A Realisation of a Construction Scale Robotic System for 3D Printing of Complex Formwork

J.B. Gardiner, S. Janssen, and N. Kirchner

Laing O'Rourke Engineering Excellence Group, Chippendale, Australia
E-mail: JGardiner@laingorourke.com.au, SJanssen@laingorourke.com.au, NKirchner@laingorourke.com.au

Abstract – The cost of producing complex formwork or moulds for precast concrete and GRC (glass reinforced concrete) is perhaps the most significant limitation when constructing architectural intentions from prefabricated concrete elements. Our contribution, FreeFAB™ Wax[1], employs a 6-axis gantry robot with interchangeable end effector tooling to coarsely 3D print and subsequently mill finish complex moulds for concrete at a construction scale. Significantly, FreeFAB moulds can be up to 30m x 4m x 1.5m with significant time and cost savings relative to traditional formwork. Furthermore, FreeFAB's print material approaches 100% reusability, virtually eliminating waste and material costs within the process. This paper presents an overview of our method for construction scale 3D printing and its realisation. Our findings suggest a construction scale 3D printing is business-viable and significantly expands the feasibility of the wide spread use of bespoke moulds.

Keywords –
Robotic 3D Printing for Construction, Precast Concrete, Additive Manufacturing, Prefabrication

1 Introduction

The Crossrail commuter rail project, a new underground rail line for the London Underground network, is currently the largest construction project in Europe [1]. Laing O'Rourke are responsible for the construction of three underground stations for the project, these stations feature three dimensionally curved transitions for many of the tunnel intersections within these stations (example shown in Fig. 1), which results in a requirement for approximately 1400 unique moulds to create the Glass Reinforced Concrete (GRC) cladding. Laing O'Rouke's Operations Director of the Project Delivery Department identified the procurement of these moulds as a significant project cost and risk, due largely to the small number of UK mould suppliers.

Figure 1 - Photo of Crossrail tunnel intersection mockup (courtesy of Laing O'Rourke)

Further to this, there are a number of methods to fabricate moulds for precast concrete and GRC, significant examples include: moulds fabricated from timber & steel, milled from foam and formed with flexible materials such as polyurethane rubber. These methods require significant materials, which are generally not reusable and often not recyclable, and require significant machining times and/or manual labour. This yields relatively expensive moulds that must be used a number of times to ameliorate the costs. These limitations of the current approaches for mould production inherently limits design intentions as the need to ameliorate mould costs through mould reuse drives design standardisation and/or design repetition. FreeFAB was devised and realized in order to relieve these limitations. FreeFAB™ Wax (referred henceforth as FreeFAB) is a construction scale robotic system for 3D printing of complex wax formwork.

3D printing, also known as Additive Manufacturing and Rapid Prototyping, was first developed and commercialized in the 1980's [2]. The process generally works by incrementally adding or solidifying material in layers to build an object. There are three main categories of fabrication of any object; subtractive

[1] FreeFAB was developed by the Engineering Excellence Group Sydney – an innovation lab within Laing O'Rourke. Technologies incubated within this lab, are tailored to the needs of the company and the construction industry in general.

(carving an object from a block), formative (making a mould and casting a settable material) and additive (building an object with blocks) [3]. Construction 3D Printing, also known as Additive Manufacturing for Construction, was first developed in the mid 1990's [4], although more than 20 different technologies have been developed since (most after 2010), none to date have demonstrated a compelling advantage over existing construction techniques. Existing construction 3D printing techniques are either unable to deliver the unique capabilities of 3D printing (fabrication of complex three dimensional forms) or 3D printed materials do not match existing construction materials performance [5]. Only one technology Winsun concrete 3D printing technique has been demonstrated to be production ready to date [6], however this technique is limited to fabricating geometrically simple structures that do not fully take advantage of 3D printing.

The primary manner in which FreeFAB differs from these technologies is its intelligent use of an additive (3D printing) and subsequent subtractive (Milling) manufacturing method which highlights the advantages of each method whilst they inherently negate the limitations of the other. FreeFAB is a novel method for producing moulds suitable for use in standard precast and GRC concrete prefabrication that yields time, waste, and cost savings. FreeFAB aims to disrupt traditional mould production and drive a paradigm shift in precast concrete and GRC mould production.

This paper presents an overview of the realised FreeFAB system; both technical (Section 2.1) and business grounding (Section 2.2). Findings from a numerical and empirical exploration that probe the aforementioned potential time, waste, and cost savings are presented in Section 3. These findings are then leveraged to facilitate a discussion. Following this, conclusions are drawn and the potential of FreeFAB is extrapolated with mention of relevant future work.

2 An Overview of FreeFAB

FreeFAB (Fig. 2) aims to deliver a paradigm shift in the fabrication of moulds for precast concrete and GRC. This shift is enabled by the pairing of two technologies (3D printing & Milling) that each have particular have advantages and that's inherent limitations can be negated by the other's strengths. Specifically, it aims at significantly reducing the cost of producing a single mould for a single panel so that it is no longer prohibitively expensive and only possible for projects with excessive budgets. This would present a unique opportunity within the construction sector, as bespoke and one-off elements can become a common feature on buildings, within interiors, on bridges, noise walls and for structural elements such as columns and beams. The following sections present an overview of FreeFAB; Section 2.1 focuses on a technical overview and Section 2.2 focuses on the accompanying business grounding and context in which FreeFAB is deployed.

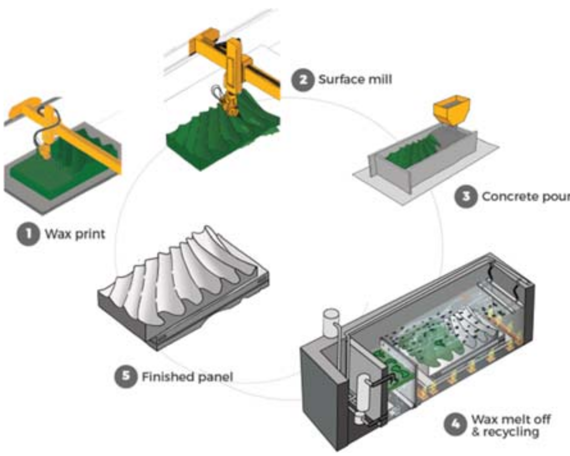
Figure 2 - Photo of FreeFAB Wax gantry installed at GRC UK plant, UK (courtesy of Laing O'Rourke)

2.1 The FreeFAB Wax technique

Figure 3 presents a conceptual overview of FreeFAB; FreeFAB first 3D prints a relatively coarse mould from wax (1) which is then milled to yield the required tolerances and surface finish (2). This mould is then used directly in place of a traditional mould (3), and without significant process change. Once set, the mould with panel in-situ is placed in a recycling station that melts the wax off the finished panel and collects it for use again in printing (4). The finished panel emerges from the recycling station ready for use (5).

The primary manner in which FreeFAB differs from the previously mentioned technologies is in its utilisation of a reliably reusable material; our specially devised and designed wax. By employing this material which is highly reusable the cost of materials and waste for each mould becomes negligible, significantly eliminating a major cost of mould manufacture. Furthermore, the wax we devised, designed, and realised for this technique, has excellent 3D printing properties allowing for very large beads of material (30mm x 10mm) to be deposited at high flow rates (up to 400L per hour). By 3D printing at this rate, while fabricating hollow tessellated internal structures – relatively large moulds can be fabricated at a fraction of the time relative to milling from a solid block of material, or traditionally constructed moulds.

However, whilst this high material throughput printing allows for significant amounts of material to be rapidly deposited in this additive process the surface finishes is not of a comparable quality to traditional techniques. A post printing complementary process is employed to counter this. Once the mould is fabricated using 3D printing the surface is then milled (removing approximately 5mm of wax at the surface) to achieve micron accuracy smoothness. By combining these two techniques the strengths of both are extracted and leveraged, while negating the limitations. For instance, 3D printing large moulds to micron accuracy would require very small layer heights, which would result in unpractically lengthy build times, by printing 'fast and dirty' we eliminate this limitation. Conversely, milling from a solid block often requires long roughing times to remove large volumes of excess materials. By removing the need for roughing and using 3D printing to fabricate the net shape, the accuracy of milling can be leveraged without the roughing time and waste costs.



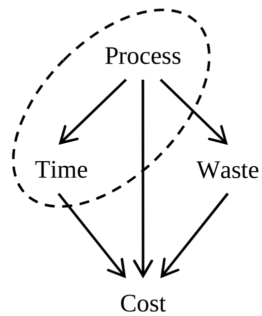
1. Wax print
2. Surface mill
3. Concrete pour
4. Wax melt off & recycling
5. Finished Panel

Figure 3 – A conceptual illustration of FreeFAB process (courtesy of Laing O'Rourke)

Contrasting FreeFAB with typical mould production methods provides further context and grounding. The previously identified, and typical, alternative mould manufacturing techniques predominately require a relatively large component of labour. For metal and steel moulds, sheets must be cut, handled and joined together and then the joints must be filed, sanded or ground down and then polished. With the milling and wire cutting of foam moulds the surface quality achieved in this relatively cheap material is generally not high enough to meet surface finish standards. Hence a further tooling paste must be applied to the foam to achieve a durable and high quality surface. This procedure requires a lot of manual labour for the application of the paste and subsequent polishing and sealing. The fabrication of polyurethane and silicone moulds requires the production of a positive 'buck' to pour the liquid mould material into, this process can be both machine and labour intensive.

2.2 Business Context and Grounding

This section builds the business context and grounding for FreeFAB – a realised effort in robotics and automation in construction. Figure 4 presents a simplified representation of the factors that drive mould cost. The three predominate factors are Process – the steps involved in the operation. Time – the time each process step consumes. These can include process steps and time consumers such as design time, order lead time, delivery time or may be focused on the fabrication time. Process and Time are often mistakenly considered as being entirely overlapping. This is not necessarily the case though, consider the case where a process step is removed and as a result the prior and post process steps proportionally increase in their Time cost. In this case the Process cost may have changed while the Time cost



has not. The third cost factor is Waste – again this can be broad and consider a number of factors or focused on the cost of lost material for instance.

Figure 4 Factors affecting mould fabrication cost

Underpinning this model representation is a set of formations for both the traditional approach and the FreeFAB approach. The formations for the traditional approach as specified by the aforementioned UK suppliers are intended to provide benchmarks against which to evaluate FreeFAB. The formations are devised and described as follows:

$$Time_{trad} = E_{rough} + P_{app} + P_{set} + P_{finish} \quad (1)$$

where $Time_{trad}$ is the time taken to fabricate a mould using the traditional method, E_{rough} is the rough-machining time, P_{app} is the time to apply the tooling paste, P_{set} is the time required for the tooling paste to set, and P_{finish} is the finish-machining time.

$$Time_{FreeFAB} = W_{print} + W_{cool} + W_{finish} \quad (2)$$

where $Time_{FreeFAB}$ is the time taken to fabricate a mould using the FreeFAB method, W_{print} is the 3D printing time, W_{cool} is the cooling time of the printed wax, and W_{finish} is the finish-machining time.

$$Waste_{trad} = E + P \quad (3)$$

where $Waste_{trad}$ is the amount of waste produced while fabricating a mould using the traditional method, E is the amount of expanded polystyrene used in the mould, and P is the amount of tooling paste used in the mould.

$$Waste_{FreeFAB} = W \times \frac{R}{100} \quad (4)$$

where $Waste_{FreeFAB}$ is the amount of waste produced while fabricating a mould using the FreeFAB method, W is the total amount of wax used, and R is the percentage of reusable wax.

$$Cost_{trad} = \frac{Q}{A} \times A_{avg} \quad (5)$$

where $Cost_{trad}$ is the cost of a mould fabricated using the traditional method, Q is the quoted price for a mould by an external supplier, A is the surface area of the quoted mould, and A_{avg} is the average surface area of a range of typical moulds.

$$Cost_{FreeFAB} = L + M + I + O \quad (6)$$

where $Cost_{FreeFAB}$ is the cost of a mould fabricated using the FreeFAB method, L is the cost of labour, M is the machine maintenance cost, I is the electricity cost, and O is the overhead costs. Initial capital expenditure for the FreeFAB installation is not included.

3 Findings

This contextually specified model employs fiduciary insights from business, suppliers and logistics channels along with insights and numerical findings from piecemeal empirical evaluations and simulations to build a consolidated mechanism for comparison. The following sections exploit this model to build quantitive data to facilitate the exploration of the aforementioned primary comparisons of fabrication time, waste and cost.

3.1 Fabrication Process & Time

The model was first employed in order to investigate the relative mould fabrication times of traditional and FreeFAB methods. Specifically, each process was broken down into a sub-processes and computer simulations used to calculate the duration of each sub-process. The process does not include lead time, which would be dictated by the workload of the factory.

The typical method for fabricating a 3D curved mould involves machining a base of expanded polystyrene to a rough finish, applying a 40mm layer of tooling paste, allowing this paste to set and finally machining the top surface to the desired form. This process is costly, time consuming and wasteful. The FreeFAB process differs by 3D printing the rough form of the mould in wax, allowing this print to cool and then machining the top to create a high quality mould. Table 1 presents this breakdown of times for both traditional and FreeFAB mould fabrication methods.

Table 1 Fabrication Time Comparison

Traditional	**Time (mins)**
Rough-machining	58
Applying Paste	15
Setting Paste	720
Finish-machining	140
Total	**933 (15.6hrs)**

FreeFAB	**Time (mins)**
3D Printing Wax	24
Cooling Wax	96
Finish-machining	27
Total	**147 (2.5hrs)**

The data presented in Table 1 is derived from (1) for the traditional method, and (2) for FreeFAB. For clarity and to facilitate a depth of engagement, the time data is deconstructed into the key process steps. As can be seen from the table, the traditional mould fabrication method consists of four sub-processes totaling 15.6 hours. The first sub-process is rough-machining of the expanded polystyrene substrate to remove large quantities of material and reach the desired form. The second is the application of the viscous tooling paste. The third is the hardening of this tooling paste, and the final sub-process is the finish-machining of the tooling paste to obtain the casting surface of the mould.

Conversely, the FreeFAB mould fabrication method consists of three sub-processes totaling 2.5 hours. The first sub-process is the 3D printing of the wax, where a bead of semi-molten wax is extruded from a nozzle to create the rough form of the mould. The second is the cooling of this printed wax. The final sub-process is the finish-machining of the top surface of the wax mould to leave a high-quality finish for casting.

As can be seen, the FreeFAB process requires fewer sub-processes and yields a significant reduction in the overall mould fabrication time – a 6.5x reduction. The most significant time saving is achieved by using wax instead of tooling paste, thus reducing the setting time from 12 hours to only 1.5 hours.

Another factor affecting the mould fabrication time is the rough-machining time. The traditional method starts with a block of expanded polystyrene and must remove large quantities of material to reach the desired form. The FreeFAB method 3D prints material only where required, thus reducing the necessary initial rough machining time. The rough-machining is eliminated and replaced by the faster 3D printing process. As 3D printing only places material where it is actually needed, this cuts 49 minutes from the process. The finish-machining is also expedited by utilizing a 5-axis milling head, thus allowing it to more closely approximate the final surface with fewer passes compared to the 3-axis milling heads typically used with the traditional method.

3.2 Fabrication Waste

The model was subsequently used to investigate the amount of waste generated by traditional (on average over a range of comparable designs on file) and FreeFAB mould fabrication methods. Each was evaluated based on the weight and volume of material waste. Table 2 shows the amount of waste generated by both traditional and FreeFAB mould fabrication methods. The data presented is derived from (3) for the traditional method, and (4) for FreeFAB.

Table 2 Waste Comparison

Traditional	**Waste**
Expanded Polystyrene	5.8kg (291L)
Tooling Paste	12.8kg (20L)
Total	**18.6kg (312L)**
FreeFAB	**Waste**
Printed Wax	97.5kg (99.5L)
Loss (1%)	1.0kg (1.0L)
Total	**1.0kg (1.0L)**

As can be seen from the table, the traditional mould fabrication method uses expanded polystyrene for the substrate and tooling paste for the top surface of the mould, with a total of 18.6kg of material used. Once the mould has been used, it is discarded, thus all of this material is considered waste. Conversely, the FreeFAB mould fabrication method uses 97.5kg of wax, but is able to reuse ~99% of this material, a waste of ~1.0kg.

It can be seen that the FreeFAB method has 18 times less material waste than the traditional method by weight. If comparing waste volume the savings are even more significant. The FreeFAB mould uses three times less volume as it is able to create the mould with hollow internal support geometry. By reusing most of this material, the process reduces wasted volume to only ~1.0L; ~300 times less than the traditional method.

3.3 Fabrication Cost

The model was finally employed to investigate the relative cost between traditional and FreeFAB mould fabrication. The cost of both a single mould and five repeats of the same mould were compared. Figure 5 presents an illustrative comparison of traditional and FreeFAB mould fabrication methods for one-off and five-off conditions. The data presented is derived from (5) for the traditional method, and (6) for FreeFAB.

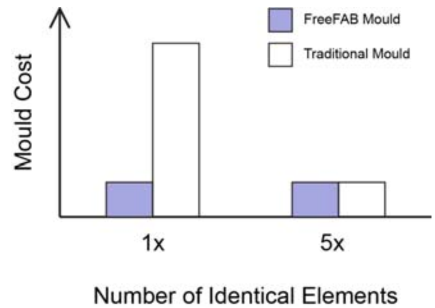


Figure 5 Illustrative comparison of mould fabrication costs using traditional and FreeFAB technologies for one repeat and five repeats.

As can be seen, the left most pair of bars compare the cost of a single-use mould using the FreeFAB and traditional fabrication methods. In this case, the FreeFAB method is approximately five times cheaper than the traditional method. The second two bars compare the cost of a mould that is reused five times. In this case the cost is comparable between the two methods as the FreeFAB mould must be fabricated and recycled for each casting. The significance of this is that there are no additional cost associated with one-off moulds when using the FreeFAB. This enables the designer with increased freedom as it relieves the requirement to standardise or repeat elements of the design to secure the cost benefit of ameliorating the mould cost over a number of castings.

Note: A significant portion of the high cost of traditional moulds is the cost of the raw materials. The tooling paste represents approximately 25% of the total cost of the mould using traditional methods. By comparison, the wax material used in the FreeFAB process is 2-3 times cheaper and can be reused hundreds of times with only 1% loss of material per cycle.

4 Discussion

In Section 2 we have devised and constructed a business-context placed and grounded model to provide a mechanism to benchmark FreeFAB with traditional approaches. This model was then utilised in Section 3 to produce a set of quantitive number to facilitate comparison. Our findings, presented in Section 3, support our claims that FreeFAB results in Time, Cost, and Waste savings relative to traditional mould approaches. Specifically, in Section 3.1 we showed that the FreeFAB fabrication method is significantly faster than traditional methods – 15.6hrs compared to 2.5hrs. With the FreeFAB system, a new mould can be created in hours, compared to the traditional method taking days (8-12hrs per work day). This means the production throughput of the FreeFAB system is much higher, increasing profit for the fabricator. Furthermore, this unlocks designers who are now able to implement a design that requires a relatively larger number of unique moulds. In Section 3.2 we showed that traditional mould fabrication consumes relatively large quantities of material to FreeFAB – 312L compared to 1L.

However, perhaps the most compelling finding was presented in Section 3.3 where we demonstrated the pressure that the expense of traditional mould fabrication places on designers – who are motivated to reuse moulds multiple times to reduce per casting cost – and how FreeFAB reduces the cost of moulds significantly, making it cost effective for designers to use moulds only once and significantly expanding the scope for feasible design. For instance, consider the enabling impact of the 5x lower cost FreeFAB on the design intentions described in the Crossrail project (Figure 1) where a large number of unique moulds are required to achieve the overall design intentions.

In order to further explore the potential of FreeFAB and to deliver Crossrail, Laing O'Rouke has commissioned the GRC/FreeFAB factory in the UK's East Midlands (Figure 2); to be on line June 2016.

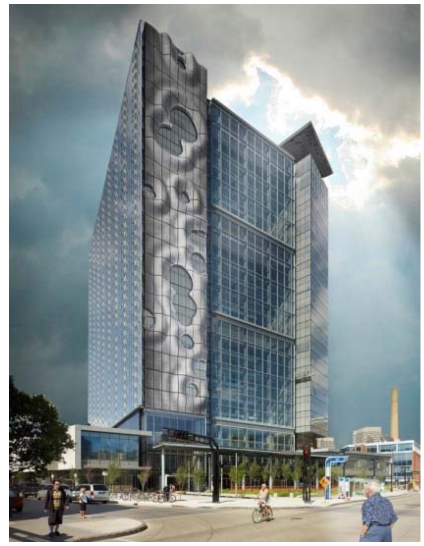


Figure 7 - Rendering of non-repetitive bespoke high rise building cladding (courtesy of Laing O'Rourke)

5 Conclusions

In this paper we have demonstrated that FreeFAB enables previously cost-prohibited design intentions to be achieved through its Time, Waste, and Cost savings compared to traditional approaches.

Further significant benefits lie in the use of the technology for projects that take advantage of the strengths of the technique in the production of highly bespoke buildings and infrastructure projects – two illustrative examples are given in Figure 6 and 7. This presents a unique opportunity within the construction sector, as bespoke and one-off elements can become a common feature on buildings, within interiors, on bridges, noise walls and airports. The cost of producing a single mould for a single panel is no longer prohibitively expensive, which frees the designers and engineers to add value (functional or aesthetic) where this was formerly out of reach.

Figure 6 - Rendering of non-repetitive design Freeway Noise Walls (courtesy of Laing O'Rourke)

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