SISTEMA NERVI

Sustainable Production of Optimised Floor Slabs Through Digital Fabrication

OWEN OLTHOF[1], ANASTASIA GLOBA[2] and PAOLO STRACCHI[3]
[1]*Author*
[1]*owen.olthof@gmail.com*
[2,3]*Co-Author*
[2,3]*{anastasia.globa|paolo.stracchi}@sydney.edu.au*

Abstract. 'Sistema Nervi' (the Nervi System) invented by Pier Luigi Nervi greatly economised the production of complex concrete forms optimised in both material usage and structurally. However it did not translate well into other contexts due to labour and material considerations (Leslie, 2018). This paper explores novel methodologies of producing optimised floor slabs and concrete structures, using digital fabrication techniques, focusing on both labour economisation and sustainability principles. A module from the Australia Square lobby slab has been used as the set geometry and was reproduced using differing techniques of fabrication for a comparative study. The study was conducted at scale (1:20). The viability for production at full scale (1:1) for manufacturing is discussed. The assessment criteria for the tests are divided into four categories: Cost, Time, Performance, and Sustainability. 3D printing of PLA plastic and ceramic clay extrusion printing has been used to produce removable or degradable formworks. These technologies have been selected due to their current market availability and associated costs. This study hopes to introduce improved methodologies for producing optimized concrete forms, as well as the sustainability potentials of a degradable formwork such as ceramic clay. Both systems were ultimately able to produce workable formworks for optimised shapes and showed promise for reducing labour involved as well as presenting with material sustainability for discussion.

Keywords. Concrete formwork; Sustainability; Degradable formwork; Optimised concrete; Advanced fabrication.

1. Introduction

In pre-WW2 Fascist Italy, political embargoes limited Italy's access to steel. In a country without a rich natural supply of the material, what imports were allowed were directed to the production of armaments and munitions (Stracchi, 2019). In response to these conditions Nervi developed Ferrocement. This thin cement system with reduced steel reinforcement was developed in conjunction

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with the ‘Sistema Nervi’ (The Nervi System) to produce permanent formworks that could create optimised ribbed floor slabs that were greatly optimised in the use of materials as well as static loads (Antonucci and Nannini, 2019). The Nervi System proved a success in the context of 1940s Italy, with its limited access to steel and an abundance of cheap labour (Leslie, 2018).The process of the Sistema Nervi (Figure 1.1) requires several steps and mouldings to create the final permanent formwork (Seidler, Dupain and Williamson, 1969).This extended labour-intensive process, detailed below, is the main reason for the poor translation of the building technology into other contexts.

1.1. THE PROBLEM

Economic factors meant the Nervi System was not widely adopted. Optimised material usage provides us with economic and sustainability opportunities which are especially relevant today as we find ourselves in a similar position to Nervi with a need to reduce our material usage. Concrete and its production is a major contributor to global emissions. Slab structures are estimated to make up to 85% of a buildings weight (Georgopoulos and Minson, 2014) using portland cement, accounting for an estimated 5.2% of global CO_2 emissions (J. Hawkins et al., 2016). Highly complicated, non unitized, systems such as ‘Smart Slab’ (Figure 1.2), developed by ETH Zurich which is an optimised ribbed slab system (not dissimilar to the outcomes from the Nervi system) have reduced the amount of concrete required by 70% compared to a standard floor slab (Aghaei Meibodi et al., 2018). However this requires an expensive methodology and complex digital fabrication systems. By employing modular formwork The Nervi System takes a much simpler approach to creating optimised ribbed structures and appeals to structural, aesthetic and sustainability needs. However, it currently falls short economically. 3D printing has been chosen as the technology to create formworks due to the its viability to be employed in current construction. The focus is on reducing the complexity of production and utilising 3D printing to lower the labour costs. 3D printing in PLA and ceramic clay have been identified as the materials due to their availability, cost and sustainability potentials.

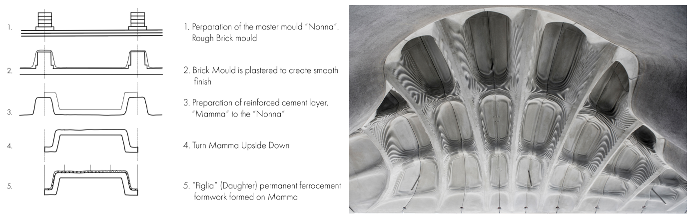


Figure 1. (Left to right) 1.1 Sistema Nervi Process, 1.2 Smart Slab (ETH Zurich 2018).

1.2. HYPOTHESIS

The hypothesis of this study is that PLA (Polylactic Acid) extrusion formworks and mouldings for permanent formwork will produce the most viable results. They are expected to be regular and have a high-quality finish but be more expensive to produce. They will also be the least labour-intensive. Ceramic formworks are expected to be irregular, so problems with the 3D printed form and setting concrete will be encountered.

2. Case Study (Geometry)

The Nervi slab of Australia Square will serve as the case study and geometric focus for the purposes of this paper. The slab was designed and built in 1962-1967 and implements a system of seven repeating modules to manufacture the radial slab. These permanent formwork modules were then placed on site where additional reinforcement was added and concrete was poured into the formwork (Figure 2.1). A single module has been selected and reproduced for the purposes of this study (Figure 2.2).

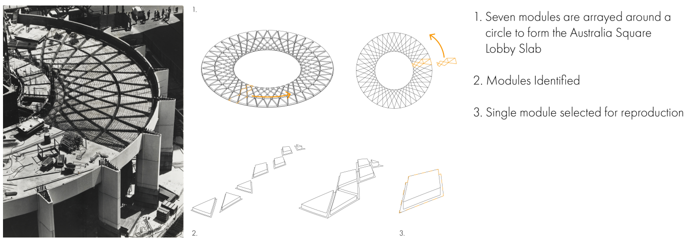


Figure 2. (Left to right) 2.1Construction of the Australia Square Nervi Slab (Dupain, 1967), 2.2 Selection of Module from Australia Square.

3. Methodology

To produce the selected module several methodologies were tested and the results have been analysed via a comparative analysis. The original methodology and output delivered in Australia Square acted as the control and final conclusions have been compared to this. The tests are divided into three groups:

1. PLA extrusion printing (Test group 1)
2. Ceramic print air-dried (Test group 2)
3. Ceramic print wet (Test group 3)

Each method was then analysed by the following criteria:

- Cost ($AUD)
- Time (Hr:Min:Sec)
- Performance (exterior finish and cracking)
- Sustainability (of formwork and printing material)

3.1. MOULD AND FORMWORK TYPES

Several forms of moulds and formwork types were explored to find a successful product. Maintaining a simple form was key as it would need to be scalable to remain viable. Cost and time implications were also very important for the viability of the method. Ultimately all the formworks were designed around having a bounding volume with a negative of the module to be removed (Figure 3).

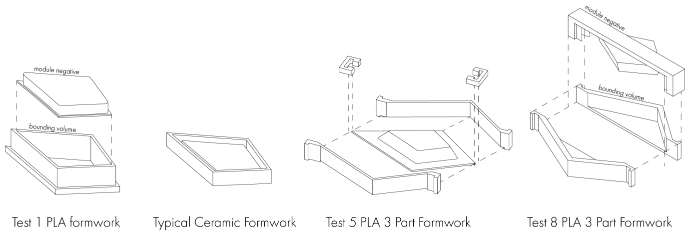


Figure 3. Typical 3D printed formworks.

3.2. FABRICATION OF MODULES

Modules were produced within a four-step process, pictured in figure 4:

1. Printing of formwork.
2. Cleaning of 3D prints.
3. Pouring Cement. (Ratio: 500g cement, 200g water, 5ml water reducing additive)
4. Demoulding.

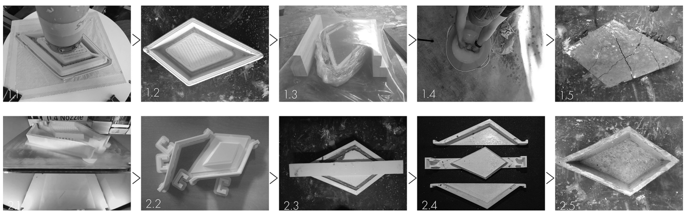
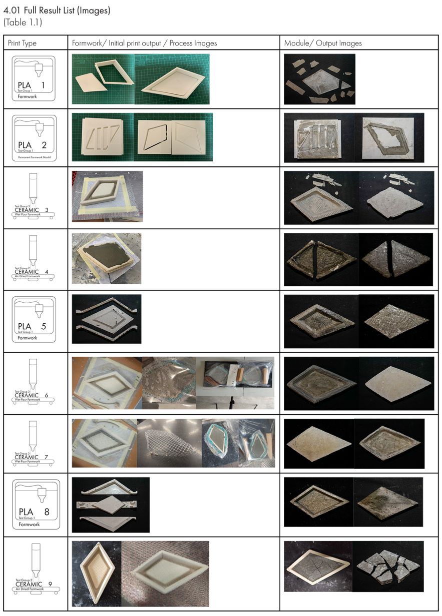


Figure 4. Process images, 1.1 Ceramic Printing , 1.2 Cleaned ceramic formwork, 1.3 Concrete pour and environmental control, 1.4 Washing and cleaning of module, 1.5 Outcome, 2.1 PLA printing, 2.2 3D formwork removal and cleaning, 2.3 Release agent application and Concrete pouring, 2.4 Demoulding, 2.5 Outcome.

4. Summary of Results and Discussion

The experiments have provided with two possible methods for creating formwork for optimised ribbed structures using digital fabrication. These were PLA with a multi part (3 or more) formwork design and release agent (as seen in experiments 5 and 8), and wet ceramic contained within a closed environment to control moisture (as seen in experiments 6 and 7). These methods will be the focus of the discussion and analysis of the comparative study criteria. Both presented methods with a low labour intensity and possibilities for reuse or recycling of the formwork material. The sustainability of these materials merits further study to draw conclusions about their true sustainability and recyclability. All other experiments experienced severe cracking or difficulties releasing from formwork. A full tabulated results list (table 1) of experiment images (section 4.01) and observations (section 4.02) have been included. Production of mouldings for permanent formworks was not possible at the set experimental scale (1:20), but was trialled in experiment 2.

Table 1. Results tables (Left to right) 4.01 Experiment records in images, 4.02 Experiment observations and data.



4.02 Full Result List (Module Production)
(Table 1.2.)

Print Type	Cost (AUD) (operational machine + materials)	Time (Hr:Min:Sec)	Observations and issues ('+' and '-' indicate positive and negative outcomes)	Material Usage
PLA 1 Test Group 1 Formwork	$30	08:02:10	- Poor finish, cracking and instabilities in the concrete - Demoulding was destructive and difficult to remove - Issues with the finish and strength of PLA formwork noted. Printings are required to be thicker for greater structural strength.	• 127.37g PLA • WD40 Lubricant as release agent • Destructive mould (mould was destroyed in the removal process) • Comparatively small amount of PLA used in construction
PLA 2 Test Group 1 Permanent Formwork Mould	$70	19:43:39	- Exterior finish was inaccessible due to inability to demould - The scale of the permanent formwork module was too thin and fragile to remove from the mouldings of PLA	• 239.07g PLA • WD40 Lubricant as release agent • Destructive mould (destroyed in process of demoulding) • Large amount of PLA material used in the mould
Test Group 3 CERAMIC 3 Wet Pour Formwork	$10	02:12:00	+ Underside has moulded to the formwork and kept a strong face + Top side finish is strong and clean - Outer walls showed signs of cracking and instability	• Degradable formwork with water • 1kg of ceramic clay used
Test Group 2 CERAMIC 4 Air Dried Formwork	$10	02:09:00	+ The underside of the module is strong with an imprint of the clay print, displaying a well cured mould - Dry concrete and clay show signs of visible cracking - Side walls are unstable - Module has split in half through the outer wall and centre.	• 1kg ceramic clay • Petroleum jelly
PLA 5 Test Group 1 Formwork	$21	05:06:02	+ External finish is high quality with sharp edges + No cracking + No signs of uneven drying - Some bubbles on the surfaces - could be more related to concrete mix / pour or the petroleum jelly release agent	• 106.97g PLA • Petroleum jelly • Formwork is reusable and was not damaged in removal
Test Group 3 CERAMIC 6 Wet Pour Formwork	$12	03:10:00	+ Firm and strong finish - Cleaning difficult with wet ceramic - Difficult to clear around reinforcement - Cleaning of the wet mould and reshaping due to warping the concrete edges are not as sharp in some places - Inconsistent finish with pockets from placing reinforcement in wet ceramic mould.	• 1kg ceramic clay • Additional steel reinforcement used • Surrounded by wet Chux (cloth) and sealed in a bag (closed environment)
Test Group 3 CERAMIC 7 Wet Pour Formwork	$12	02:40:00	+ High quality finish and conformed to the shape of the mould well - Manual working of the mould resulted in some inconsistencies - Residue of clay has been left on module with difficulty cleaning	• 1Kkg ceramic clay • Surrounded by wet Chux (cloth) and sealed in a bag (closed environment)
PLA 8 Test Group 1 Formwork	$32	5:40:21	+ Smooth finish + Easy release from mould + Mould undamaged and able to be reused - Some bubbling from release agent	• 130.84g PLA • Petroleum jelly
Test Group 2 CERAMIC 9 Air Dried Formwork	$17	02:12:15	+ Cracking displayed and continues through entirety of module + Water appears to have been drawn from the concrete to the mould - Possible issues with the application of the release agent	• 1kg ceramic clay • Wax finish painted on interior

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4.1. FABRICATION TECHNOLOGIES

A plethora of advanced fabrication technologies are available today and selecting the most appropriate systems for interrogation is important. Fundamentally the explored fabrication techniques needed to be be adaptable to custom products, have potential to reduce labour intensity from the current Nervi system, be readily available commercially and have possibilities for sustainability credentials in operation and material usage. For these reasons prefabricated systems such as waffled slabs and Holedeck, being unable to provide bespoke opportunities, were not explored. 3D printing of concrete has also been explored previously but is most commonly applied to simple unoptimized structures, with complex structures being possible but requiring highly complex and niche machinery (Zhang et al., 2019). CNC (computer numerical control) routers are readily available and the routing of foam is a fast method for formwork creation, but the foam and wastage of material were deemed unsustainable for the objectives of the study. Similarly, vacuum forming employed unsustainable non-recyclable Perspex. Wax printing has also been used to create formwork for optimised structures. The material was found to be unpredictable, (Oesterle, Vanteenkiste and Mirjan, 2012), (Hermann et al., 2018) and this technique was not able to be explored due to the availability of wax printers. Both PLA plastic extrusion printers and ceramic printers are readily available in the market, relatively cheap, and the materials which they use are highly sustainable and low cost. Both materials are biodegradable, reusable, and recyclable. PLA printing was able to be used to explore the production of moulds for permanent formworks as well as removable formworks. Ceramic printing, due to its inherent limitation for creating self supporting, removable formwork was only able to be used to explore removable and degradable formworks. An 'Ultimaker 2+ connect' developed by 'Imaginables' (Ultimaker 2+ Connect, 2020) was the 3D PLA plastic printer used and a linear actuator, or, 'Potterbot extruder' by '3dpotter' (3DPotter, 2020) was the ceramic printer used.

4.2. FEASIBILITY OF SCALING

The 'Ultimaker' and 'Potterbot' are good case studies when operating at the 1:20 scale, but would not be viable for commercial production. Products made for industrial use or custom rigs would therefore need to be explored to draw conclusions on the feasibility for these methodologies. Commercial viability for large scale industrial ceramic printing has not been extensively explored. Experiments by Anya Gallacio have been developed as installations but would appear to exemplify the difficulties of printing wet medium at a large scale (Anya Gallaccio, 2015). It does however show that the creation of larger ceramic printers is possible, however accuracy is currently low. The method which produced the most viable outcomes using wet ceramic printed formwork required an enclosed environment. It could be difficult to provide these conditions on-site. Therefore a factory or controlled location would be needed to produce the formwork and concrete slab, then transport to site. The most successful test prints were the PLA test group. Large scale 3D printing of PLA and plastic structures has been commercially available for several years. Thinglab's 'Bigrep' series (Thinglab 2020), among other firms, produce industrial scale printers with print beds of above 1m3. Using a printer to produce a module for the Australia Square slab at 1:1 scale would require multiple interlocking pieces and could be a complex construction. However, if this complexity could be managed PLA has proven to be a good formwork for concrete structures and could become a commercially viable formwork for complex designs. It is assumed that the current method of outer bounding formwork with 3D printed complex formwork could be implemented at 1:1 scale as shown in figure 5.

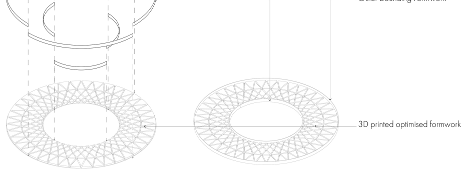

Figure 5. 1:1 scale technique implementation.

4.3. RESULTS OF ASSESSMENT CRITERIA

The test outputs were not of the same quality as the Australia Square slab. They did, however, indicate that an appropriate finish was achievable with the methods but may require more time and research into release agents, concrete composition and vibration to reduce cavitation. Cost, Time, Performance, and Sustainability can be discussed in context with the experiment but it is difficult to draw conclusions about the viability for the technologies in the current manufacturing industry without 1:1 experiments.

4.3.1. Cost

Ceramic prints for moulding formwork were significantly cheaper than the PLA prints (Figure 6.1), ranging from 14-50% of the total cost of some PLA prints. Both material and machine-use time were cheaper than the PLA printers. A note should be raised that because of the required operation and observation of the ceramic printer during use a labour cost could be included and alter results.

4.3.2. Time

Similarly, to cost calculations, a deeper understanding of, and comparison to, standard slab construction would help to situate the results. The time for production of ceramic extrusion prints ranged between 47minutes to an hour. PLA prints varied from approximately 4 hours to 10 hours (Figure 10.2). Ceramic prints required monitoring and machine calibration while the printing process was underway and thus were more labour intensive. The less labour-time intensive method was PLA printing but the faster overall time for production was ceramic printing.

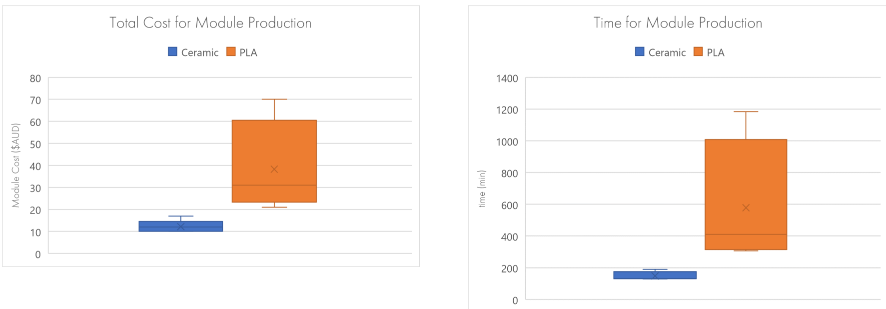

Figure 6. Box and Whisker Plot Results (Left to right) 6.1 Cost, 6.2 Time) .

4.3.3. Performance

The finish and consistency of PLA formwork were of higher quality in all aspects to Ceramic printing but lower than that of the existing Nervi System. PLA edges were sharper and faces were cleaner than that of the ceramic clay and the final product from PLA prints were much more reliable and regular. This was largely due to the liquid nature of the ceramic clay causing inconsistencies and inaccuracies. Additionally, the manual calibrations of the 'Potterbot' contributed to inaccurate final products. Malformed prints required manual working to correct the alterations and reform some portions of the moulds. Ultimately, the manual work proved less consistent than the PLA formworks which required no interventions. There is room however for finer calibration and control of the 'Potterbot' to produce more uniform outputs and reduce the need for manual intervention, greatly increasing the performance and ability to produce regular formwork. Ultimately both systems showed promise, but PLA was the more immediately successful in the scope of the conducted experiments.

4.3.4. Sustainability

The Nervi system is well documented as reducing material usage by approximately 24% of a regular slab construction (Magan 2016) so in this aspect the system is clearly more sustainable. Sustainability is a blanket term that can cover many aspects of a product. For the purpose of this study it relates to materials. Specifically, the re-usability, recyclability and biodegradability of the materials which were printed. All clay used in the ceramic extrusion printing was able to be retained. This clay, however, had concrete chips dispersed through it and could not be directly reused through the printer. Cleaning and filtering of contaminants would be required to reuse the clay for printing. At a 1:1 scale it is expected that there would significant amounts of clay required for the formworks. PLA on the other hand could be used to produce the formworks with a much reduced volume of material. When used with appropriate release agent PLA formworks were able to be retained for reuse. The release agent would need to be removed from the formwork prior to its recycling and would need to have appropriate environmental credentials (being non toxic). PLA itself is biodegradable and technologies for recycling the plastic are available but in their early stages. Products such as Filabot's 'Filabot Reclaimer' (Filament Maker, 2020) granulates waste plastic and melts the resultant particles into new filament. This could be a viable method for recycling, however research into the effects of a release agent on the reclaimer machine would need to be explored. Commercial viability for the recycling and reuse of either of these materials is possible but would require further research into the feasibility for commercial use. Water use for the demoulding of ceramic formwork was extensive with each test requiring approximately 15L to remove the clay suggesting again that the intensive use of water for the formwork removal would be substantial for a full-sized slab.

4.4. LIMITATIONS

The study had three major limitations. Time, funding, and consequently scale. The time period set for the study was 4 months and the cost was to be below $350 (AUD). Due to these limitations the scale of the study was reduced and prohibited the investigation into permanent formworks. These constraints inherently limited the number of possible iterations and test subjects. The cost and time limitations this study was subjected to draw parallels with many projects. This is why these limitations also helped to direct the study toward the most appropriate avenues for methods and technologies which would ultimately be viable for real world construction.

4.5. FUTURE STUDY AND WORK

Further study into the sustainability credentials of the materials used is needed. Whilst both appear to be recyclable or reusable more data is needed to draw a conclusion. Test prints at a larger scale are needed to gather a clearer indication of the costs for using these construction methods. Additionally, testing of the material strength is required to ascertain its viability for real world applications. Construction methodology including connections between the produced modules as well as an analysis of the structural qualities for the optimised rib slabs are targeted.

5. Conclusions

The study was set to explore possible methods to reduce the labour intensity of creating optimised floor flabs in the ilk of the Nervi System. The experiments suggest possible avenues for further study using the explored technologies. Both Ceramic and PLA extrusion printers were able to produce workable formwork for complex ribbed concrete structures. Wet ceramic formwork in a closed environment and PLA formworks with a release agent both showed promise as methods to reduce the labour intensity of creating optimised floor slabs. The methods have also presented opportunities for exploration for material sustainability with technologies for their reuse available, or biodegradability showing potential. Ultimately the PLA formwork when used in conjunction with a release agent yielded superior results, however the time for production was extensive. The table below summarises and illustrates what is a classical engineering/production dilemma: two processes with apposing costs of materials and labour (table 2).It is this authors opinion that the PLA technology is the more likely, with the results of further research, to be the more successful technology.The results of the study support the hypothesis that PLA would be the more successful method of production but also the more expensive, whilst ceramic clay would encounter problems with consistency and accuracy of printing.

Table 2. Conclusions Table.

	PLA	Wet Ceramic
Cost	• High cost of materials • Low cost of labour	• Low cost of materials • High cost of labour through high labour content to finished product
Time	• High print times • Low labour requirement • High design and computation time	• Low print times • High labour requirements
Performance	• High quality finish with use of release agent	• Lower quality finish due to manual interventions
Sustainability	• High embodied energy of the initial production of plastic • Biodegradable • Recyclable	• Biodegradable • Recyclable

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