Localized Design-Manufacture for Developing Countries:

A Methodology for Creating Culturally Sustainable Architecture

by Ella Peinovich

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Signature of Author .... Ella Peinovich
Department of Architecture
January 19th, 2012

Certified By .... John Fernandez
Associate Professor of Building Technology
Thesis Advisor

Accepted By .... Takehiko Nagakura
Associate Professor of Design and Computation
Chair of the Department Committee on Graduate Students

Committee

John Fernandez
Associate Professor of Building Technology, Massachusetts Institute of Technology

William O'Brien Jr.
Assistant Professor of Architecture, Massachusetts Institute of Technology

Dr. Kamau Gachigi
Lecturer of Mechanical and Manufacturing Engineering, University of Nairobi
Chairman of the University of Nairobi Science and Technology Park

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Abstract

Can improved technology uptake in developing countries promote cultural sustainability and enable the production of endogenous solutions for development?

This thesis, which focuses on technology dissemination for the benefit of under-served communities, is aimed at building capacity locally for self-sustained manufacturing processes using Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) tools suited to create solutions for local infrastructures. Unlike imposed exogenous solutions, an approach is needed which promotes localization of the design-manufacture process to encourage cultural sustainability. The research is threefold: 1) catalogue cultural artifacts that can benefit from digital reproduction for widespread methodological adoption 2) build capacity locally through sustained educational channels and 3) implement technological manufacturing processes that are culturally sustainable and replicable.

Thesis Supervisor: John Fernandez
Title: Associate Professor of Building Technology, MIT

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"The failure to look at process instead of image has led entire generations of architects to overlook transfer technologies and transfer processes. The new architecture will not be about style, but rather about substance — about the very methods and processes that underlie making."

From Refabricating Architecture by Stephen Kieran & James Timberlake

Introduction

In Kenya, and across Sub Saharan Africa, there is a new industrial movement afoot that has the ability to revolutionize technology dissemination globally and further enable the practice of architecture in developing countries. Enabled by the global distribution of FabLabs and connectivity provided by the Digital Age, developing countries have the most to gain from cutting-edge technology available today. I prescribe to the theory that technological progress in Sub-Saharan Africa must be based on a combination of 1) national effort, 2) selective utilization of scientific and technical achievements of developed countries and 3) united recognition of African inventors and innovators. In this way, "Africa would avoid a technological recolonization." (Science and Technology in Africa)

< As interpreted from the quote by Stephen Kieran & James Timberlake, what is proposed is a methodology of design-manufacture, resulting in a substantive productive process for global development.

Democratizing Innovation: CAD/CAM for Development Solutions

Users' ability to innovate is improving radically and rapidly as a result of the steady improvement of computer software and hardware, improved access to easy-to-use tools and components for innovation, and access to a steadily richer innovation commons. Today, designers and even individual hobbyists have access to sophisticated programming tools for software and sophisticated CAD design tools for hardware. These information-based tools can be run on a personal computer, and they are rapidly coming down in price. As a consequence, innovation by an ever widening base of designer/users will continue to grow.

However, the expert knowledge needed to innovate around important issues is widely distributed, as a result the traditional pattern of concentrating innovation-support resources on a few individuals is hugely inefficient. "High¬cost resources for innovation support cannot efficiently be allocated to "the right people with the right information:" it is very difficult to know who these people may be before they develop an innovation that turns out to have general value." (Democratizing Innovation (Chapter 9) by Eric von Hippel) As the cost of high-quality resources for design and prototyping, as found in the FabLabs today, is reduced these resources are being diffused more widely, and the allocation problem is being resolved through the development of a distributed network of localized industries. The result will be an open, democratized opportunity for creation, placing the role of the designer into the hands of the user.

In the Book "Making Do", Steve Daniels outlines 'who these [users] may be' within the development context, as the craftsman, known as the Jua Kali, who work within micro and small enterprises (MSEs). He outlines the potential for those performing within the informal sectors of the Kenyan economy to adopt new technologies in order to graduate to the formal labor sector, stating "The New Industrialization has the potential to rework globalization in the favor of the informal sector, allowing them to grow on a foundation of indigenous innovation that both provides for the needs of the local economy and brings in new capital through investment and export." It is this "New Industrialization" or distribution of CAD/CAM tools that will frame the context of this thesis proposal, and the introduction of new technologies as the vehicle by which it will be explored.

Before discussing the potential of technology introduction it is important to understand the origin of CAD/CAM technology. Historically, innovations on technology often evolve nearly organically from a process of discovery, though retrospectively they may appear to be driven by a linear and clear process of intentional development, this is due to the designer/engineer's intuitive process of investigation.

History of Mass Customization and CAD/CAM Technology

Digital Fabrication Methods

Digital fabrication is a term used to explain the process of manufacturing through computational means. Digital fabrication is a successor of Computer Numerical Controlled processes (CNC) developed and patented by John T. Parsons in 1958. His discovery came from the necessity to control machinery for punching shapes out of the material required for aircraft airfoils, using numerical coordinates. The CNC process eliminated many mundane tasks of human calculation and fabrication that had been the earlier process with the use of numerical data extracted from accounting machines. Digital fabrication has been present in automotive, aerospace, mechanical, marine, and industrial engineering since approximately 1946 and more recently has found a place in the architectural profession with works by architects Frank Gehry and Norman Foster.

Aerospace Engineering

Digital fabrication was first used in the production of aircraft components around 1952. Having realized the numerical power of the data produced through calculation, Parsons used the data as geometrical information to guide devices to precisely cut the necessary shapes from material. Aircraft engineering uses a monocoque process of fabrication (Lagace 2002). Monocoque fabrication is the production of a structured frame that is bound by a skinning material such as aluminum. This approach aided in defining the geometry for three dimensional shapes seen in the airfoils of aircrafts.

Automobile Engineering

Automobile engineering is also at the forefront of digital fabrication processes. Automobile engineering symbolizes the design and fabrication process of highly complex components that are taken through the production line of manufacturing and assembly. Unlike aerospace engineering, the automobile engineering process is known to be highly monopolized (Maclauren 1954) based on the technology and the scale variances of the fleet that is needed to satisfy the demand with a great deal of supply (Flink 1972). The process of automobile engineering uses CNC fabrication in the stages of design and development and is then carried out through mass production.

Architecture

By comparison to other industries, the use of CAD/CAM adoption in architecture has been slow. It was not until recently, architects such as

Frank Gehry, Bernard Cache, and Foster and Partners have used digital fabrication processes in the field of architecture for building complex building forms. This approach to design and architecture has allowed these architects to express architectural form in seemingly limitless variation, revamping the approach to design methods. The dilemma with adapting this process is manifested in the massive cost associated with the production of the uniqueness of one building rather than the common manufacturing of products within the previously mentioned fields of engineering. Rather within architecture, though the digital tools are highly adept at customizing a design in model space, the methods of customized digital fabrication are an inefficient use of time and materials. Studies done in the field of architecture have extrapolated on methods of technology that can potentially support an approach to architecture as a product for manufacture after the design processes (Allen 1970).

Digital Design Tools (Today)

The CAD/CAM discussions occurring in the field today are dominated by the intellectual/academic class seeking new material developments and manufacturing efficiencies. This kind of further industrialization draws parallel to the industrial revolution that was funded by the aeronautical developments and mass production of the 1970s. Arguably, however is whether this is the right direction for the architectural profession today. In the writing by Dan Willis and Todd Woodward they define "Where we [the architectural professionals] are today", as a differentiation between "smart" and "dumb" drawings separated by their linked 3D and parametric information. They go on to state, "Architecture is, now as much as ever, a collaborative endeavor."(pg203) These efficiencies of highly coordinated drawings sets, however providing labor-saving efficiencies in large corporate sponsored structures, further promote the narrowing of the profession's client to the super wealthy patron. As a profession we have pursued the use of labor-saving efficiencies of capitol-saving ones and thus this method of working is not viable for the use in the development context and as a designer proposing work in the this context one must reevaluate ones use of design tools and materials.

This thesis explores methods of creating labor-saving techniques as a means of liberating the individual or "Master Builder" from the need to create a drawing set at all by eliminating the need to translate a unique design for collaboration with other professions (see Chapter Participatory Design); democratizing design and making the client the designer, fabricator, and creator.

As pointed out by Willis and Woodward, "Architecture students, magazines, and probably most practicing architects believe that the [The Master Builder's] primary job is to create form" (pg203) However, increasingly designers like Kolarevic working in digital composition do not model a final form but rather input parameters and a generative logic from which they can selectively pursue refinements for a balance of functionality and aesthetics. Such a process requires that the architect give up control of form to a computer-generated algorithm to redirect their control in areas like joinery and material selection. Again, to put this use of digital tools into the development context a designer may reevaluate the design criteria to be inputs of the locally available materials and associated costs in order to find the most efficient and/or affordable solution. Due to the limited material options in Kenya a trained craftsman could provide this same function, evaluating the design based on sourcing and pricing information, while remaining current and flexible with the ever-changing market.

It is misguided to think that CAD/CAM is "adopted to eliminate costly details" as Willis and Woodward may suggest. Computer design and fabrication, though liberating an architect and builder from having to be an engineer and carpenter, transitions the role of the designer into that of an assembler and design-for¬manufacturing (DFM) expert. Bernard Cache observed what most fabricators and craftsmen know well, "As nothing in "real" reality is truly exact, and as the software is fully exact, we also had to define small gaps to account for "errors" in the production and assembly, such as adding the paint or varnish after machining, which can make the parts sufficiently thicker to introduce inaccuracies into the process". (Towards a Fully Associated Architecture, in Architecture in the Digital Age, pg 144).

A Novel Approach

This thesis however goes beyond finding new and creative ways to digitize the value scales provided by craft and experience brought to a design or assembly, but rather explores the necessity of craft, in the areas of building construction where efficiency of human sense and evaluation is inefficient, if not irreplaceable, by that of the digital tools today. This is in direct contrast to the digital design and fabrication workflow which aims for an "effortless transition from digital to physical artifact" (Botha, 2006, p. 15). If this can be established as true then the role of labor in design and manufacturing is in need of further consideration. While methods for pre-manufactured construction processes offer the repeatability and precision that a craftsman may lack, the development context neccessitates that this be achieved combination with most labor-generating, capitol-saving practices. CNC processes instigate and imply the future expectation of architecture using digital fabrication, and the social and economical impacts that are attached with the implementation of such processes.

This thesis research engaged diverse audiences through the use of CAD/CAM technologies, enabling them to create relevant technologies for their own communities, which are manufactured locally for maximum impact in a process known as mass customization. The design process utilizes cutting-edge technologies based in field test experience and illustrates a methodology for local adoption that produces accurate and replicable architectural and infrastructural solutions to real-world problems.

CAD/CAM Technology for Development

Technology Transfer

In developed countries, computer technology has the ability to revolutionize production processes for systematic development that meets the demands of a growing population. However, until now, the initial cost of technology implementation in manufacturing processes is one of the largest barriers to using new technology in developing countries. In an economy where most residences live on less than $2 a day, disposable income is nonexistent and most people live day to day. These residences have limited to no disposable income, therefore as consumers consider affordability before longevity. Those that are able to invest in their future desire to see a positive income in one month for a new technology investment and must have paid off capital investment or microloans within one year. (Polak, 2008) There are four divergent approaches which designers and engineers operate to address affordability when working in developing countries; charity, mass production, minimalism, and mass customization.

Charity work by numerous aid organizations, NGOs and missionaries is most often intended to provide housing to displaced communities, in which case large complexes and gated communities are built quickly in response to emergency. Most methods of disseminating charitable products are often plagued with limited resources in both time and money and therefore lack proper community engagement, producing structures with little consideration for autonomy and quality of living. Mass production methods are a high-cost operation used to mass-produce and then import core and shell systems to be assembled on-site. This can be seen by Jean Prouvé mass produced steel panels for refugees and poor with his Tropical House. Amy Smith from the Development Lab (DLab) at MIT has engineered widely successful product solutions for development in a method known as Minimal design and fabrication. Minimalist designs are created using low-cost technologies for a broad audience and shortest payback.

A more recent form of affordable solutions for development is a process of design-build using digital design tools to explore mass customization, used by Larry Sass and Oxman in the modeling and construction of pop-up, mono-material homes illustrated in the

Instant House. The Instant House assembly is derived from a generative process where the material limits predetermine the building limits, stating "rules for plywood are based on rules for the manipulation of flat sheet stock. Laser cutting cardboard flat stock material acts the same as the cutting of plywood; in essence the rules of the material are the same." (Oxman and Sass, 2005, p. 336). An assumption made by Oxman and Sass in this study is the seamless transition from digital model to physical artifact, defining digital design as "a self-contained way of designing exclusively within a computational environment" (p. 333). However, computational and systems theory show this to be an unachievable ideal. (Kamath, p.20)

While each of these methods of technology transfer has an appropriate and different application, each of these methods has yet to prove it can effectively scale for architecture and infrastructure solutions on the ground. Charity, minimal design, and mass production all promote an import culture and a need to look outside local means for solutions. In addition to the cost, lack of resources and maintenance infrastructure, and educational understanding of new technologies, it is the *imposition* of technology that often limits its long-term impact in a community, often associated with doing more damage than good.

Democratizing Technology Access

As the cost of digital tools drop and become increasing more accessible the developing world has the most to benefit by implementing the use of these low-cost, industrial strength machines to create small-scale, innovative solutions for big change. Keeping in mind that developing nations should aim to "invent indigenous technology while at the same time exchanging information with the developed countries." (Science and Technology)

The Center of Bits and Atoms at MIT, has enabled the deployment of fabrication laboratories at a global scale, allowing state-of-the-art technologies to infiltrate the trade industries in under-served communities around the world. Neil Gershenfeld, director of the Center of Bits and Atoms, aims to give people the tools to build literally anything they can imagine, stating "this concept is potentially life-altering in the developing world. A FabLab with just $20,000 worth of laser cutters, milling machines and soldering irons can transform a community, helping people harness their creativity to build the things they need, including tools, replacement parts and essential products unavailable in the local market." (NY Times) This thesis aims to stretch the imaginative minds in the local community to create solutions for progress and development.

Knowledge Transfer

This thesis recognizes that introducing new technologies, defined in most methodologies as *technology transfer* carries the burden of assumed accountability and dependence. Rather, within the context of this discussion, *technology transfer* should only be considered after efforts of nurturing existing *technology uptake* and *knowledge transfer*. The methodology in this thesis is distinctive from other affordable infrastructural solutions for development in that it engenders technology uptake of existing community implemented programs (i.e. FabLabs), which are positioned to gain invaluable input from community involvement and hands-on experience. These programs use solely locally available materials, manufacturing, and labor to ensure a product which is both environmentally and culturally sustainable.

FabLabs have proven to be a place for successful technology uptake by local organizations, but have yet to prove sustainable without government or institutional seed funding. As a foreign entity, the complexities of a societal and cultural nuances cannot be predicted or controlled during implementation; it is in cases like these that the knowledge and accountability should be transferred to the community itself. For that reason, this proposal aims is to put the design tools in the hands of the people that will use the tools in the production of commerically viable products.

Within the broad potential applications of this methodology my design-research focus is on the technology uptake of thin-shell, pre-cast concrete in fabricating architecture, to save on local material resources and reduce green-house gas emissions. Formal studies were conducted which sought balance in environment and economic resources, time, and applicability by first evaluating the best allocation of digital and analogue (craft) production. (See Chapter Distributed Manufacturing)The context for this thesis assumes the wide-spread adoption by the Jau Kali in using digital design and fabrication tools, for which I impliment a new methodology for fabricating architecture. There are many contextual elements which should be considering to customize to each localized design-manufacture process including: the tool and material availablility and local knowledge.

Material Craft

When working with CAD/CAM technology, materials are the remaining and most restrictive design limitation, due to their site specificity and user preference. Additionally, a builder must select a material for its environmental impact and life cycle, treating sustainability as a social imperative. Although the continent of Africa contributes no more than 4 to 5 per cent of global greenhouse gas emissions, the Intergovernmental Panel on Climate Change's Fourth Assessment Report in 2007 said that Africa would experience some of the most severe effects of climate change; since witnessed in the flooding in the Namibian desert and major drought-related famines in Eastern Africa. Building materials must be considered (in no particular order) for their availability, renewability, emissivity in addition to workability, durability, maintainability, universality, and applicability. In order to achieve economies in final construction, material must be considered simultaneously for their constructability and structural or thermal properties. The assembly and structural properties are incorporated into the methodology of fabrication as a material saving measure and therefore environmental contribution.

Discussions about the limitless capabilities of digital design and fabrication to create any shape, similar to those stated by Oxman & Sass, is an over-simplicity of the fabrication techniques and materials. CNC machinery and rapid prototyping has an inherent bias to sheets of monolithic materials with uniform thickness. CNC machinery results in a limited number of construction assemblies that can be categorized as:

1. Striated, laminated, Layered (derived from sheet material)
2. Two-directional axis, friction-fit Dado (assembled mass-customized kits)
3. Raified, Pointilized (driven by a raw material size)
4. Shell and Panelized (material as structure with joint)
5. Cladded (material as surface applied to substructure)

This thesis engages in a number of design exercises researching reusable, low-cost molds built up out of CNC milled parts, for use in creating thin-shell, precast ferrocement building elements. The resultant thin-shell, monolithic form has many benefits. The material maintains the ductile nature of the integral reinforcement material, so that the form (though limited) can take many fluid, yet precise shapes.

Material tolerances are second-nature to craftsmen who know material behavior well, from thermal expansion and weathering to the workability and ergonomics of building assembly. This knowledge base qualifies the craftsman and builder to facilitate the CAD and assembly process and after learning the limited set of tool tolerances, the CAM process. In his thesis on integrating craft into the digital design and fabrication (DDF) methods, Ayodh Kamath rightfully makes a distinction between "craft as 'incomputable' and error as indeterminate in a digital model." He goes on to distinguish that methods of manual craft that are "not incompatible" with DDF, stating "The digitizing of indeterminate material properties and the digitizing of the results of indeterminate processes in digital [Sensing-Evaluating-Shaping] SES systems allow an individual to analyze the construction system and spontaneously react to indeterminacies within a digital design environment while making use of digital fabrication."

Roles of Labor

The trajectory of digital manufacturing tools within the architectural profession would suggest that "all decisions have to be taken before production starts... [and] the assembler cannot use his experience to assemble a number of pre-manufactured parts because the assembly sequence is already determined by the designer. As a consequence, any mistake during design process is irreversible if manufacturing of parts has taken place." (Papanikolaou, 2008, pp. 22, 23) However, within the development context these "streamline" processes must be reconsidered due to an abundance of skilled "assemblers".

The use of technological equipment capitol in place of human capitol is under serious scrutiny by political and economic figures of developing nations where labor is cheap and abundant. Unemployment is high in nations like Kenya, where 90% of the workers are earning day wages in an informal economy. (Kenya.gov)

There is a distinction that needs to be made about the classifications of technological progress; one being labor-saving, and the other capital-saving (that is when higher levels of output can be achieved with the same quantity of labor or capital inputs). While, each of these types of progress are distinct a laborer must always be cautioned once capitol has been invested in a piece of machinery, if progress halts and production output needs to be adjusted, it will be most often the laborer that is let go before equipment is sold off, capitol-saving can quickly turn into labor-saving when progress is slowed.(Science and Technology in Africa) In Africa, the stage of development suggests that what is needed is capital-saving technology because of the existence of abundant labor.

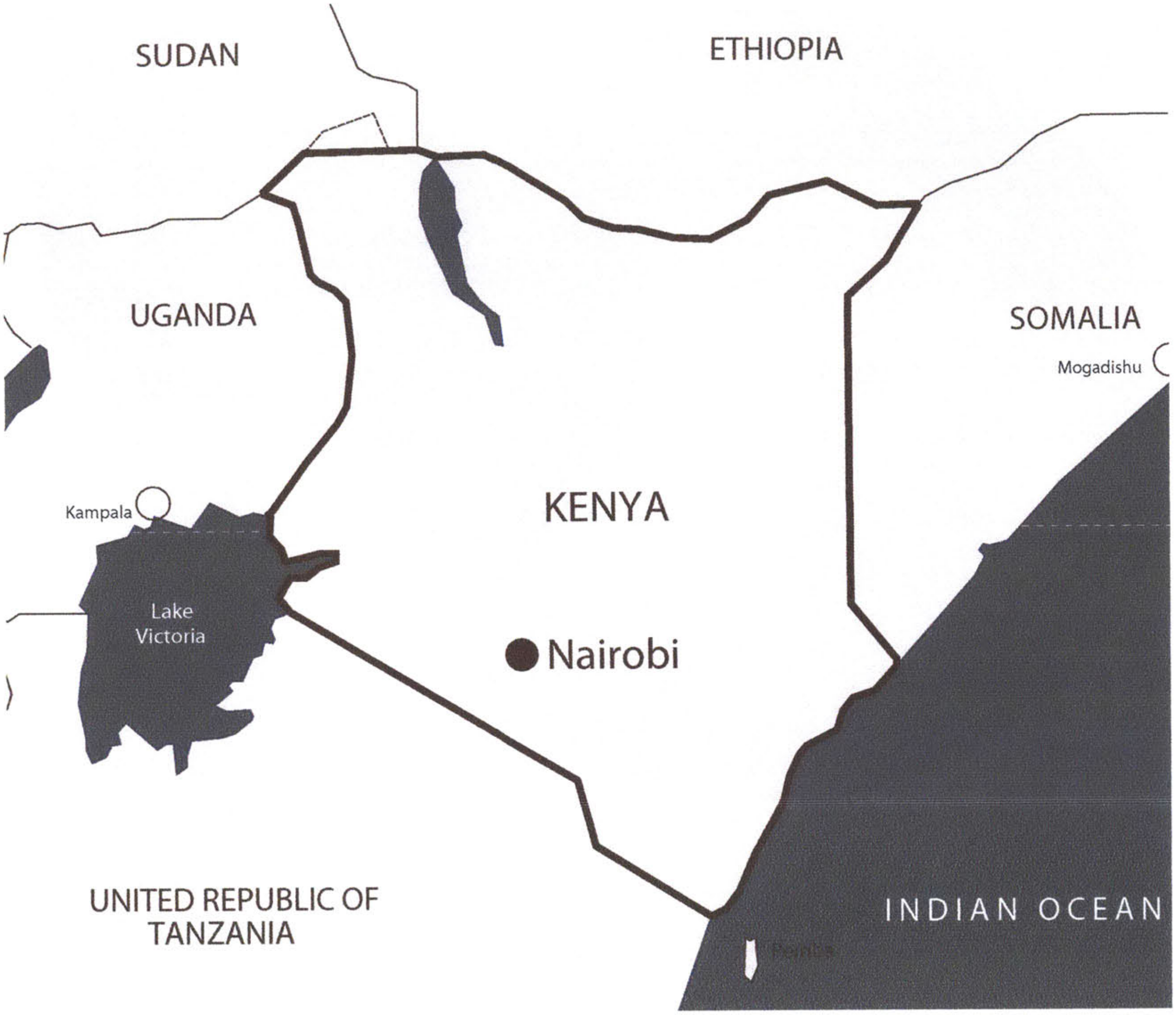
Methods of capitol-saving in architecture is a difficult deliberation considering that structural demands and life-safety require higher levels of coordination and system design necessitating tool assistance. Digital design software and digital fabrication equipment reduces the number of persons required to see the design through completion yet enables the self-employed craftsman, democratizing the design process.

Synergy of Technology and Labor

As this thesis illustrates CAD/CAM methodologies are positioned for widespread adoption because they provide additional services to the craftsman, including replicability and scalability, without compromising existing time-tested procedures, including customization and creation time. Though digital tools may require more time to produce a first working prototype compared to traditional hand-crafted methods, it is far more productive over time due to its ability to be iterated and replicated quickly. If the initial investment of time and resources are evaluated as an worth-while sacrifice, the profitability of this new method should prove to be a viable solution for local entrepreneurs.

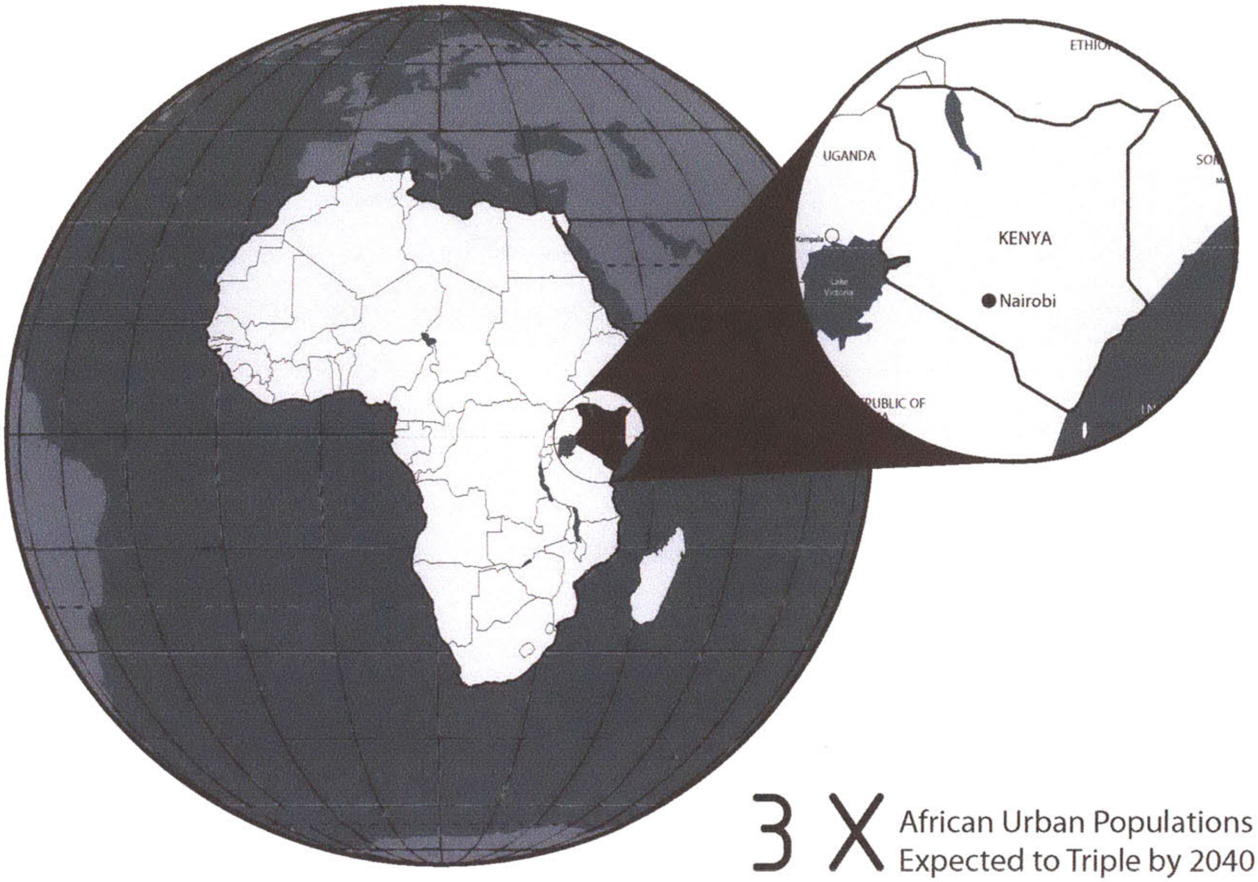
This thesis outlines a methodology which considers technology, labor, energy sources, tools, and materials within an adjusted, contextualized spectrum; evaluating each for their ability to promote economic progress that addresses the present housing crisis and improves living standards for future generations. The focus of this thesis is to outline the many factors that contribute to technological progress in Sub Saharan Africa on a local level from established African inventors like the Jau Kali to the decentralized manufacturing processes provided by the FabLab network. This thesis will highlight the eminent industrial age of Sub-Saharan Africa (UNIDO, 2010), in particular Kenya, and aims to outline how architecture may play a major role in that revolution, as it addresses both culture and technology.

LOCATION | Kenya, Africa



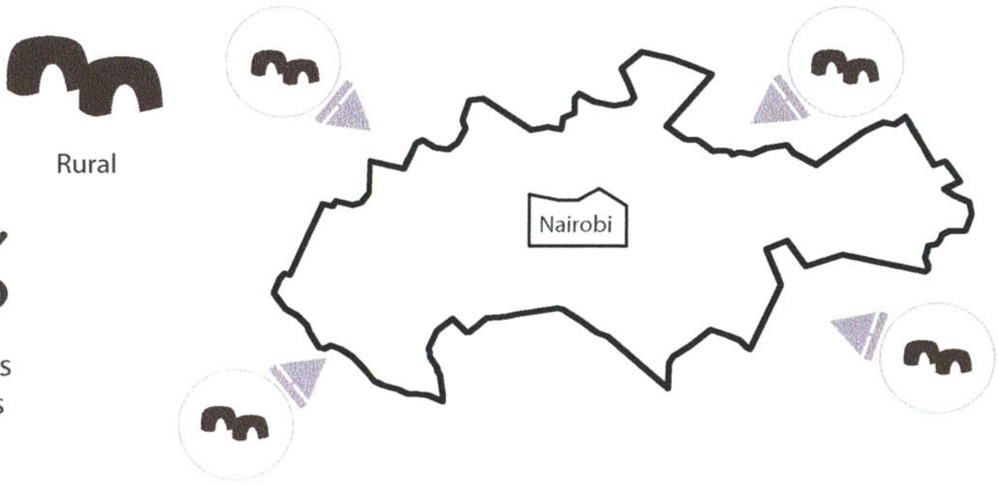
LOCATION | Nairobi, Kenya

Capital of the eastern African country of Kenya, Nairobi, just over a hundred years old, has developed into one of the most international cities in the world. As one of the four United Nations (UN) cities along with New York, Geneva and Vienna, and host to the headquarters of some of the main UN bodies, it is thoroughly tied into a global network of policy-making, diplomacy and governance. A frequent location of large international conferences, such as the World Social Forum 2007, it possesses the infrastructure to become a focal point of global exchange of ideas and communication. With a population of approximately three to four million inhabitants, being the largest city in eastern Africa, it has experienced one of the highest urban growths rates worldwide, mostly based on rural-urban migration. The city is seen as a place of potential, offering economic and social possibilities.



3 X African Urban Populations Expected to Triple by 2040

Urbanization Without Industrialization



6 2 %

of Urban Residents
Live in the Slums

City of Nairobi

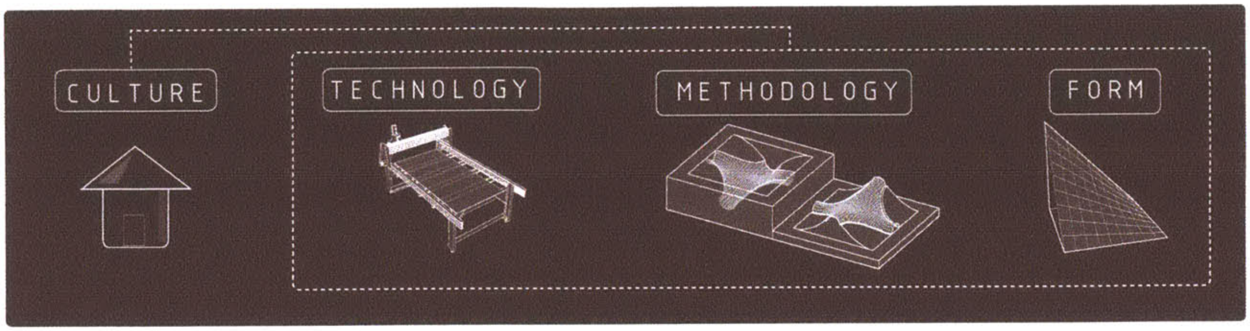
Informal Settlements Around Nairobi

Urban Migration

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, urbanization is associated with more job opportunities and improved human development; however, this 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 urbanization 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.

Cultural Sustainability | Definition

"Meeting the needs of the present without compromising the ability of future generations to meet their own needs" is the definition of sustainable development put forward by the World Commission on Environment and Development for the United Nations General Assembly in 1987.



Localized Design-Manufacturing

Localized Design-Manufacture has one primary goal - achieving viable endogenous solutions for developing regions. Based in real-world experience working within these regions for over 2 years the methodology as demonstrated in this thesis, intended as a case study, approaches each design solution by first attempting to understand and synthesize the cultural implications for each the technology introduction, the construction and methodological implementation, as well as the the cultural perceptions of the final form. This process neccessitates the involvement of local skilled and unskilled practictioners and community members, which elevates the role of the designer to also a policy maker, technical expert, educator, and community advocate. This methodology represents a new form of aid, one that turns recipients of aid into producers, allowing them to be agents of change in their own communities.

This thesis focuses on the use of concrete in prefabricating architecture. The context of my thesis highlights the wide-spread adoption of workers using digital design and fabrication tools, with whom I have worked to develop a new methodology for fabricating architecture, creating solutions for local development.

The goal of this thesis is to exemplify a design process which utilizes cutting-edge technologies based in field experience with the intent to illustrate a methodology for local adoption that produces accurate and replicable design solutions to real-world problems. Though it utilizes the proposed methodology throughout, this thesis in itself is not meant as a catch-all, but rather an example of the power of this methodology to inspire others.

CULTURAL CONTEXT

In Kenya, and in developing countries worldwide, the urban informal settlements 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 resulting diseases kill 1.5 million children each year and comprise 10 percent of the global disease burden (UN Habitat). 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. This situation will worsen as the population living in slums is expected to grow from 1 billion people to 1.6 billion by 2020.

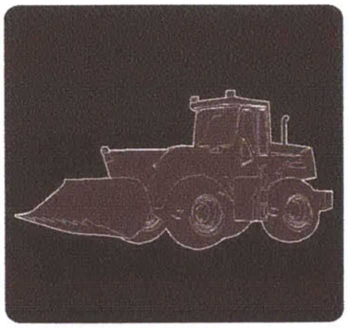
Most residents living and working within these informal settlements are employed within the informal craft sector, made up primarily of the Jau Kali who are entrepreneurs and craftsmen with trained skills that represent a wide spectrum of local production practices. The Jau Kali way of working can be 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, the quality of their production can be unpredictable.

The informal craft sector continues to produce over 90 percent of new jobs in Kenya annually and employs an estimated 80 percent of the labor force (Kenya National Bureau of Statistics, 2009). In 2007, the Government of Kenya announced Kenya Vision 2030, a plan to develop targeted economic zones around the country to generate 10 percent annual growth in GDP. However, the plan has been criticized because it does not promote, much less mention, the informal sector jobs. As Kenya aims to position itself within the global economy, many living and working within the informal economy fear further marginalization.

For advocates of sustainable development the question remains, "Why use highly technical exogenous machinery when there is an abundance of local labor?" This thesis aims to address that question.

UPGRADING | Human eviction

The motive to upgrade the informal settlements threatens the community and therefore influences the lack of permanence and infrastructure.

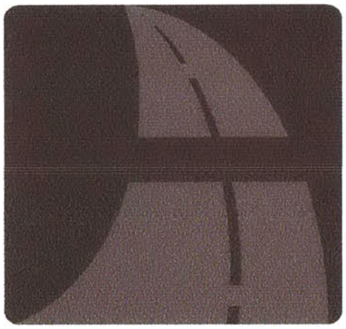


LAND | Tenure Rights

The lack of land makes it difficult for community members to build permanent structures.

ACCESS | Roadways

Limited or no road access impacts the freedom to transport goods and resources to and from the communities. The absence of a transportation thruway significantly reduces/impacts the design of buildings and default to the availability of scrap nearby materials.

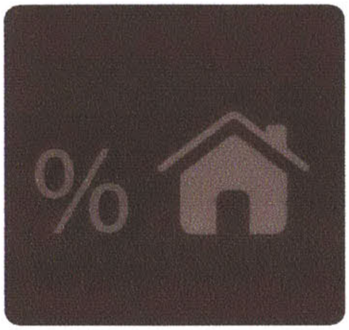


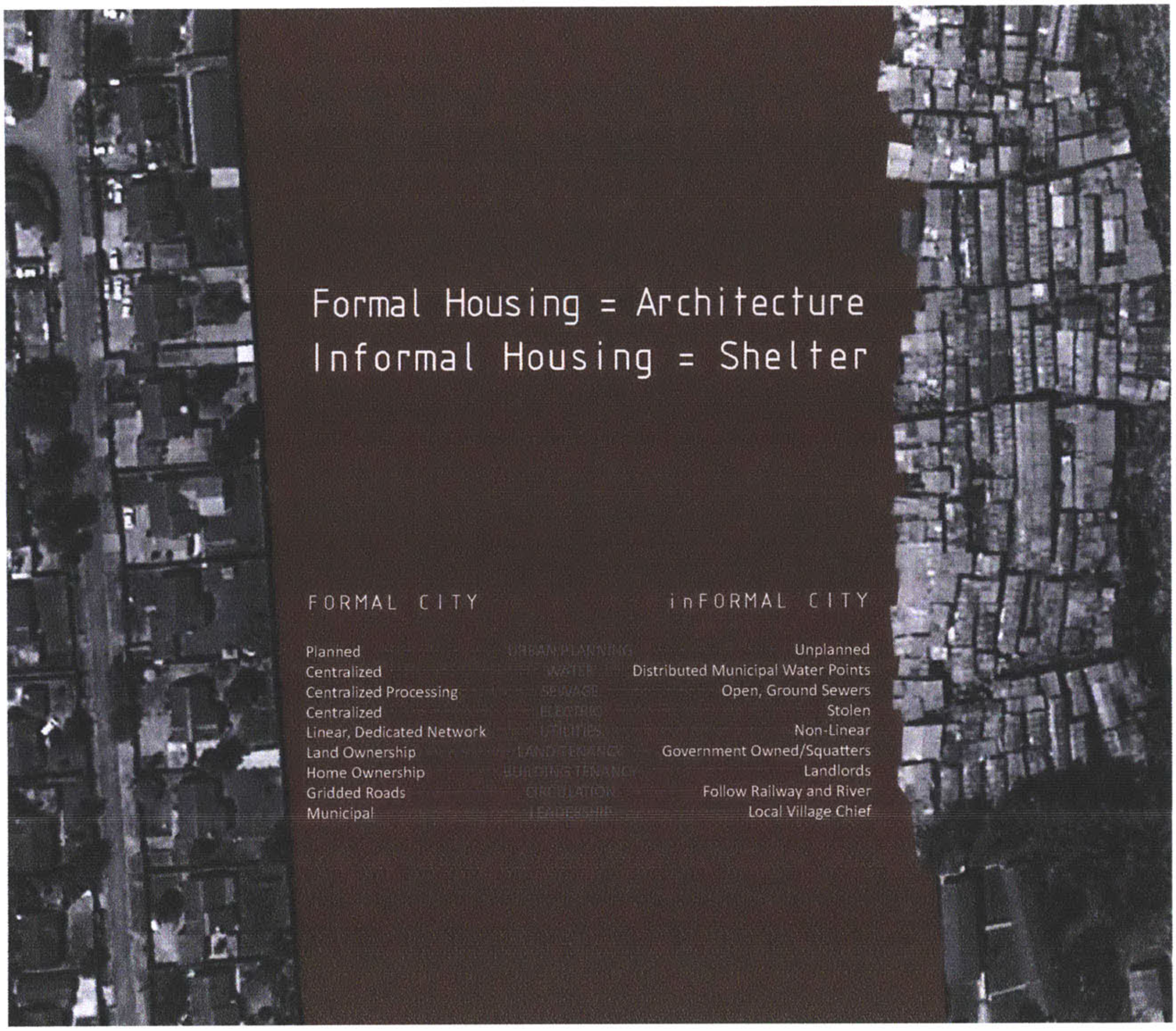
CREDIT | No access

Coupled with limited access capital, the community members have no way of proving the stability for credit.

CAPITAL | No access to money

Community members live on less that $1, which makes it difficult to invest in more than the basic necessities. As a result, the community "make do" with what's readily available.





Formal Housing = Architecture
Informal Housing = Shelter

FORMAL CITY		inFORMAL CITY
Planned	URBAN PLANNING	Unplanned
Centralized	WATER	Distributed Municipal Water Points
Centralized Processing	SEWAGE	Open, Ground Sewers
Centralized	ELECTRIC	Stolen
Linear, Dedicated Network	UTILITIES	Non-Linear
Land Ownership	LAND TENANCY	Government Owned/Squatters
Home Ownership	BUILDING TENANCY	Landlords
Gridded Roads	CIRCULATION	Follow Railway and River
Municipal	LEADERSHIP	Local Village Chief

Can we *formalize* the slums into safe habitats?

The UN defines slums as poor, overcrowded communities lacking adequate access to safe water and sanitation, public services, basic infrastructure and quality housing. Slums exist outside the official city grid, built without architects or municipal maps, and are in a constant state of transition. It is this volatility of form that gives promise to opportunities, to begin an incremental transition from informal slums into formalized, safe habitats. Due to their shear population size universally across the globe, slums require special attention from urban designers to consider their unique properties in forming an entirely new typology of urban form all together.

KIBERA | The Second Largest Slum in Africa*

Because of its unauthorized status, this government land is home to squatters from all areas, Kibera has always been excluded from official urban plans and receives next to no municipal services, such as public water, sanitation, schools, and health care.

According to the U.N. Population Fund, one in five children who live in Kibera will die before his or her fifth birthday. Insecurity and violence haunt families trying to build better lives. But with monthly rents as low as $7, this self-policed, self-organized enclave is often the first stop for rural migrants fleeing destitution in their villages to try their luck in the city.

*The true population of Kibera is unknown, estimated between 120,000 to 250,000, and rumored to be 1 million people.

How can we return cities to be what they have always implied, places of opportunity and education?

2008 marked that tipping point by which more people now live in cities than in rural areas. This triumph of urban, however, does not necessarily represent progress. One-third of these city dwellers - more than 1 billion people - live in slums. The UN forecasts that the number of slum-dwellers will double in the next 25 years. Urban dwellers are the world's fastest growing habitat.

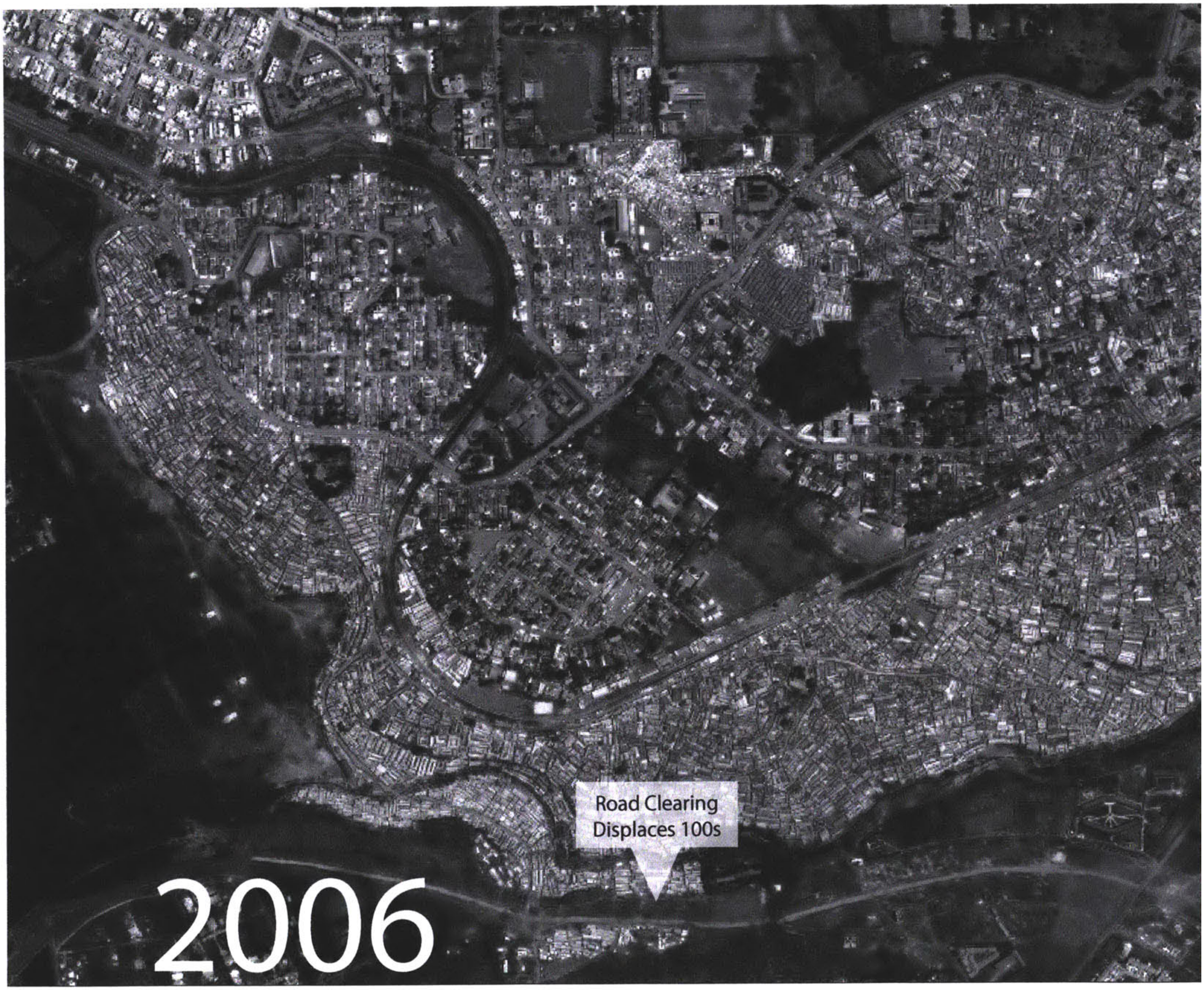
How can we design culturally sustainable architecture?

This thesis tries to answer this question by documenting and testing a methodology of production incorporating indigenous working methods along-side new technological practices. A methodology that provides a viable scaffold which promotes local, organic growth, at scale.

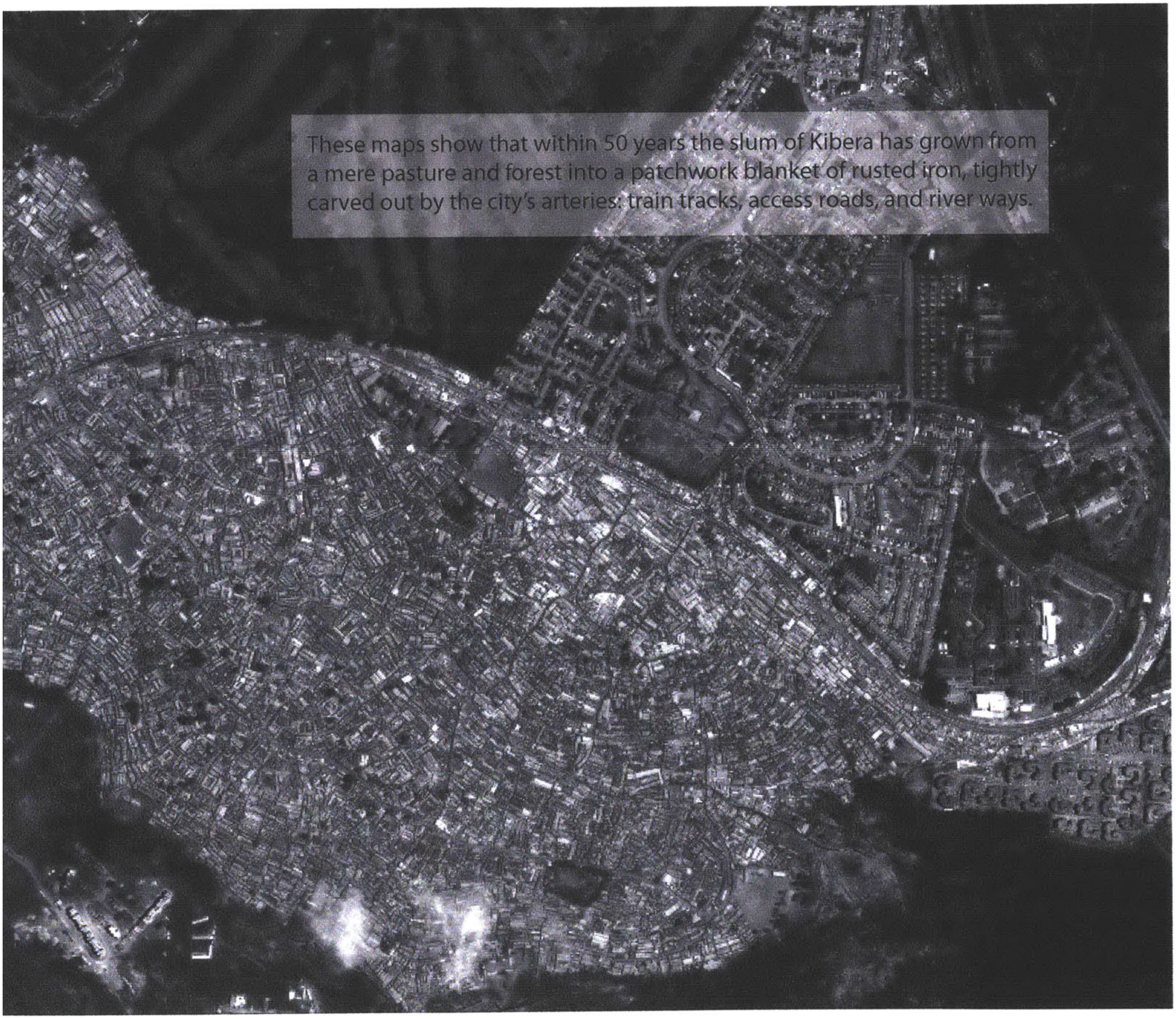
KIBERA BRITISH ARMY AERIAL PHOTOGRAPH

SOURCE: MAP KIBERA (KENYA)

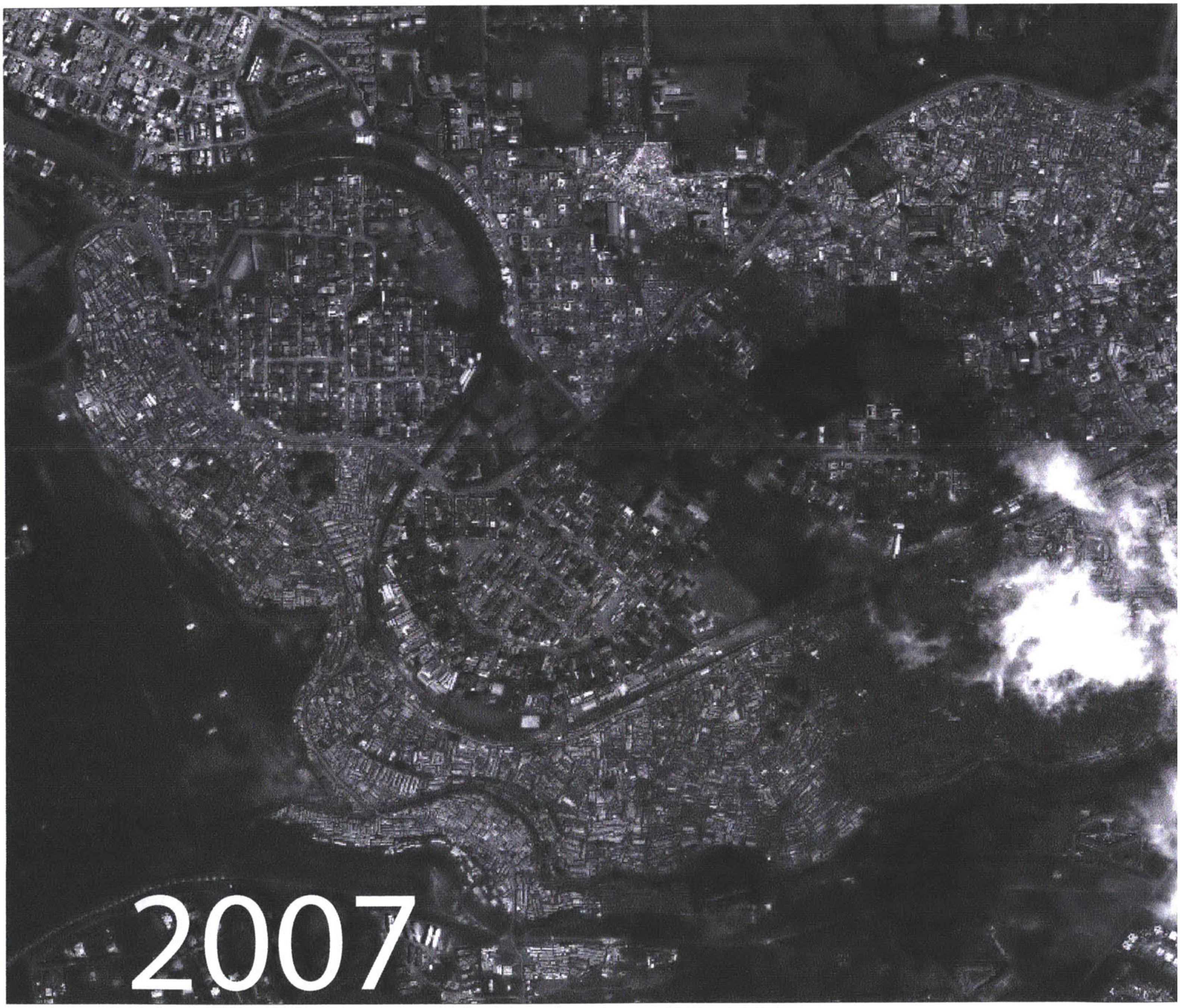
1963 Kenya's Independence from the United Kingdom



KIBERA GOOGLE MAP SATELLITE IMAGE
SOURCE: MAP KIBERA (KENYA)



These maps show that within 50 years the slum of Kibera has grown from a mere pasture and forest into a patchwork blanket of rusted iron, tightly carved out by the city's arteries: train tracks, access roads, and river ways.



KIBERA GOOGLE MAP SATELLITE IMAGE

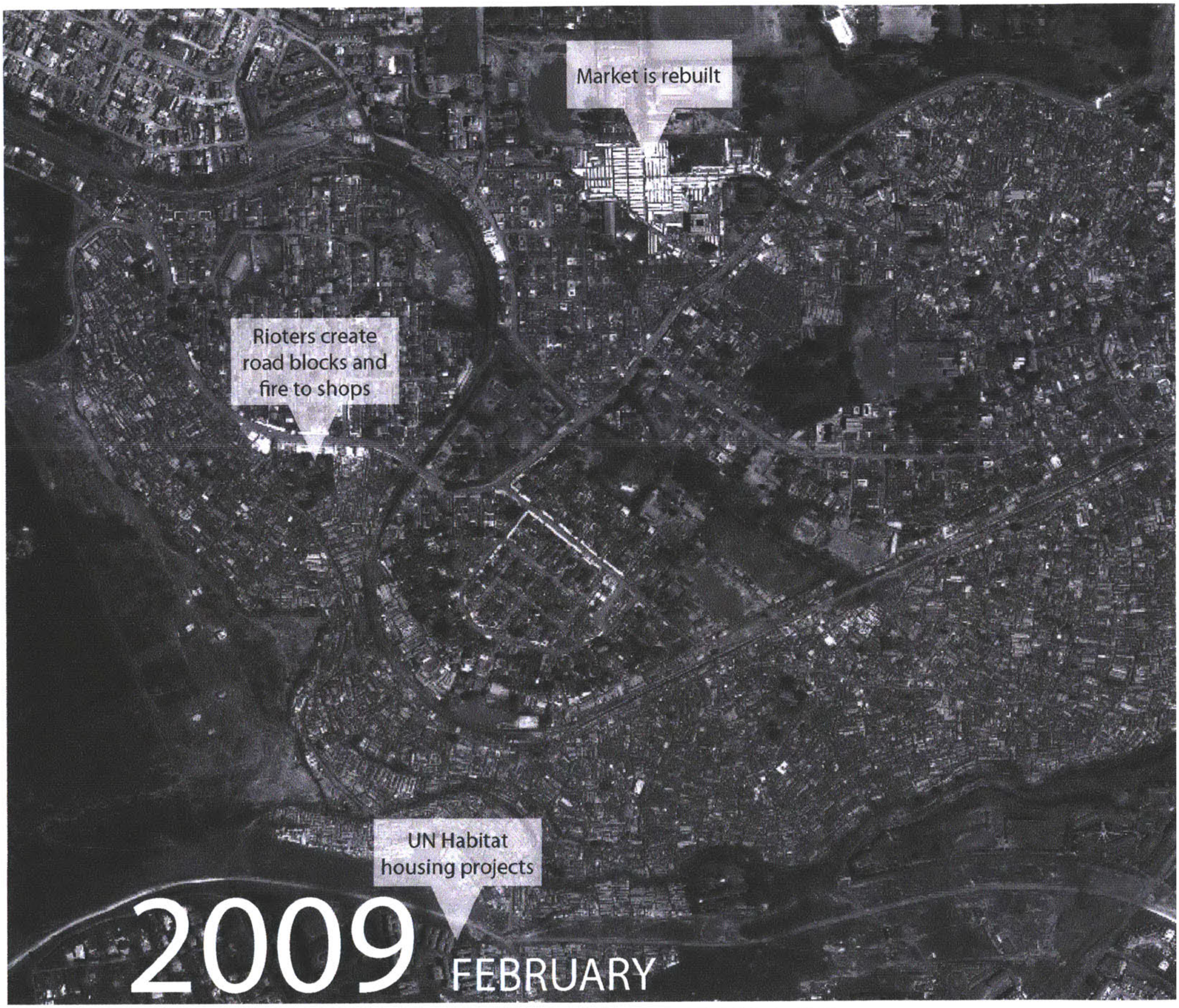
SOURCE: MAP KIBERA (KENYA)

2007

Post-Election Violence

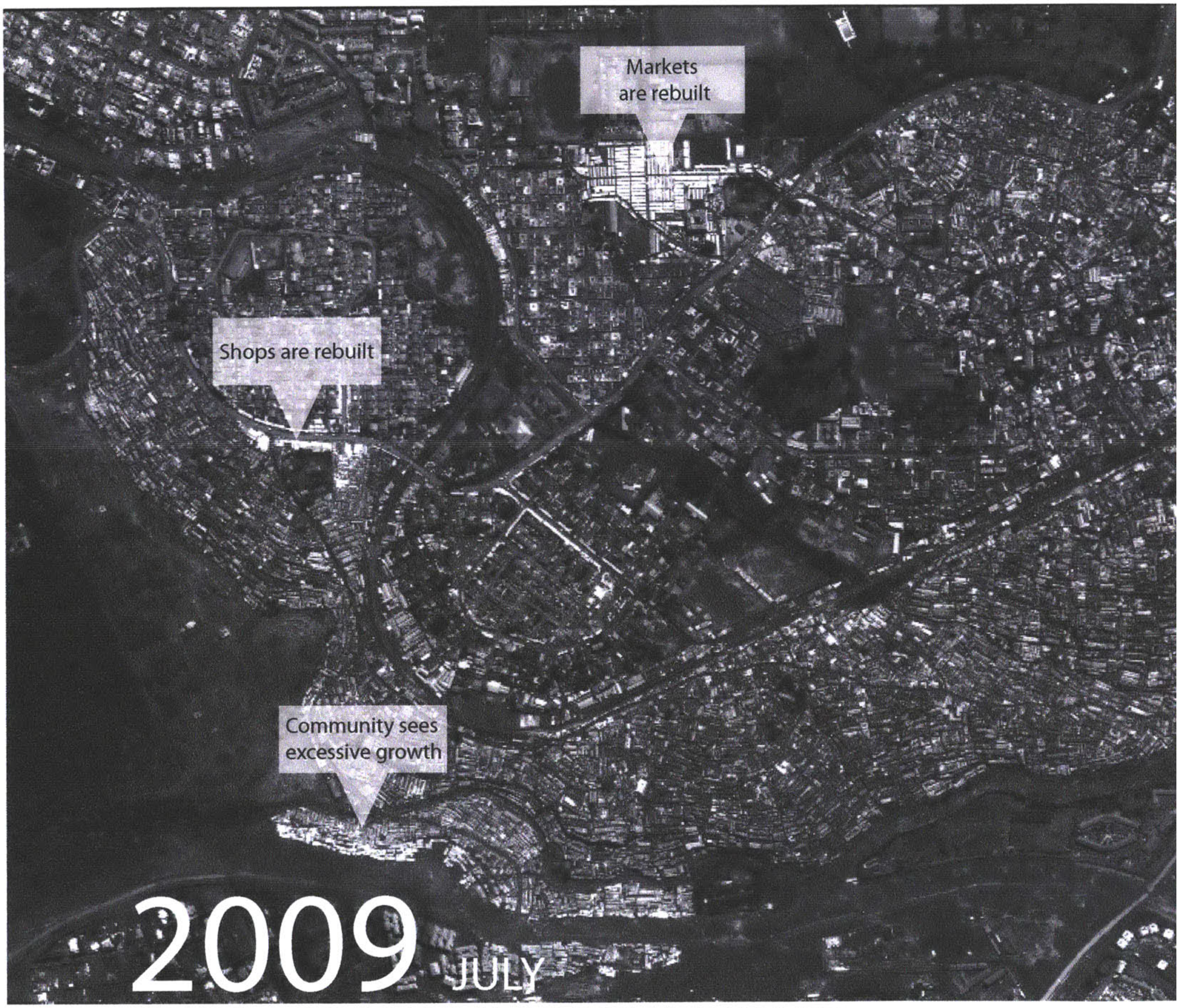
More than 300 people are killed and
some 70,000 displaced within Kibera

KIBERA GOOGLE MAP SATELLITE IMAGE
SOURCE: MAP KIBERA (KENYA)

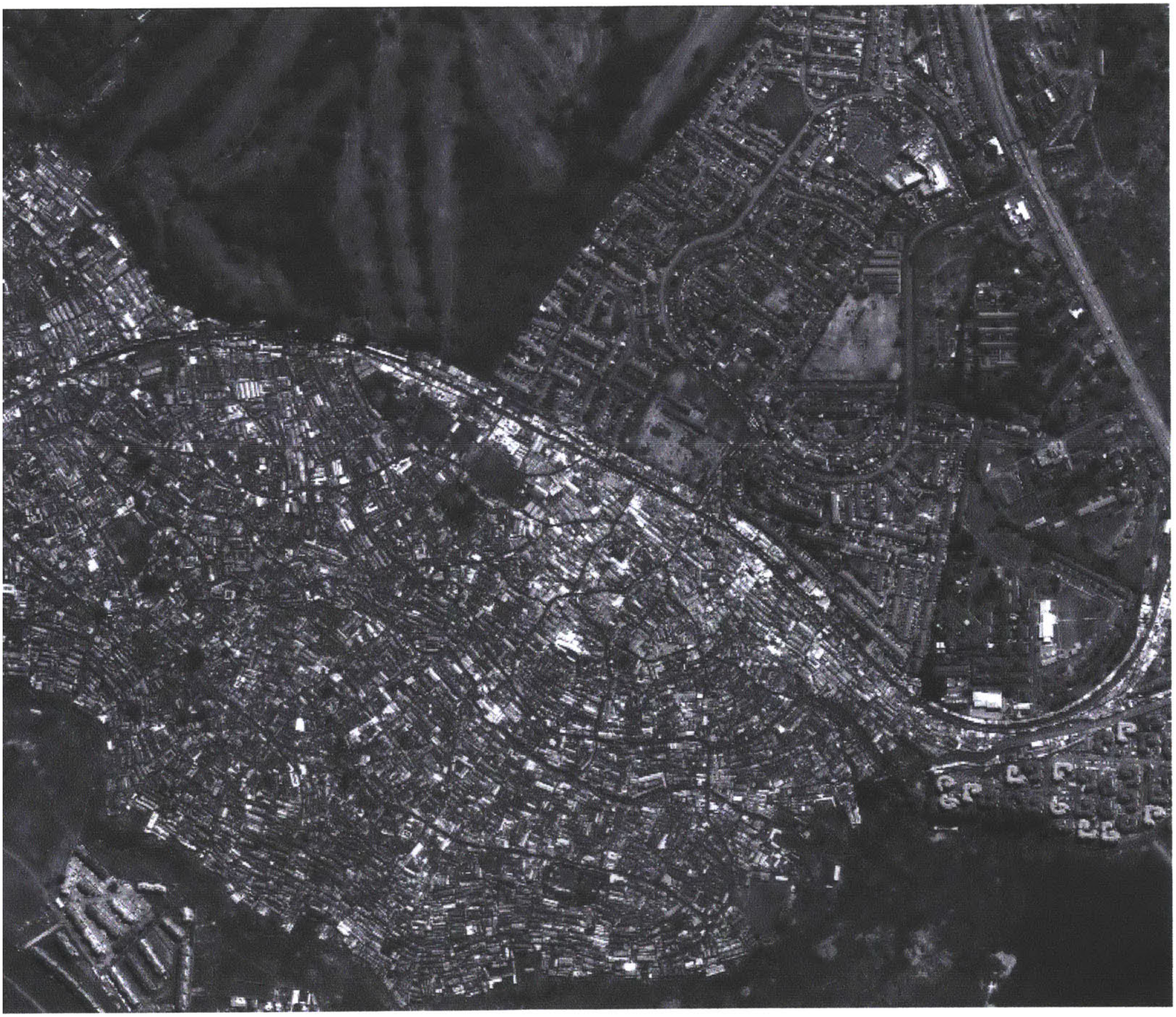


KIBERA GOOGLE MAP SATELLITE IMAGE

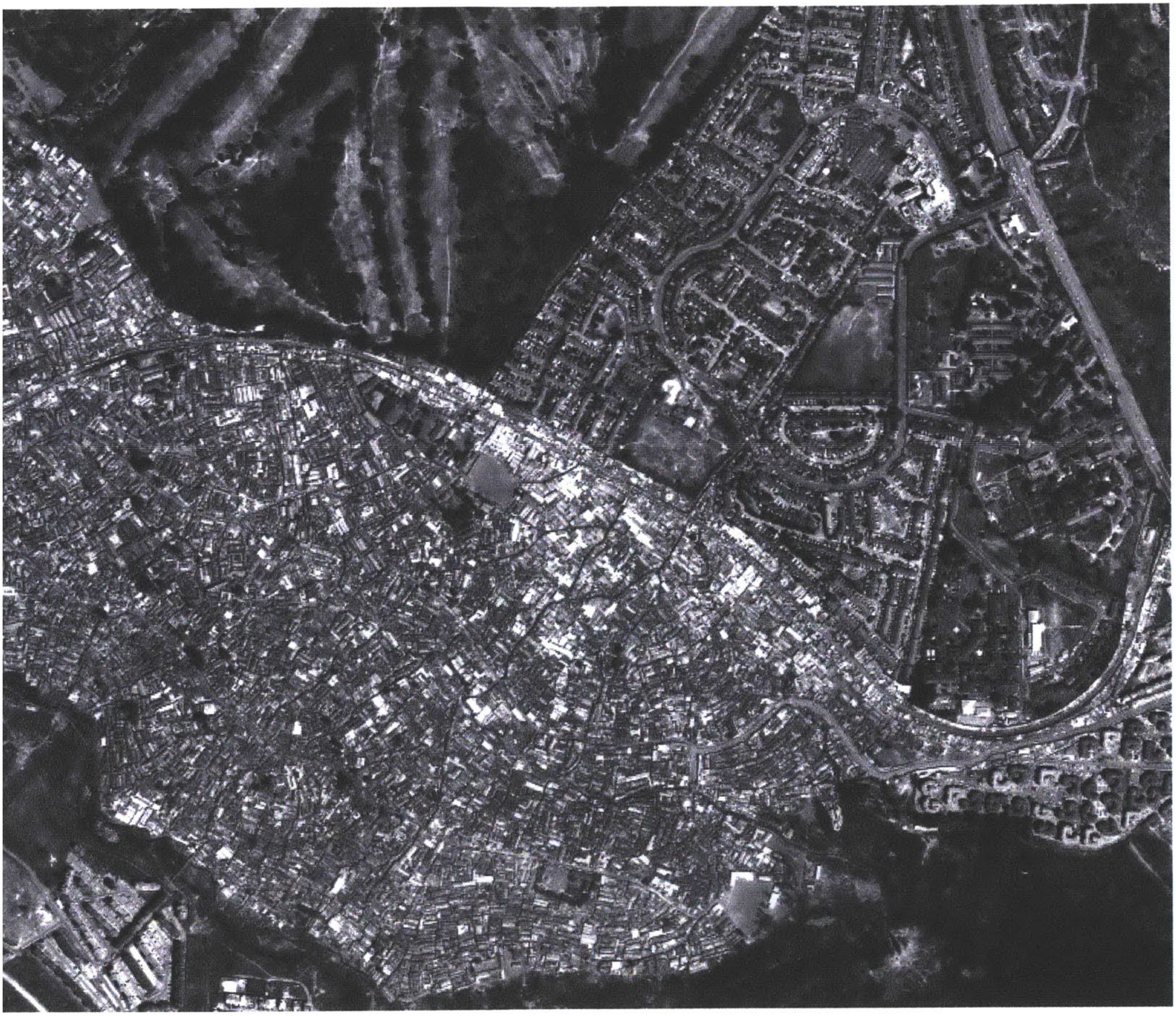
SOURCE: MAP KIBERA (KENYA)



KIBERA GOOGLE MAP SATELLITE IMAGE
SOURCE: MAP KIBERA (KENYA)

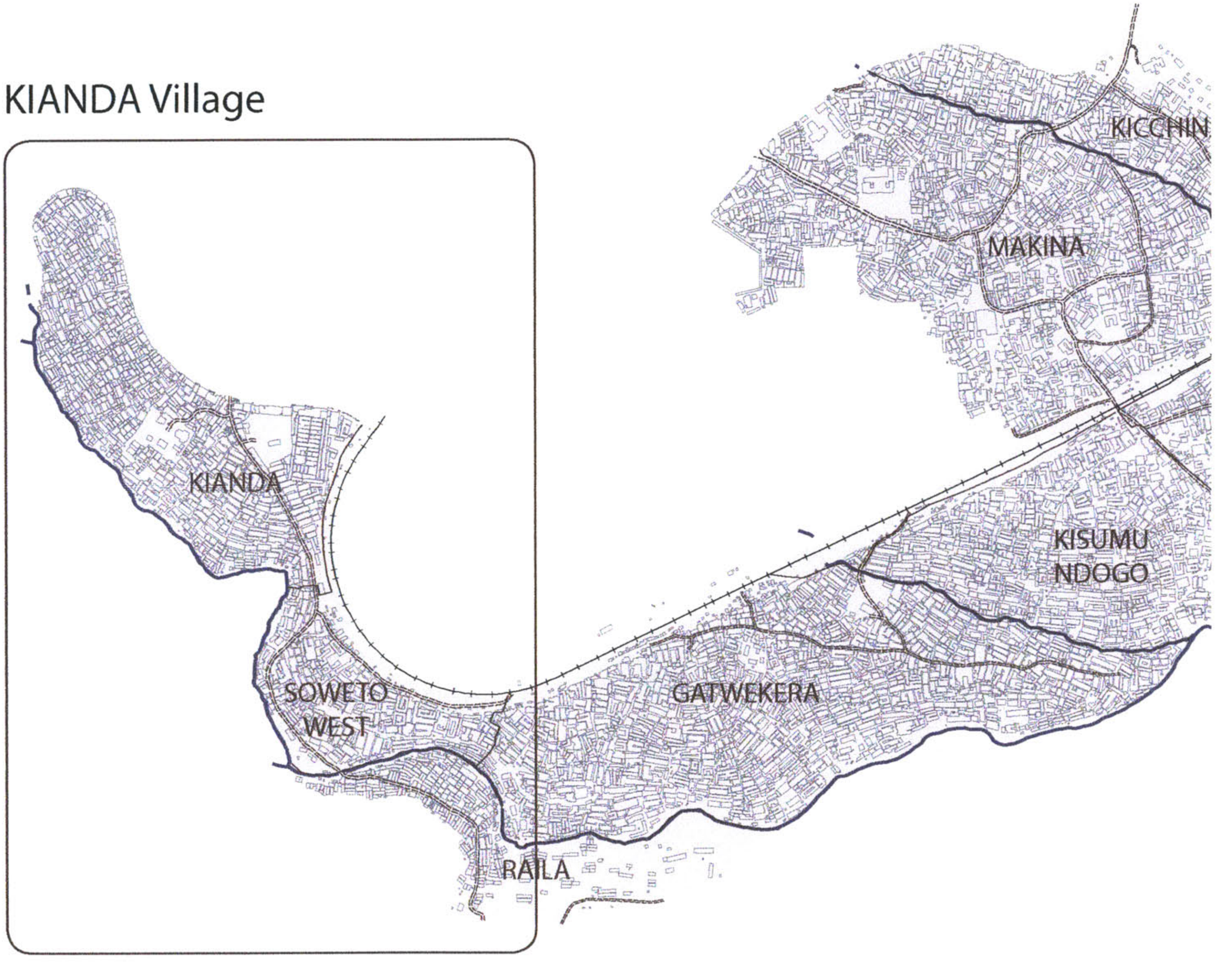


KIBERA GOOGLE MAP SATELLITE IMAGE



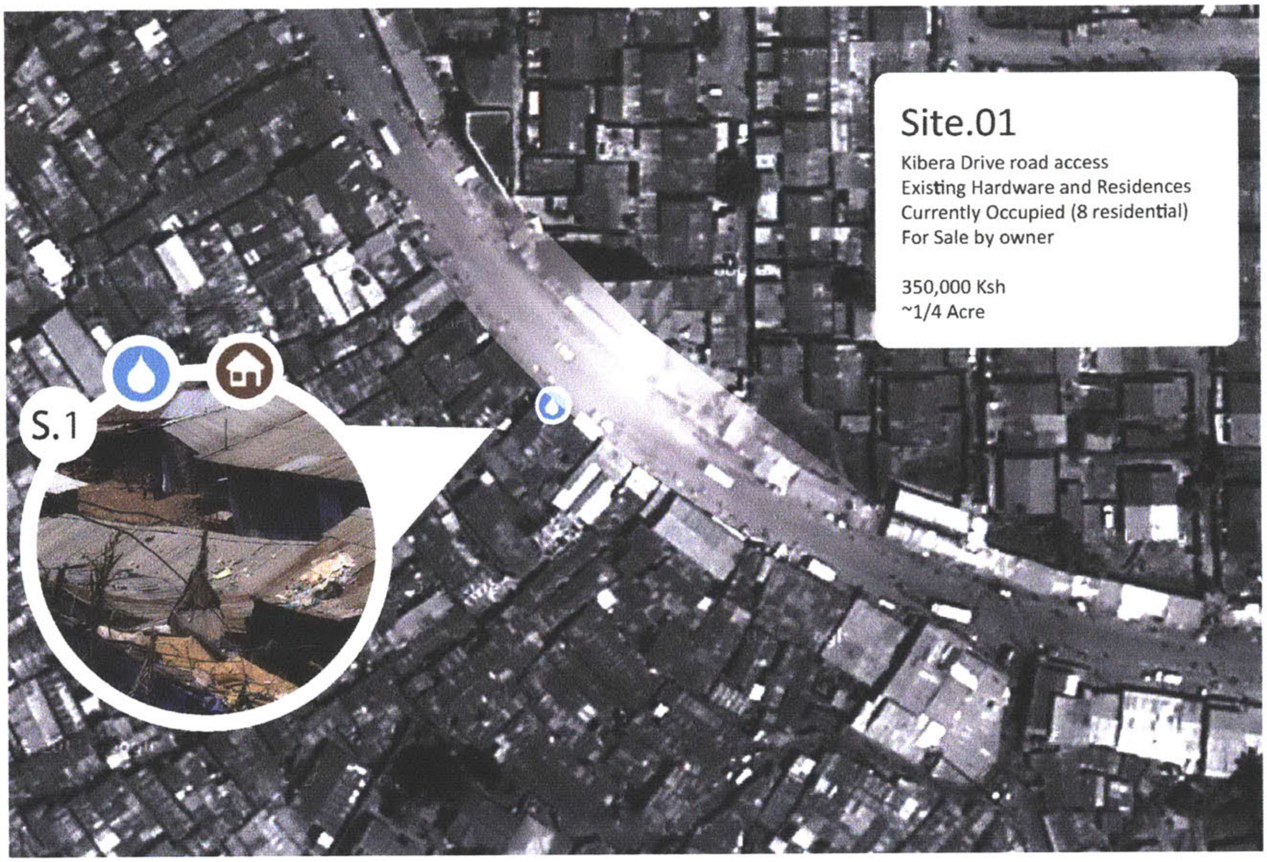
LOCATION | Kibera Settlement

KIANDA Village




NJIO
MASHIMONI
KAMBI MURU
LAINI SABA
SOWETO EAST
LINDI
SILANGA


2000 Residents
live in
10,000 m²
Site
KIANDA
OLYMPIC
NGONG
FOREST
SOWETO
WEST
RAILA
Formal Structures
Informal Structures
New Informal Construction
City Blocks
Railway
Paved Road
Walking Path
Open Sewers Improved
Open Sewers
Municipal Water
River
Water Points
KIANDA, KIBERA
100m



LOCATION | Kianda Village, Kibera Settlement

Nairobi is shaped by strong contrasts in wealth and quality of infrastructure. Nairobi is home to many slums, including Kibera settlement, more commonly known as Kibera slum, is arguably the second largest slum in Africa. With its population of approximately 250,000 inhabitants.

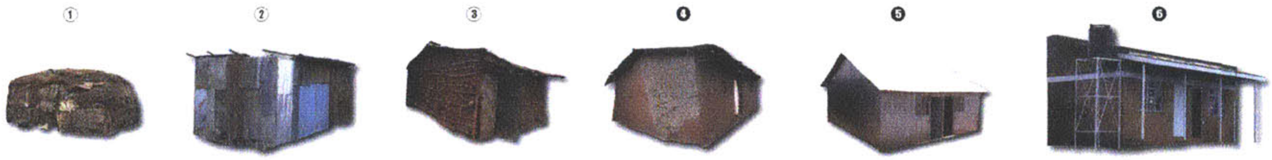
Kibera consists of twelve villages, all having their own characteristic and led by different village-elders. The topography undulates substantially, with two heavily polluted streams or rivulets running through the settlement and forming corresponding valleys. The railway line along its northern perimeter, the abandoned dam to its southern edge and infrastructure on its eastern side further add differentiating parameters to the fabric of a highly complex settlement.

SITE CONTEXT

INCREMENTAL GROWTH

Temporary

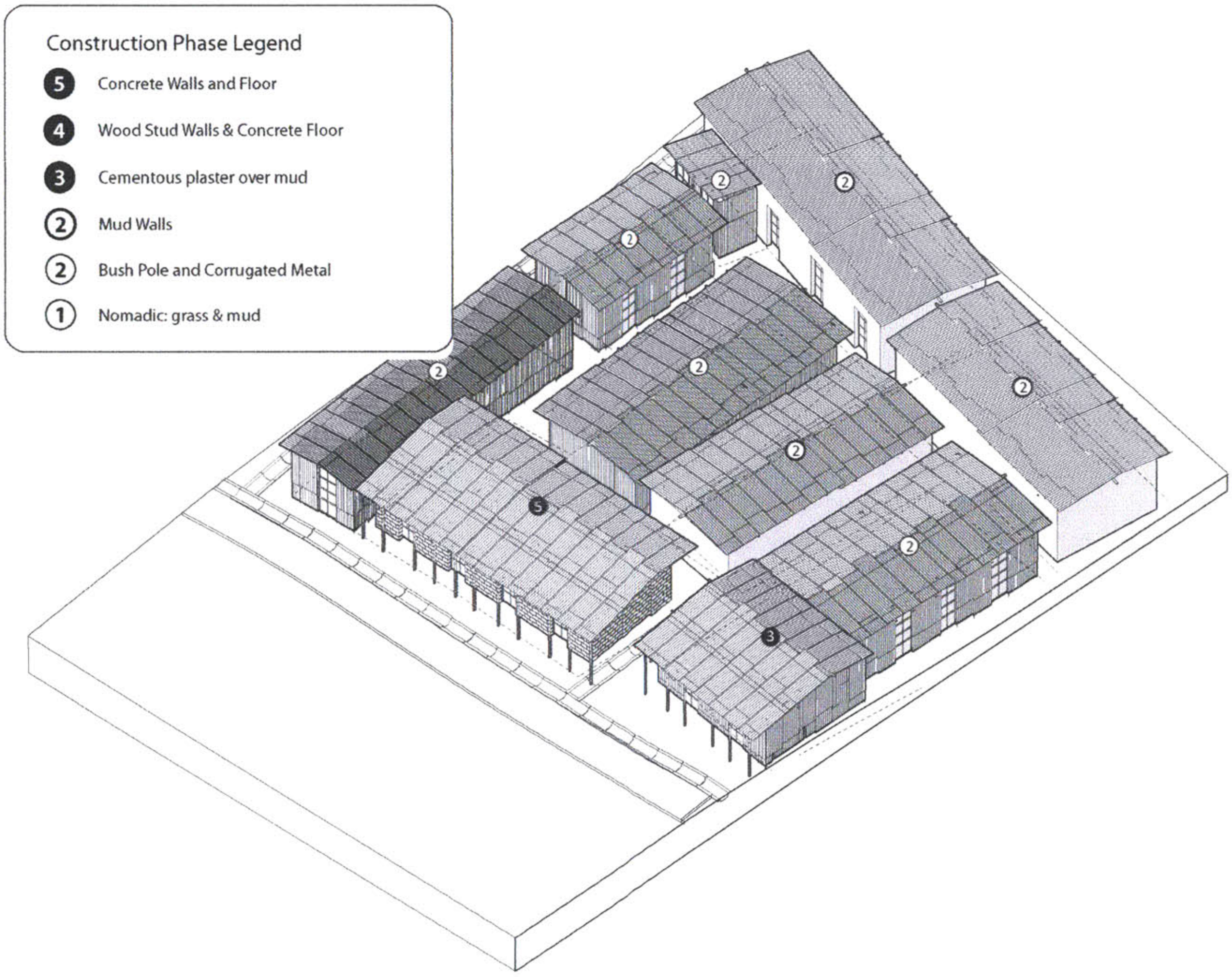
Permanent



grass + mud

concrete wall and floor

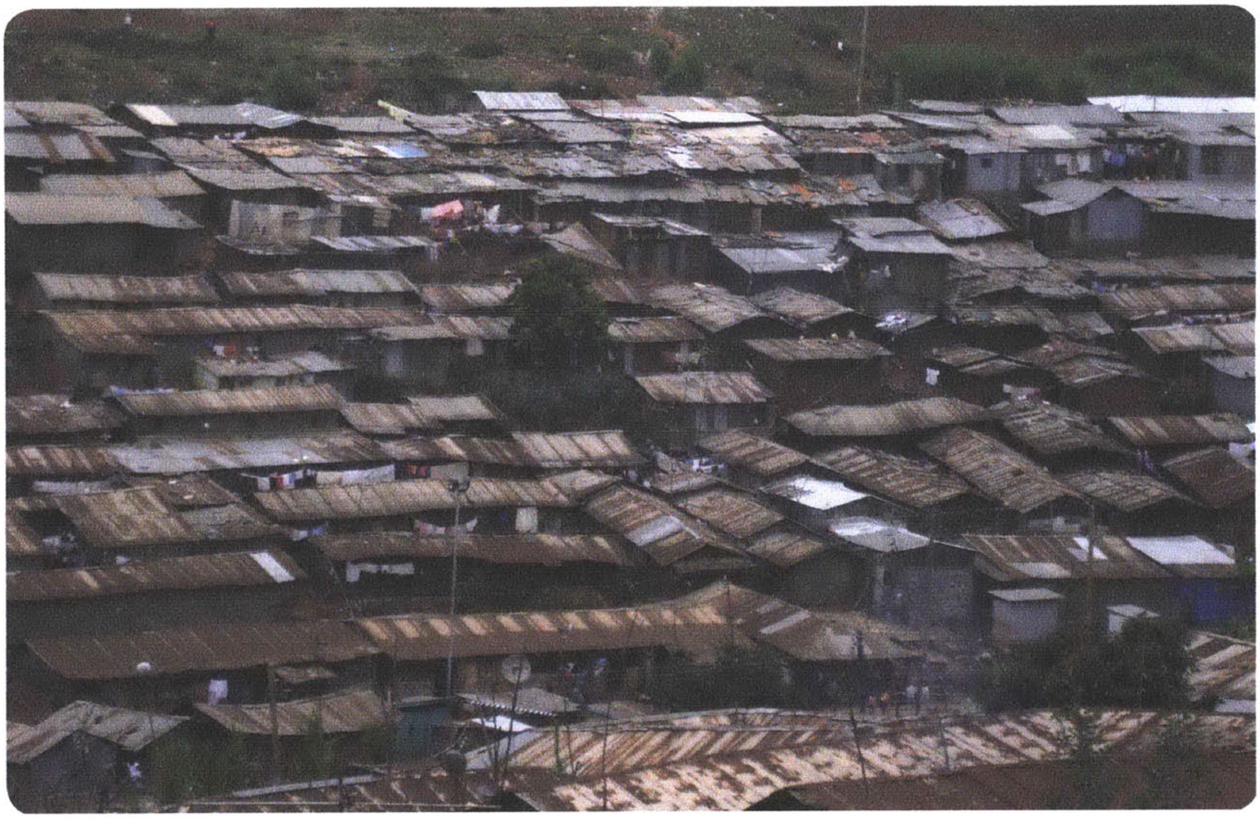
CURRENT STATE OF GROWTH



Construction Phase Legend

- ❺ Concrete Walls and Floor
- ❹ Wood Stud Walls & Concrete Floor
- ❸ Cementous plaster over mud
- ② Mud Walls
- ② Bush Pole and Corrugated Metal
- ① Nomadic: grass & mud

CURRENT STATE OF GROWTH



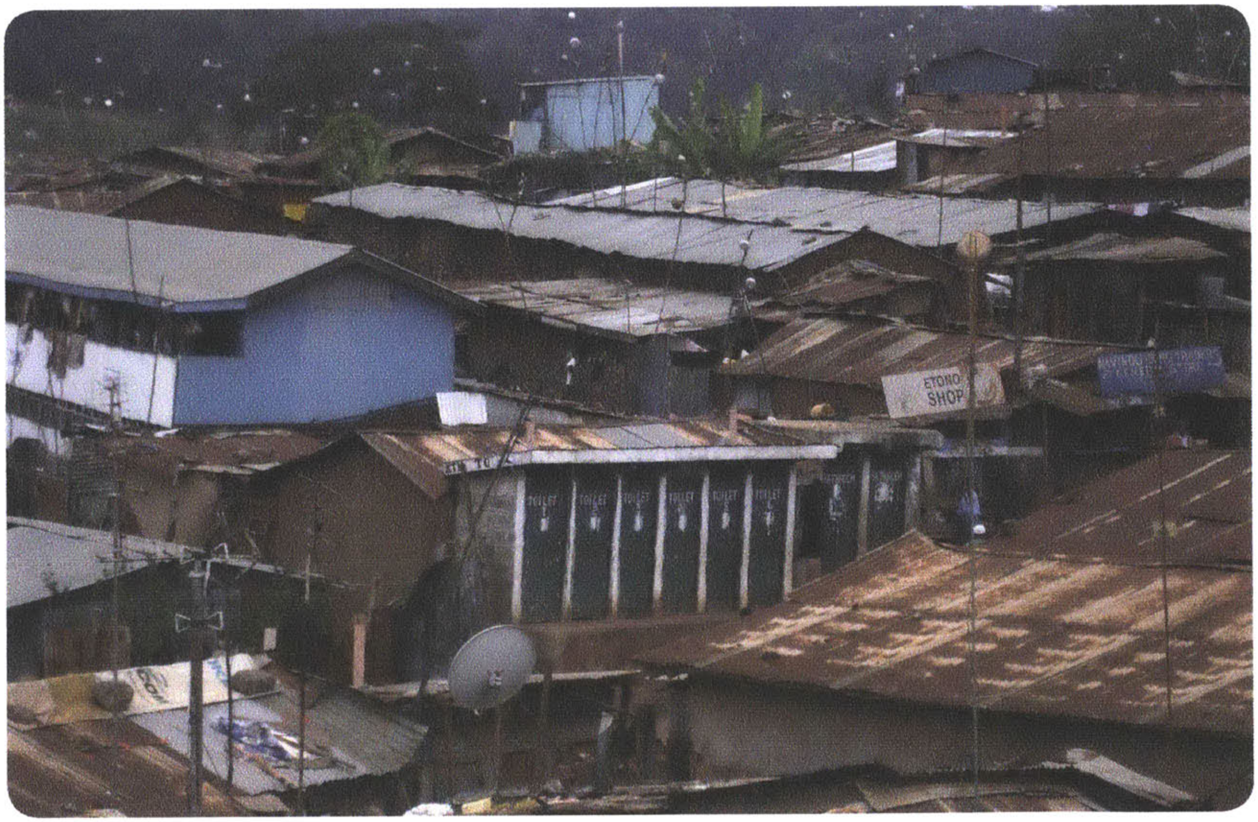
Site Image of Settlement Rooftops

Site Image of Rooftop Antennae

Site Image of Kibera Road

Site Image from Existing Railway

Site Image of Train



Site Image of Community Toilet Block

Site Image of Corrugated Metal on Bush Pole Structures

Site Image of Mud Structure

Site Image of Cementous Plaster on Mud Construction

Site Image of Corrugated Metal (Iron) Sheet Construction

Site Image of Wattle and Daub (Mud) Construction

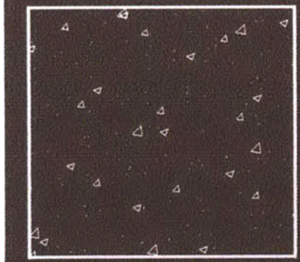
Construction Types in Kibera

70% - Mud
20% - Iron
10% - Concrete

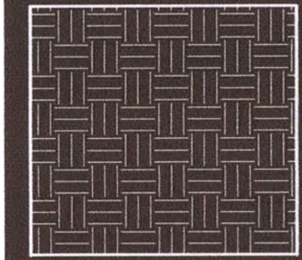
BUILDING CONTEXT | Informal Settlements

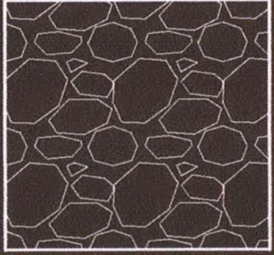
Policy

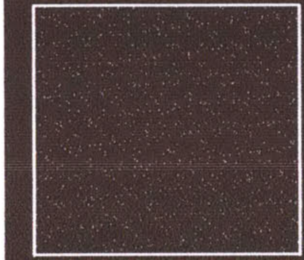
The entire territory of Kibera is government property, and it is regulated by complicated set of economic, political and social factors. For example those who hold a right to occupation of the land often totally lack economic resources, which are found outside the slum, resulting in a circulation of capital and resources already within the slum itself.

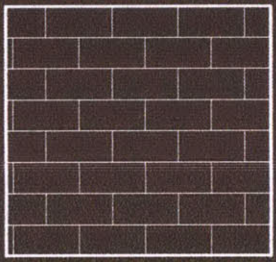

CONCRETE

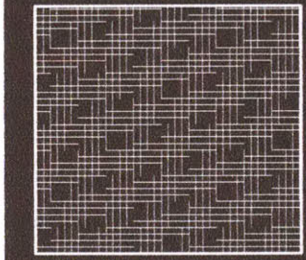

MUD/STUCCO

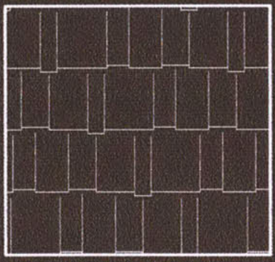

COMPACT EARTH

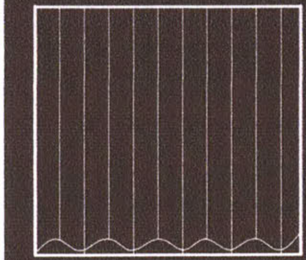

STONE & MORTAR

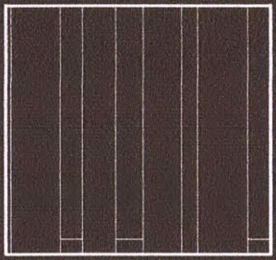

COW DUNG


BRICK


TEXTILES

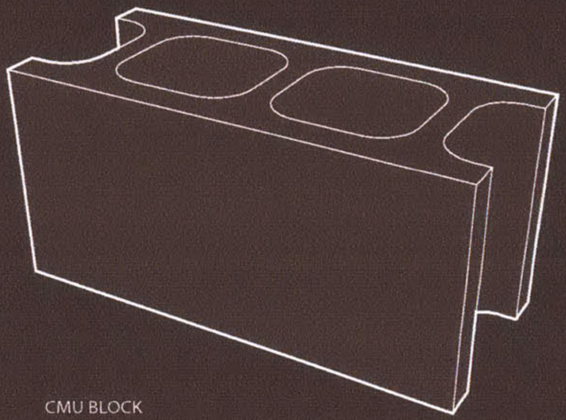

CEDAR SHINGLES


CORRUGATED METAL
"MABATI"

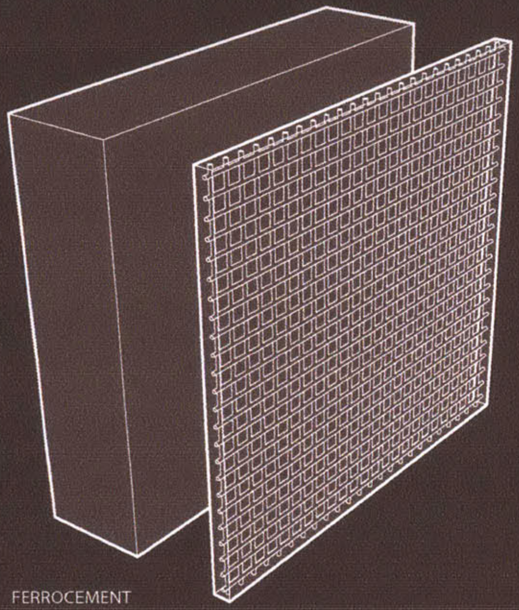

LUMBER
"BUSH POLE"

Material Costs Nairobi, Kenya
(Not yet recorded at scale)

Item		Unit	KSh	USD/Unit
Cement	kg	14	$0.17	
		Bags	730	
Sand		kg	2	$0.02
		TRUCK	11000	
"Hardcore"/Aggregate		kg	2	$0.02
		TRUCK	5000	
"Wash Dust"/Ballast		kg	2	$0.02
		TRUCK	10000	
Chicken Wire		sq m	50	$0.60
Pencil Rebar		m	15	$0.18
Corrugated Roof	sq m	125	$1.49	
30L Barrels		piece	300	$3.58
Plastering Materials			1000	$11.92
Squat Plate		piece	1500	$17.88
Oil Paint	L	375	$4.47	
Epoxy Paint		L	1450	$17.28
Transport		20km	2000	$23.84
3" Poles	No	120		
Cedar poles		NO	250	
U' Nails		KG	150	
480m Barbed Wire		ROLLS	4,500	
Binding Wire		KG	150	
3m GCI Sheets	No	620		
2.5m GCI sheets	No	505		
Ordinary Nails		KG	105	
Roofing nails		KG	150	
Chain		LM	750	
4" Hinges		NO	20	
External tower bolt		NO	67.5	
Internal tower bolt		NO	67.5	
Padlock	NO	262.5		
Water		Cans	20	
Unskilled Labor	days	300	$3.58	
Skilled Labor		days	500	$5.96
University Intern	days	1500	$17.89	



CMU BLOCK

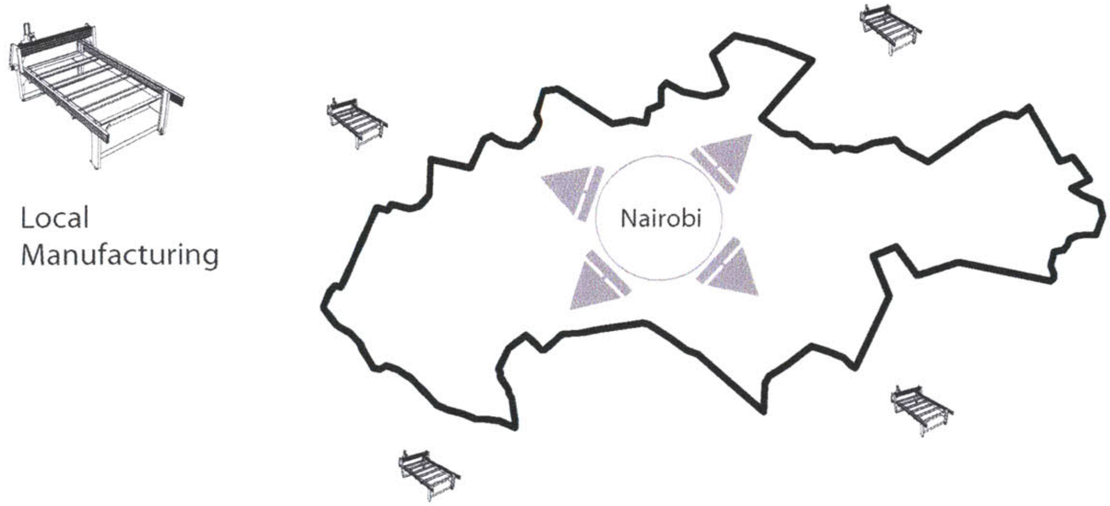


FERROCEMENT

Building Materials

Most commonly housing is made of 'waste' materials, dominated by corrugated metal sheets on bush pole, with some older communities constructed of some 50 year old wattle-and-daub structures. It can also be witnessed that the informal community as a waste stop for other communities is a city made of waste. The residents recycle the left over materials, making walls of shipping crates and old doors.

INTRODUCTION OF APPROPRIATE TECHNOLOGY



DISTRIBUTED MANUFACTURING

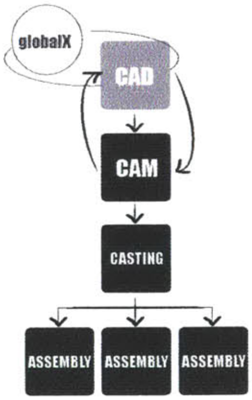
Methods of automating architecture are complex considering that structural dynamics and life-safety measures require high levels of coordination and system design. There is a distinction within developing countries about the classifications of technological progress; one being labor-saving, and the other capital-saving (that is when higher levels of output can be achieved with the same quantity of labor or capital inputs). Rather than marginalize the craftsman, within a development context digital design software and digital fabrication equipment should be made available to enable even the self-employed craftsman, or Jau Kali (Kenya), to access simulation and engineering tools that allow them to see a building design from concept to realization; democratizing the design process. Similarly, digital fabrication and mass production tools should be deployed to create new employment opportunities, generating the need for construction and assembly of pre-fabricated parts, establishing a formal, yet localized system for development. This method of distributed manufacturing using accessible technology has not always been the method for deployed technology. Until now, technology has always been driven by industry where advancements are motivated by maximum efficiency. It was not until the past decade that these technologies have been deployed in the development context.

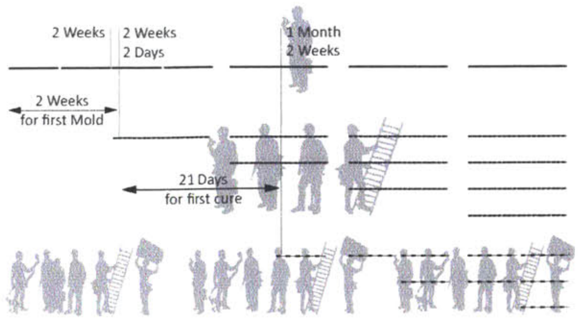
TRANSFERABLE SKILLS

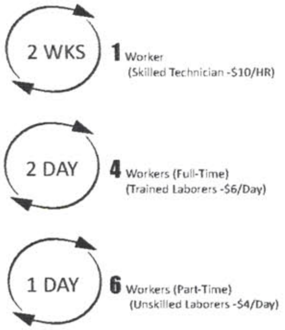
Assembler

Ferrocement

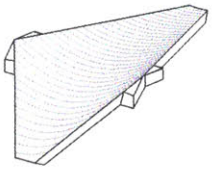
EMPLOYMENT PYRAMID



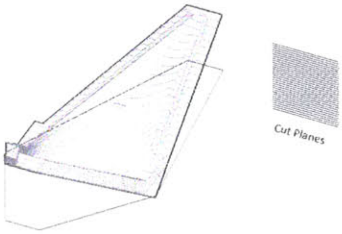




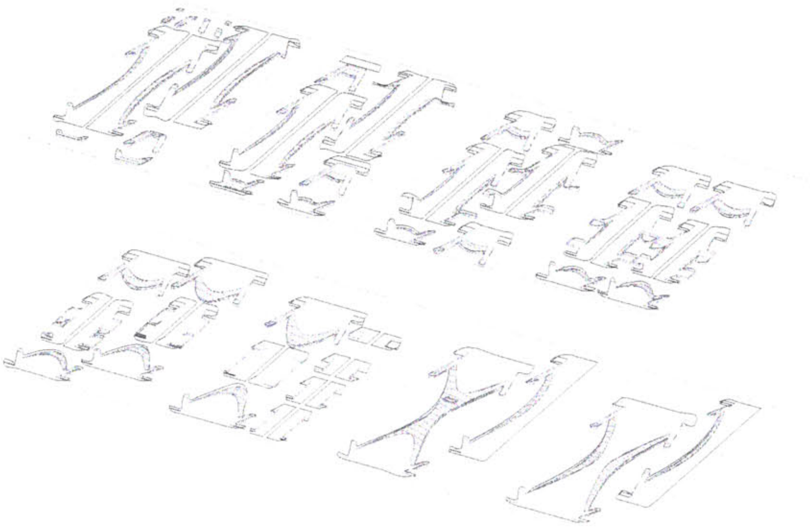
DISTRIBUTED MANUFACTURING



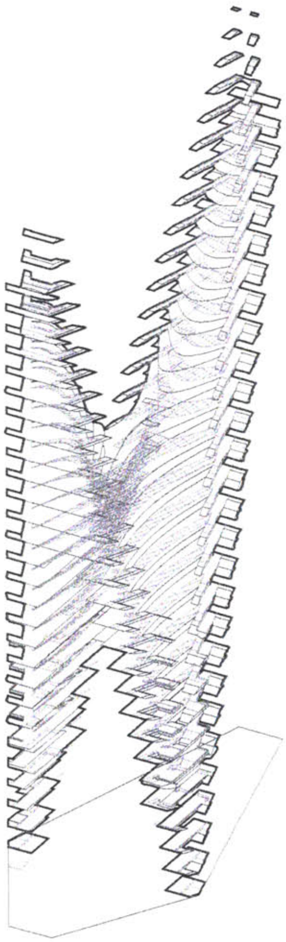
⓪ 3D Digital Model of Component



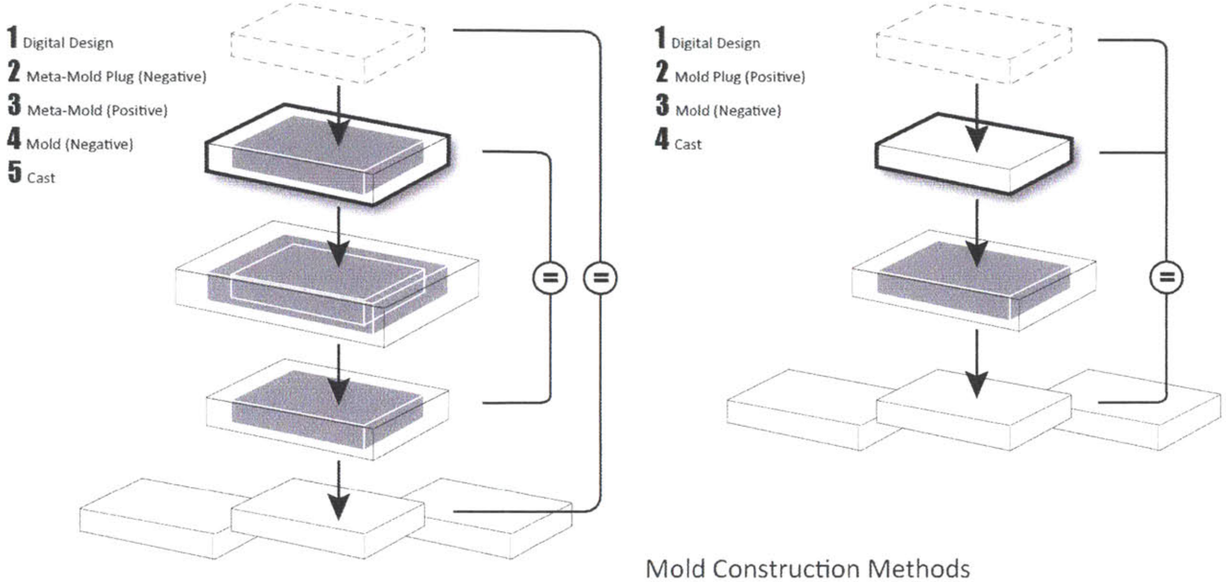
① Laterally Contour 3D Digital Plug



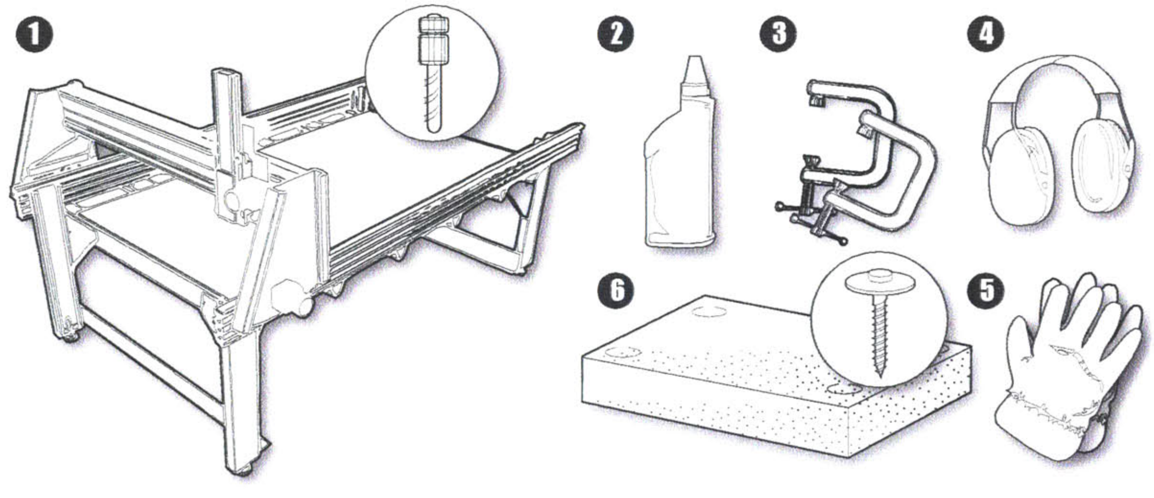
② Mill Components for Plug



③ Laminate Milled Components

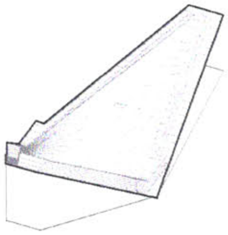


Mold Construction Methods

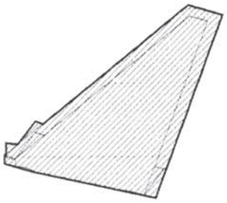


Plug Construction Materials

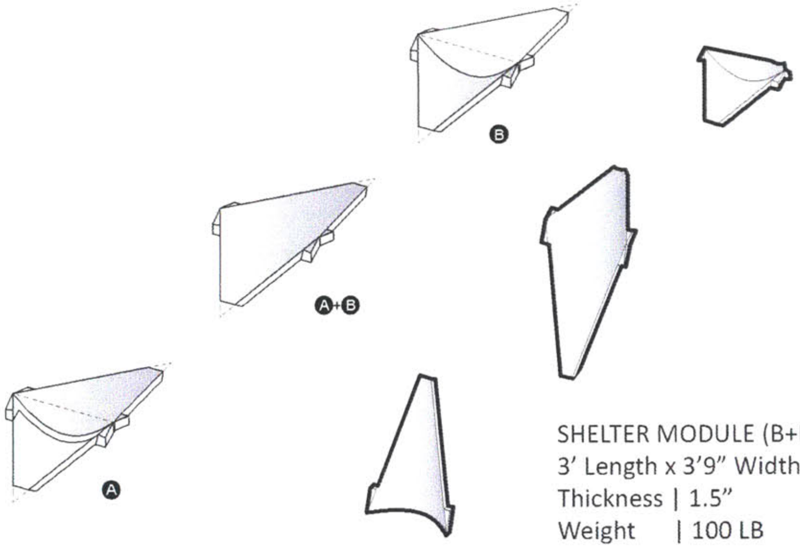
1 CNC Router
2 Ball Nose Bit
3 Clamps
4 Plywood and Wood Glue
5 Work Gloves
6 High Density Foam



④ Final Mold Plug



⑤ Extract Mold

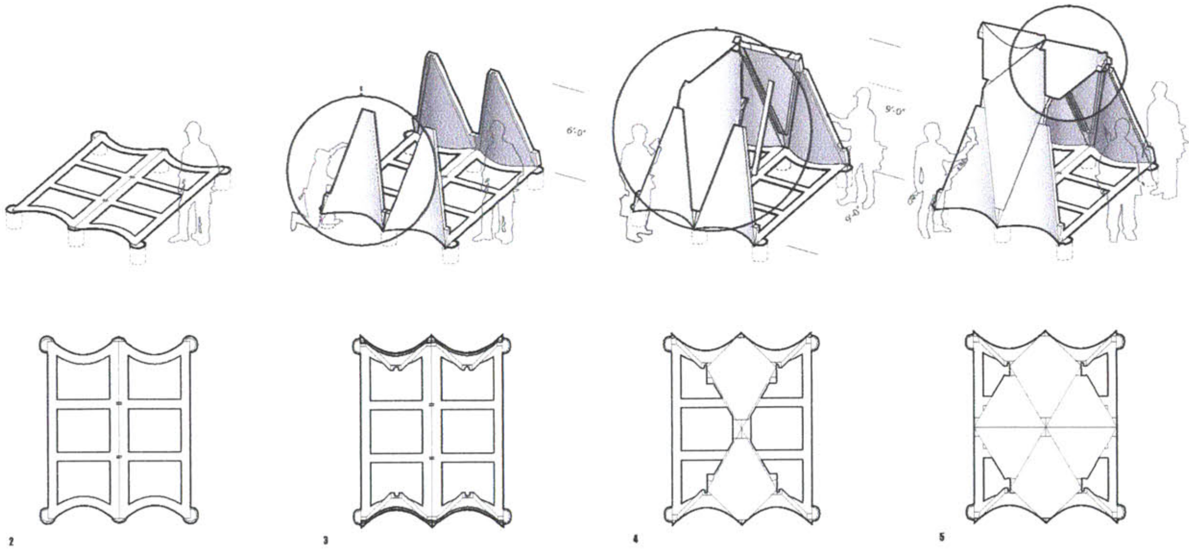


⑦ Cast Component Variations

SHELTER MODULE (B+B)
3' Length x 3'9" Width
Thickness | 1.5"
Weight | 100 LB

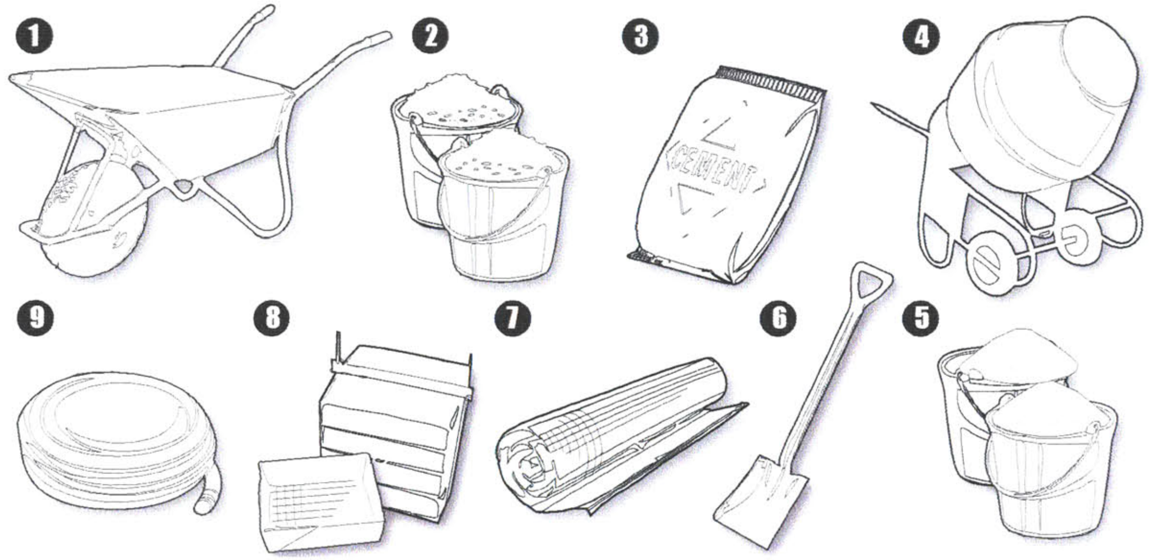
ENCLOSURE MODULE
9' Length x 3'9" Width
Thickness | 1.5"
Weight | 300 LB

FENCE MODULE
6' Length x 3'9" Width
Thickness | 1.5"
Weight | 200 LB



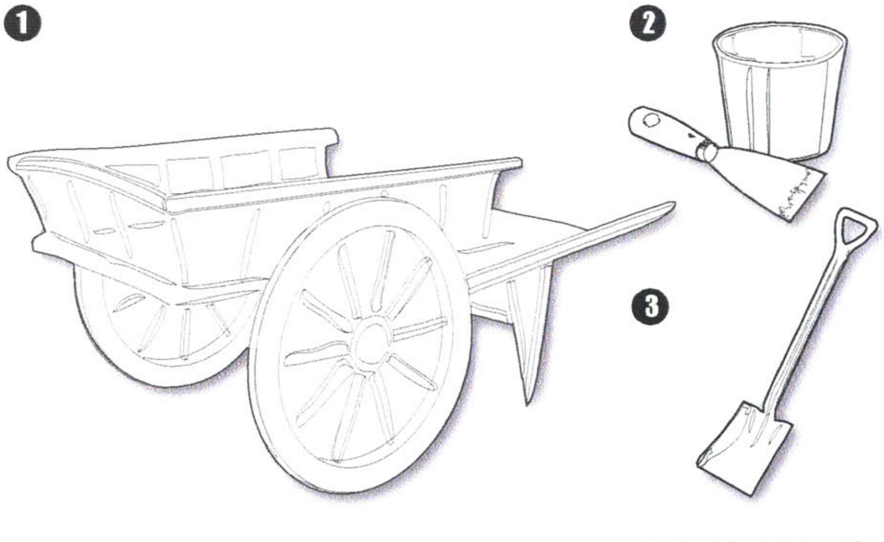
Prototypical Assembly Process

1 Foundation Posts **2** Floor Alignment Plates **3** Fence (A)
4 Enclosure (A+B) **5** Shelter (B+B) **6** Final Assembly



Casting Materials & Equipment

1 Wheel Barrow
2 Quarry Dust
3 50kg Cement Bag
4 Concrete Mixer
5 Sand
6 Shovel
7 Chicken Wire Mesh
8 Sieve
9 Water Hose

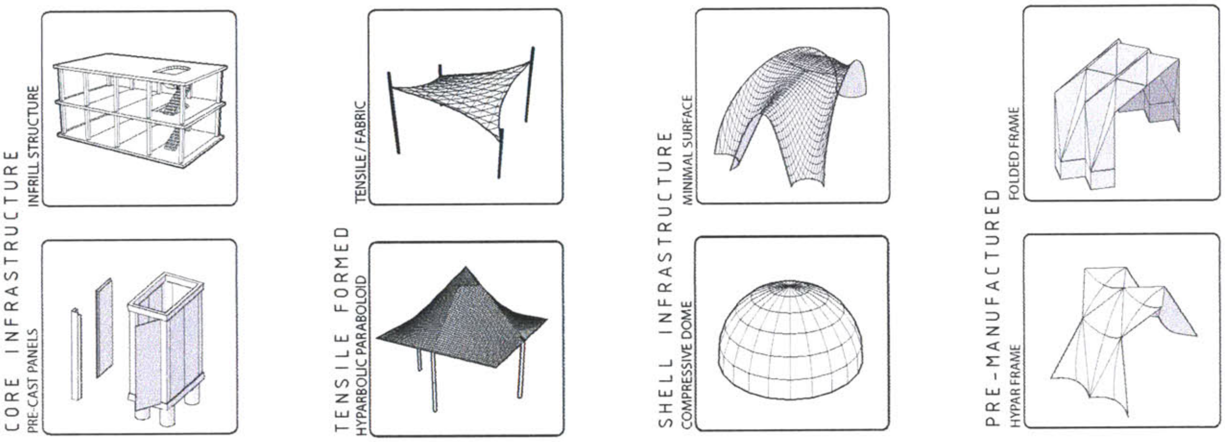


Assembly Materials & Equipment

1 Hand Cart
2 Mortar
3 Shovel

DESIGN FEATURES

PROTOTYPICAL BUILDING FEATURES

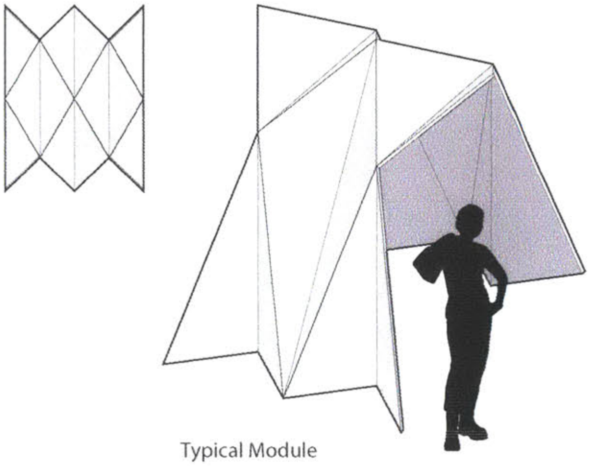


DESIGN CRITERIA

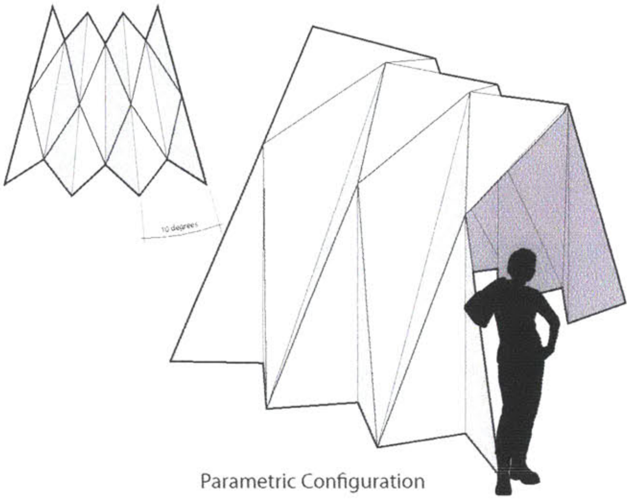
Meet Large Demand Fast!
Pre-fabricated Off-site
Reduces Material Cost
Enhances Standard of Living
Employed and Developed Transferable Skills
Fulfills Perception of Permanence
Less than $500 per Incremental Addition ($300 per 7'6" in length)
Investment in Future

300 LB Weight Limit for Ease of Assembly

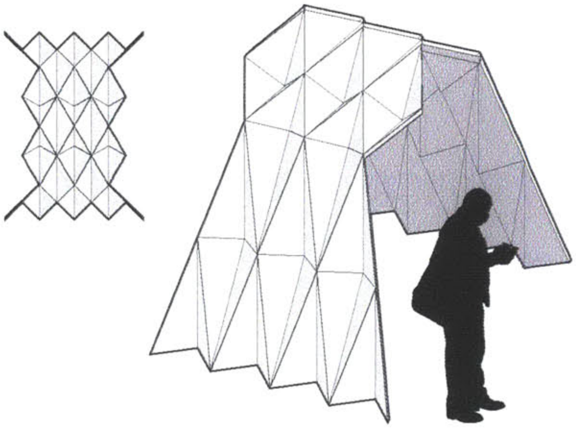
PROTOTYPICAL STRUCTURES



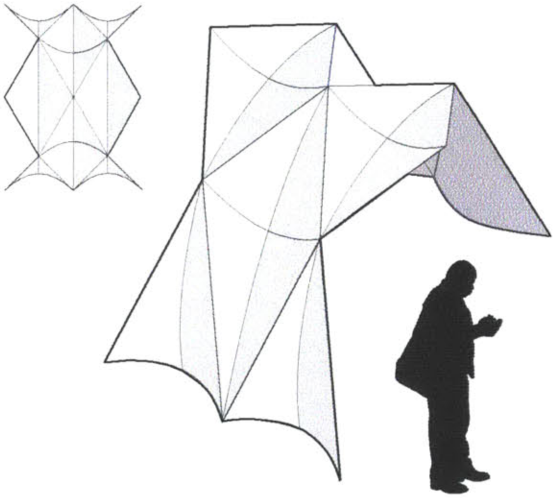
Typical Module



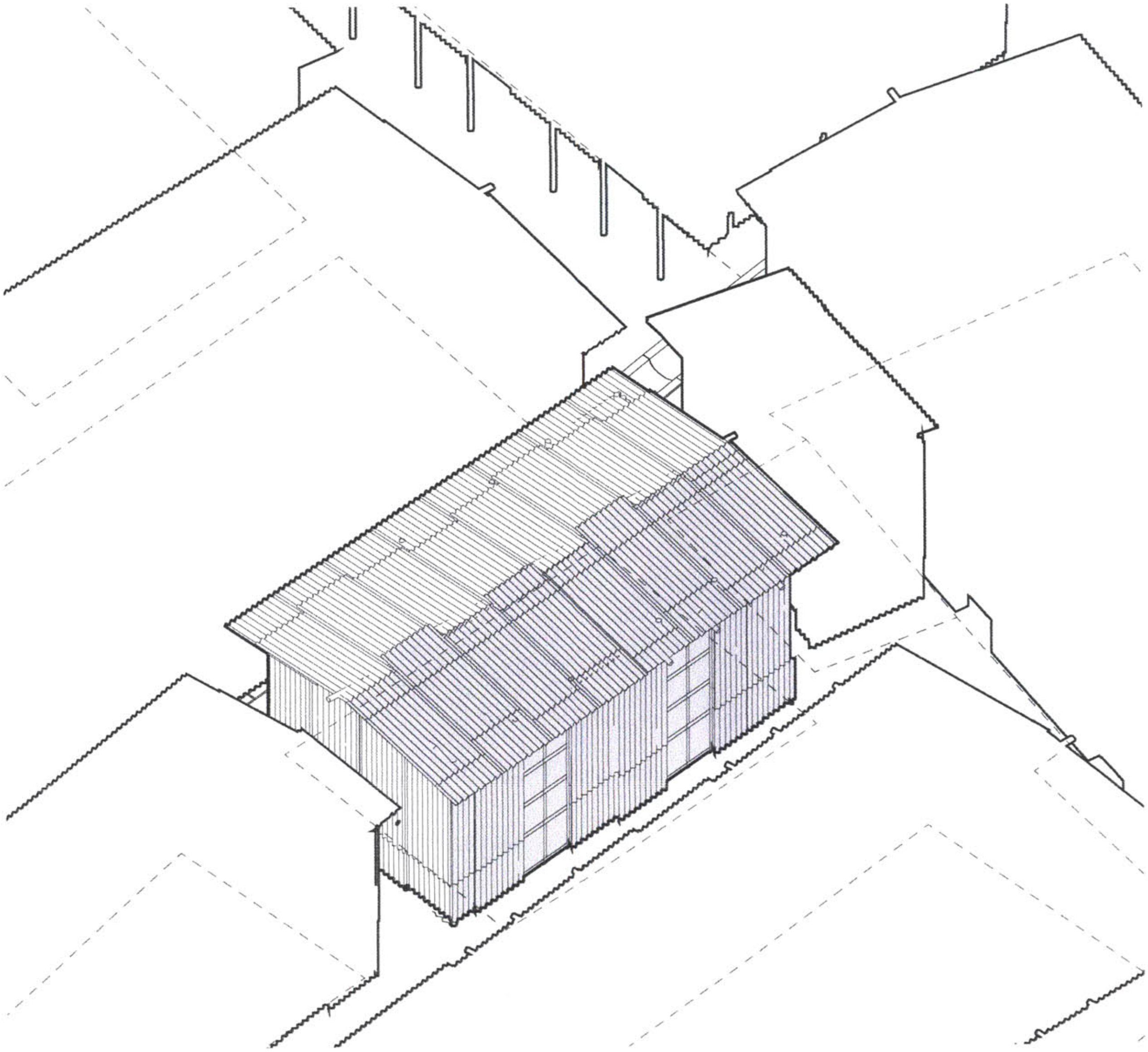
Parametric Configuration



Scalability of grain



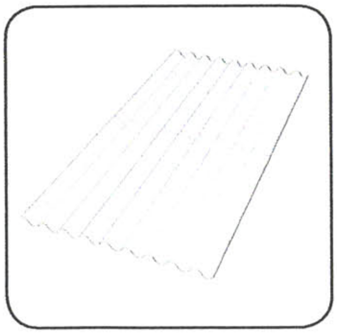
Minimal Surface

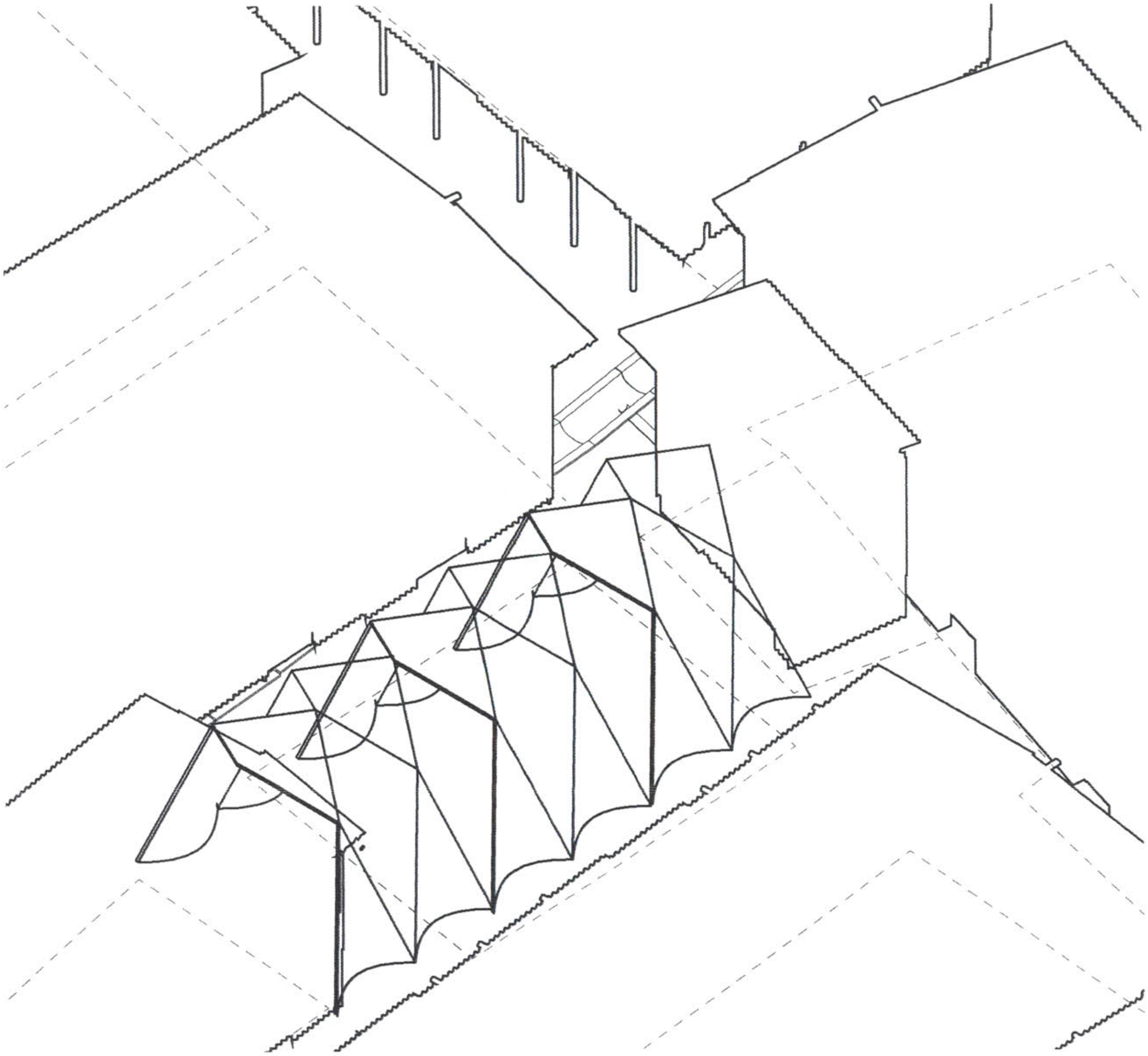


TYPICAL CONSTRUCTION

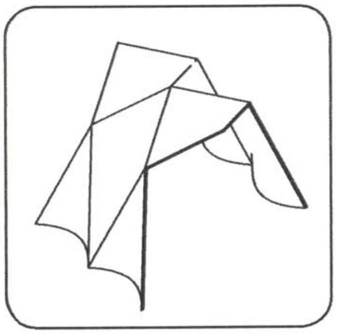
6 month -2 year life span
Flexible Assembly solutions
Incremental Growth
Looses Value Immediately

Impermanent Structures
No Homeowner Pride
Prone to theft, no windows as a result
Prone to overheating
Weather Resistant
Rain on roof makes voices inaudible





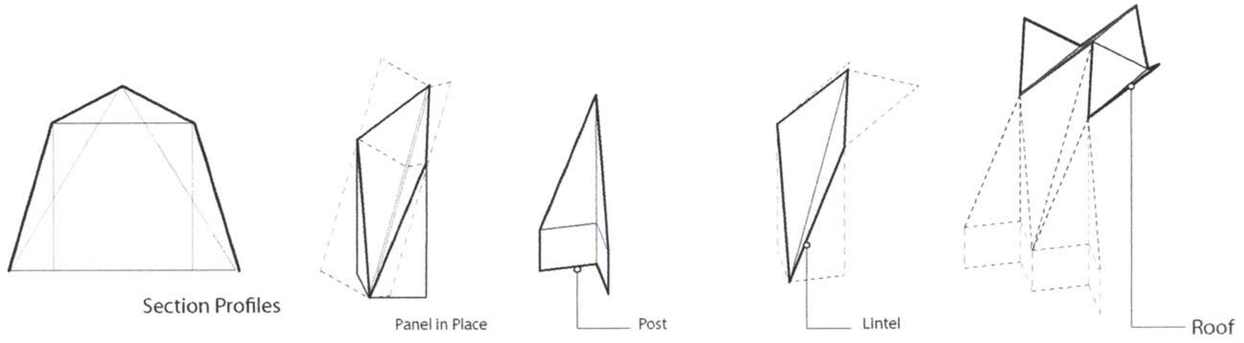
PROPOSED CONSTRUCTION

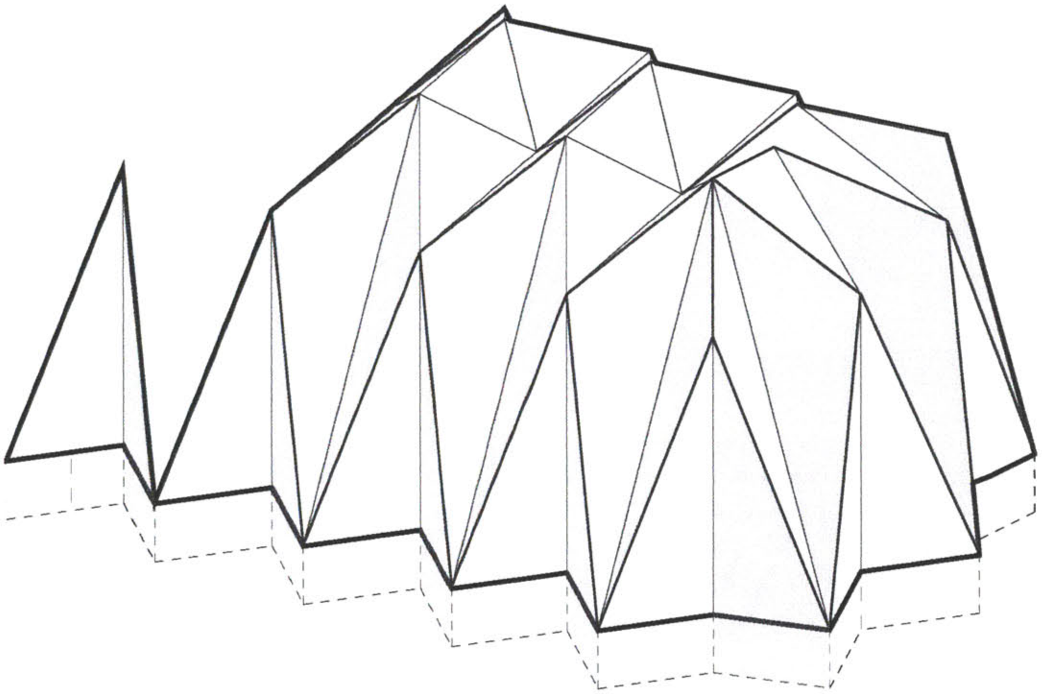


Increased Durability, 5 year minimum
Flexible Assembly solutions
Formal Incremental Growth strategy
Retains value, an investment

Perception of Permance
Source of Pride for Homeowners
More Secure from theft and destruction
Regulates thermal variability
Weather Proof
Buffers outside noise others and rain

STRUCTURE PARAMETERS
Folded Surface & Straight Frame

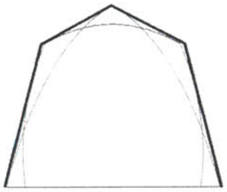




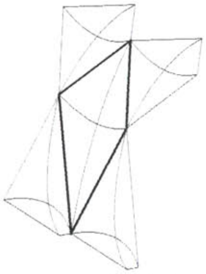
Parametric Configuration

STRUCTURE PARAMETERS

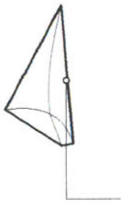
Hypar Surface & Straight Frame



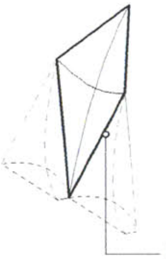
Section Profiles



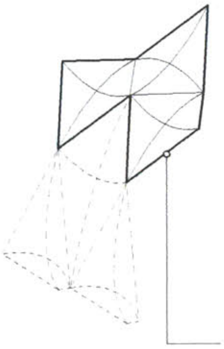
Panel in Place



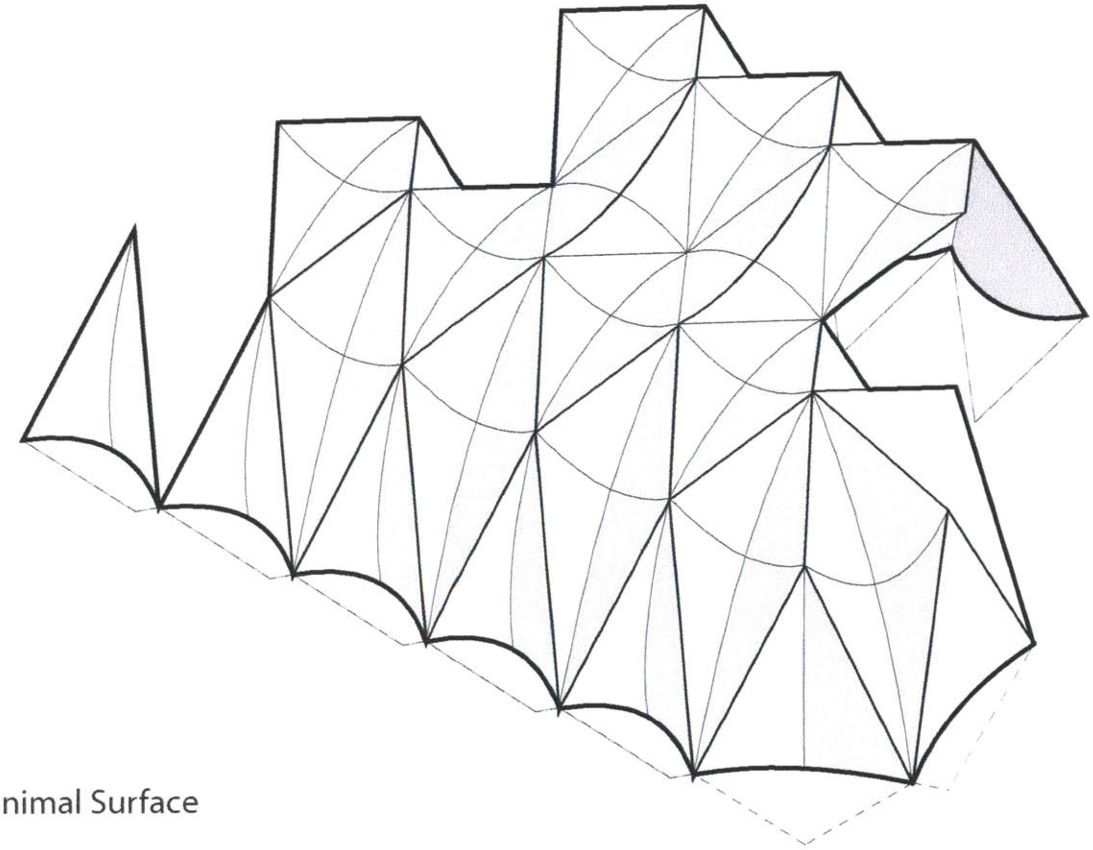
Post



Lintel



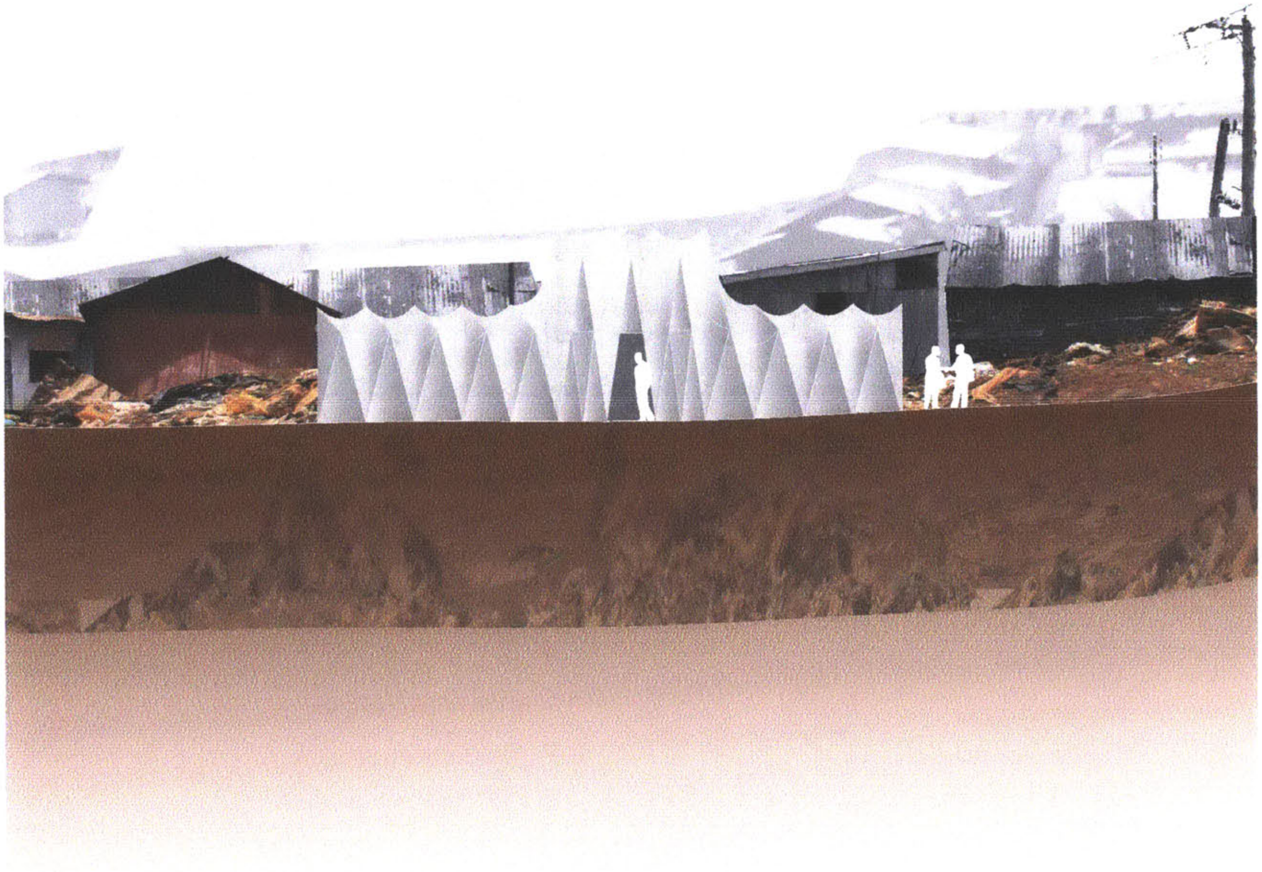
Roof

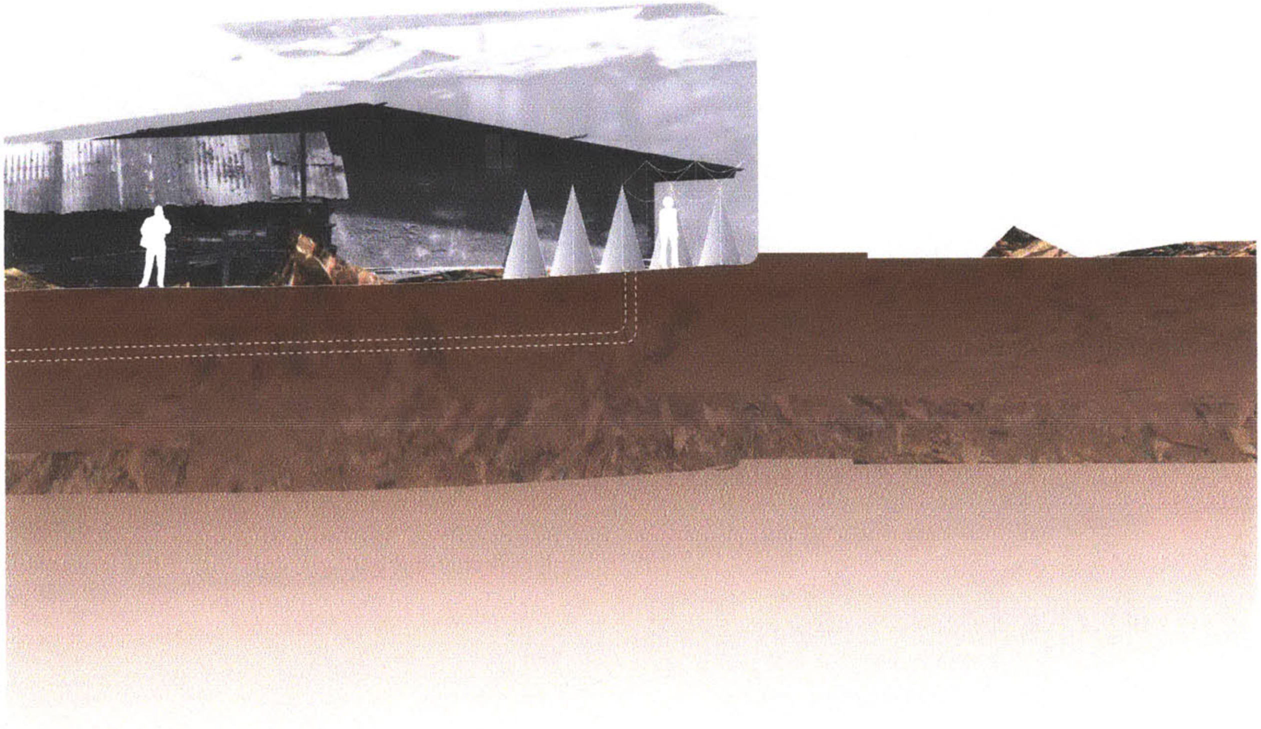


Minimal Surface

KIANDA SETTLEMENT

Site Cross Section

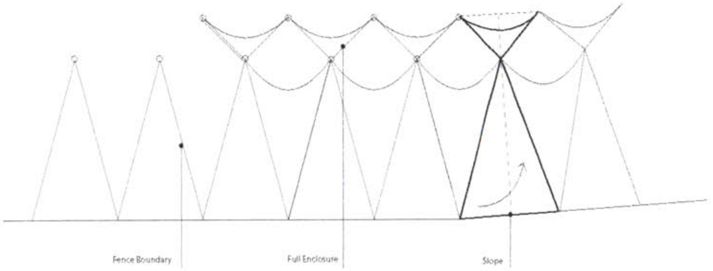


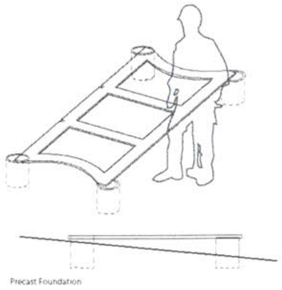


View of Existing Construction and Density
View of Double Height Structure on Site
View of Elongated Structure on Site
View of Fence Module on Site

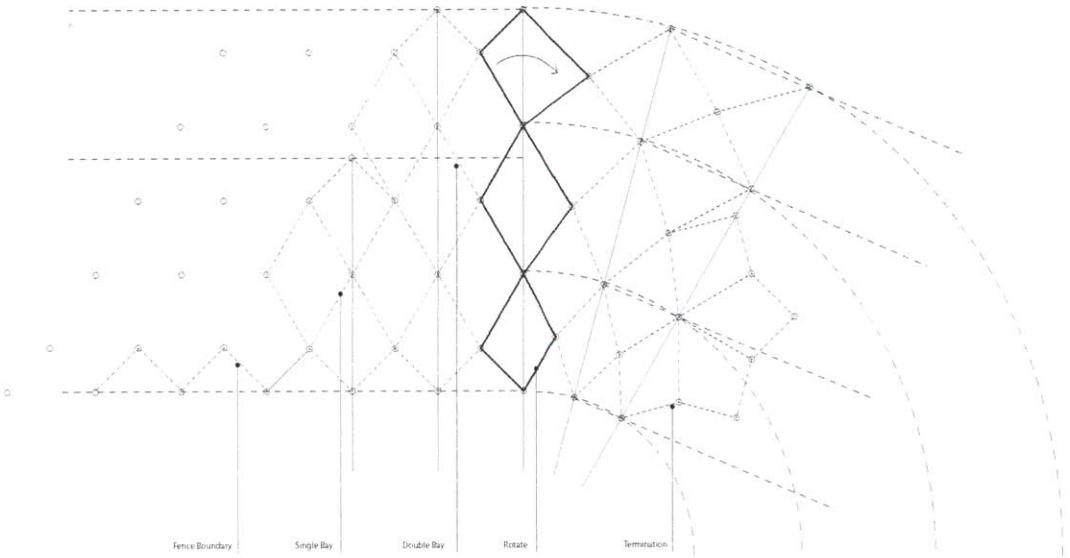
FORM

SLOPING Incremental Modularity

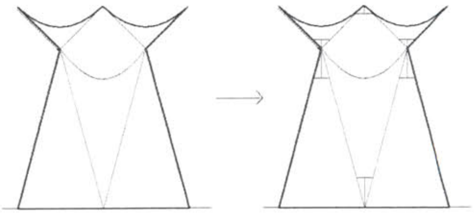


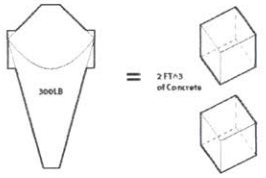


ROTATING Incremental Modularity

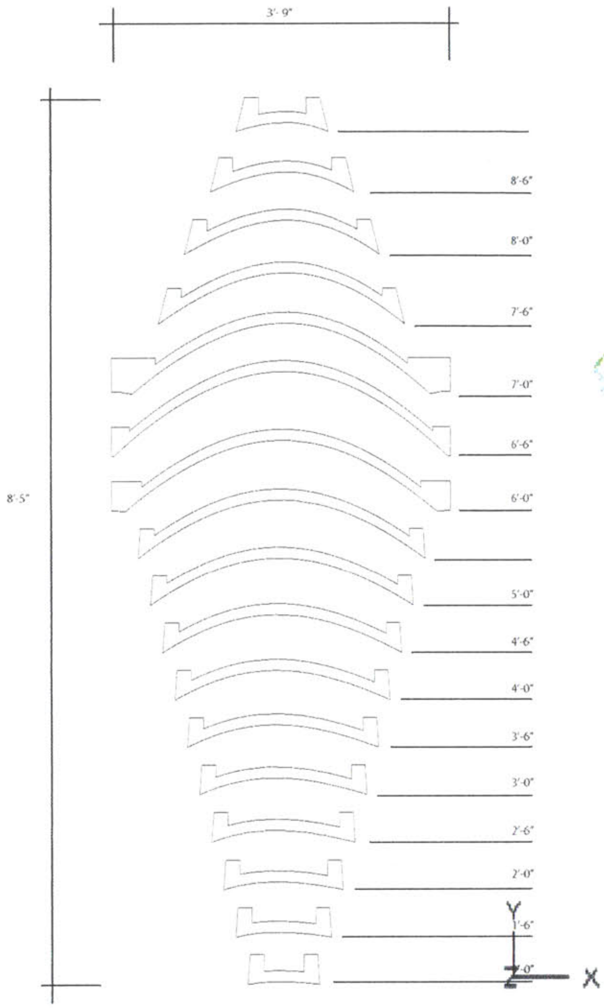


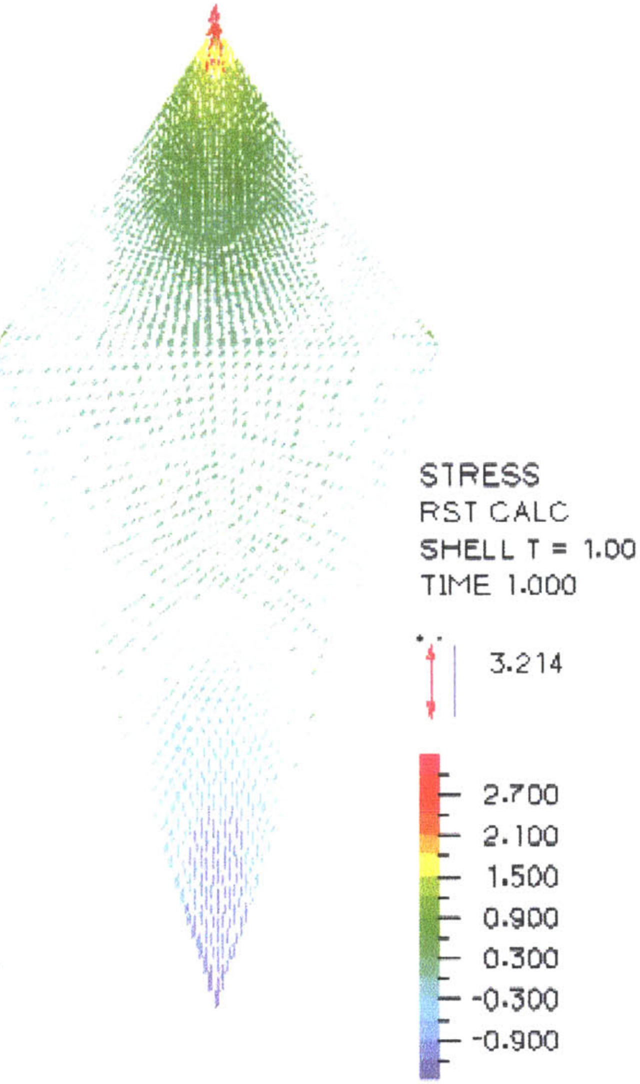
EASY TO ASSEMBLE Masonry Assembly





The assembly form was generated based on the local building fabric and trends, based on economic necessity, it is intended to be the most affordable, light weight structure possible, and thus lacks limitless flexibility in final form. It is optimized for material efficiency and engineered for demolding and transport, with a final form that is perceived as permanent by the user.



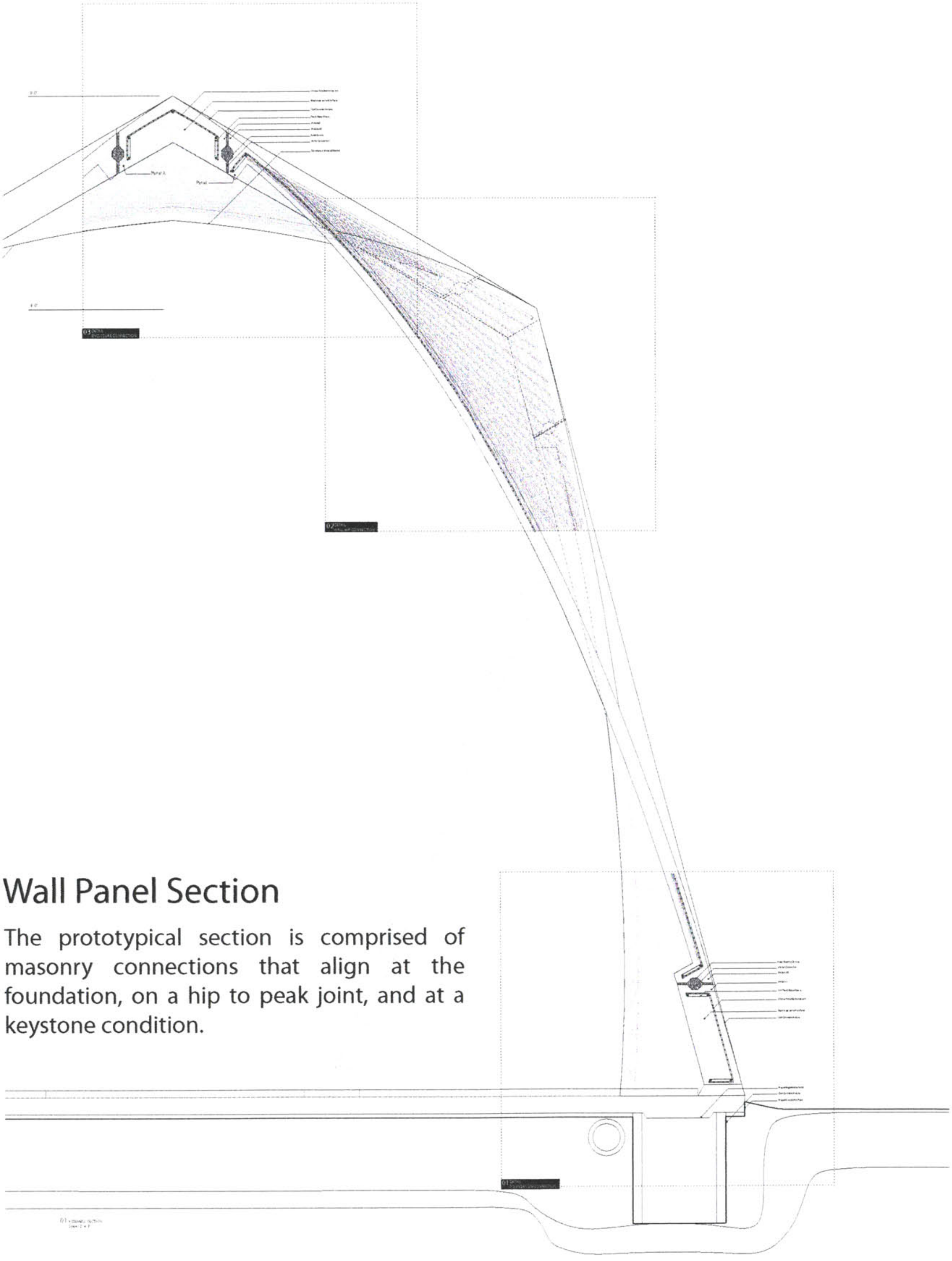


04 CROSS SECTION_02

STRUCTURAL PARAMETERS

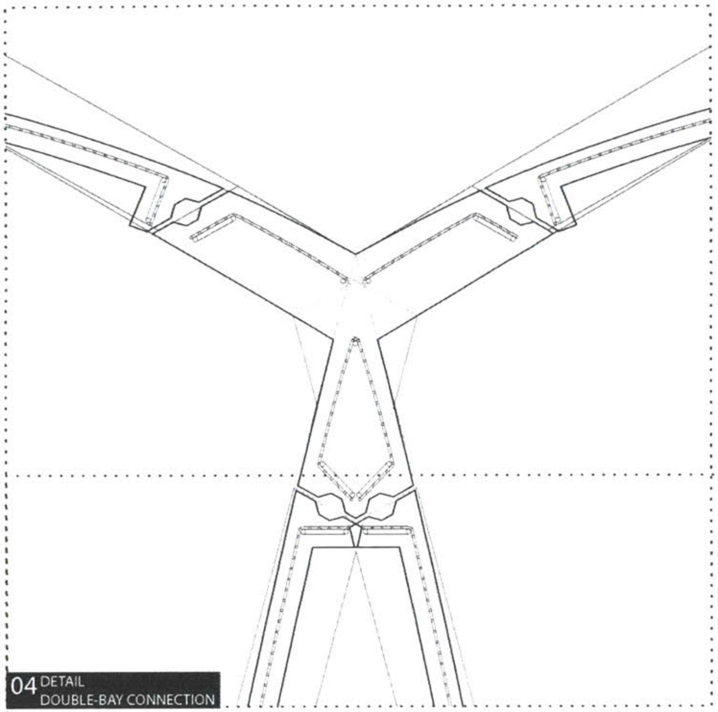
Hypar Surface & Straight Frame Structures provide an optimal shape for its minimal use of material with the added capability to join the shape with more standard building materials. The assembly was designed easily by using a computer design generator* to define the minimal surface for this straight frame, which was derived from a parabolic arch. Two-thirds of the basic building module creates the wall enclosure before the top third begins to angle to create a horizontal roof element. The original pure hyparbolic, parabolic surface was modified to meet the demolding and transportation demands; the pointed ends were split and added to the hip joint of the module to create a stacking, masonry condition, adding strength and ease of assembly.

* Rhinoceros Design Software created by McNeel and Associates

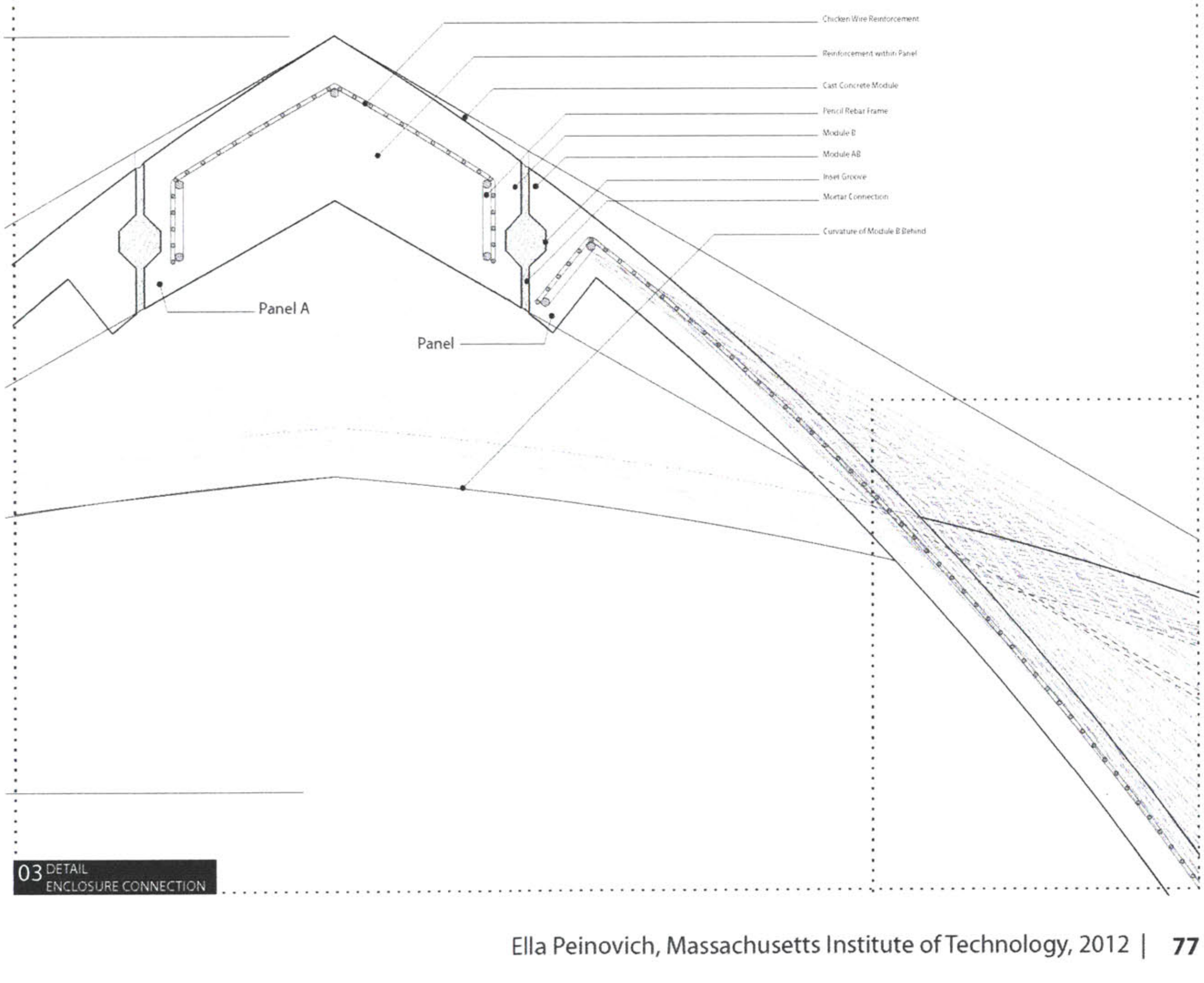


Wall Panel Section

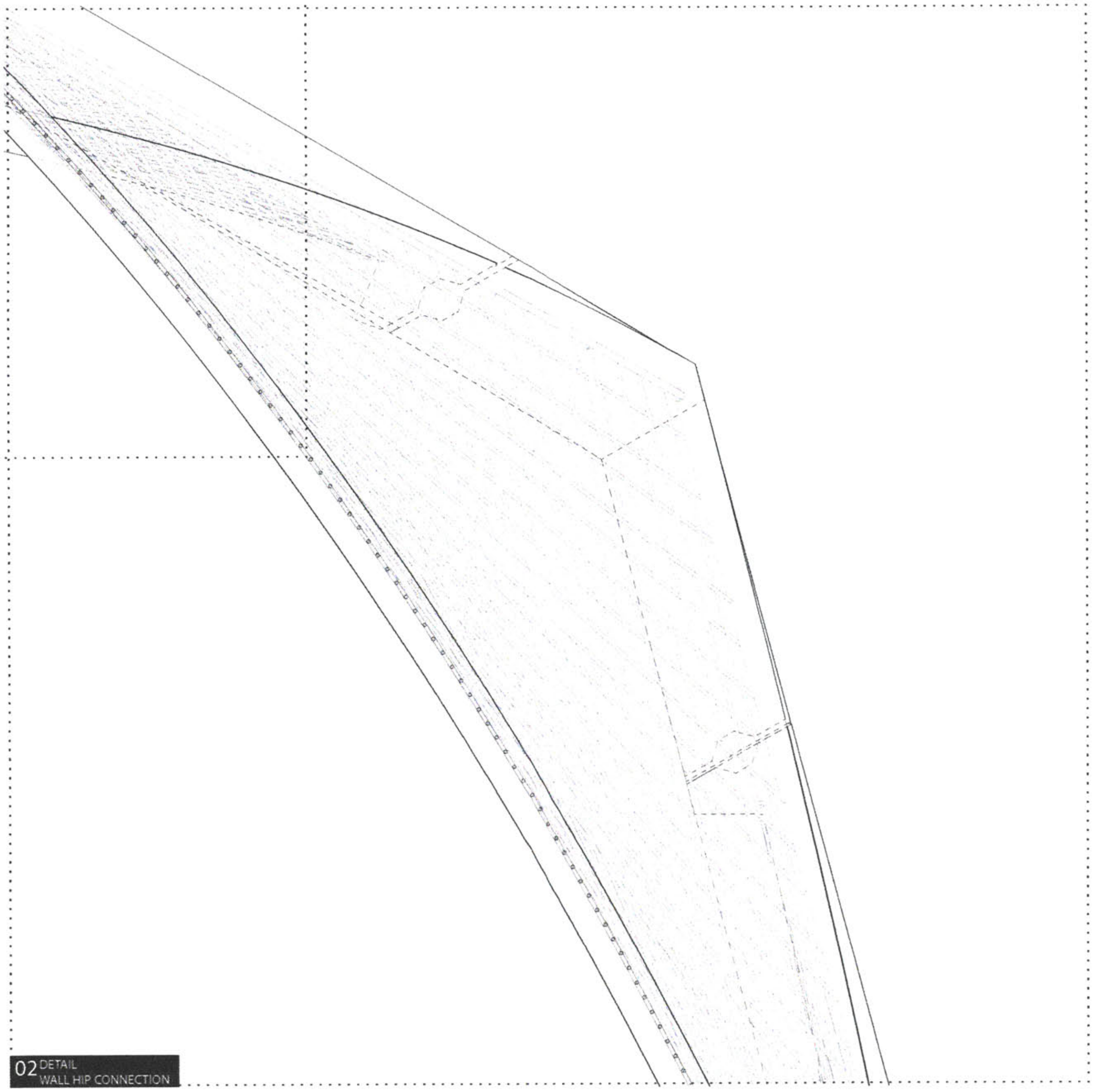
The prototypical section is comprised of masonry connections that align at the foundation, on a hip to peak joint, and at a keystone condition.



04 DETAIL
DOUBLE-BAY CONNECTION



03 DETAIL
ENCLOSURE CONNECTION

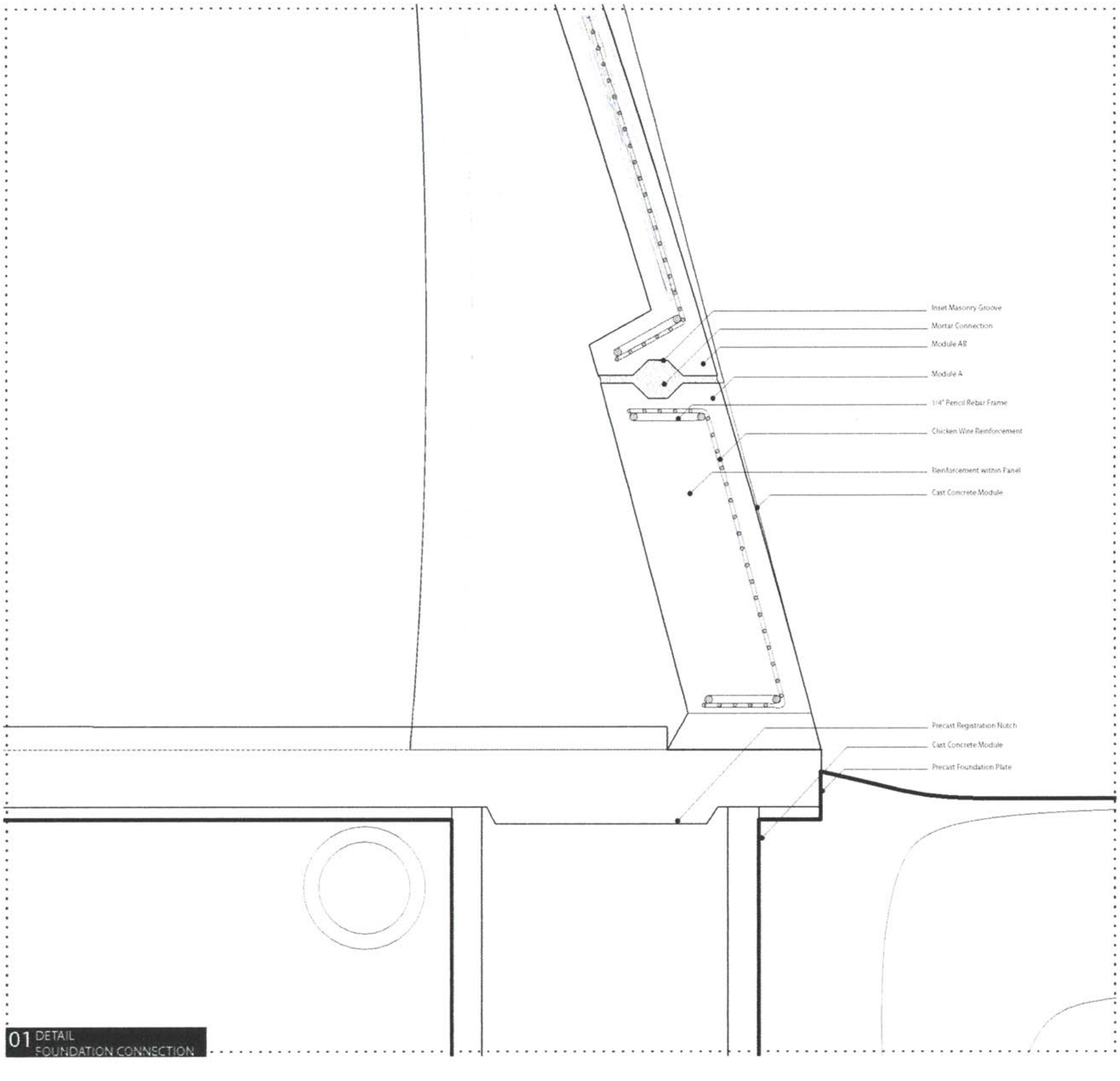


⌃ DETAIL 01 | Keystone Connections

The hip connection to the roof becomes the keystone that sets into the peak of two adjoining full wall modules.

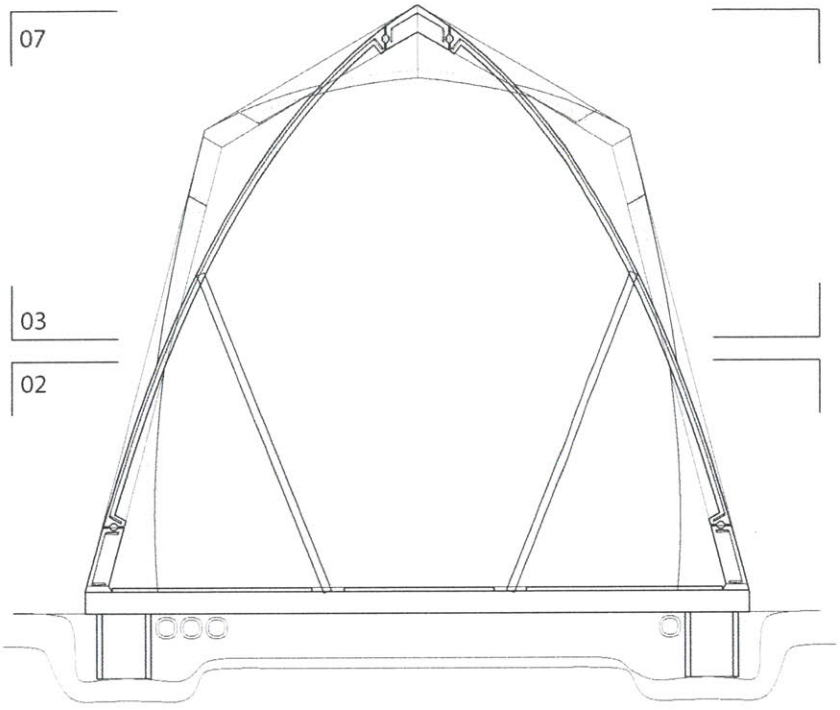
DETAIL 02 | Wall Hip Connection

The hip connection on the full panel aligns to the peak of the adjoining panel.

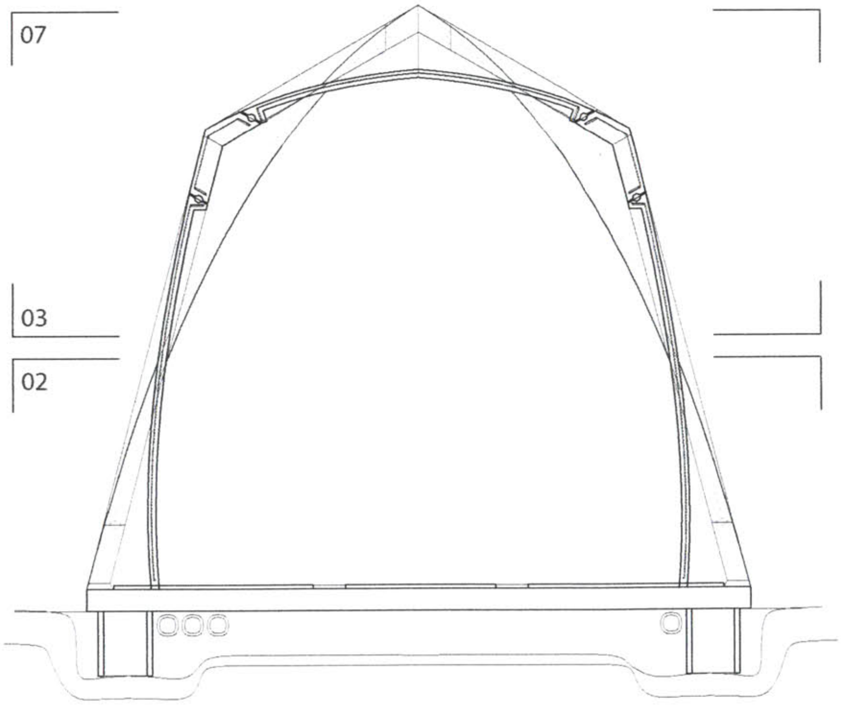


DETAIL 03 | Foundation Connection

The foundation connection is where the fence module joins to a precast foundation post. The post is brought on-site and leveled before applying the modules. The foundation can also serve as the place for services such as plumbing, electric, and sewer to enter the structure.



05 CROSS SECTION_02



06 CROSS SECTION_01

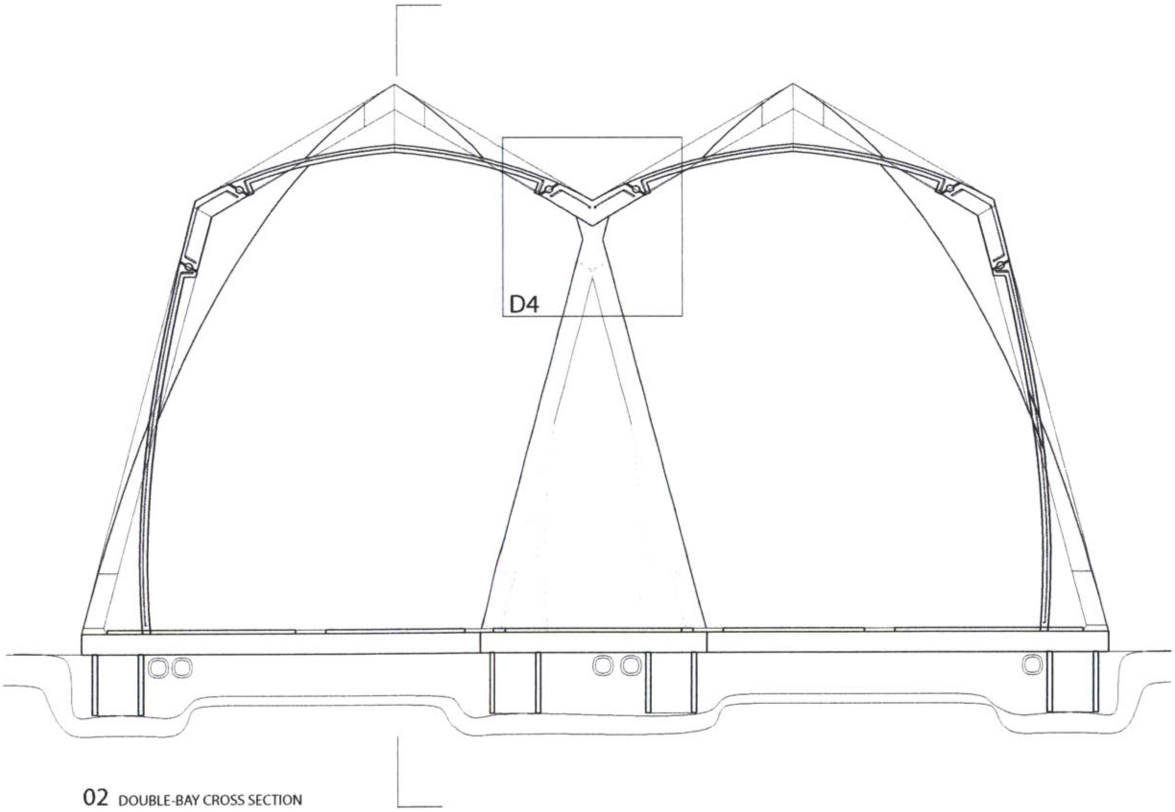
ASSEMBLY CROSS SECTIONS

The typical assembly is made of an undulating form with a constantly variating section. There are two primary cross sections; one that forms a pointed cantinary arch at the peak of two full modules and the other is a deflated cantinary arch formed by the two fence modules and horizontal roof module.

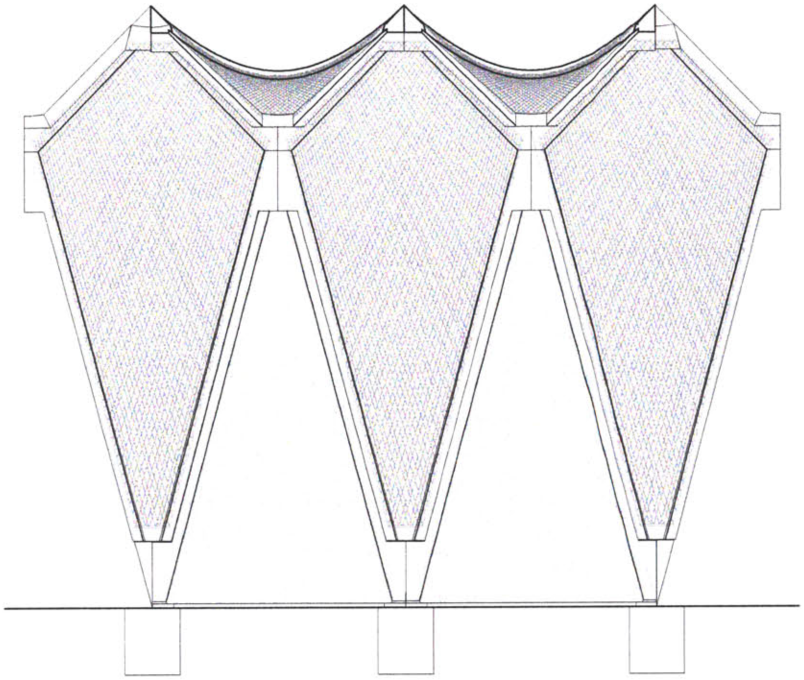
<< Section 01 | Full Wall Module with Keystone

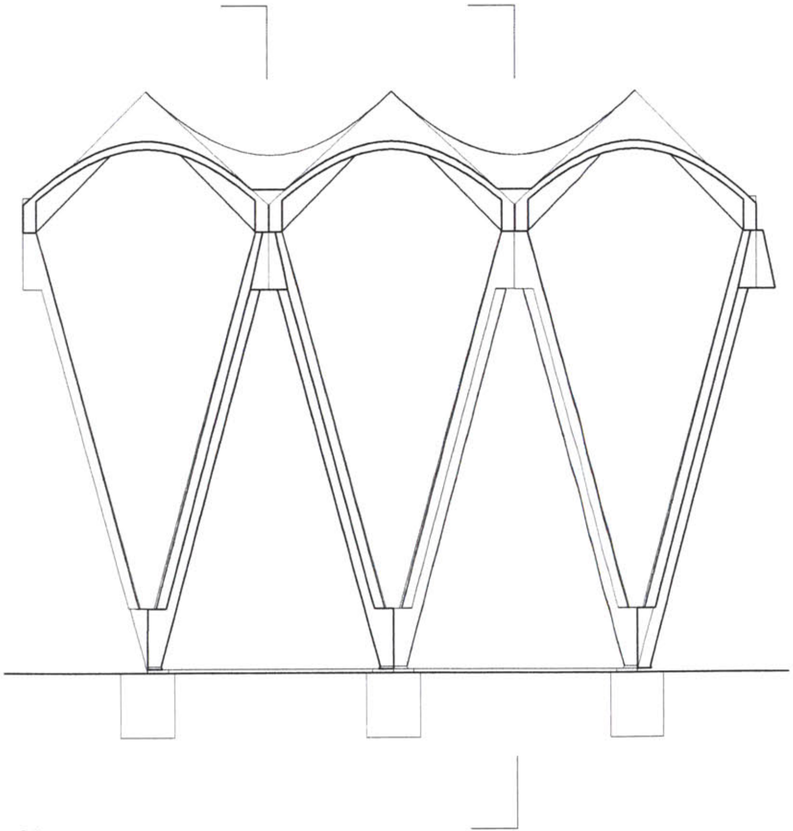
V< Section 02 | Roof and Fence Modules

V Section 03 | Double Bay with Column Unit

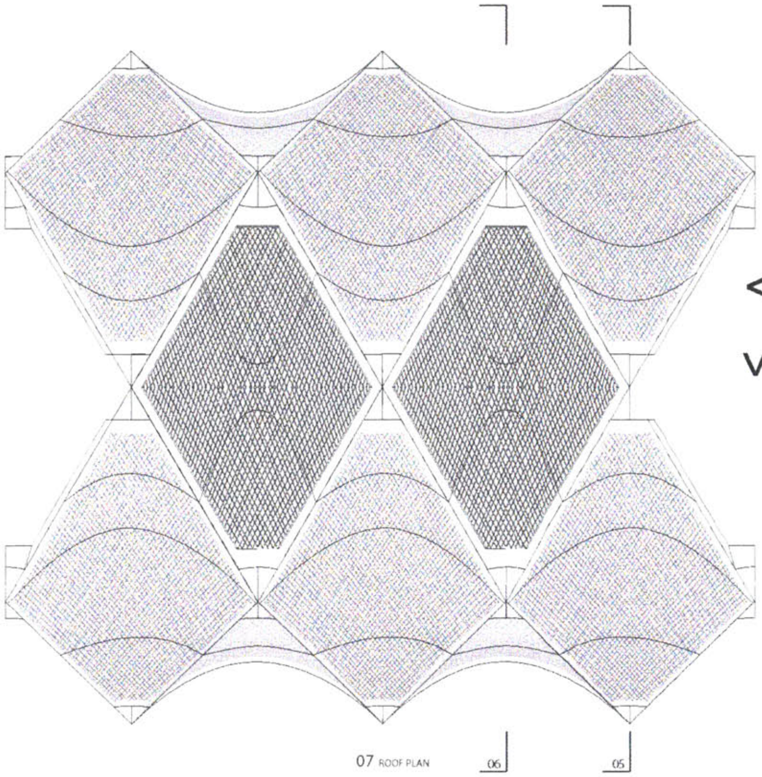


02 DOUBLE-BAY CROSS SECTION





01 INTERIOR ELEVATION



07 ROOF PLAN

ASSEMBLY STRUCTURE

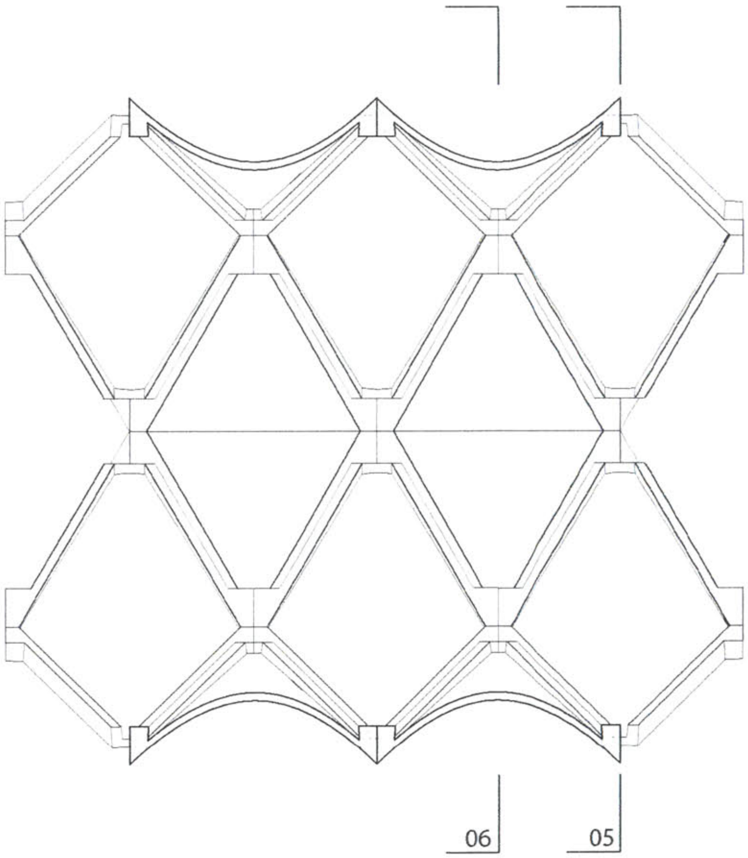
<< Section 01 | Interior Structure

V< Section 02 | Interior Elevation

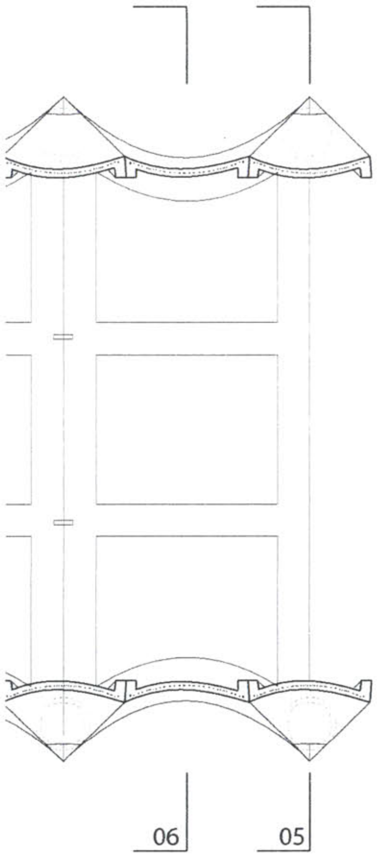
< Plan 03 | Interior Structure

V Plan 04 | Reflected Roof Elevation

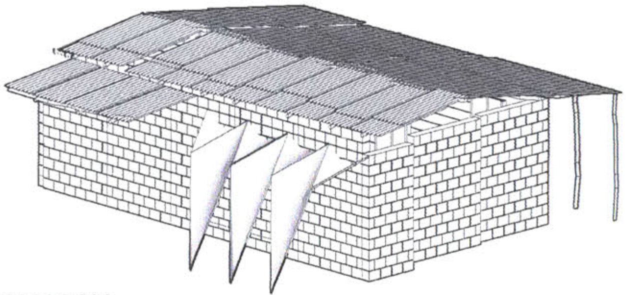
> Plan 05 | Foundation Plan



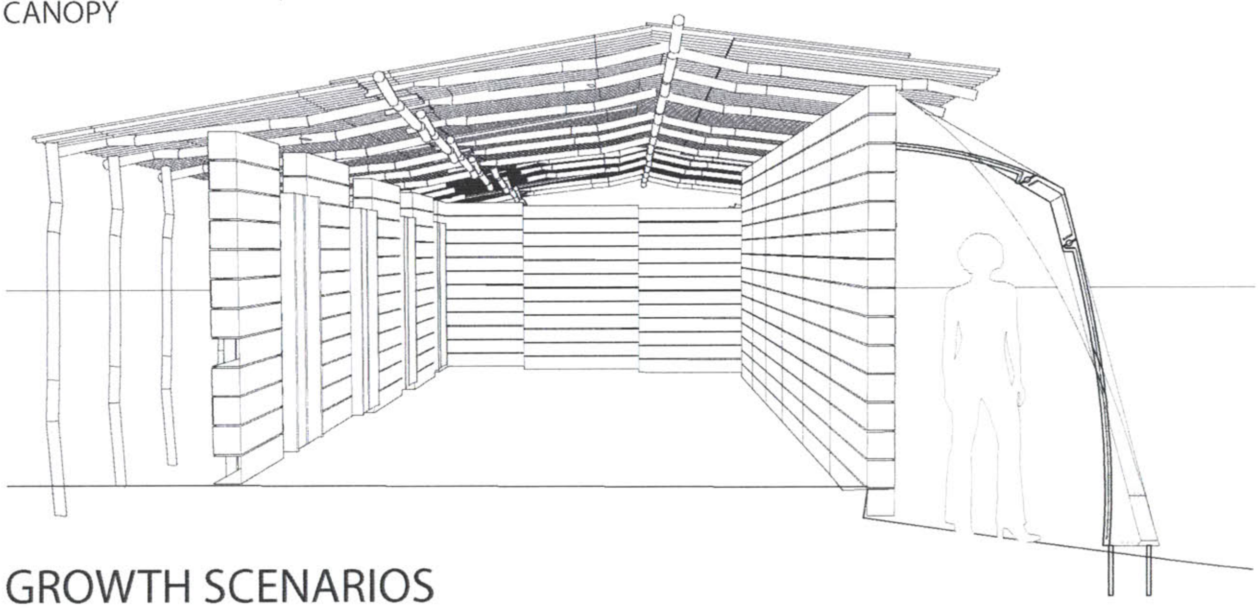
3 REFLECTED CEILING PLAN



INCREMENTAL GROWTH



CANOPY



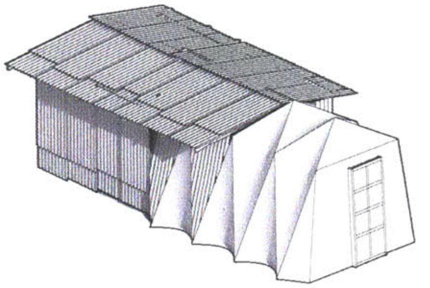
GROWTH SCENARIOS

The building modules are designed for incremental growth. The straight sides allow for the modules to be joined with standard building materials, as old buildings are replaced over time.

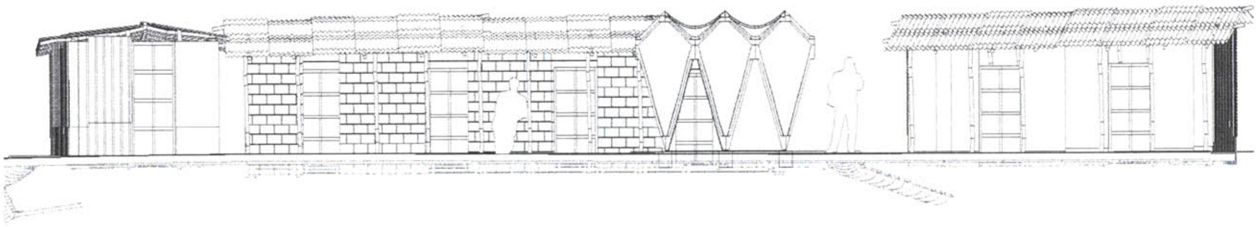
CANOPY
The canopy condition employs a full wall panel in combination with a half roof module, which can be placed against existing straight wall constructions. It can serve as a roof for outdoor storage.

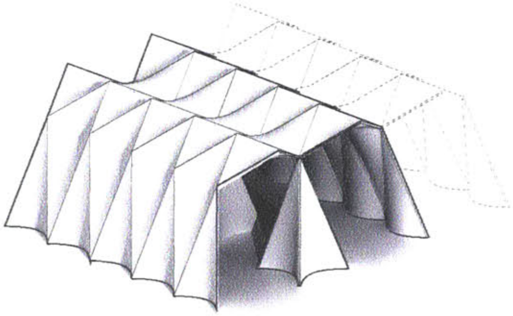
SINGLE BAY - FENCE (LINEAR GROWTH)
The fence condition can be used in the first phase of construction in combination with existing materials as buildings are replaced and the modules are built up over time.

DOUBLE BAY (BI-DIRECTIONAL GROWTH)
For larger building types a column condition can be used to expand the roof for bi-directional growth, creating a mat building condition.

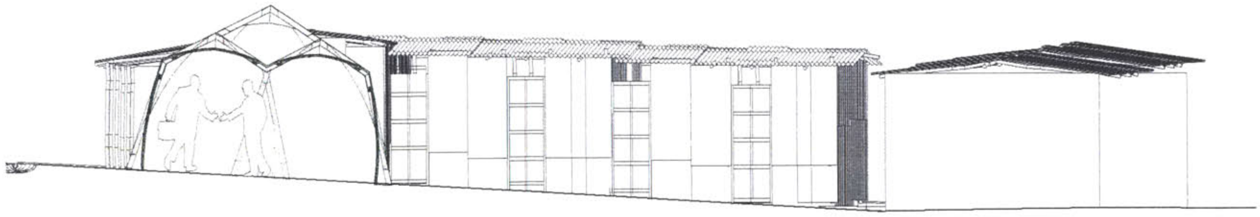


SINGLE BAY

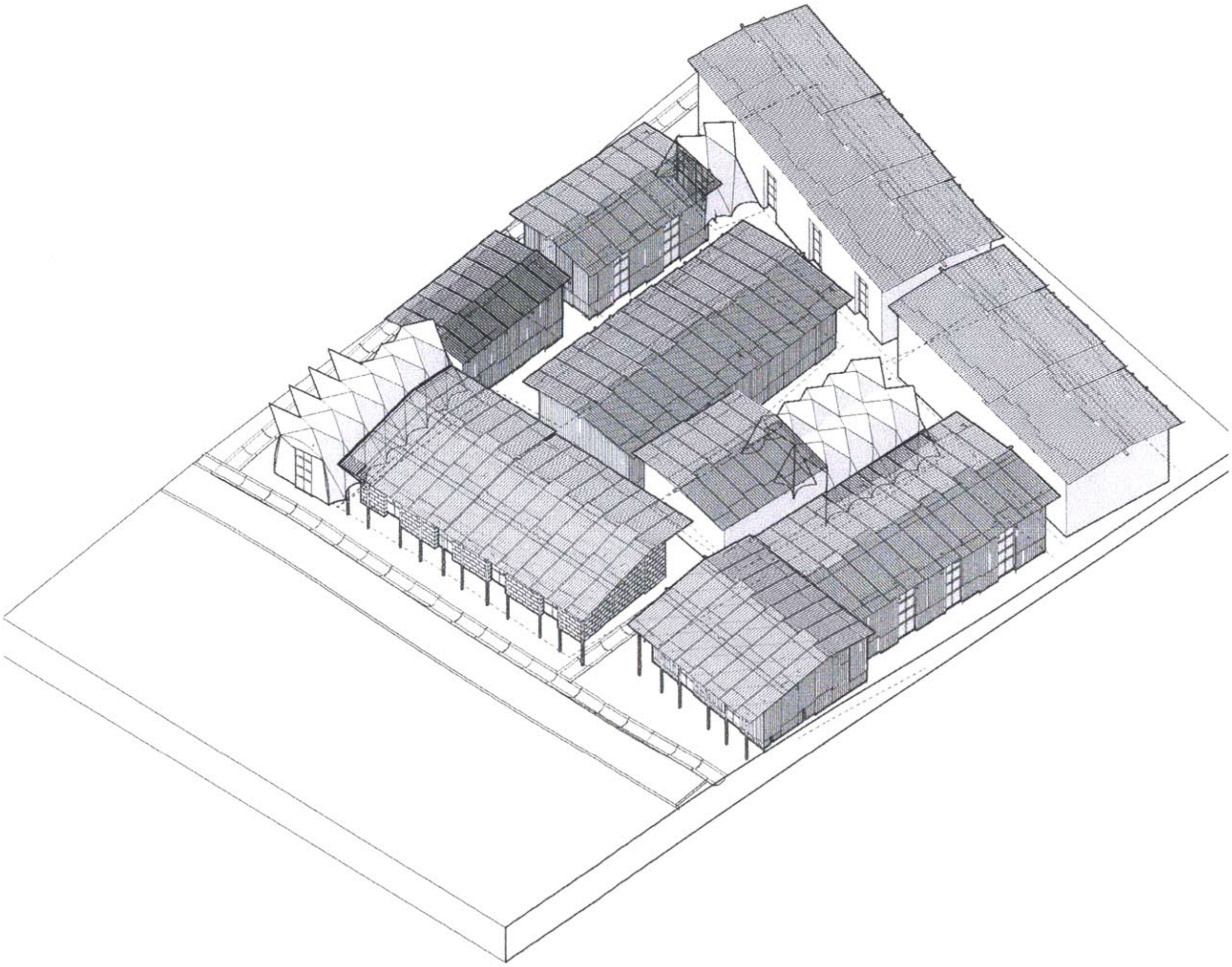




DOUBLE BAY



INCREMENTAL GROWTH OF MODULES ON SITE



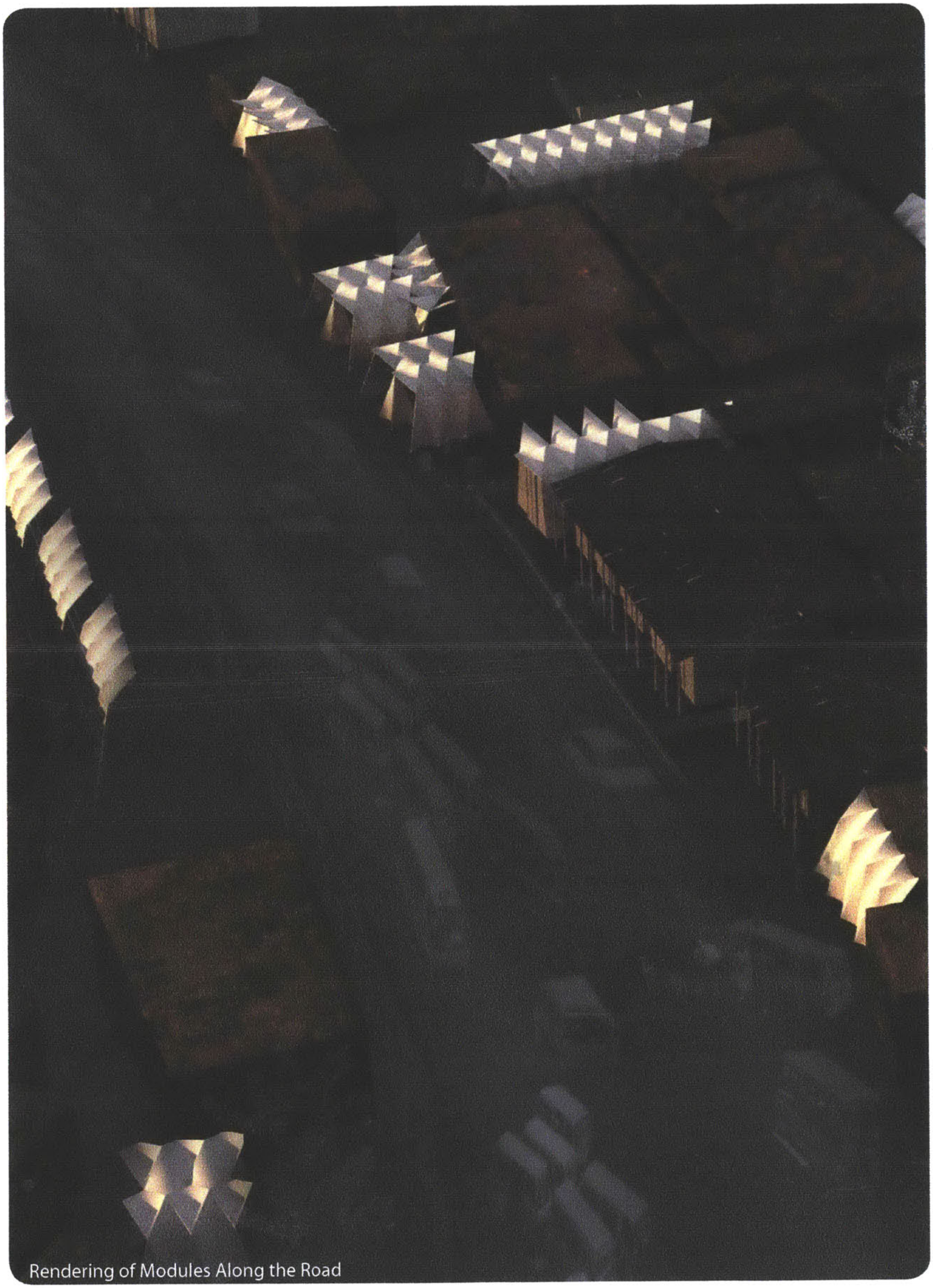
The modules will be introduced to the site over an extended period of time based on the availability of space and the economic capability of the residents to undergo an upgrade of their living environment. The site plan and axon show the modules as all stages of implementation from single fence modules to entire buildings, each uniquely altered to the site condition.

PROJECTED GROWTH OF MODULES ON SITE

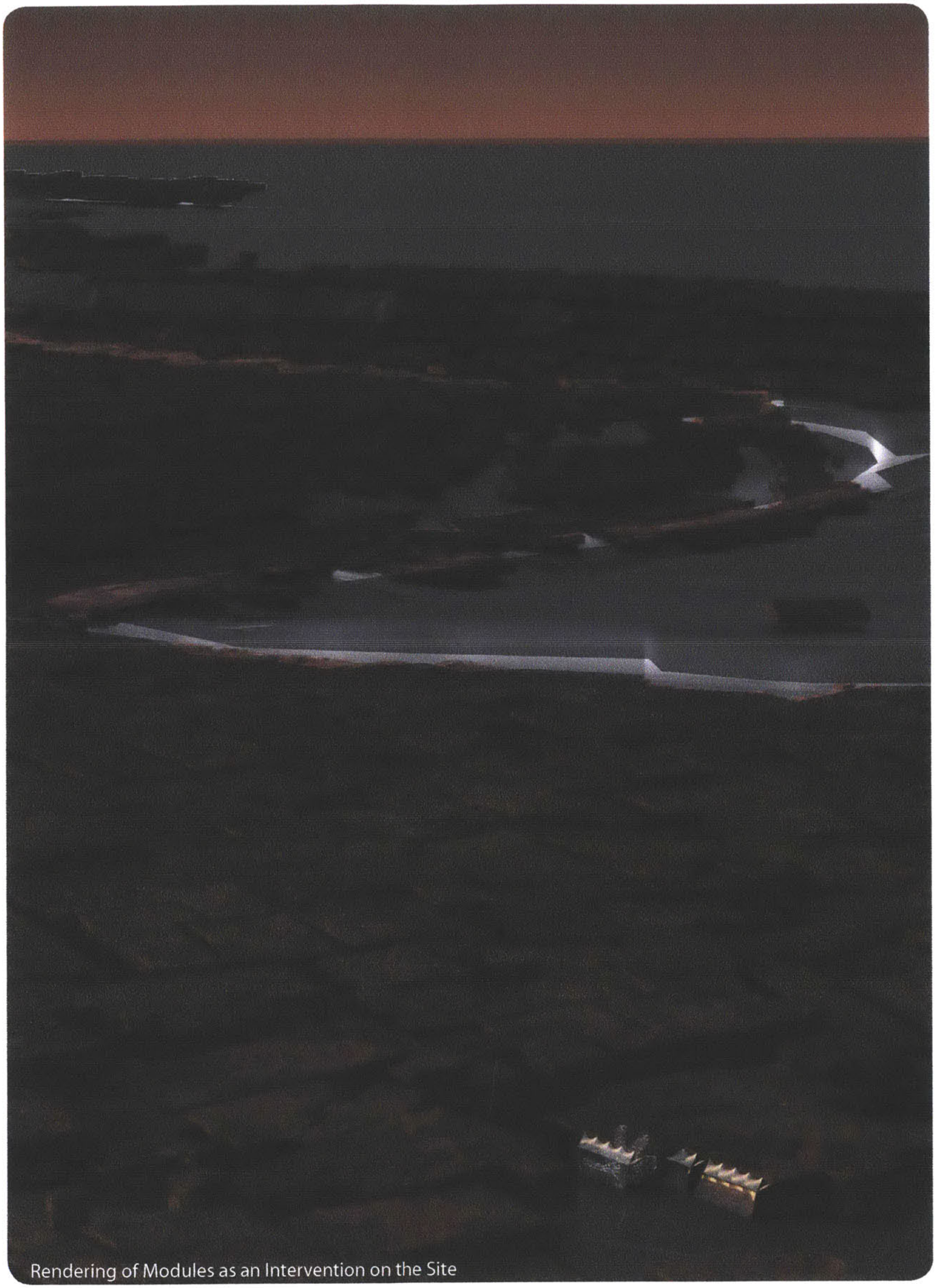
Rendering of Interior Condition
New building modules are used in combination with the existing building materials.

Rendering of Linear Building on Site

Rendering of Incremental Introduction of Modules on Site

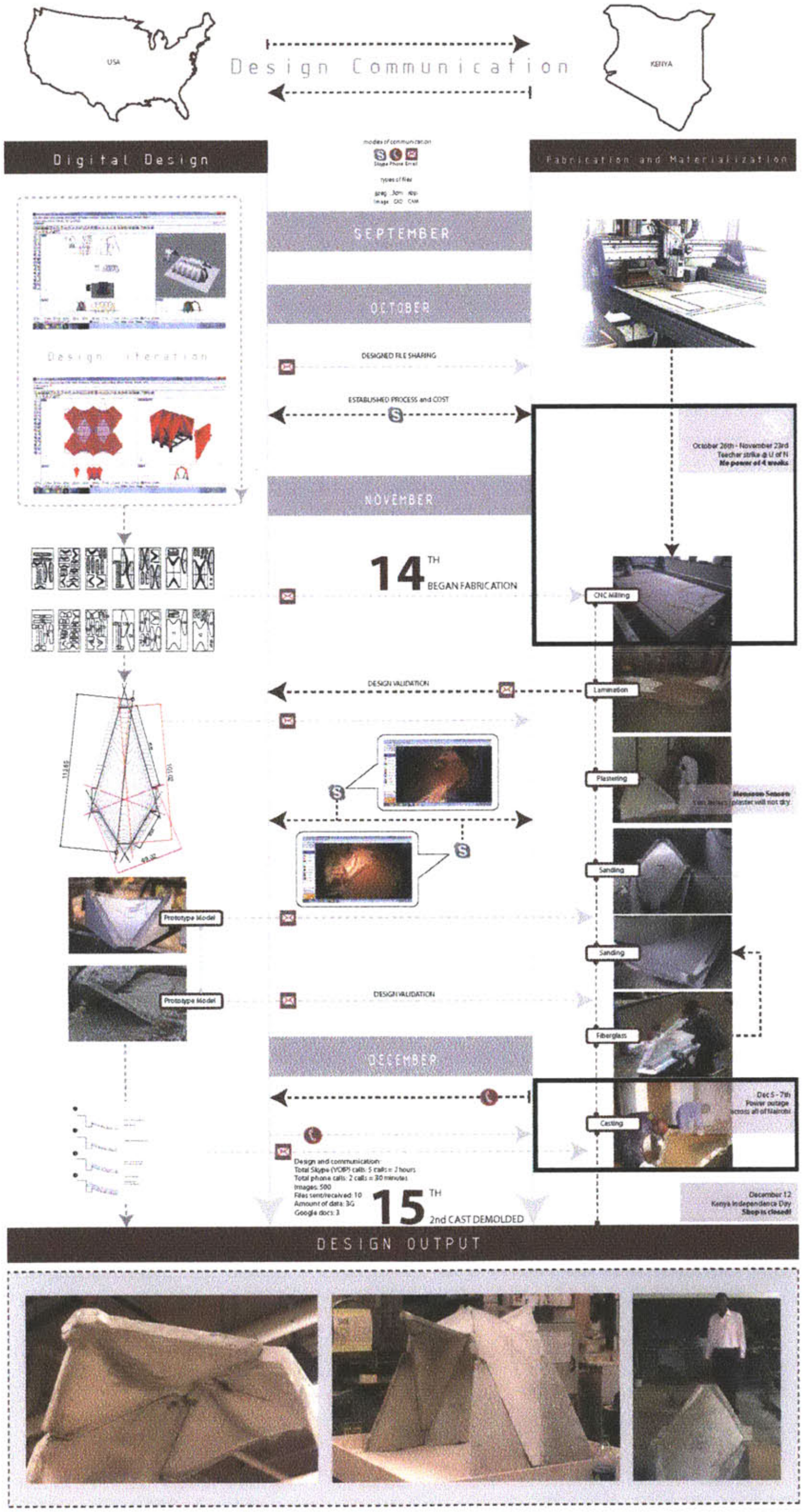


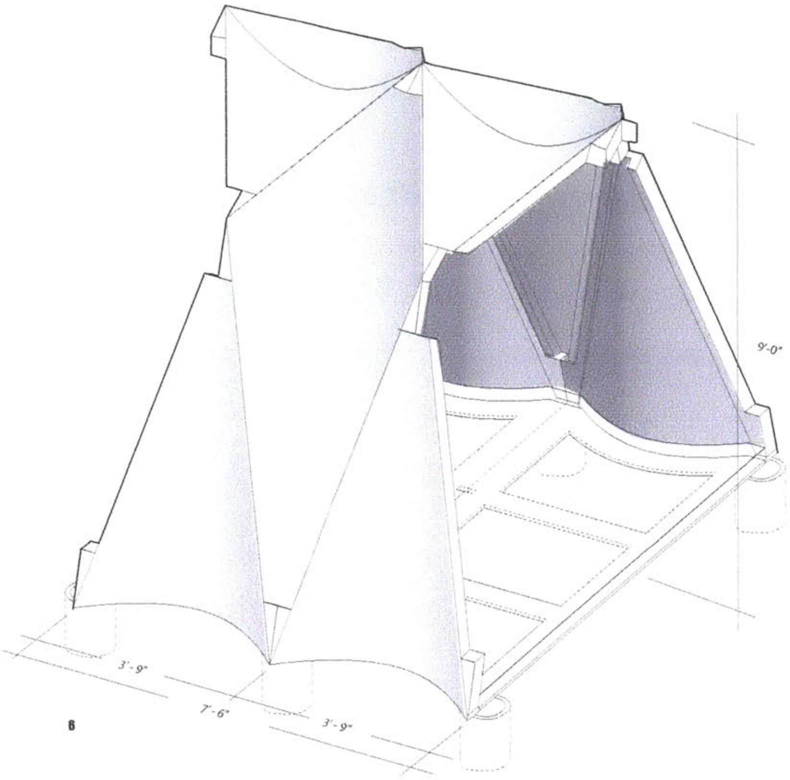
Rendering of Modules Along the Road



Rendering of Modules as an Intervention on the Site

PARTICIPATORY DESIGN





6

Participatory Design Communication

The culmination of this research was in the introduction of the design developed in the local design-manufacturing environment.

Beginning in mid-November, I worked closely with my colleagues from the University of Nairobi's Science and Technology Park to iterate the design for and create a full-scale assembly of a prototypical bay.

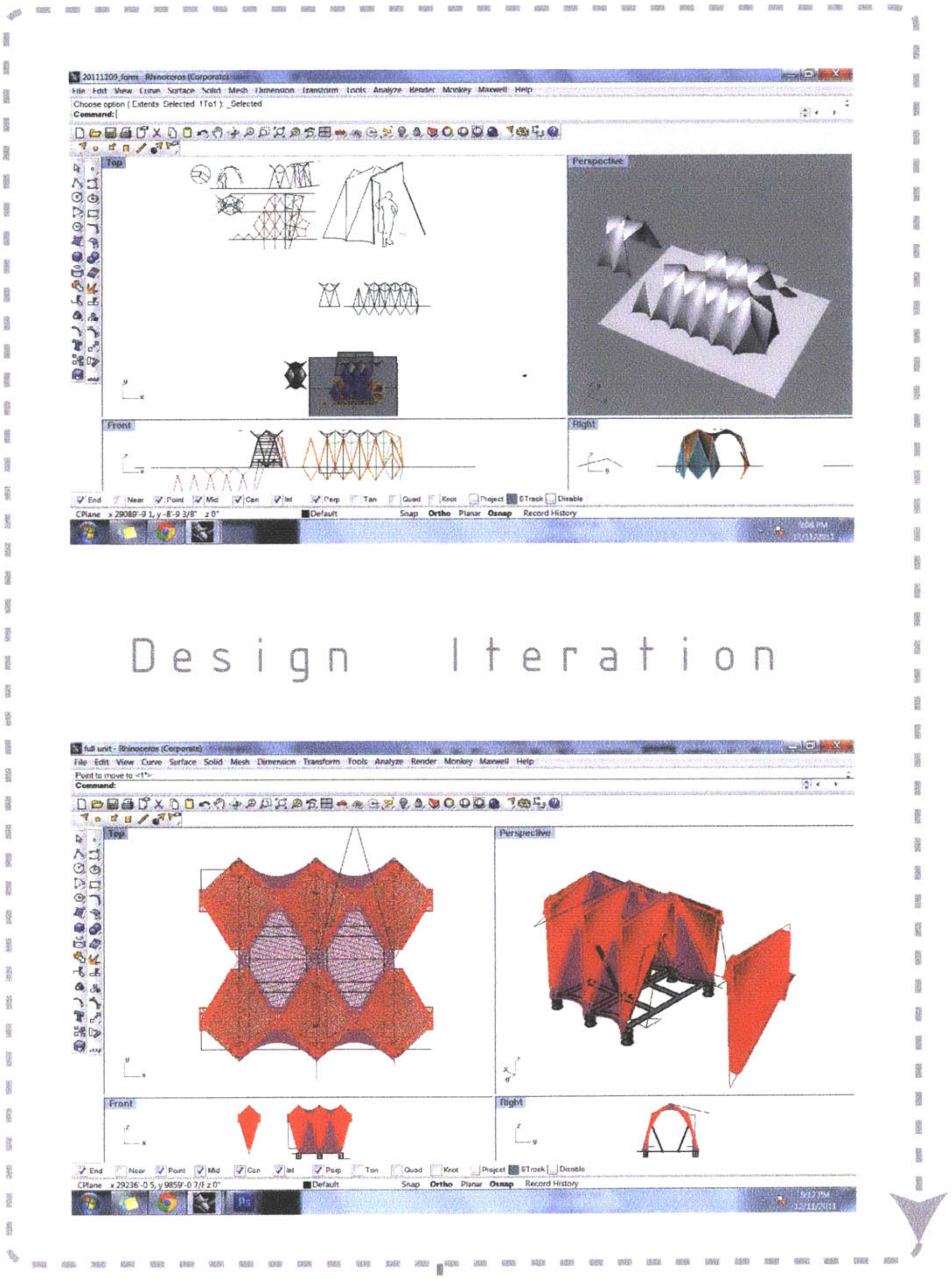
The local team leader, Tom Odoyo, worked tirelessly over four weeks through bi-weekly Skype* calls, near daily phone calls, exchanging over 500 construction photographs, 10 digital files, and 3 Google Documents[1] worth over 3 Gigabytes of data to create the fiberglass mold and a successfully demolded ferrocement panel. The work is still ongoing at the time of this thesis submission. Continuing work is currently hosted at: www.LocalDM.wordpress.com

* Skype is a proprietary voice over Internet Protocol service

[1] Google Documents are cloud-hosted office products

Design Iteration

Files were shared and improved from Concept to Construction phases



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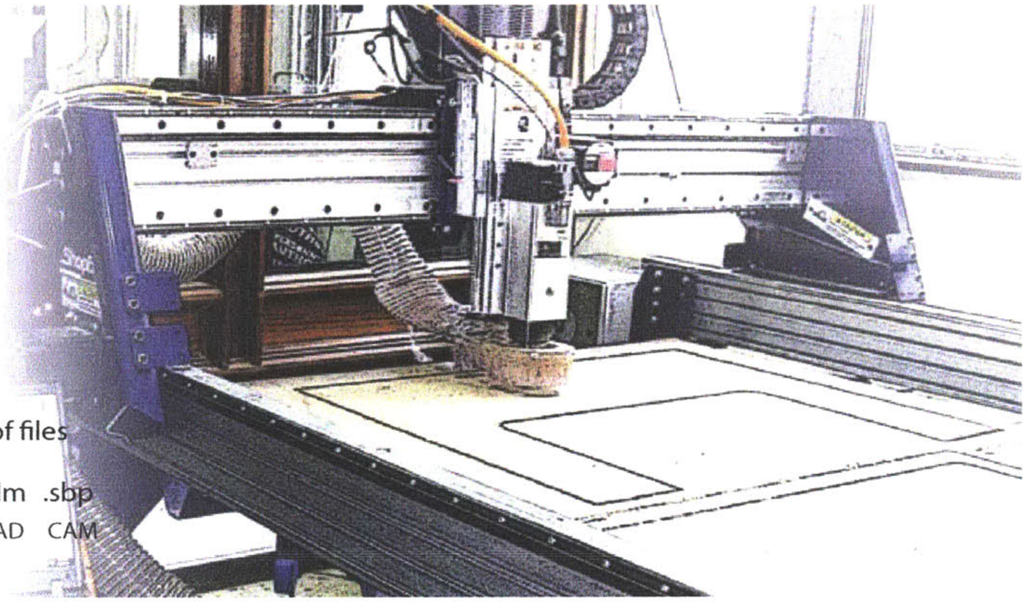
Command:

Point to move to <1*>:

Command:

Digital Tools

From Design to Fabrication to Communication



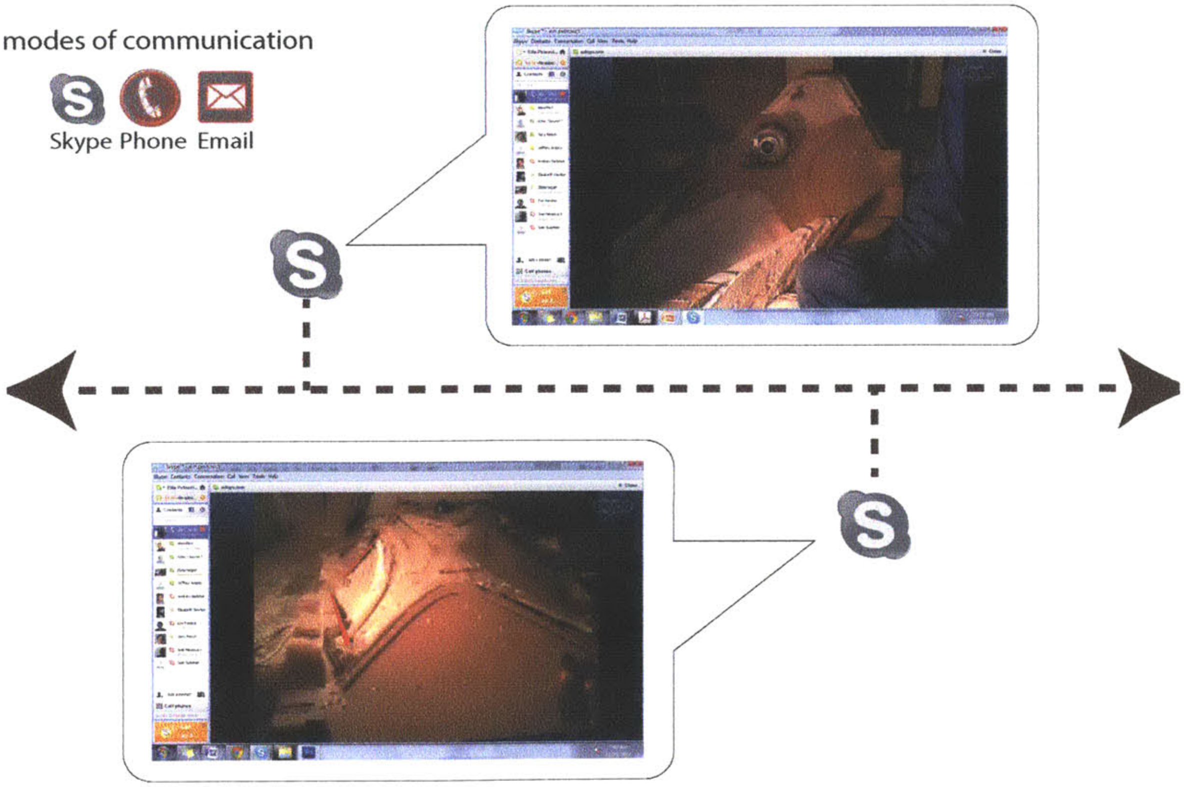
types of files

.jpeg .3dm .sbp

Image CAD CAM

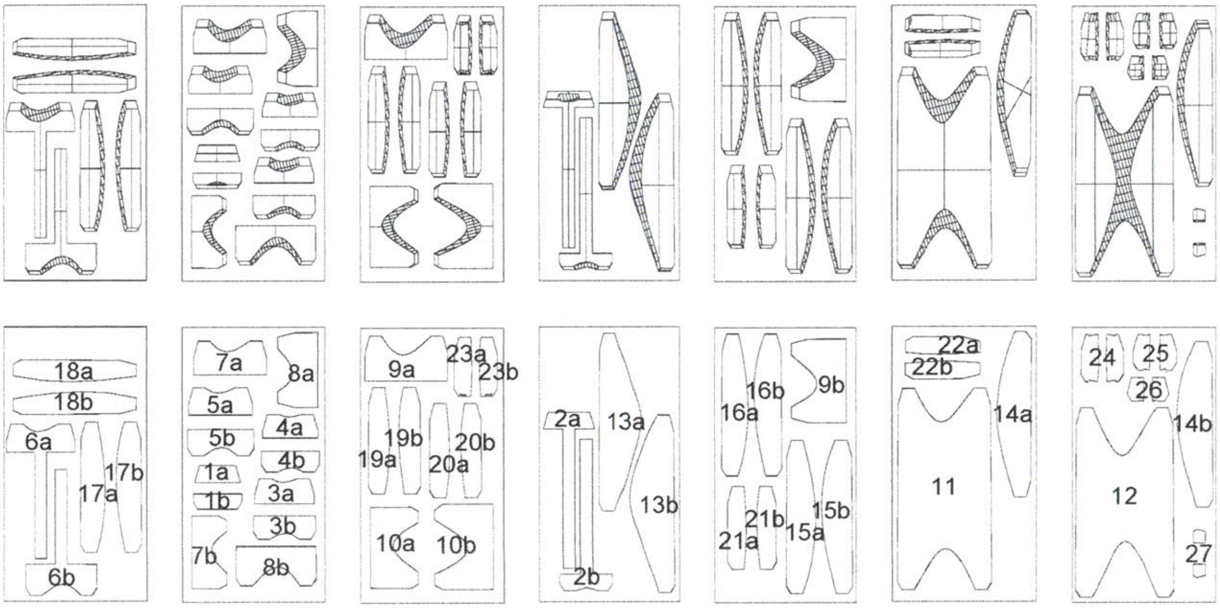
modes of communication

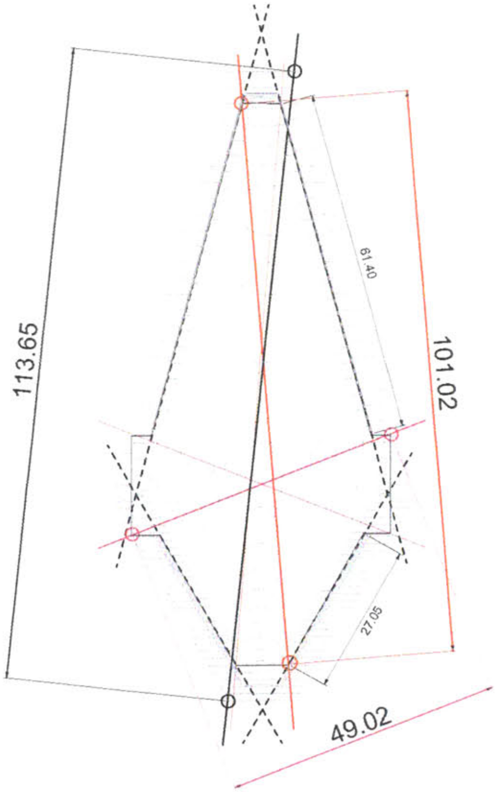
Skype Phone Email



Design Documentation & Communication

Construction files clarified the expectations and interpretation of the design





The alignment of the mold is most important to its success. The milling only helps with the surface sculpting, but it is imperitive that these dimensions be the same as the physical mold. If the dimensions do not match the casts may not match together correctly when assembling. All errors in the mold are multiplied in the cast forms.

The two most important things to check are:

1) the overall length, to ensure that the arch of the assembly is accurate

2) the straight edges are equal, to ensure that the cast edges will align without gaps or wobbly edges.

Mold #1 Alignment Verification Steps: (red and magenta measurements are the same for Mold#2)

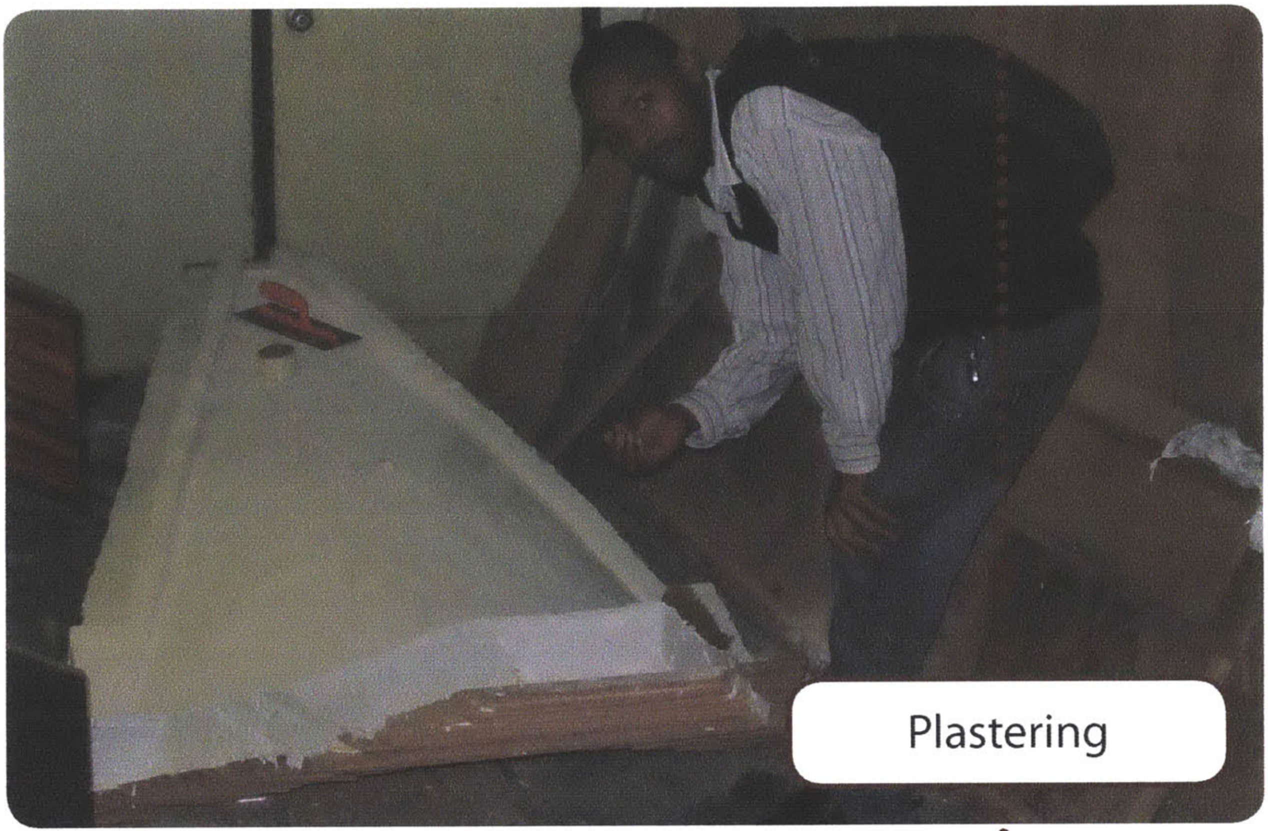
1) measure the diagonal overall 3 lengths to match the diagram dimensions above (in inches)

2) be sure to measure both diagonal dimensions to check for symmetry in the mold

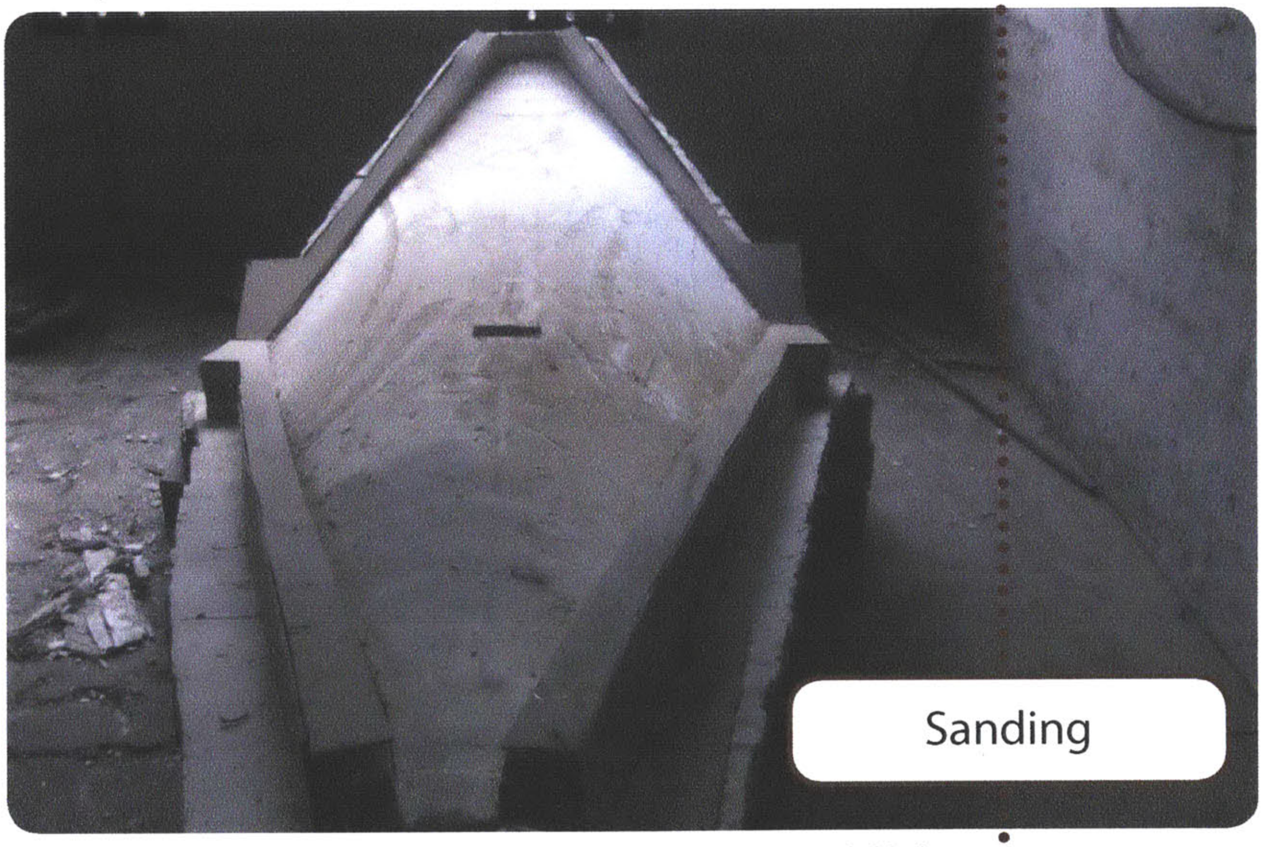
3) the dashed lines signify the edges that you must make sure are perfectly straight from point to point. The surfaces are sloped, but the edge outlined by the dashed line is the edge that must be straight.

Nov 15th | Campus-wide teacher strike forces team to borrow power and mill in the dark

Nov 24th | Individual milled components are aligned and laminated together with screws from below



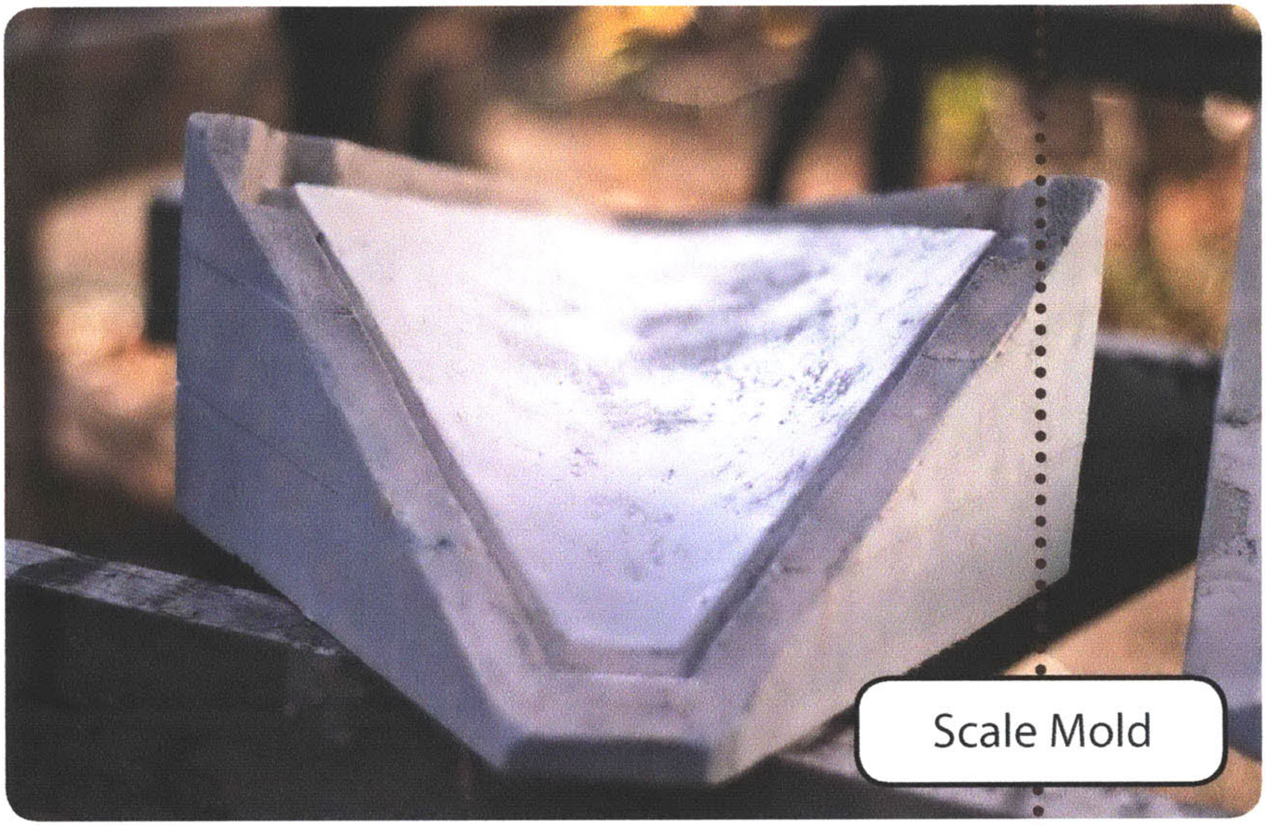
Dec 1st | Plaster was slow to dry due to rainy weather



Dec 6th | The sanding is near complete after delays due to 3 days of city-wide blackouts

Dec 7th | Photo of the single-sided mold

Dec 8th | Photo of the casting process



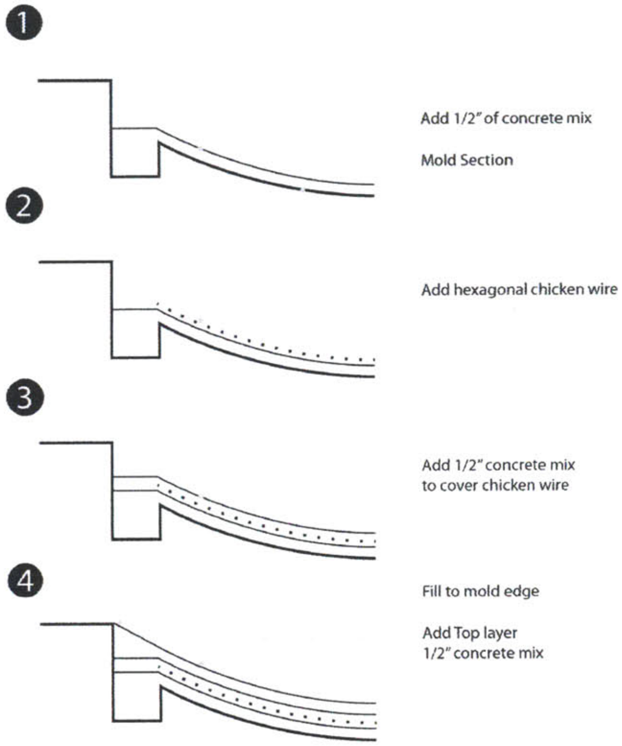
Dec 1st | Photo of the single-sided mold

Dec 3rd | Photo of typical wall module (saddle shape) cast

Iterative Process

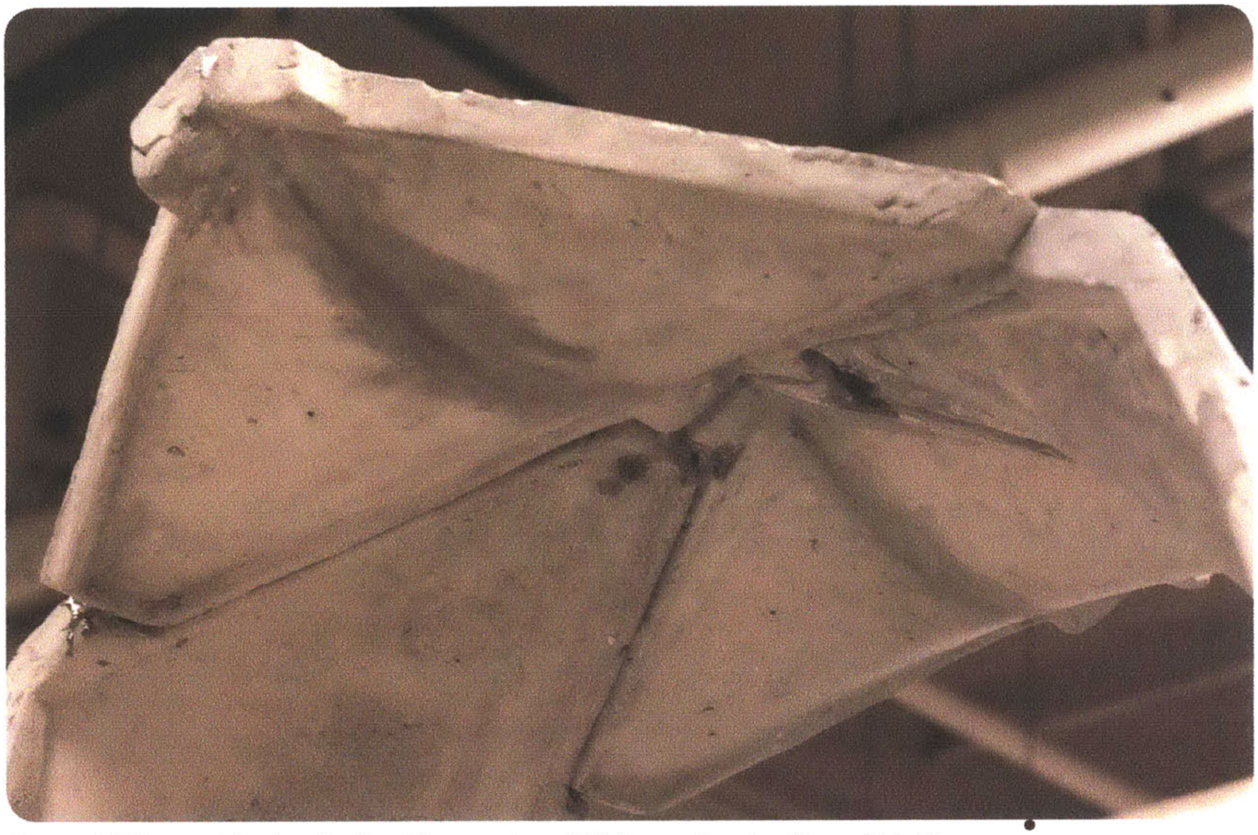
Due to the limited time the full assembly was being built at the FabLab in Kenya as I developed a scaled prototypical model in the MIT FabLab. This was to test the geometry as it related to the demolding process and the assembly in order to limit the number of unknown variables in the full-scale mold and work through solutions as needed. However, due to the fact that it was a scaled model, I was not able to test the true machine and tooling toleranes in advance.

It was learned from the scaled molding and casting process that the vertical edges at the hip joint would need to be tapered, making sure to leave the edge where the modules stacked untouched. Any taper at the stacked condition could cause the panels to rock and tip.

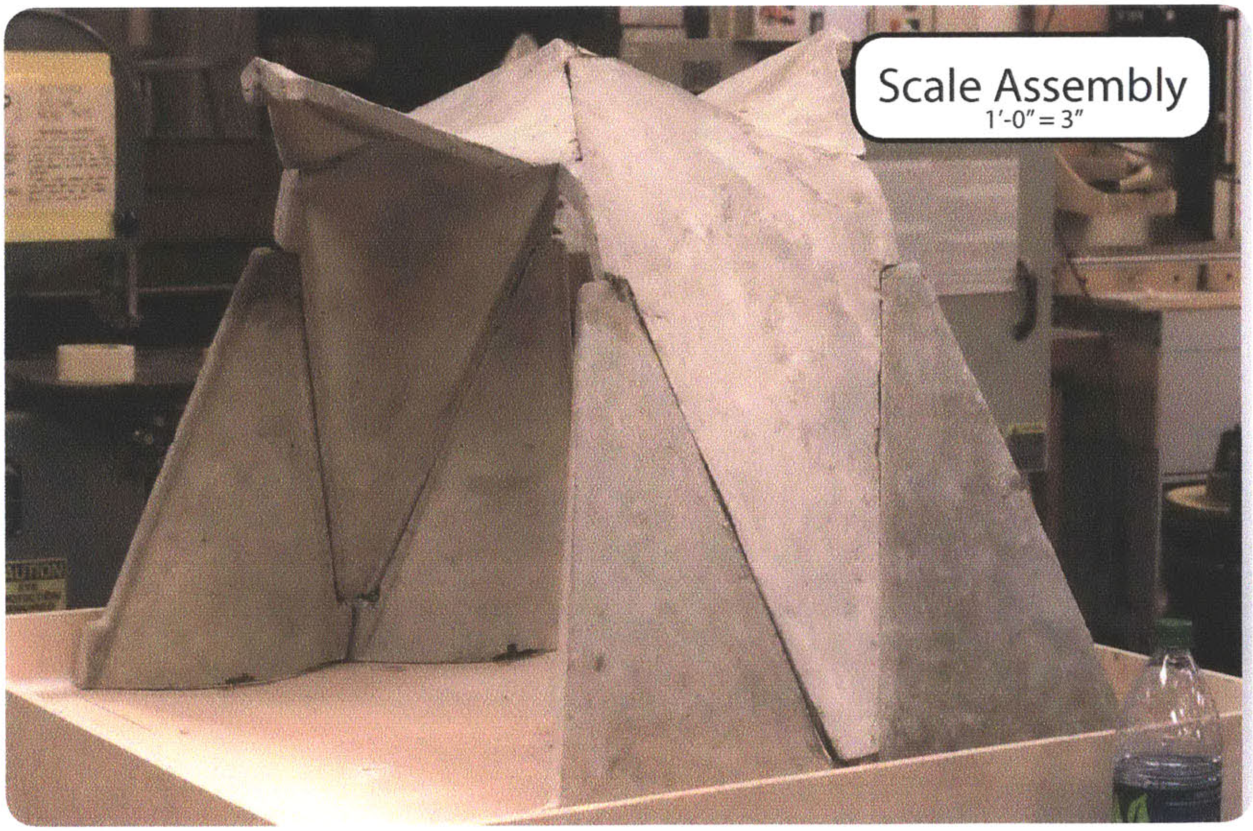


Casting Instructional >

Dec 10th | Photo of the casting process

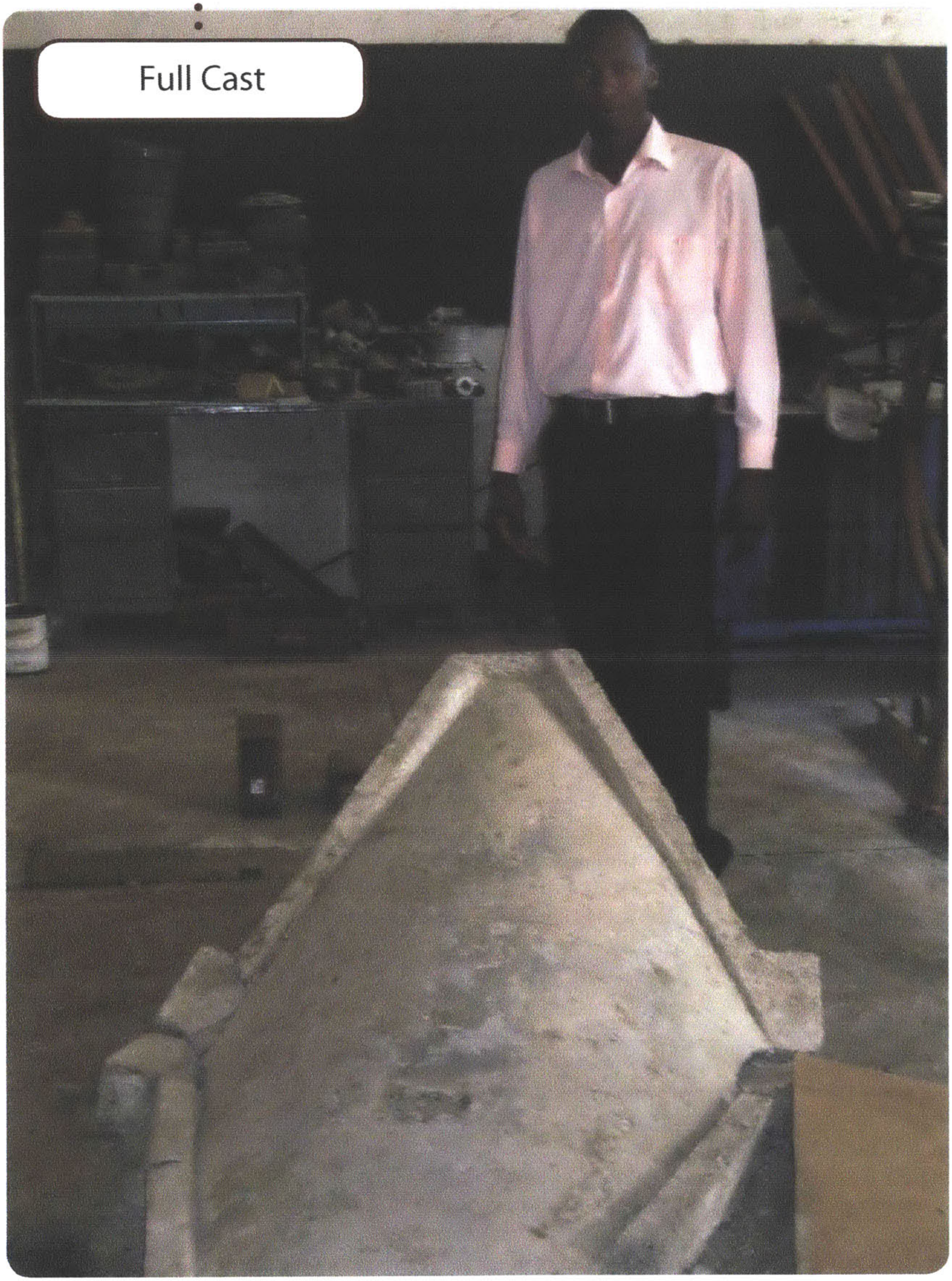


Dec 14th | Photo of the Interior Roof Connection of Miniature Construction within the



Dec 14th | Photo of the Miniature Construction within the MIT lab

Full Cast



Dec 13th | Photo of the Full Construction in the Nairobi FabLab, with Technician Tom Odoyo

Further Discussions

The methodology for using digital design and craftsmanship aims to catalyze the development of viable income-generating work within the communities in which the outputs will be sold. Unskilled construction workers will have many infrastructure and dwelling projects to assemble, granted that craftsmen see the benefit in a low-risk, revenue-infused entrepreneurial activity using these new technologies.

This thesis contributes a case study and design research that reinforces a scalable, multi-disciplinary approach for creating viable solutions for development, it is in this way that designers can meet the plight of city dwellers as described by UNHabitat be addressed. Aligning with the objectives as descibed by John Fernandez the first steps to improve the health and economic condition of city slumdwellers begins with the implementation of "mechanisms, financial, political and institutional, that provide a well-conceived 'package' of service infrastructure and the establishment of land tenure". Fernandez reasonably outlines that once infrastructure is deemed suitable it "should lead to an increased desire to upgrade the physical quality of the dwelling units themselves."

This thesis must also be tested for its possibility that the "establishmennt of land tenure" may not be resolved before the need to address the housing crisis and dwellling upgrades in urban slums. Is it reasonable to assume that land tenants would be willing to invest in a structure if it were functionally temporary, even if seemingly permanent? What is a realistic investmennt payback period in such a structure and how could phasing or incremental growth play a role in this? The design and manufacturing methodology as proposed in this thesis contributes to Fernanndez' researcch goal outlined as "the identification of [sustainable] construction methods and the consideration of innovative materials and assembly systems." If this can be achieved the final phase of slum upgrading is the adoption of maintenance procedures by the locals "in the service of establishing a [culturally] sustainable process of continual slum¬improvement after [slum upgrading] has been completed."

Closing Remark

In Kenya, and across Sub-Saharan Africa, I truly believe that CAD/CAM equipment has the ability to significantly enhance technology dissemination globally and further promote the practice of appropriate architecture in developing countries. Providing a predictable, affordable solution of construction and meeting the high demands, all while operating in a contextural economic spectrum employing local labor, as a qualification for cultural sustainability. What I hope this thesis also promotes is a more responsible practice of architecture, meeting the demands of 99% of the population without.

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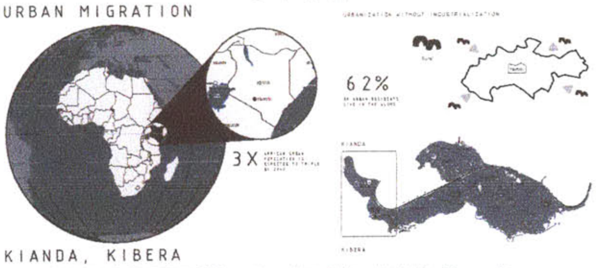
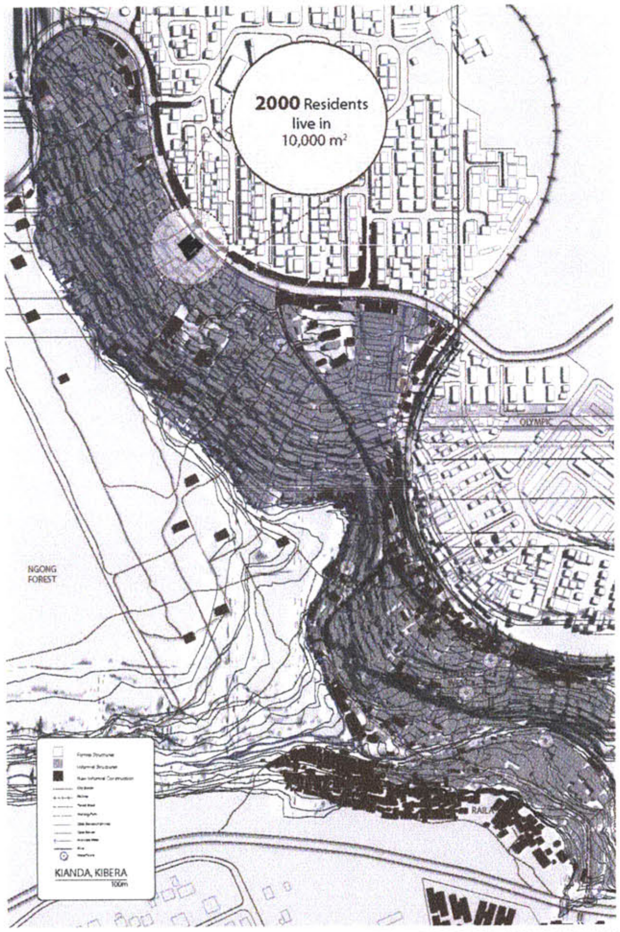
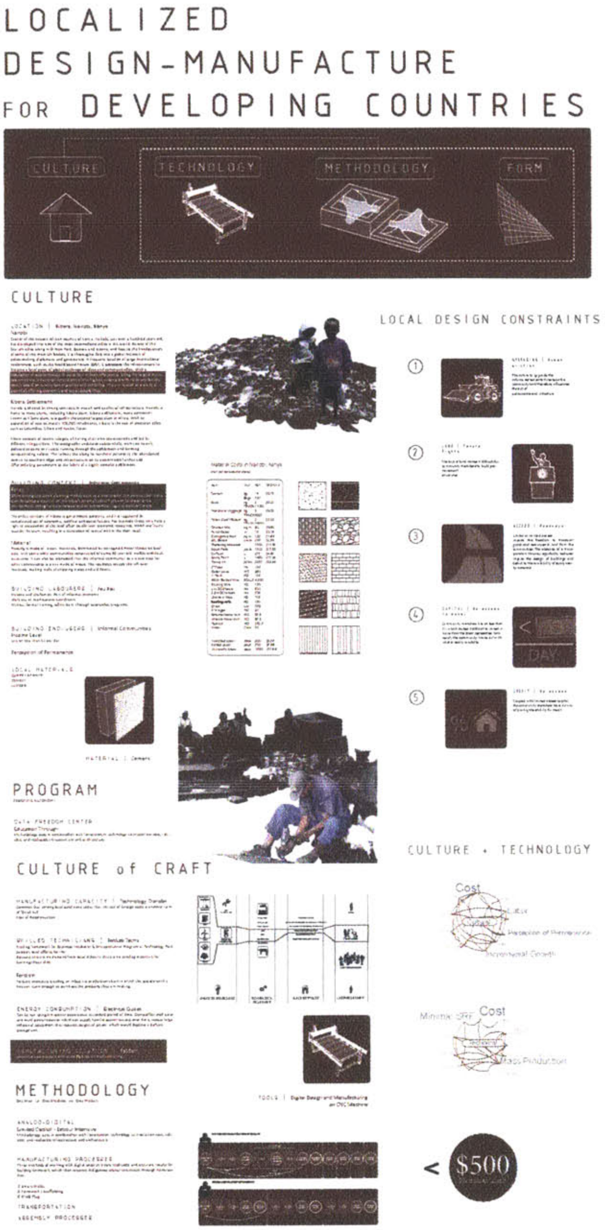
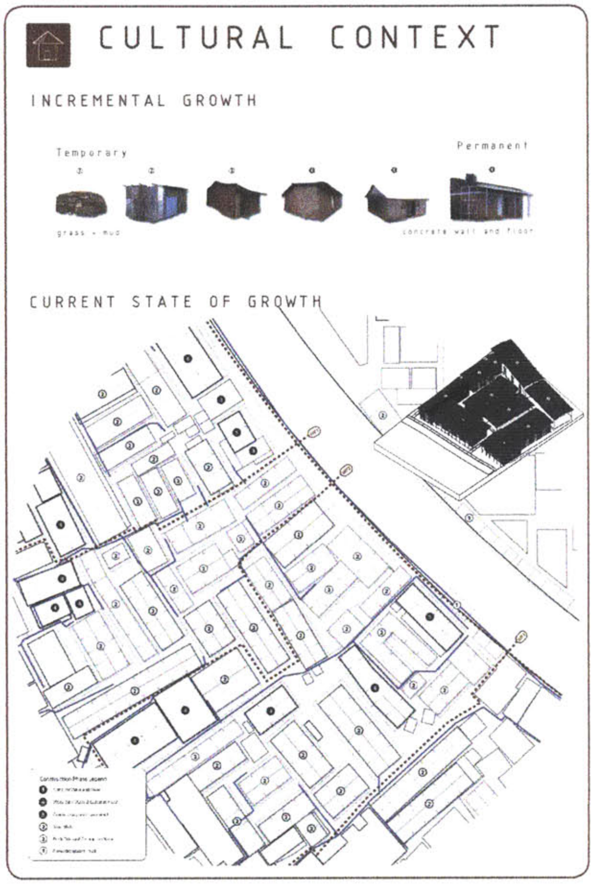
Thesis Presentation | December 15th, 2011

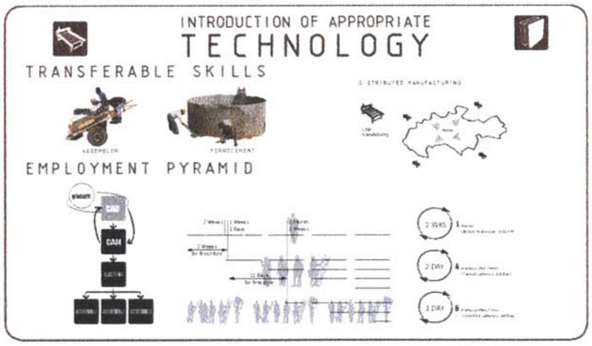
SITE





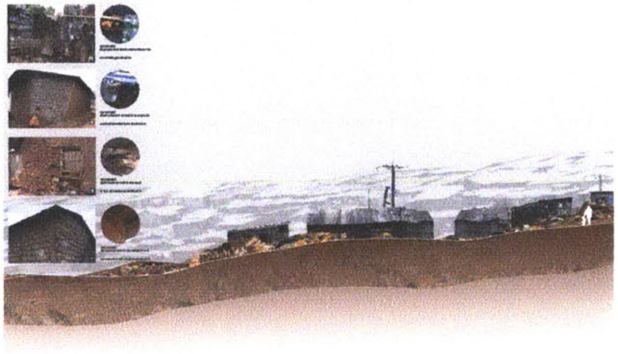


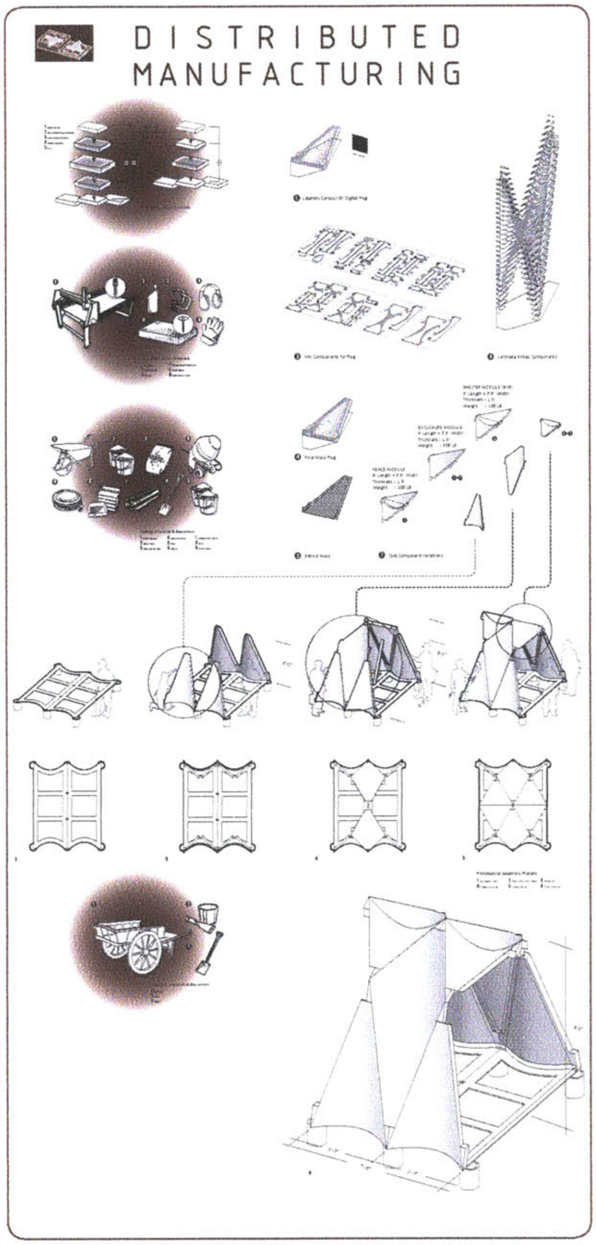




Site.01
Kibera Drive road access
Existing Hardware and Residences
Currently Occupied (8 residential)
For Sale by owner

350,000 Ksh
~1/4 Acre

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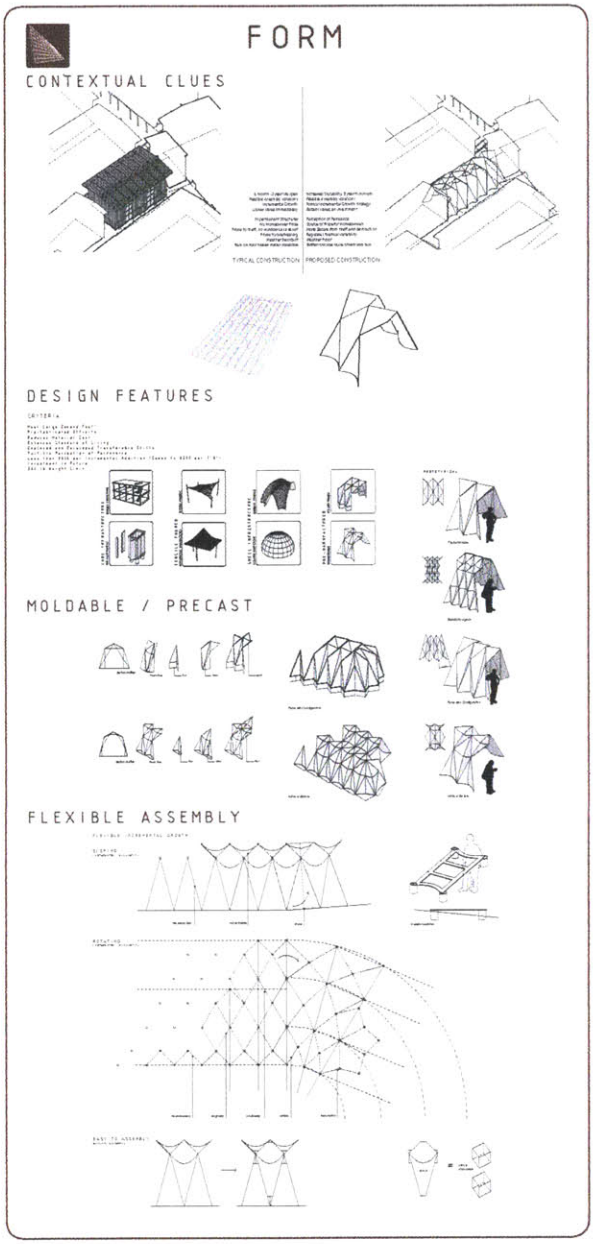
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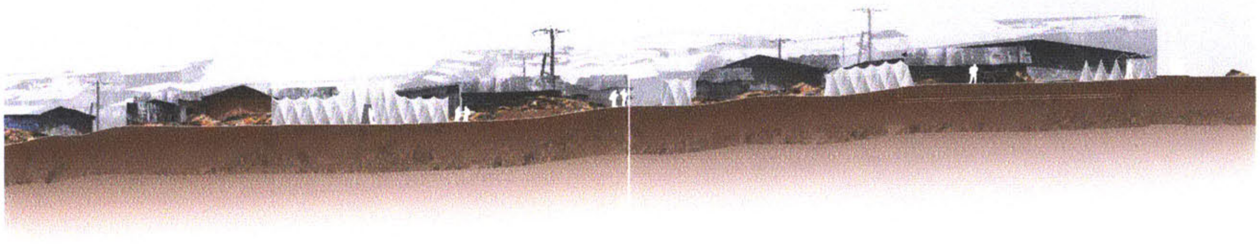
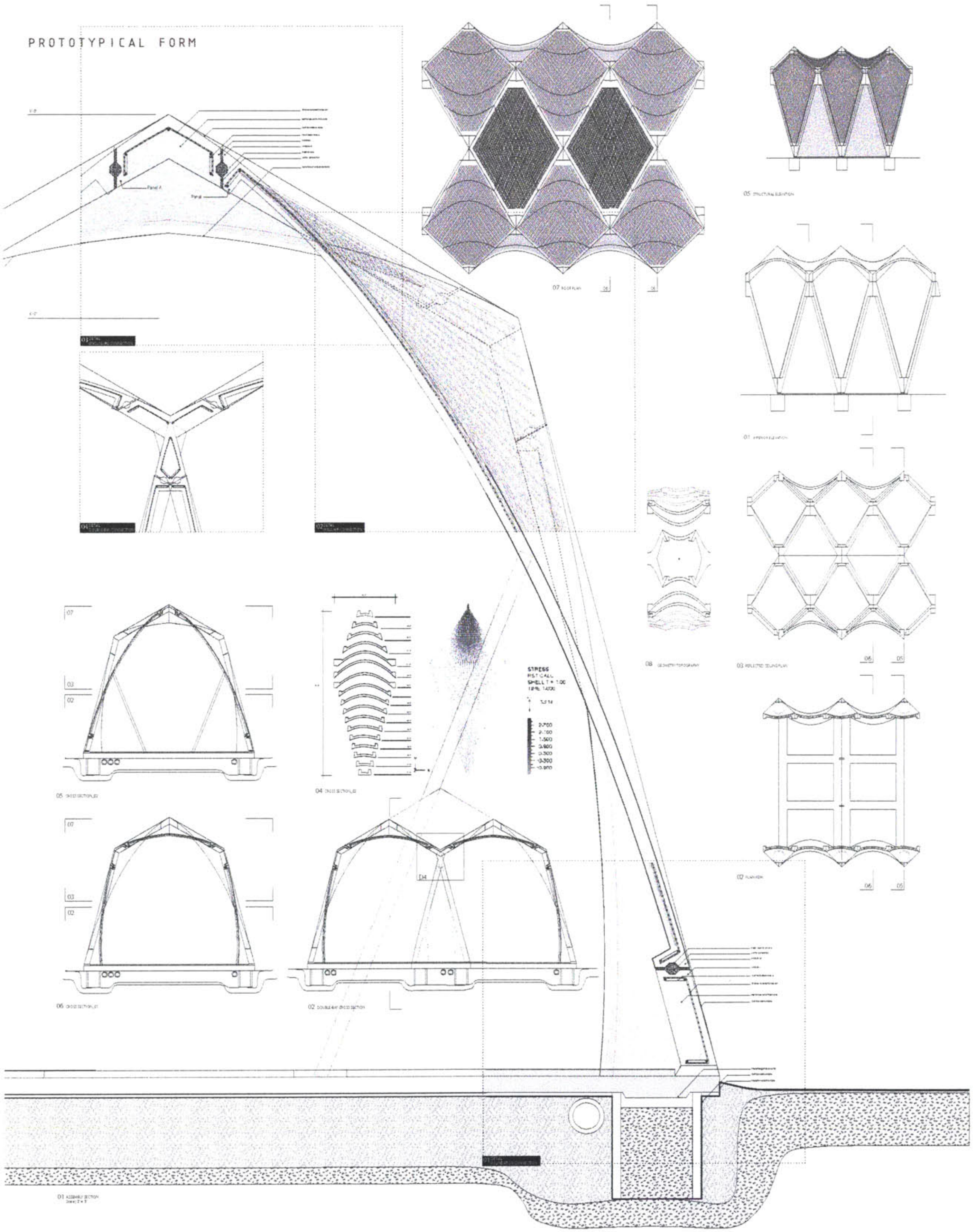
TYPICAL CONSTRUCTION
PROPOSED CONSTRUCTION
DESIGN FEATURES
CRITERIA
MOLDABLE / PRECAST
FLEXIBLE ASSEMBLY




PROTOTYPICAL FORM
Panel A
STRESS
PIST CALL
SHELL T = 1.00
2.700
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1.500
0.900
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07
03
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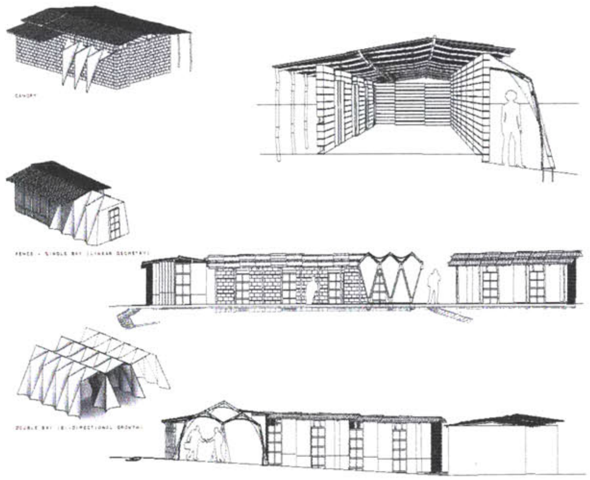
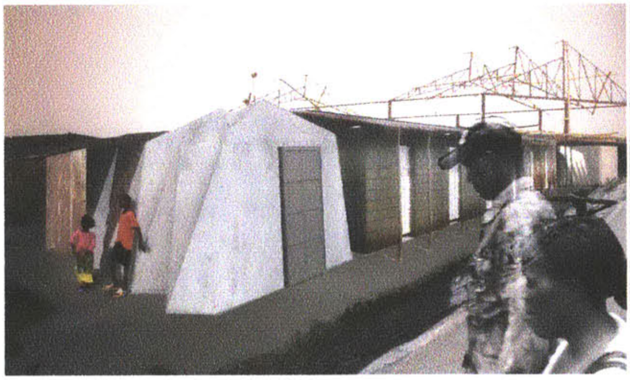
INCREMENTAL GROWTH

SCENARIOS





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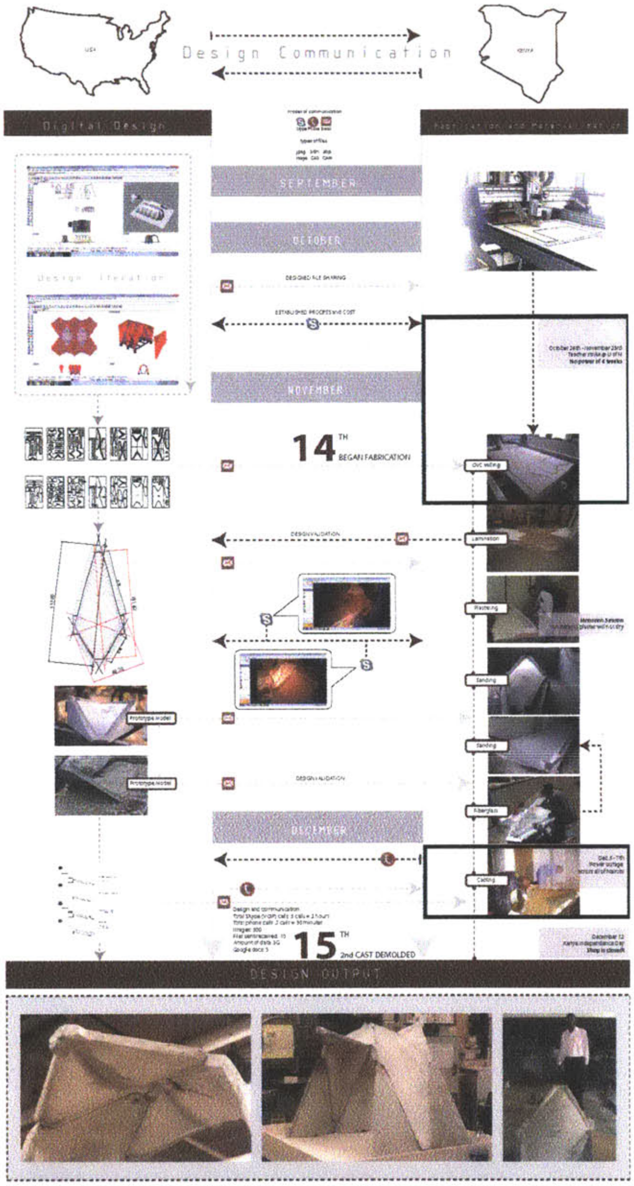


Photo from Thesis Review (photo by Judith M. Daniels/SA+P)

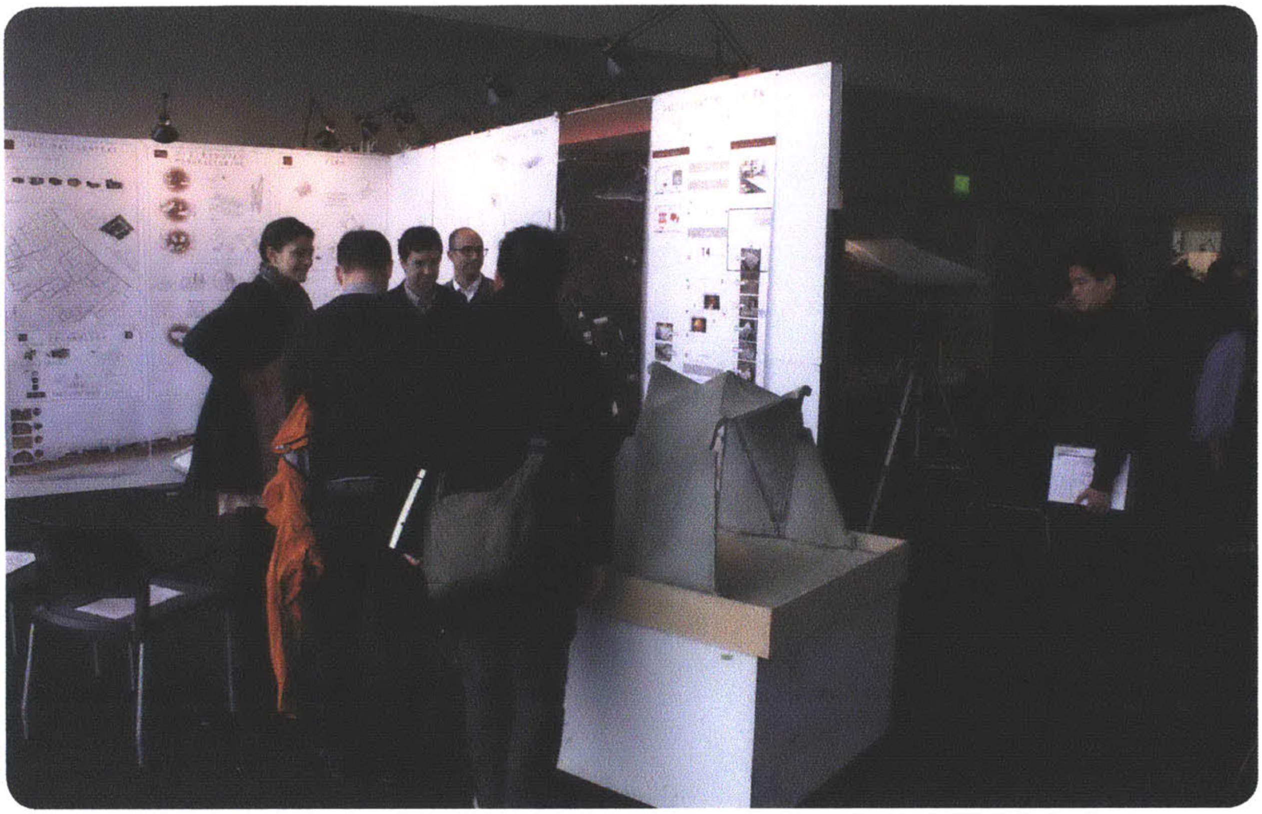


Photo just before Thesis Presentation

Photo from Thesis Presentation

Photo of individual cast panel for the scaled model

Photo of individual cast panel for the scaled model

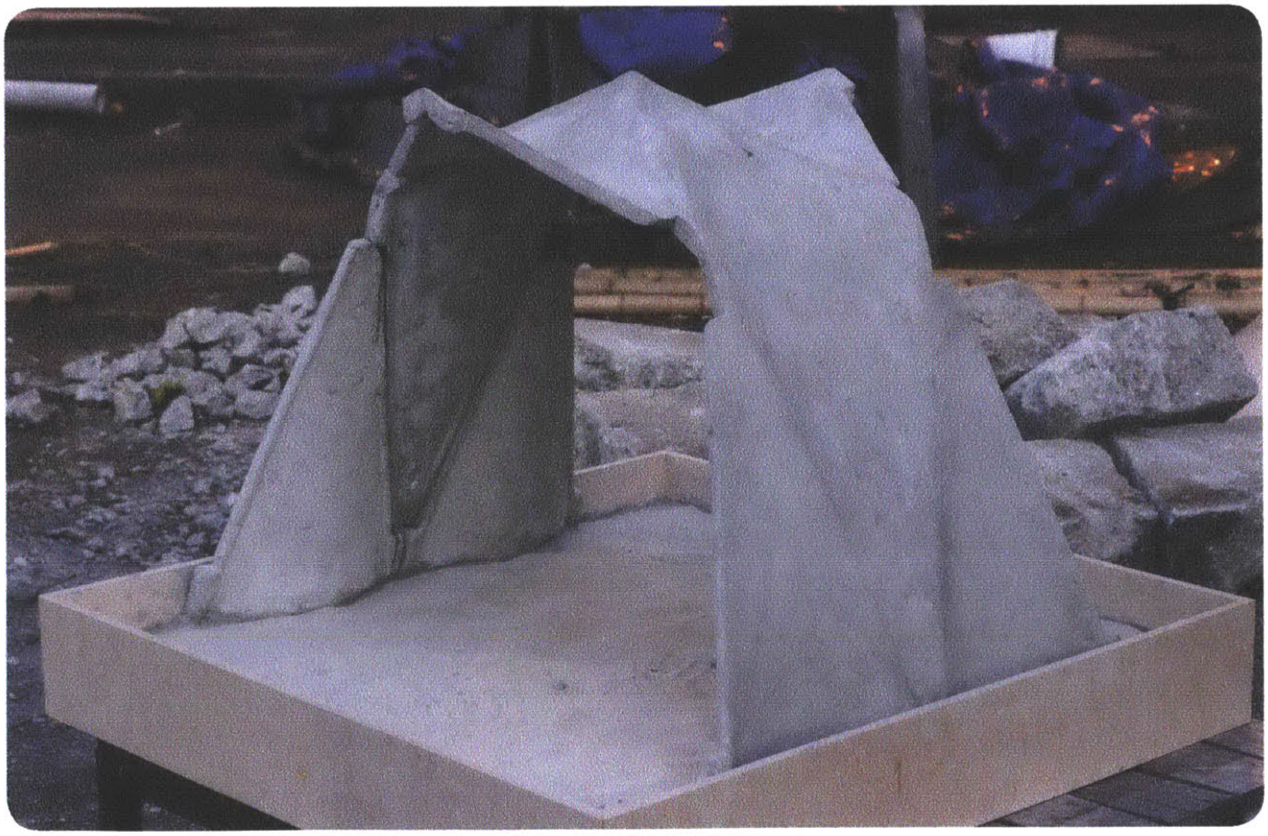
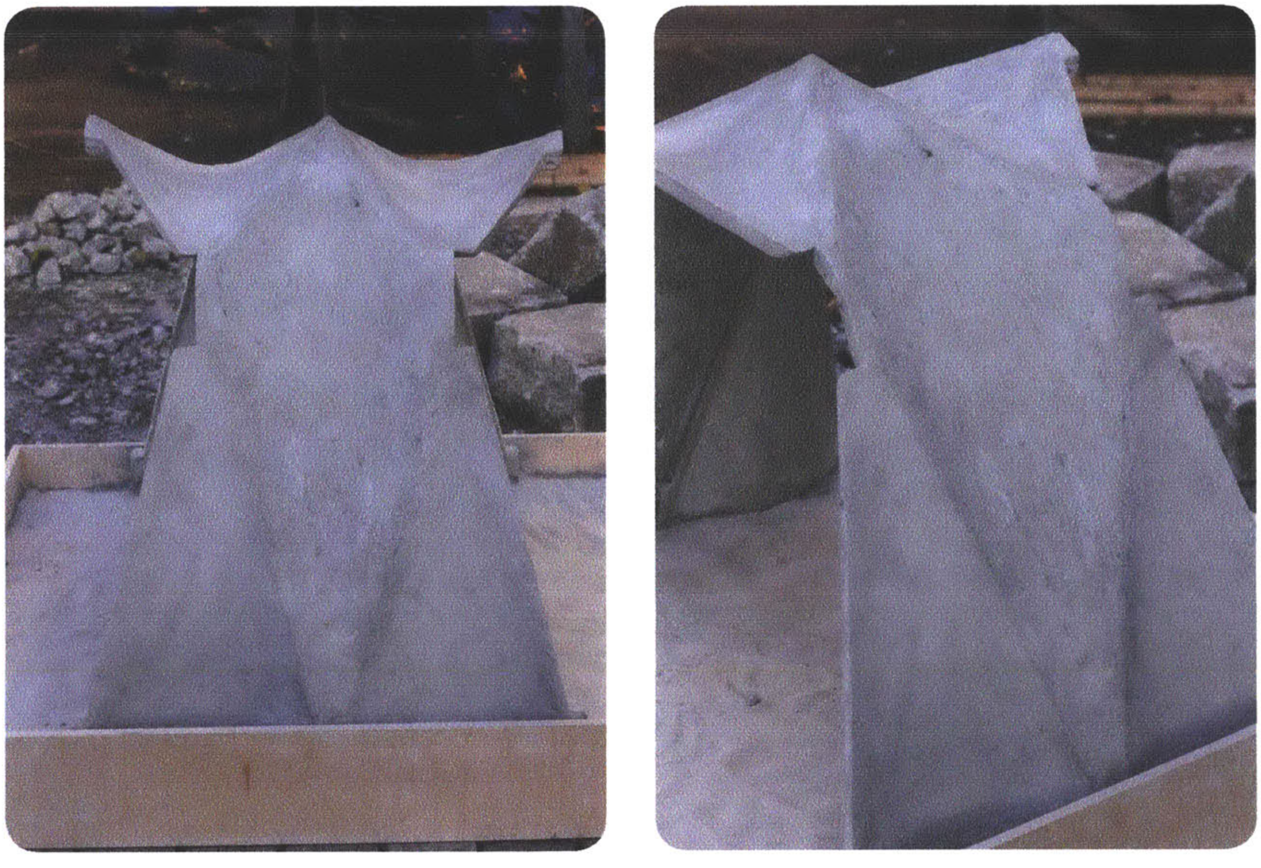


Photo from final scaled model with cementous plaster finish

Photo of molded surface finish from within the scaled assembly

Photo of roof connection after joints were filled



Photos of final scaled assembly

Appendix

Following is a paper which will be published excluding some supporting images by the Hindustan Institute of Technology and Science for the Computer Aided Architectural Design in Asia (CAADRIA) 2012 Conference.

LOCALIZED DESIGN-MANUFACTURE FOR DEVELOPING COUNTRIES:

A Methodology for Creating Culturally Sustainable Architecture using CAD/CAM

ELLA PEINOVICH, JOHN FERNÁNDEZ

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 localization 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 molds with locally available CAD/CAM tools. The molds 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, urbanization is associated with more job opportunities and improved human development; however, this 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 urbanization 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 appropriate architecture in developing countries. Enabled by the global distribution of Gershenfeld's (2005) Fabrication Laboratories (FabLabs) and connectivity provided by the digital age (Resnic, 2001), 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 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 resulting diseases kill 1.5 million children each year and comprise 10 percent of the global disease burden. 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. This situation will worsen as the population living in slums is expected to grow from 1 billion people to 1.6 billion by 2020.

Most residents living and working within these informal settlements are employed within the informal craft sector, made up primarily of the Jau Kali who are entrepreneurs and craftsmen with trained skills that represent 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, the quality of their production can be unpredictable.

The informal craft sector continues to produce over 90 percent of new jobs in Kenya annually and employs an estimated 80 percent of the labor force. (Kenya National Bureau of Statistics, 2009) In 2007, the Government of Kenya announced Kenya Vision 2030, a plan to develop targeted economic zones around the country to generate 10 percent annual growth in GDP. However, the plan has been criticized because it does not promote, much less mention, the informal sector jobs. As Kenya aims to position itself within the global economy, many living and working within the informal economy fear further marginalization.

For advocates of sustainable development the question remains, "Why use highly technical exogenous machinery when there is an abundance of local labor?"

3. Innovation

The methodology of Localized Design-Manufacture proposes 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 the assembler 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.

Localized Design-Manufacturing promotes working within the community, recognizing 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.

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

3.1. ECO-SAN DESIGN AND MANUFACTURING 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 to manufacture a low-cost sanitation center using digital design and fabrication tools available at the University of Nairobi. The principals of Localized Design-Manufacture were utilized in the process of CAD/CAM fabrication employing computer numerical control (CNC) to surface sculpt a precision mold plug for a fiberglass mold 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 labor throughout the process 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 utilizing the Localized Design-Manufacturing 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 and assembly of quality components, while reducing cost and use of materials. At 200USD to cast each unit, the cost is comparable to the more commonly used pit latrines with bush pole and corrugated metal substructure.

Durability

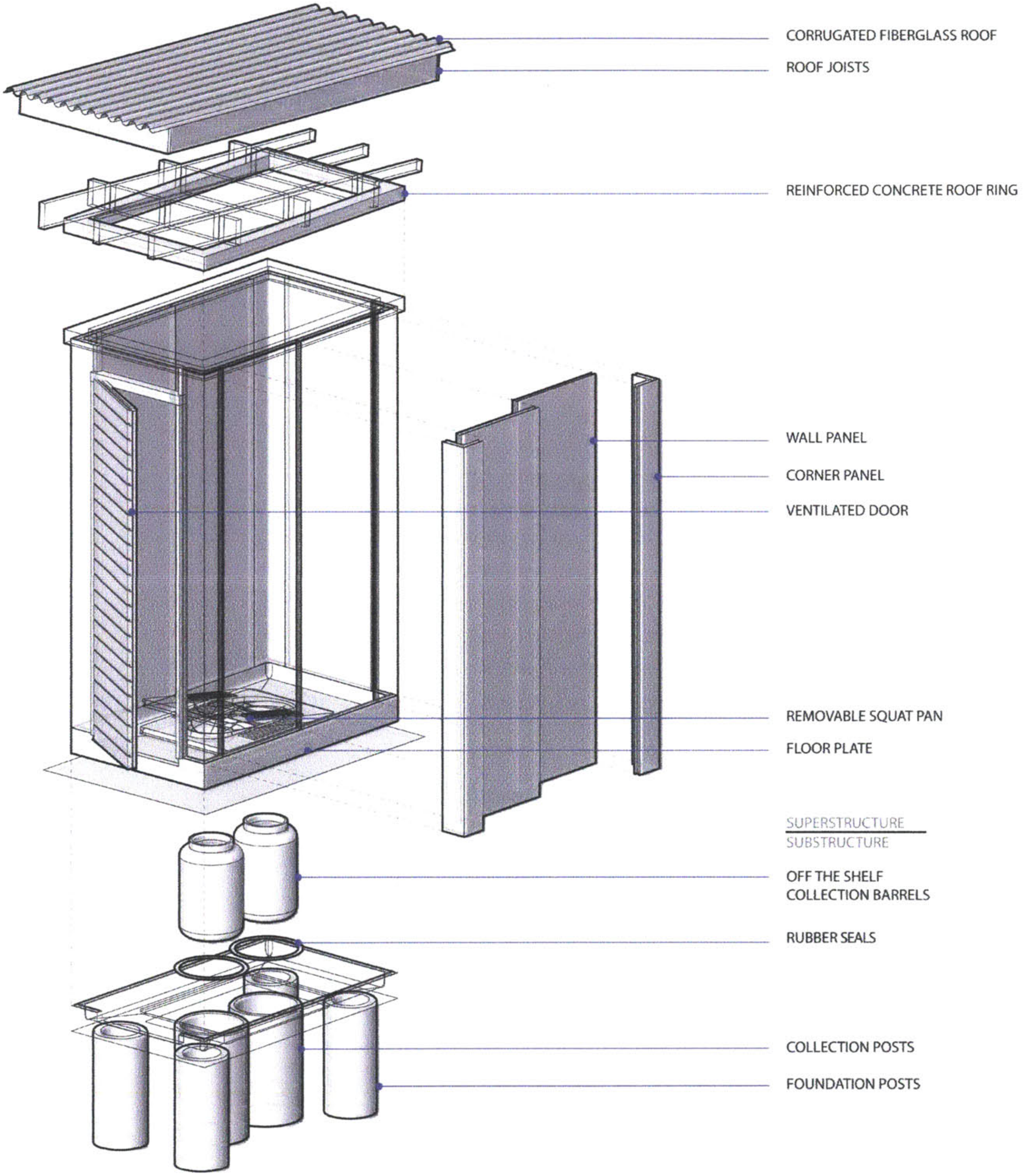
Ferrocement is both highly durable and low maintenance. The pre-cast, monolithic floor plate provides a register for the superstructure, by locking in the walls and corners in combination with the monolithic, precast roof ring. The panels are structurally engineered for the demolding and transportation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

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


CORRUGATED FIBERGLASS ROOF
ROOF JOISTS
REINFORCED CONCRETE ROOF RING
WALL PANEL
CORNER PANEL
VENTILATED DOOR
REMOVABLE SQUAT PAN
FLOOR PLATE
SUPERSTRUCTURE
SUBSTRUCTURE
OFF THE SHELF
COLLECTION BARRELS
RUBBER SEALS
COLLECTION POSTS
FOUNDATION POSTS

Cleanliness

Precision molds 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. Background

While digital modeling and manufacturing technologies 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, 2009) utilizes 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 molding device appropriate for local adoption in rural applications (Griffith, 2011). 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 little sustainable 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 Localized Design-Manufacture methodology in the design of precision molds to manufacture and deploy low-cost, water-free toilets. The local team is developing ongoing design iterations of the precision molding system for other infrastructure applications along with developing localized distribution channels for the Eco-San design to be replicated and scaled to meet sanitation needs across sub-Saharan Africa. Pre-cast assemblies are now being built and utilized within a production facility within Nairobi, Kenya. A new construction industry is being formed around the methodology of Localized Design-Manufacturing.

Photos of Eco-San toilet in operation on Kibera site, Summer 2010

5. Process

Employing the Localized Design-Manufacturing 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 technologies for the project. These tests outlined below produced an accurate and replicable design solution to the real-world problem of sanitation.

5.1. LOCALIZED 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 Localized Design-Manufacture methodology is that it necessitates a design process that incorporates craft and democratizes 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.

During the design process the team of designers focused on three interdependent factors:

1) Adapting local thin-shell, ferrocement construction for pre-fabricated architecture, saving on local material resources and reducing green-house gas emissions, while utilizing the local knowledge of the Jau Kali.

2) Utilizing capital-saving and employment-generating technology, due to the state of development in Sub-Saharan Africa where there is an abundance of unemployed laborers.

3) Navigating the volatile land tenancy rights issues by providing a temporary construction, while satisfying the desire of residences and business operators regarding the security and perceived permanence of the structure.

5.1.1. Community Sensitivity

To aid in community adoption, during the design process the design team must best understand the community or user group for who a design solution is intended. Mobile surveys supplemented with on-site observations are an effective combination of ethnographic research. Within developing countries the proliferation of mobile phones has provided access and communication with remote and differing communities, allowing designers and researchers to overcome social barriers.

The sensitive, personal nature of the information the design team sought for the Eco-San solution, including personal hygiene and toilet usage, necessitated a tool for mediation. The design team conducted user mobile surveys and field research in the slums of Nairobi throughout the design and post-construction stages. It was through these surveys that the team learned of the importance of perceived permanence of new construction in the informal settlements due to the history of unwarranted home removals.

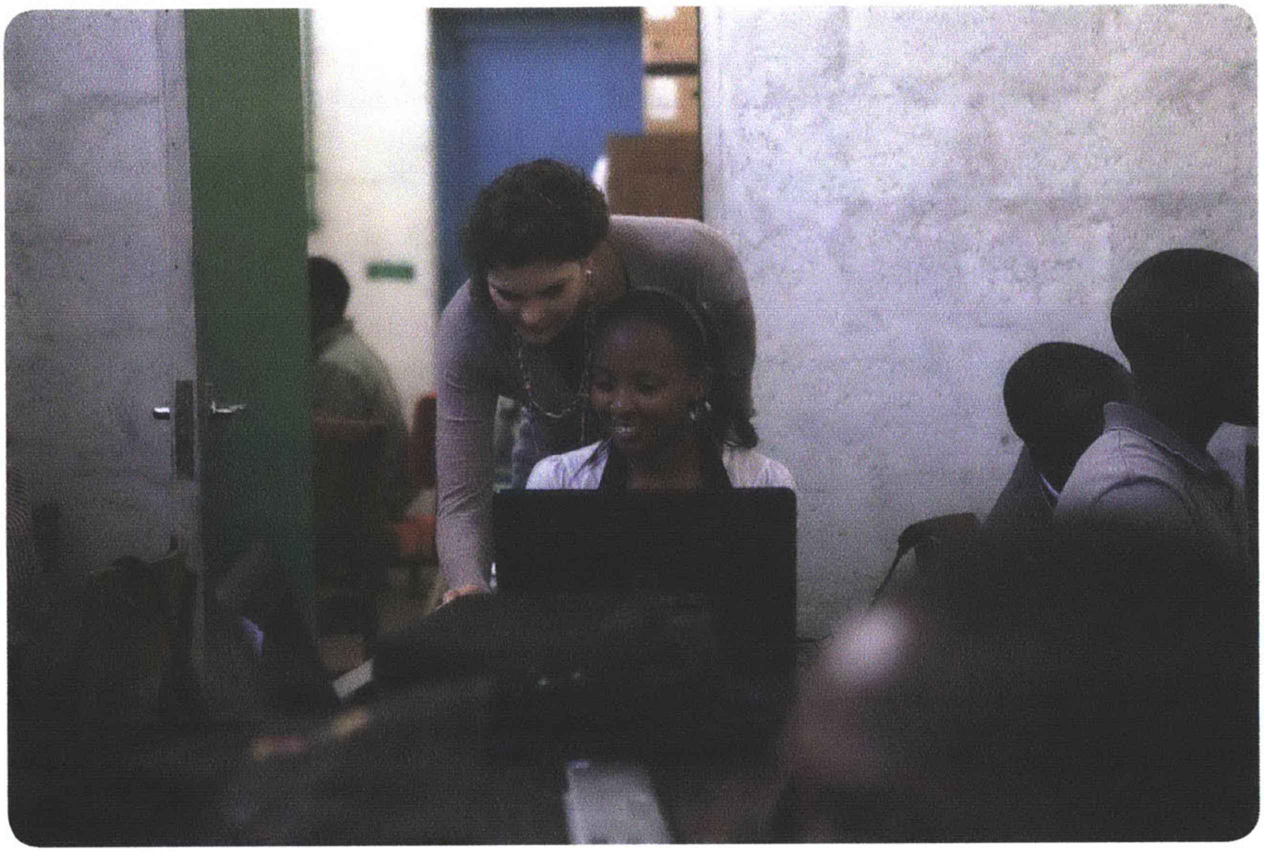
5.2. LOCALIZED MANUFACTURING PROCESS

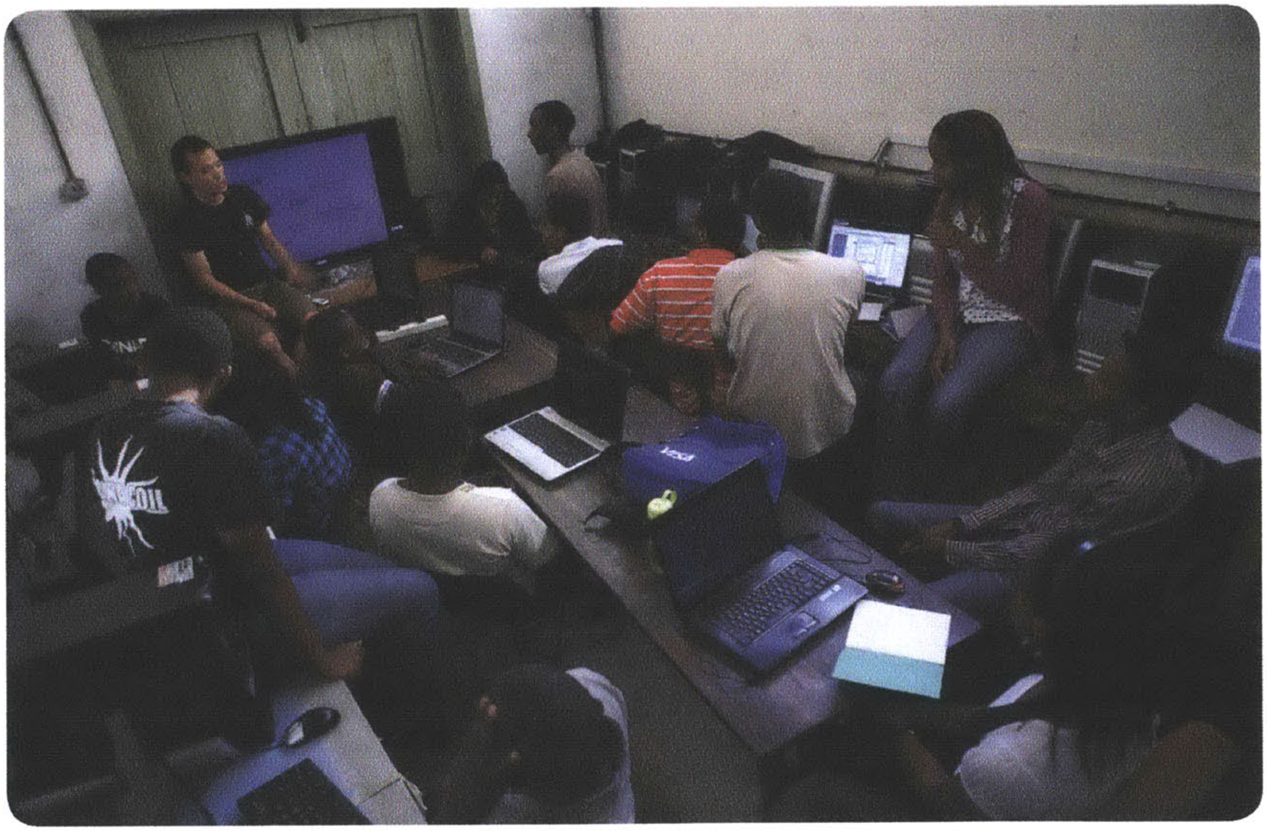
As stated above, when approaching localized manufacturing the process must first consider available local tools and skills. In Nairobi, there are few highly technical machines and manufacturing processes aside from large and established industries such as the Nairobi Railway. However, in 2009 the Science 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 customization. "Real mass customization" has been defined as varied architectural components, not restricted by industrial repetition (Bechthold, 2009). 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. The Jau Kali became convinced of the value of the investment in these new processes as productivity and profitability were improved through the pre-cast, precision mold manufacturing process.

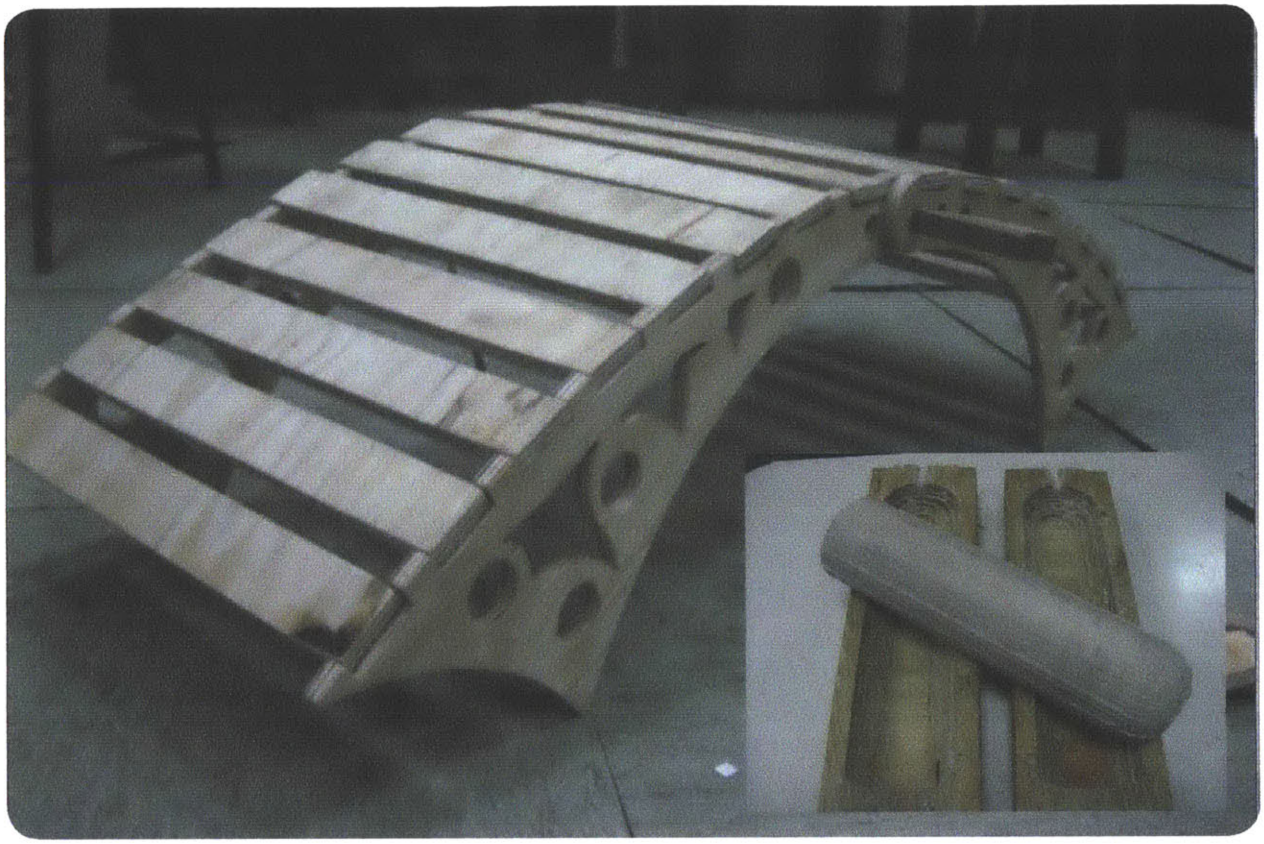
5.2.1. Capacity Building

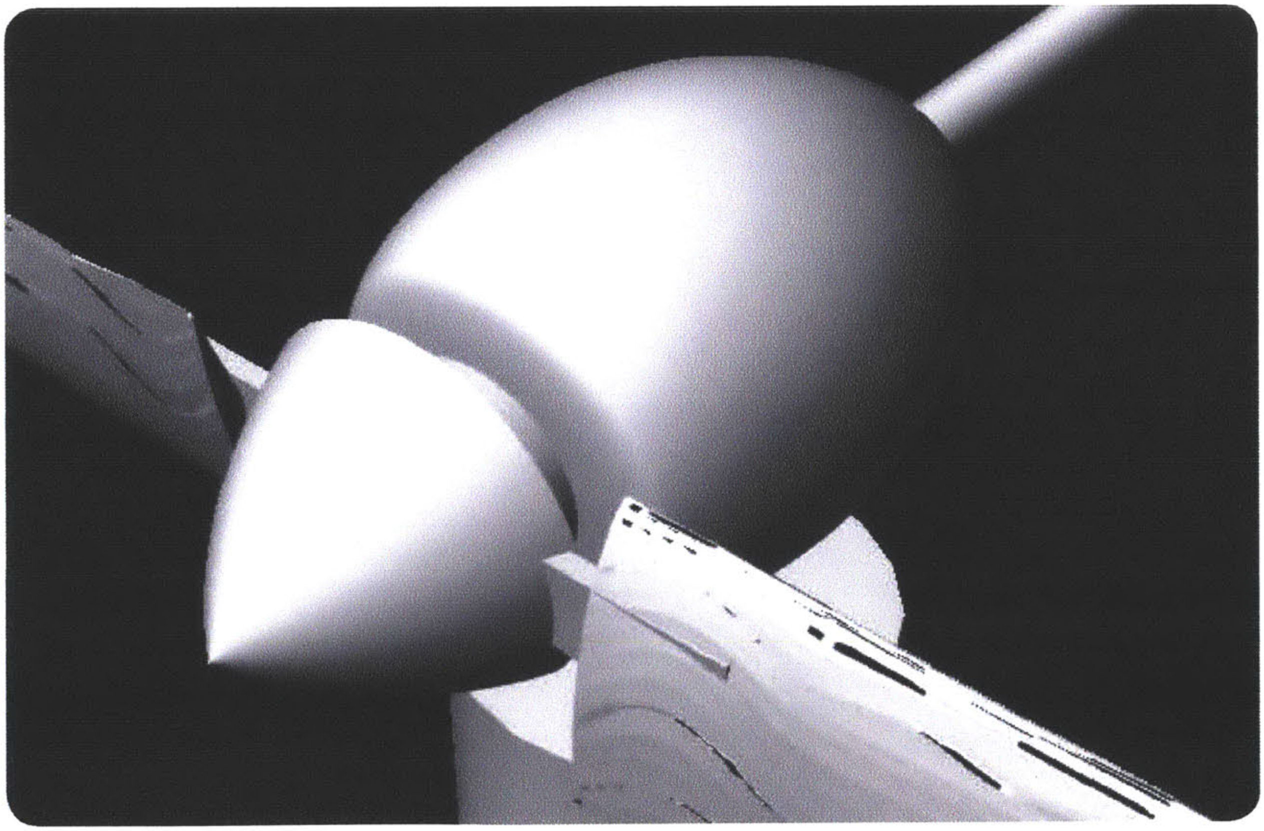
Throughout the manufacturing process there are opportunities for building local capacity. During the summer of 2011, in partnership with the University of Nairobi's Science and Technology Park (FabLab), the design team hosted a digital modeling and fabrication workshop for a multi-disciplinary group of university students. Participants learned basic digital modeling 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 modeling a design related to their own research, proceeding from conception to realization. Many of the students have since contributed to the development of the Eco-San solution and continued investigations utilizing their digital design skills.





Photos from crowded classroom at Design for Development Workshop, Summer 2011





Student works from the Design for Development Workshop at the UoN, Summer 2011

5.3. 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 labor required on-site, thus reducing the final cost and increasing access of the final assembly to the community.

Utilizing computer-generated designs and digital fabrication within the FabLab the design team partnered with a local technician and engineer to iterate the design of a precast sanitation unit rapidly and replicate positive results in constructing a mold for casting the ferrocement building elements. The team began the fabrication process with a 3D modeled component representing the final cast form. The digital model was used to test in virtual space, before production, that the proper tolerances are built into the precision mold and that the resultant cast components would fit together in the final assembly. This digital mold-plug, which represented the physical mold plug, was then laterally sliced in model space per the thickness of the material available. Using a 2.5D CNC machine the router bit was limited from creating undercuts which ensured components were easily released from the mold. The Figures 2-5 below illustrate the fabrication process of the floor plate mold from digital model through mold fabrication.

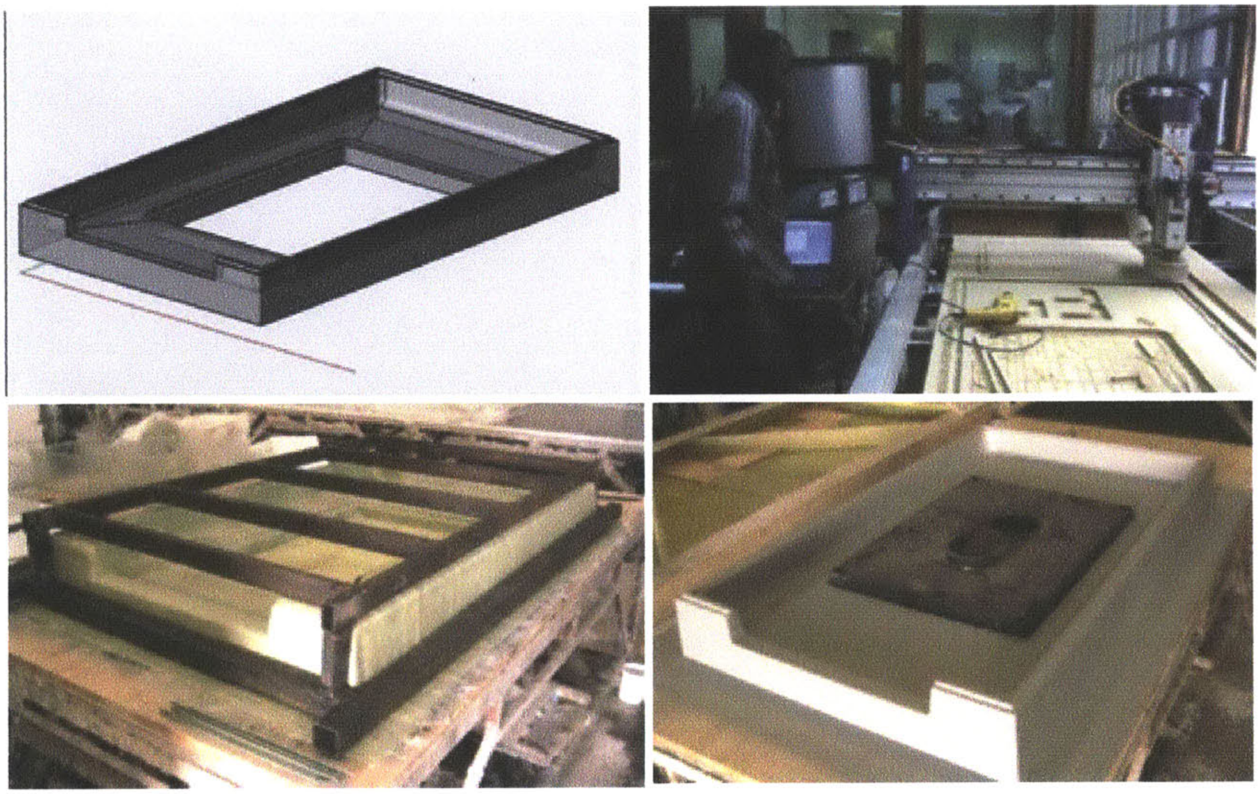


Figure 2. Floor mold design as digital 3D model. Figure 3. Milling positive plug from composite board in Nairobi FabLab. Figure 4. Fiberglass mold and steel frame made from plug. Figure 5. Final fabricated floor plate plug.

5.3.1. Pre-Cast System

The molding process used in making the Eco-San floor plate used computer numerical control (CNC) technologies to surface sculpt a precision mold-plug for a fiberglass mold used in pre-manufacturing highly accurate ferrocement components.

Within Nairobi, the center of East Africa's industrial production, ferrocement construction is 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 the precision mold. The pre-cast process utilizes the Jau Kali's transferable skills from plastering on-site to casting and assembly. The pre-cast system provided many benefits in cost savings, quality control, as well as easy, on-site assembly and maintenance, while employing local labor.

5.4. MATERIAL DEVELOPMENT

Localized-Design Manufacturing contributes to the identification of sustainable construction methods and the consideration of innovative materials and assembly systems (Fernandez, 2006). Independent material and fabrication research was conducted with two cost-reducing technology development goals. The first goal was to develop and test a concrete mix that would be efficient yet structurally sound, using local materials. The second goal was to create an accurate and replicable means of manufacturing the casting molds with the tools available at the Science and Technology Park.

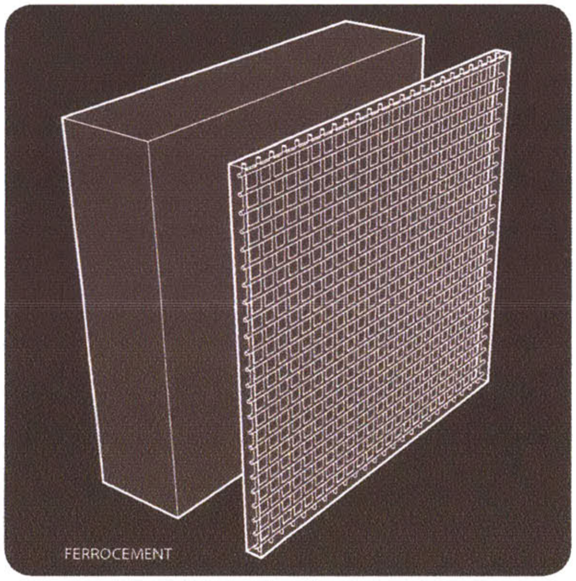
Within the Concrete Materials Lab within MIT's Department of Architecture the team sought efficiencies in compositions and configuration for the lowest feasible weight and cost of assembly. The investigations included cost-reducing concrete mixtures, including recycled and affordable waste materials for aggregate, while others incorporated admixtures found in Kenya like volcanic ash and fiber reinforcement.

Ferrocement | Definition

Ferrocement is a highly versatile form of reinforced concrete made of wire mesh, sand, water, and cement, which possesses unique qualities of strength and serviceability. It can be constructed with a minimum of skilled labor and utilizes readily available materials.

Ferrocement | Mechanical Properties

In general, a composite material consists of a matrix and a reinforcement which act together to form a new material with superior characteristics than either of the materials alone. Ferrocement, a homogeneous composite material which typically contains a high percentage of ductile steel wire mesh with a high surface area to volume ratio in a cement-mortar matrix, enables the matrix to assume the ductile characteristics of the reinforcement.



5.4.1. 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 & 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.

The order for creating the molds and cast is as follows:

1. Design and Develop molds for casting
    a. Steel or fiberglass molds allow for a smooth finish
    b. Use hinge joints on mold to allow for undercut geometry
    c. Add cross bars to keep mold from deflecting under weight of concrete
    d. Use a more systematic method in order to make all mold parts interchangeable
    e. Allow for a reasonable tolerance in the final cast forms in addition to the tolerance in the mold.
    f. Machining the plug (using FabLab equipment) for the mold helps to reduce this overall tolerance.
2. Prep Reinforcement
    a. Using wire shears cut round bar to length and weld frame
    b. Wrap chicken wire around the frame, using wire ties to secure it
    OR
    c. Cut mosquito netting to length
3. Mix concrete
    a. Add all dry materials and admixtures before adding water
        1) The gravel aggregate is too large to be workable in the thin mold with tongue and groove connection around the perimeter of the mold, a quarry dust was preferred.
        2) The measurement of water used in the mix varied greatly depending on the variation in aggregate, the aim is to have a mix that is still able to be handled, without forming water puddles.
    b. Use recycled plastic pellets to reduce environmental impact
4. De-mold between 2 days and 1 week
5. Perform structural testing at 28 days

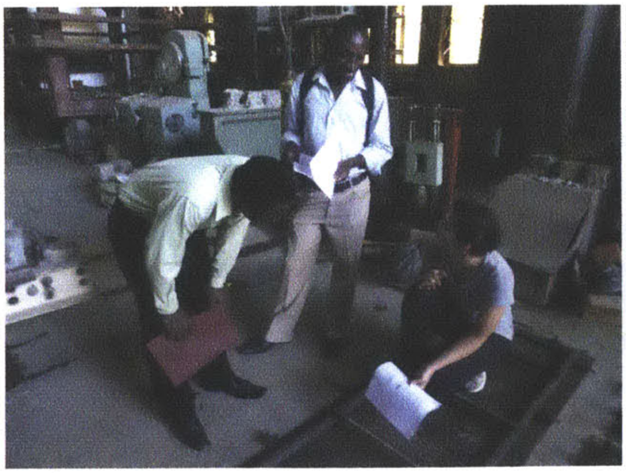


Figure 6. Discussing the mold design

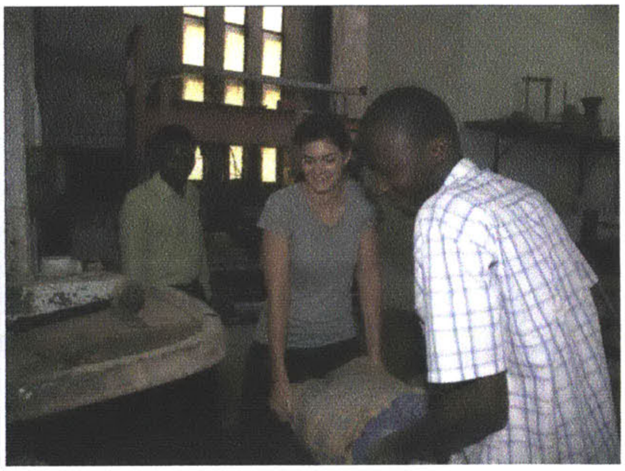


Figure 7. Adding the cementous mix to the mixer.

Control Test Mixtures

Materials

Test #1: Control Mixture in 7' x 2' x 1.5" mold, using **coconut & motor oil** mold release agent, with vibration

Material in Kenya	Material in US	Amount	Units	Notes
Cement	Portland cement Type 1	25	kg	
"Quarry Dust"	Pea Gravel	25	kg	black pea gravel
"River Sand"	All-Purpose Sand	25	kg	ballast made of sandy gravel
10-12.5mm Gravel	3/8" Gravel	25	kg	**Replace with "Quarry Dust" in wall panels, use gravel only in floor mold
Rheoplast 1100	Glenium BASF	200	ml	super-plasticizer for high-strength, durable concrete
Pozzolanic	Pozzolith BASF	125	ml	accelerator, retarder and water-reducer
Fibers	Fibers	10	g	shrink reducer
Chicken Wire	Chicken Wire	2.5	m sq	single layer of 1/2" to 3/4" openings, hexagonal, 20 gauge or less, tied on rebar frame
Round Bar	Rebar/ Welding Rods	18	lf	1/8", R6 in 12 foot lengths
Coconut Oil	Water-based Mold Release	500	ml	mold release
Water	Water			(solid weight/2)

Test #2: Control w/Chicken Wire sub Mosquito Net

	Mosquito Netting	10	m sq	4 layers at .2 inches apart, 7' long and 2' wide

Test #3: Control w/Aggregate sub Recycled Plastic Pellets

	Plastic Pellets	75	kg	

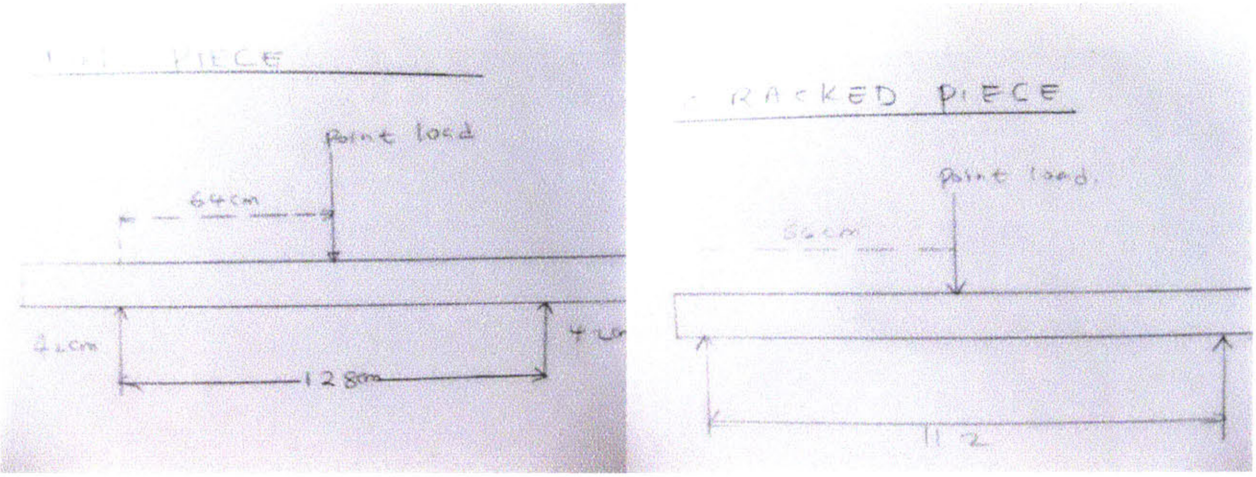
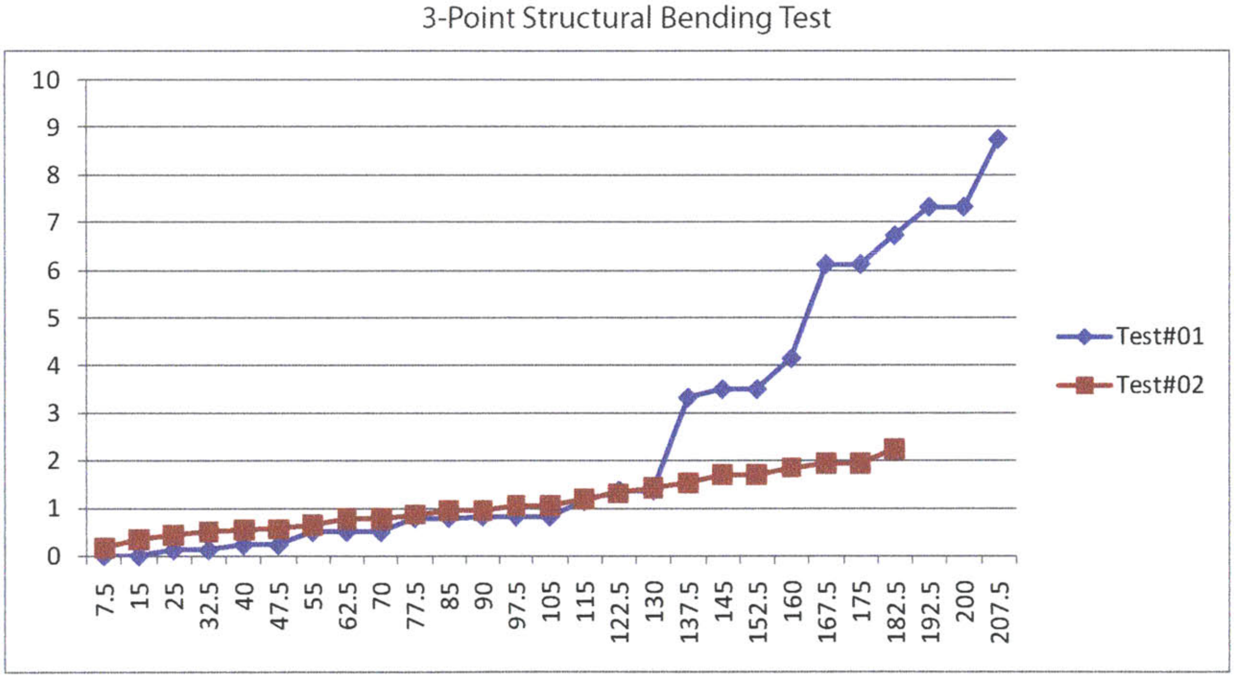


Figure 7. Sketches from the field team of the varied point loads, due to a crack in one of the panels. This was another viable that made the results difficult to compare and require further analysis for structural stength.

Figure 6. Three-point bending test of panels for use in pre-cast assemblies. Figure 7. Section of panel with mosquito netting after catastrophic failure.



3-Point Structural Bending Test

Figure 6. Comparison of each panel in Deflection (mm) to Loading (kg)

In the end only two of the three panels were structurally tested. It was found that four layers of distributed mosquito netting roughly .25 inches apart saved time and reduced cost compared to the chicken wire reinforcement which required a welded steel frame to lay in flat. 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.

5.5. RESULTS

The efforts of design to manufacturing, capacity building, and seeking efficiencies in the local resources 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.

5.5.1. Broader Applications

Scalability is the most critical element to technology transfer. Once a process and product can be 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 standardized 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 Localized Design-Manufacture methodology offers a framework for localized design and manufacturing of other architectural and infrastructure solutions requiring precision manufacturing within developing countries. As a substantive productive process, concerned with craft and assistive digital technologies for global development operating at a local level, the Localized 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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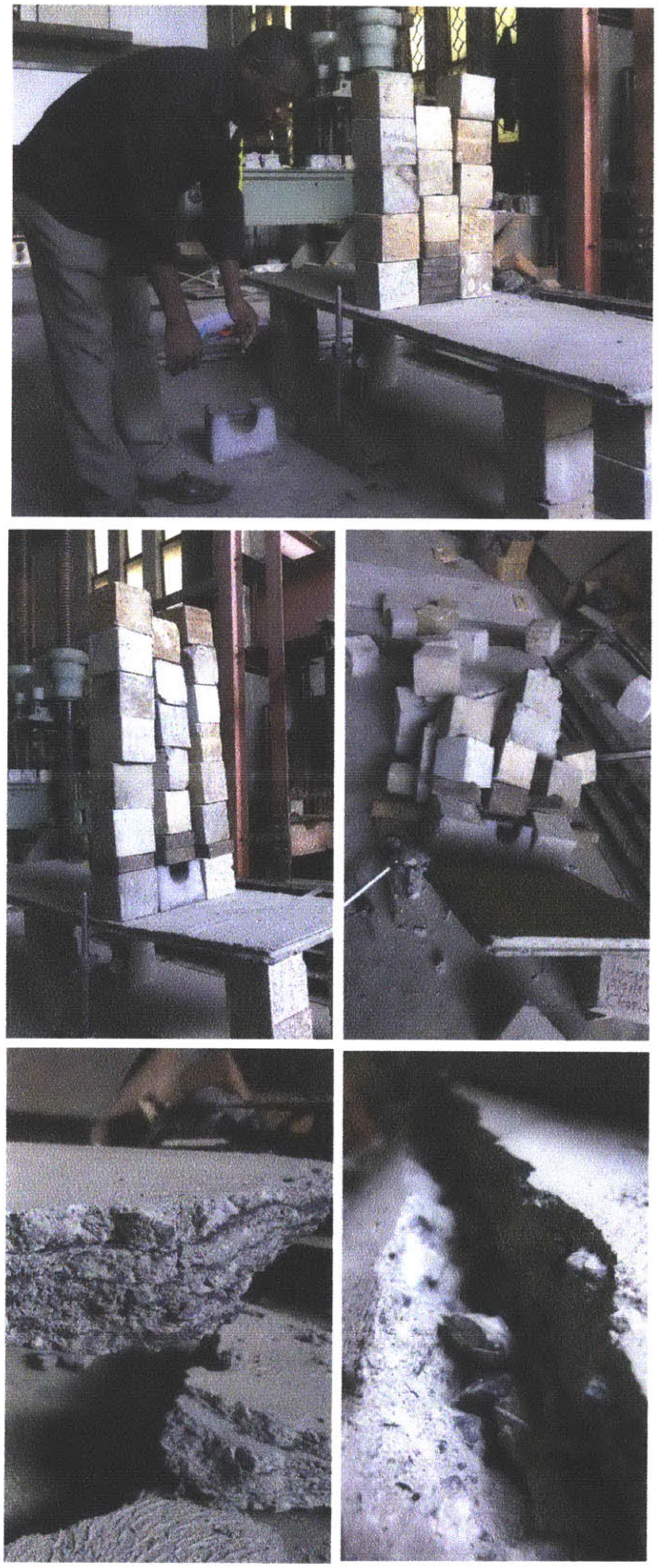

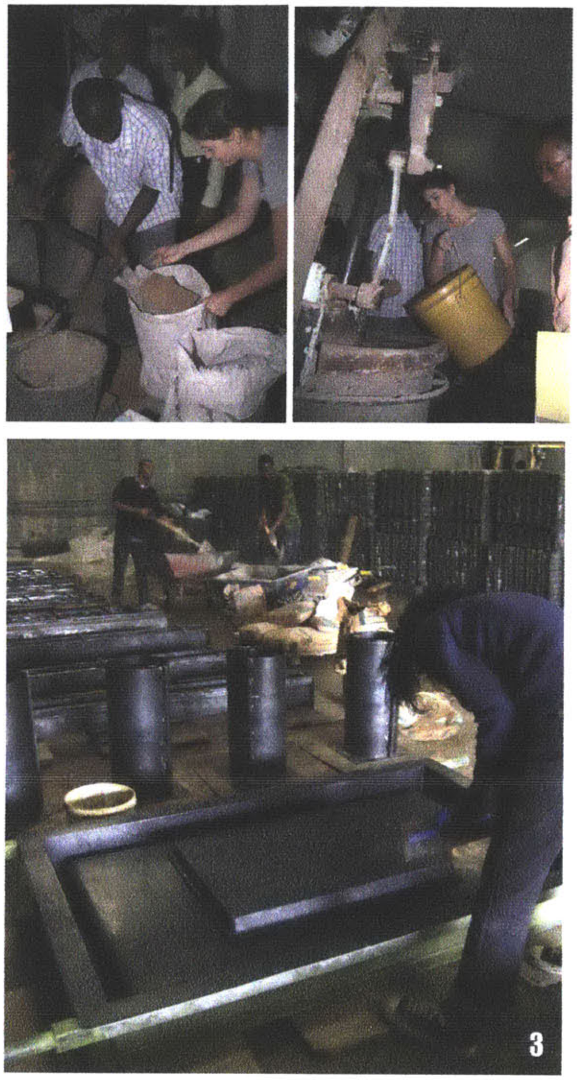

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