T. Fischer, K. De Biswas, J.J. Ham, R. Naka, W.X. Huang, *Beyond Codes and Pixels: Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia,* 285–294.

LOCALISED DESIGN-MANUFACTURE FOR DEVELOPING COUNTRIES

A methodology for creating culturally sustainable architecture using CAD/CAM

ELLA PEINOVICH AND JOHN FERNÁNDEZ
Massachusetts Institute of Technology, Cambridge, USA
ella_p@mit.edu

Abstract. This paper demonstrates the production of endogenous solutions for global development when applying local workforce skills in the design-manufacturing process using available computer-aided design and computer-aided manufacturing (CAD/CAM) tools. The methodology outlined in this paper improves technology uptake in developing countries by promoting localisation of the design-manufacture process coupled with local knowledge to promote culturally sustainable technology dissemination. This paper documents a set of design rules and manufacturing methods used to create precision moulds with locally available CAD/CAM tools. The moulds shown here were used by local craftsmen in the casting and construction of a prototypical precast architectural system deployed in the urban slums around Nairobi, Kenya.

Keywords. CAD/CAM; CNC; cultural sustainability; assembly systems; global manufacturing.

1. Introduction

African urban populations are expected to triple over the next 30 years. Around 2030, Africa's collective population will become 50 percent urban, leading to an exponential increase in the demand for shelter and services. Globally, urbanisation is associated with more job opportunities and improved human development; however, th is is the reverse of the socio-economic conditions currently prevailing in African cities. Demographic expansion is continuing regardless of ever-growing shortfalls in housing, services and livelihood opportunities (UN-Habitat 2010). It is clear that the challenges of African urbanisation will not be met through the current architectural design and construction industry. Already, basic services are not accessible to many African urban residents. What is needed are new ways to promote multiple benefits through novel methodological solutions. These solutions are needed for humane development that can be scaled and widely implemented. In Kenya, and across Sub-Saharan Africa, CAD/CAM equipment has the ability to significantly enhance technology dissemination globally and further promote the practice of architecture in developing countries. Enabled by the global distribution of Gershenfeld's (2005) Fabrication Laboratories (FabLabs) and connectivity provided by the digital age (Resnick 2002), the process of development and building infrastructure can significantly move forward with the use of appropriate CAD/CAM technologies coupled with sustainable methodologies. This paper presents an initiative that intends to demonstrate the value of these technologies within a specific context.

2. Context

In Kenya, and in developing countries worldwide, the urban informal settlements (slums) not only require solutions for adequate housing, but also basic service infrastructure including water, electrical, and sewage systems. The lack of sanitation infrastructure is a crisis of incredible magnitude. Over 2.6 billion people – 40 percent of the world's population – lack access to adequate sanitation. The problem is particularly acute in slums, where high population density combined with the lack of sewage infrastructure and resources result in no access to sanitation for 80 percent of slum dwellers. Most residents living and working within these informal settlements are employed within the informal craft sector. This sector is made up primarily of the Jau Kali who are entrepreneurs and craftsmen with trained skills representing a wide spectrum of local production practices. The Jau Kali way of working can be described as bricolage, in which necessity and recycled materials become the cornerstone of each creation. Their way of working is iterative, reworking until the product performs its intended task; resulting in minimal product waste. The Jau Kali are creative and ingenious inventors, although limited by their materials; thus, the quality of their production can be unpredictable. As Kenya aims to position itself within the global economy, many living and working within the informal economy fear marginalisation with the introduction of new technologies. For advocates of sustainable development in regions like Kenya the question remains, "Why use highly technical exogenous machinery when there is an abundance of local labour?" This paper describes the benefits and synergies that arise when new, appropriate technology is adopted by local craftsmen within a network of distributed industries in an approach described here as Localised Design-Manufacture.

3. Innovation

The methodology of Localised Design-Manufacture is based on the principle that within the development context production processes must consider the local abundance of skilled technicians and assemblers. Unlike traditional manufacturing which aims to streamline the production process, this methodology promotes building local capacity by incorporating a feedback loop that links a local engineer to a local assembler, or craftsman, throughout the design and production processes. In this way the local craftsmen can be involved in the development of their own community, as the consumers and producers.

Localised Design-Manufacture promotes working within the community, recognising the skill of the local informal workers while augmenting that capacity through the introduction of new, global technologies. The precision and efficiencies provided by highly technical machinery can bring noticeable material cost savings while maintaining safety measures in the construction of architectural and infrastructural assemblies.

3.1. ECO-SAN SOLUTION

In the summer of 2010, a team of engineers and designers from the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, USA partnered with an engineer and technician from the Science and Technology Park at the University of Nairobi (Nairobi-FabLab) to manufacture a low-cost sanitation centre using digital design and fabrication tools available at the University of Nairobi. The principals of Localised Design-Manufacture were utilised throughout the process of CAD/CAM fabrication to surface sculpt a precision mould plug for a fibreglass mould used to pre-cast ferrocement components. The team addressed the lack of sanitation in slums with a low-cost solution that could be pre-manufactured and easily assembled on-site, employing local labour throughout the design and manufacturing processes from skilled fabrication technicians to on-site assemblers. The development of the Eco-San toilet for the informal settlements of Nairobi can be seen in Figure 1. As a result of utilising the Localised Design-Manufacture methodology in the development of the Eco-San solution the assembly achieves technical performance and community adoption while enhancing skill sets and digital expertise. Features of the assembly include:

Pre-Fabricated, Pre-Cast Materials A precast ferrocement assembly with integrated tongue and groove connections allow for rapid production

Figure 1. Application and production process used to solve a real-world sanitation problem utilising local resources and labour (2010).

and assembly of quality components, while reducing cost and use of materials. At $200 USD to cast each unit, the cost is comparable to the more commonly used pit latrines with bush pole and corrugated metal substructure.

Durability Ferrocement is both highly durable and low maintenance. The pre-cast, monolithic floor plate provides a register for the superstructure, by locking in the walls and corners in combination with the monolithic, precast roof ring. The panels are structurally engineered for the demoulding and transportation of the pre-cast parts.

Assembly and Flexibility Due to its compact, modular size the assembly can be implemented on site at the block level where it is needed most. In order to eliminate an on-site staging area and formwork, foundation posts are pre-cast which allow for levelling the floor plate during the assembly process. In this way, the assembly can be placed on sites undesired for other types of construction.

Designed for Lack of Sewer Infrastructure The waste is easily accessed from within the unit by lifting the light-weight, rotationally moulded, plastic squat plate on a daily basis. This no-flush design is important in slums where there is minimal existing water and no sewer infrastructure.

Cleanliness Precision moulds allow for the design to incorporate complex curves like filleted corners along the low-wall of the floor plate and in the L-shaped corner panels. This adds to the durability of each component while eliminating crevices that normally collect dirt, increasing the perceived cleanliness of the toilet assembly. Water-reducing measures are particularly important for communities within Sub-Saharan Africa where the cost of water, a commodity used in cooking and cleaning and drinking, is often more expensive than a fruit juice or soda.

4. Localised Design-Manufacture Eco-San Process

Employing the Localised Design-Manufacture methodology to create the Eco-San solution the team relied heavily on a series of field tests and processes for arriving at the best mix of innovative and appropriate technologies for the project. These tests outlined below produced an accurate and replicable design solution to the real-world problem of sanitation within the informal settlements around Nairobi, Kenya.

4.1. LOCALISED DESIGN PROCESS

When working within developing countries, meeting the formal necessity is not a catch-all solution; for maximum impact and uptake, one must consider the cultural implications of the process in which it is achieved. The novelty of the Localised Design-Manufacture methodology is that it necessitates a design process that incorporates craft and *democratises* the CAD/CAM process, while maintaining cultural sensitivity. Achieving these goals is what transforms the methodological proposal into a design exercise in which design sensibility is deployed to achieve cultural sensitivity. It is the combination of appropriate technology and local context that can facilitate development in a culturally sustainable manner.

4.2. LOCALISED MANUFACTURING PROCESS

In Nairobi, a hub of East Africa's industrial production, there are few highly technical machines and manufacturing processes aside from large and established industries such as the Nairobi Railway. However, in 2009 the Science and Technology Park at the University of Nairobi built a FabLab that houses a set of prototyping equipment that is accessible to budding entrepreneurs. Projects which have been successfully incubated within the FabLab include a flexible biogas digester, a vehicle tracking system, a set-top box to convert analogue TV to digital, and a wireless mesh network system called Fabfi.

CAD/CAM processes are well positioned for widespread adoption by providing benefits to the craftsman, including repeatability, precision, replicability and scalability, without compromising customisation. "Real" mass customisation, as defined by Schodek et al. (2005), is a manufacturing process which creates varied architectural components, not restricted by industrial repetition. Though digital tools may require more time to produce a first working prototype compared to traditional hand-crafted methods, long-term productivity is dramatically enhanced due to ease of iterative design improvements and repeatability. Within the Eco-san development the Jau Kali on the team became convinced of the benefits of investing in these new processes as productivity and profitability potential were improved through the pre-cast, precision mould manufacturing process.

4.2.1. Benefits of pre-cast ferrocement

As stated above, when approaching localised manufacturing the process must first consider available local resources and local production methods that can benefit from digital production. Within Nairobi ferrocement construction is one such process that can benefit from digital fabrication, commonly used for water storage tanks and other monolithic forms, traditionally cast in-situ. The technique is well established with the Jau Kali who construct these thin-shell concrete structures reinforced with hexagonal chicken wire mesh. The Eco-San design team used ferrocement in a pre-cast system to control the quality of the assembly with a digitally fabricated, precision mould.

Pre-cast precision moulds are used similarly to the local technique of sand casting, another process that can benefit from the precision of digital production. Where the precision mould is milled from solid material, a sand cast is a reductive process of removing or packing ground material until a negative can be formed in which a craftsperson can cast their monolithic form. In sand casting, the first cast form is used in subsequent casts as a plug to create future moulds in the sand. In each process the quality of and reusability of the plug saves on time and cost. The pre-cast process used in the Eco-San solution utilised the Jau Kali's transferable processes and skills. The pre-cast precision mould, however, provided many benefits in cost savings, quality control, as well as easy, on-site assembly and maintenance, while employing local labour.

4.3. DIGITAL FABRICATION

The Eco-San solution was designed to front load the effort of skilled technicians during the digital design and fabrication of the precision molds to limit the amount of skilled labour required on-site, thus reducing the final cost and increasing access of the final assembly to the community.

The manufacturing process used in making the Eco-San floor plate used the process of CAD/CAM fabrication employing computer numerical control (CNC) technologies to surface sculpt a precision mould-plug for a fibreglass mould used in pre-manufacturing highly accurate ferrocement components. Utilising computer-generated designs and digital fabrication within the FabLab the design team partnered with a local technician and engineer to iterate the design of the precast sanitation unit rapidly and replicate positive results. The Figures 2–5 below illustrate the fabrication process of the floor plate mould from digital model through mould fabrication.

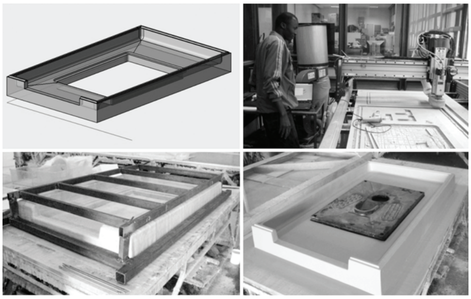


Figure 2–5 . Floor mould design as digital 3D model. Milling positive plug from composite board in Nairobi FabLab. Fibreglass mould and steel frame made from plug. Final fabricated floor plate plug.

For non-industrial manufacturing of infrastructural components, as promoted in the Localised Design-Manufacture process, the design team had to create high precision moulds without the need of energy consuming equipment for injection blowing, vibration, and compression. This can was achieved by creating a single-sided, open-face mould, leaving just one plane of the cast volume to be trowel finished.

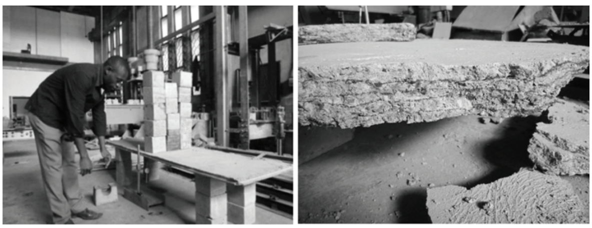
Creating a single-sided mould has many benefits. Technical benefits include the relative simplicity of the fabrication equipment required to mill the plug, it is predictable and can be achieved on most 2.5D CNC routers, as found in the local FabLab. Additionally, it reduces the amount of material to create the mould, a goal for any production process when working within a material-restricted area, as is Nairobi. In general, moulds are more affordable and consume less energy to transport than casts, promoting localised and distributed manufacturing. The design team began the mould fabrication process with a virtually modelled component representing the final cast form. The digital model was used to test in virtual space, before production, that the proper tolerances were built into the precision mould and that the resultant cast components would fit together in the final assembly. The technical challenge came in designing the form for a single-sided mould. The design had to make sure all precision elements, including the framing edge and joints, were cast within the finished mould for higher accuracy in the assembly. Undercuts, as found in the integrated joinery elements, were avoided by locating all joint connects onto one surface of the mould – the bottom.

Capacity building Throughout the digital design and manufacturing processes there were opportunities for building local capacity, a necessary step in the Localised Design-Manufacture process to ensure the eventual community uptake and full integration of new technologies. During the summer of 2011, in partnership with the Nairobi-FabLab, the design team hosted a digital modelling and fabrication workshop for a multi-disciplinary group of university students. Participants learned basic digital modelling skills through a lesson demonstrating the process of exporting a digital model to the digital fabrication tools found within the local FabLab. Each student was then assigned the task of modelling a design related to their own research, proceeding from conception to realisation. Many of the students have since contributed to the development of the Eco-San solution and continued investigations utilising their digital fabrication skills.

4.4. MATERIAL DEVELOPMENT

Localised Design-Manufacture contributes to the identification of sustainable construction methods and the consideration of innovative materials and assembly systems (Fernandez 2006). During the Eco-San development, independent material research was conducted within the Concrete Materials Lab within MIT's Department of Architecture with the goal of material efficiency for cost-reduction. The team worked to develop and test a concrete mixture and configuration that would be efficient, yet structurally sound, using all locally sourced materials. The investigations included cost-reducing concrete mixtures found in Kenya; including plastic pellets, a recycled industrial by-product, for aggregate, while others incorporated admixtures like volcanic ash and fibre reinforcement.

Structural testing During the month of January 2011 the design team led a casting demonstration for students and local craftsman with the University of Nairobi's Civil Engineering Department. The casting demonstration included a series of ferrocement wall panels with the goal of performing structural tests showing the effectiveness of each cast, shown in Figures 6 and 7. The tests included the control sample which replicated the mixture used in the Eco-San solution built in the summer of 2010, chicken wire reinforcement within a 1.5 inch thin concrete slab; as well as two variations on the control sample, one used layers of distributed mosquito netting as a substitute for chicken wire and another used recycled plastic pellets to replace the quarry dust aggregate. The variables compared in each cast included; self-weight, tensile and compressive strength limits, as well as the catastrophic failure point, and associated cost of each mixture. It was found that four layers of distributed mosquito netting roughly .25 inches apart saved time in casting and reduced cost compared to the chicken wire reinforcement which required a welded steel frame to lay flat in the composite. Structurally, the chicken wire with rebar could carry a larger load before catastrophic failure. However, the chicken wire cast showed early deformation compared to the mosquito netting which failed suddenly at a higher weight.



Figures 6 and 7. Three-point bending test of panels for use in pre-cast assemblies. Sec tion of panel with mosquito netting after catastrophic failure.

4.5. ECO-SAN RESULTS

The efforts of design to manufacturing detailed above culminated in the form of a sanitation solution that is environmentally, culturally, and financially sustainable and provides hygienic sanitation to those living within the informal settlements around Nairobi. Additionally, local capacity building was achieved for the engineers and craftsmen that were employed throughout the process. To further understand the potential of this system the local team has continued to scale-up the production and assembly efforts to span new geographic locations.

5. Improved community uptake

While the digital modelling and manufacturing technologies used in the Eco-San solution are not new, researchers, engineers and designers have only recently introduced the use of CAD/CAM in developing regions. The Instant house (Botha and Sass 2006) utilises CAD/CAM to fabricate plywood components into a bi-lateral assembly. The investigation of an interlocking concrete block assembly by Griffith uses CAD/CAM to manufacture a cradle moulding device appropriate for local adoption in rural applications (Griffith et al. 2012). Each of these techniques proposes a feasible methodology for creating designs in a virtual environment to physical output for production in the local context. However, following their trajectory of digital manufacturing tools in the global context would suggest that "all decisions have to be taken before production starts…" and that the craftsman cannot use his/her experience, becoming merely an assembler of pre-manufactured parts because the assembly sequence is already determined by the designer (Papanikolaou 2008). As a result, there is limited capacity growth within the local craftsmen to maintain the production methodology without exogenous assistance.

Thus, during the development of the Eco-San solution the team addressed the problem of inadequate sanitation in Nairobi's slums using the Localised Design-Manufacture methodology in the design of precision moulds to manufacture and deploy low-cost, water-free toilets. The local team is currently developing ongoing design iterations of the precision moulding system for other infrastructure applications along with developing localised distribution channels for the Eco-San design to be replicated and scaled to meet sanitation needs across sub-Saharan Africa. A new construction industry is being formed around the methodology of Localised Design-Manufacture generated by local need and local labour.

5.1. BROADER APPLICATIONS

Scalability is the most critical element to increased technology uptake. As the Localised Design-Manufacture process and products are replicated and scaled across nations, skill levels, and functions they will prove to be independent of their creator. It is this autonomy, or transfer of accountability, which represents a complete technology adoption, no longer reliant on exogenous resources. In the developing world context, scalability also offers the prospect for the creation of new modes of employment and enhanced skills not otherwise possible. Once a methodology is found applicable for wide-spread adoption, combining craftsmanship with CAD/CAM tools, the broader design, engineering and economic implications of this synthesis can be further explored. Additionally, once the tools and design documentation are standardised globally, the co-creation and bi-directional exchange of new developments can be shared and open-sourced through sustained channels of communication among diverse academic and industrial communities.

6. Contribution

The prototype using the Localised Design-Manufacture methodology offers a framework for localised design and manufacturing of other architectural and infrastructure solutions requiring precision manufacturing within developing countries. Further research has been committed by the local technicians for the development of housing modules, bio-gas digesters, food storage, and networked sanitation systems. As a substantive productive process, concerned with craft and assistive digital technologies for global development operating at a local level, the Localised Design-Manufacture methodology is evaluated quantitatively on performance and local socio-economic criteria, as a qualification for cultural sustainability. As this paper demonstrates, when designing within developing countries it is important that designers exercise flexibility in rethinking the entire production process and acknowledge the coupling of technology and local context.

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