical) - Post processing. - Painting. - Shipping and handling.
Disruptive events during printing process	- Model export errors. - Undetected prototype errors. - Import and printing errors. - Operation errors. - Printer breakdown. - Printing material shortage. - Sudden running out of consumables. - Holidays.	- Model export errors. - Undetected prototype errors. - Import and printing errors. - File delivery errors. - Shortage of consumables. - Operation errors. - Printer breakdown. - Holidays.

procedures are easy and simple and thus could be done by students, and others are difficult and hazardous and should be applied by a trained technician with the aid of special equipment and in controlled facilities (especially when chemicals are used to remove the support materials).

Colour is a critical variable to be taken into consideration during post processing. It may not be relevant for developing test and working models for architectural design, but models for exhibitions and final presentations require special care. Not all printing devices are capable of producing rich colour 3D prototypes. Some 3D printing technologies offer affordable colour outputs such as 3DP (Z corporation), others offer a limited array of colours like Polyjet Matrix (Object Technologies) or ABS (Stratasys and others). If more colours are required, a professional model painter is needed for further model enhancement (delivery time and cost are increased).

The following table (Table 2) describes a comparative study of prototype creation scenarios (data collected by students and researchers).

Choosing the right technology

Testing 3D rapid prototyping techniques and technologies in both scenarios was a challenge. The teams had to overcome many obstacles, starting with a minimum knowhow about 3D modelling for rapid prototyping production. The main obstacles that team members faced were: choosing the right 3D printing technology, finding the adequate 3D modellers, the limitations of architectural software concerning exporting data to printing devices, changes in production strategies in day to day studio activities and the design process, the users' skills required for developing the task and the amount of additional training required, selecting good practices for rapid prototyping for architectural design, technology limitations, time and cost estimations,

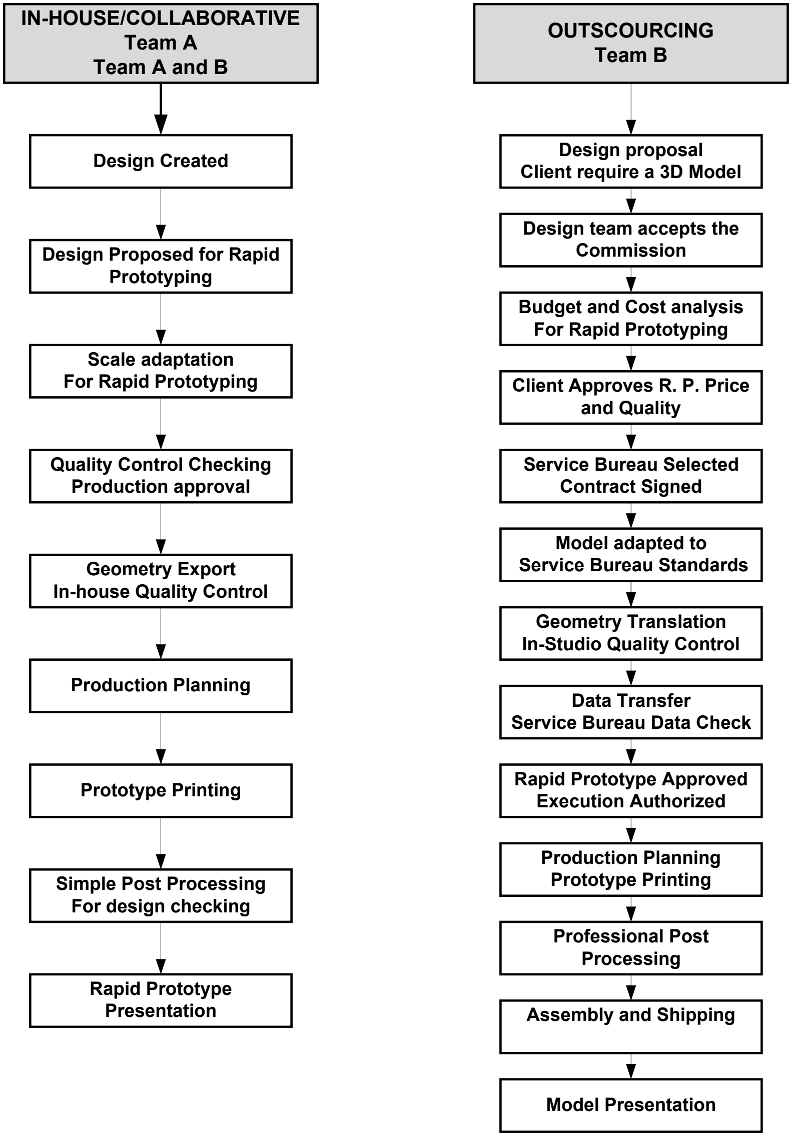

Figure 1
Comparative Workflow analysis of in-house/collaborative and outsourcing activities

and hiring qualified personnel.

Choosing the appropriate 3D rapid prototyping technology is not straightforward, each technology available is better suited to certain criteria: accuracy, quality or cost. The team members made an initial study to identify the most economic 3D prototyping technologies in the global market, their major characteristics and an estimated cost per cubic centimetre. 3 rapid prototyping technologies were analysed: Zcorp, Object and Dimension technologies.

Main findings

1. Team work scenario:

In-house production proved to be less stressful: rapid feedback accelerates decision making, corrections are faster, work is remodelled on time, mistakes are tolerated and changes negotiated.

The outsourcing scenario is more stressful due to cost and time constraints, negotiation is intensive during cost definition and model quality control, error tolerance is low, feedback is slow, and final results could be disappointing.

2. Collaborative skills:

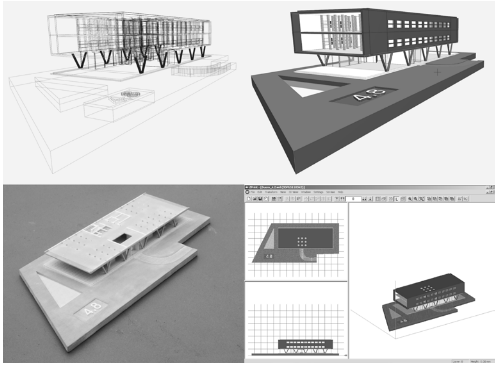

Figure 2
Screen captures of modeling stages, print preview software and photo of partial 3D print of collaborative students project.

The two scenarios revealed the complexity of 3D modelling activity for Architectural rapid prototyping. The in-house process was conditioned by: modelling experience, required level of detail, required finished quality, partner participation and the in-house workload. The outsourcing process was determined by: rapid prototyping cost, execution time, level of detail, fragility of components. Although the time and cost were not so critical in this case, in-house production revealed problems like translation errors and defective output work.

Table 2
Comparative Study of prototype creation scenarios (data collected by both teams).

TASK	GENERIC MODELLING	BIM MODELLING	RAPID PROTOTYPING
Methodology	Trial and error	Trial and error	Trial and error
Process	Indirect. Requires workarounds. Intensive Craftsmanship.	Indirect. Requires simplification. Limited Craftsmanship.	Direct Scale 1/1 is used. Limited Craftsmanship.
Main execution phases	- Generic. - Scale & details adapted to device standards. - Model exported to generic format. - Working model printed - Colour models, require post processing. - Model exported to printing software. - Integrity checked. - Model sent to printer. - Model post processing.	- Architectural. - Scale & details adapted to device standards. - Model exported to generic format. - Working model printed - Colour models, require post processing. - Model exported to printing software. - Integrity checked. - Model sent to printer. - Model post processing.	- Mechanical. - Scale & details adapted to device standards. - Model exported to generic format. - Working model printed - Colours are applied directly if required. - Model exported to printing software. - Integrity checked. - Model sent to printer. - Model post processing.
Maximum Scale allowed	Any scale or prototype size	Any scale, better for big scales (1/100 and above)	Any scale, Usually 1/1

Zcorp restriction	Zedit pro slices Models bigger than print tray.	Zedit pro slices Models bigger than print tray.	Zedit pro slices Models bigger than print tray.
Object and Dimension restriction	Model should be sliced manually, or divided into a kit of parts.	Model should be sliced in BIM program, or organized as a kit.	Model should be sliced in design program, or organized as a kit.
Level of Detail	- Any desired. - User skill dependent. - Device dependent.	- Any desired. - User skill dependent. - RP device dependent.	- Any desired. - User skill dependent. - RP device dependent.
Colour finishing	- Requires workarounds. - Skilled User required. - WRML format used.	- Requires workarounds. - Skilled User required. - WRML format used.	- Straightforward. - Some direct export to native printing language.
Data export to printing device	- Printer native format. - Generic STL - Generic WRML or 3ds	- Generic STL - Generic WRML or 3ds.	- Printer native format. - Generic STL - Generic WRML or 3ds
Translation Problems	- Geometry errors. - Importing model into printing software.	- Geometry errors. - Importing model into printing software.	- Geometry errors. - Importing model into printing software.
Final result quality	- Ready working model. - Post processing needed if presentation model.	- Ready working model. - Post processing needed if presentation model.	- Ready working model. - Post processing needed if presentation model.
Span of 3D printing activity	- Long. - Size and complexity dependent. - Depends on Modeller. - Requires organization for model maintenance. - Critical Post Processing.	- Medium - Size and complexity dependent. - Depends on BIM software. - Requires organization for model maintenance. - Critical Post Processing.	- Short. - Size and complexity dependent. - Depends on Modeller. - Requires organization for model maintenance. - Critical Post Processing.
Speed of execution	- Slow for novice. - Medium for expert.	- Slow for novice. - Medium for expert.	- Slow for novice. - Fast for expert.
Motivation	- Slow learning speed. - Slow, time consuming.	- Slow learning speed. - Slow, time consuming.	- Fast learning speed. - Slow, time consuming.

3. Modelling activity:

Although some users consider them similar, our experience showed that procedures and strategies for 3D modelling for rapid prototyping are not similar to 3D modelling for rendering and animation.

It is not a straightforward process; a lot of work has to be done before sending the geometry files to the rapid prototyping software. Modelling is not the only critical activity, quality control and model checking are required, and rapid prototyping requires error free models. Colouring and texturing are also critical; they require testing before using them in presentation models.

Architectural prototyping development methodology is still in its infancy. For the time being trial and error is the only alternative for acquiring its basic skills.

The minimum printable size factor is critical in architectural rapid prototyping, removing unnecessary components and adjusting critical sizes is essential. Post processing is necessary to ensure the resistance of finished objects.

4. Data Processing:

Translation operations were critical, especially when the modelling task required using several 3D programs. Too many translations increased the number of errors. One colour rapid prototype printing was easy and straightforward, errors were low. Colour printing, however, was tedious; it required several post processing activities that increased the

Table 3
Comparative study of economic printing technologies (data gathered by team members).

TECHNOLOGY	ZCORP	OBJECT	DIMENSION
Printing Material (Consumable)	Proprietary powder + binder.	Polyjet material + support	ABS material + support
Minimum sickness	3 mm.	2 mm.	2 mm.
Tray max Size	254x381x202 mm.	300x200x150 mm.	300x200x200 mm.
Oversized Models	Automatically cut with proprietary software.	Printed as an assembly kit.	Printed as an assembly kit.
Colours	16 million colours.	Black, gray, blue, White, transparent and a mix of these.	Ivory, blue, red, black, yellow, nectarine, olive green, grey.
Speed	Fast, could print several objects.	Medium, depends on model complexity.	Medium, depends on model complexity.
Prototype complexity	Depends on model complexity.	Complex objects are difficult to clean.	Simple prototypes.
Model repair	Model components couldn't be repaired.	Model components could be repaired.	Model components could be repaired.
Training	Check model integrity. Post processing.	Check model integrity. Post processing.	Check model integrity. Post processing.
Post processing costs	Final models finishing.	Cleaning components. Model painting.	Cleaning components. Model painting.
Estimated Cost	€0.10 per cm3	€0.50 per cm3	€0.30 per cm3
Street price for printing cm3 & post processing	€0.40 €0.70 for Cyanoacrylate €0.55 for Epoxy.	€1.50 €1.60 for cleaning. Painting not specified	€3.00 Including cleaning Painting not specified
Total cost	Low.	High.	High.
Application	Working and Presentation models	All purpose	All purpose Final products

volume of errors.

5. Post processing and finishing:

All the rapid prototyping technologies require post processing. For working models it doesn't require training and could be done by non-professional personnel. Others are complex and require both trained personnel and special equipment. Finishing the final output is critical, special care is necessary for a professional final look and because of the fragility of some of the components.

6. Transportation and logistics:

Rapid prototyping models proved to be fragile, requiring special attention to packaging and transport of the output. Special packaging was necessary and some couriers refused to assume responsibility for transporting it.

Proposal for Future Actions:

Starting with the two aforementioned university teams it seems to be necessary to build a university-expert-network and a collaborative knowledge base with the following advantages:

7. Introducing a facility that can be accessed by other universities, which want to introduce 3D-print technology into their schools (finding the right technology, solving the problems in software-adaptation, printing and post-processing.
8. Becoming an accepted discussion-and-development partner for 3D-printer manufacturers given that 3D printing machines are developed for mechanical engineers, not for architects. The practice shows that even those who market the machines do not understand the problems

architects have and are not able to solve them. Future generations of 3D printers could be developed for architects' needs.

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