Catalyzing Equitable Access to Building Construction Through Advancements in Global Building Machine Technology

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Globally we are experiencing an unprecedented housing crisis. On December 26th 2019 as the United Nations called for the "Implementation of the Right to Adequate Housing", they attribute our growing global housing crisis to unequal access to adequate housing caused, for the first time, by socio-economic inequality rather than access to building materials. As the wealthy buy and sell housing as a commodity, they increase their financial gains while driving the poor deeper into poverty. Among those driven deeper into poverty are more than 1 billion people living in informal settlements and more than 1.8 billion people lacking adequate housing . While inequity currently contributes heavily to our global housing crisis, we are experiencing a crisis of overlapping problems such as labor shortage, an ongoing pandemic, and worsening climate change.

Compounding the global demand for housing is a lack of Architectural machines authentic to the practice of Architecture. The current machinery used in building production is generally borrowed from assembly lines and industrial applications and are inaccessible to the masses due to cost. However, this research seeks to empower individuals by granting them access to advanced building technology built from standardized parts through Open-Source frameworks.

The authors are using a self-built 3-axis gantry-based machine as a base for modification and testing of building processes to develop a universal building machine, (UBM), capable of processing materials common to architecture, handling these materials, fabricating building components, and assembling these components. The development of this UBM is based on the universal principles of Architect Konrad Wachsmann who practiced between 1940-1980 and developed joint connectors, several prefabricated building systems, industrial fabrication methods and a visionary building machine - the 7-axis Location Orientation Manipulator (L.O.M.). The UBM serves as a testing ground to distribute the means of building construction to individuals directly in need of housing.

INTRODUCTION

Today, we are facing an unprecedented global housing crisis. Unlike any previous crisis of its kind, according to the Guidelines for the Implementation of the Right to Adequate Housing published by the Human Rights Council in December of 2019, rather than being caused by a decline in resources or economic downturn, the ongoing crisis is being caused by "economic growth, expansion and growing inequality". As the wealthy buy and sell housing as a commodity, they increase their financial gains while-simultaneously making housing inaccessible to the poor. Among those driven deeper into poverty are more than 1 billion people living in informal settlements and more than 1.8 billion people lacking adequate housing. While inequity as the root of this housing crisis is unprecedented, the global housing crisis is not.

In our recent global past, housing crisis can be attributed to mass population migrations of refugees displaced by climate, disaster, and war - on top of a massive population expansion. In 2013, 22 million people lost their homes to natural disasters. Additionally, as of 2015, 59.9 million people have been forcibly displaced from their homes either within their own country or to other country. These refugees and displaced people typically spend 12 years in camps that are supposed to be "temporary". "Temporary" solutions typically include informal settlements or tent cities erected on borrowed land susceptible to intersecting disasters such as floods, droughts, extreme heat events, wildfires, and COVID-19. Additionally, environments of displacement often lack the basic infrastructure necessary to life, health, and sanitation.

In addition to the mass displacement of population, our global population is ever expanding. As of 2015 the world's population was 7.3 billion people. The United Nations Department of Economic and Social Affairs Population Division projects that by 2030 the world's population will increase to 8.5 billion people, reaching 9.7 billion in 2050. It is expected that more than half of this world population growth will occur in nine countries: Democratic Republic of the Congo, Egypt, Ethiopia, India, Indonesia, Nigeria, Pakistan, the United Republic of Tanzania, and the United States of America. This is going to put extreme pressure on these nine countries to produce housing for approximately 0.6 billion people. By 2025, California alone will need 1.5 million more homes; many of which should be affordable.

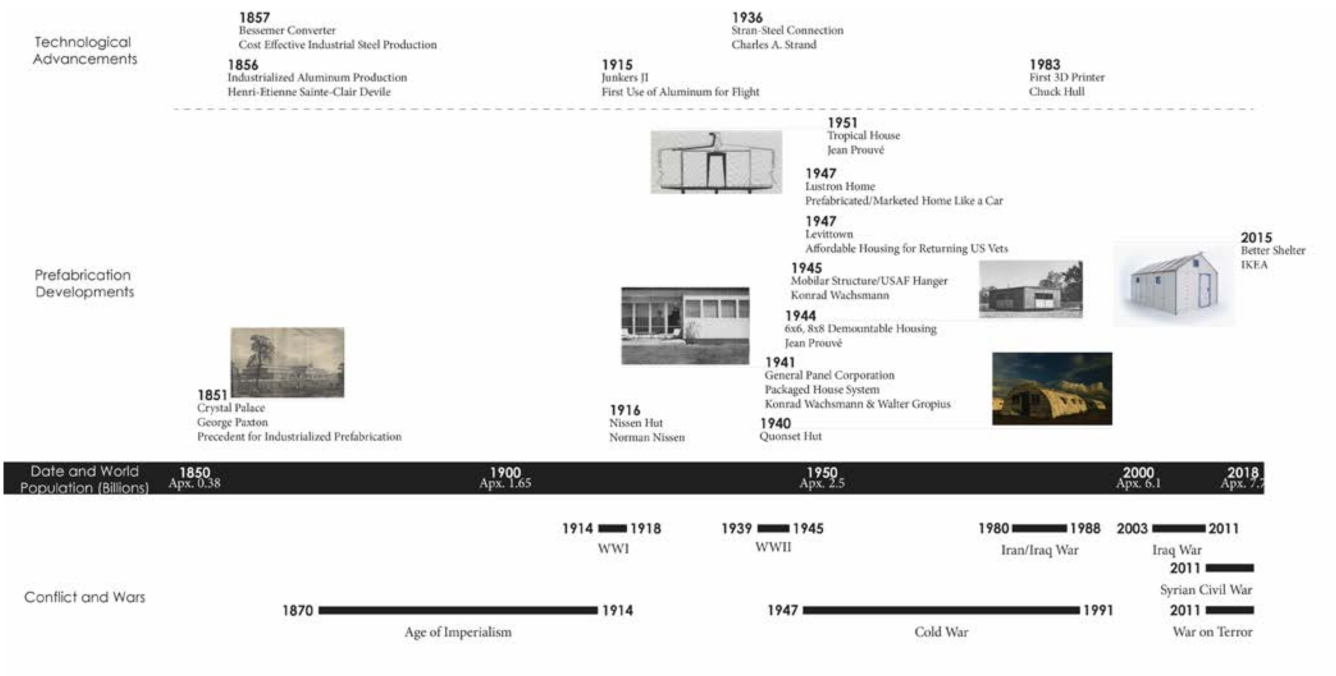

Figure 1. This timeline of prefabrication compares technological advancements to architectural developments as well as conflicts and wars. Elizabeth Andrzejewski.

To re-iterate: globally we are running out of some materials and there is a skilled labor shortage, but what compounds this problem is a global lack of *access* to housing and housing construction fueled by a deepening economic inequity. This paper discusses historic examples of prefabrication deployed in times of housing crisis and how this approach could be applied to a compounding contemporary housing crisis. Furthermore, the authors present a Universal Building Machine, or UBM as a solution that directly addresses access to contemporary building technologies. The development of the UBM subverts a lack of access by delivering the means to produce adequate housing directly to the individual in need of housing.

CONCISE HISTORY OF HOUSING CRISIS AND PREFABRICATION

For the past 170 years, architectural prefabrication and mass production have been utilized to meet demands for large scale constructions, efficiency, and speed in the built environment as seen in figure 1. The Industrial Revolution, which lasted from about 1720-1890, transformed the building industry by introducing methods and industrial materials which could be produced with accuracy and consistency using low-skilled or un-skilled labor. Through the 1800s and leading up to the 1900s, there was an introduction of centralized power plants were introduced in Industrialized nations, which allowed for the implementation of electric engines and machines capable of manipulating building materials through additive, subtractive, and die forming methods . This revolution transformed how the world-built housing. It opened the door for modern mass-produced building parts, and materials such as steel, plywood, engineered lumber, plastics, reinforced concrete, and new polymers yet to come. In addition to revolutionary new building materials, prefabrication as a process enabled the building industry to produce homes and buildings as quickly and easily as a factory-made product.

The *Crystal Palace* (1851-1936), built by Joseph Paxton for the 1851 World Exhibition in Hyde Park London, was the biggest and most prominent demonstration of the prefabricated building assembly process. The modular design of its cast iron framing and plate glass envelope was fabricated in factory conditions, and then assembled on site in approximately five months - a huge technological achievement for its time. The Crystal Palace exemplified the viability of prefabrication to reduce labor costs, increase speed, and produce industrialized buildings quicker than traditional construction methods for architects of the 1900s such as Konrad Wachsmann, Walter Gropius, and Jean Prouvé. The factory-produced parts and specially designed joining members facilitated a system in which no waste material was produced on site and the erection of the structure was quick. Sixty-three years after the Crystal Palace, the beginning of WWI in 1914 created a new global housing demand and simultaneously spurred an increased development of prefabricated military housing which escalated during WWII.

During WWI (July 28, 1914 – November 11, 1918) and WWII (September 1, 1939 - September 2, 1945), there was a high demand for both temporary and permanent housing that could be produced and constructed quickly. Mass produced prefabricated housing offered a solution for the military to house temporary and transient workforce during the war and to rebuild homes destroyed by the war domestically. The militaries of the world, and the labor force supporting them, became mobilized and mechanized. Additionally, the destruction caused by the wars created a housing demand for quick permanent housing as European cities were rebuilt after the conflicts. Militaries and governments were involved in developing the *Nissen Hut* in 1910, the *Quonset Hut* in 1940, the *Packaged House System* in 1941, and the *8x8m Demountable House* in 1944.

The British and U.S. military utilized the semi-circular Quonset Hut, (1940-presnt day), largely based on the Nissen hut, for civilian housing and military bases in varied climates. It's metallic frame and skin could be easily erected by teams of ten men and could be easily assembled and dissembled. This quick construction was made possible by the unique Stran-Steel connection, essentially a reusable metallic nailing strip. At approximately the same time in the US, Wachsmann and Gropius were developing the *Packaged House System*.

The wooden panelized Packaged House System of 1941, by Wachsmann and Gropius, utilized a unique joint, the wedge connector, which allowed teams of 1-2 unskilled laborers to assemble the house on a prepared site in a day. German-born architects Konrad Wachsmann and Walter Gropius began working together in 1941 on a system for prefabrication that Wachsmann had brought with him to the United States in 1939 when he fled conflict in Europe. They aimed to take advantage of the wartime need for housing with their prefabricated system, the *Packaged House System*. Initially targeted for military use as temporary housing for transient workers, the system was factory-produced and fitted with the specialized universal joint, the *wedge connector*, that allowed for fast assembly on site. As the war ended, their target market changed to the typical suburban American homeowner and returning war veterans until the corporation failed in 1951.

Toward the end of WWII, Jean Prouvé designed, prototyped, and began producing the 8x8m and 8x12m demountable house, which serves as a European example of prefabricated housing solutions for the post-war crisis in contrast to the *Packaged House System*. In 1944, Jean Prouvé was commissioned by the French government to manufacture and deploy 800 temporary demountable homes for the homeless in Lorraine and the Vosges. These 8x8m units would leave the factory on a truck and be assembled by a small team of 4-5 men in one day. Yet again, prefabrication was proven to be a successful measure to produce mass housing quickly and efficiently. These temporary constructions exemplified how industrialized prefabricated housing could be lightweight, easily transportable, and easily mountable and dismountable, and how it could serve as a housing solution for displaced populations and the homeless.

In the latter part of the 1900's and into the early 2000's the global housing crisis evolved. Similar to the early 1900's population migration due to war and conflict contributed to a need for housing, however, the problem was compounded by destruction by natural disaster, population expansion, and population migration from global climate change. In 2005 Hurricane Katrina destroyed approximately 850,000 homes, in 2013 - 22 million people lost their homes to natural disasters and in 2015 - 59.9 million people were displaced from their homes by conflicts. Again, mass produced prefabricated housing was proposed as a better solution to "temporary" camps. The Better shelter, a flat packed shelter partnered with IKEA, delivered small housing units to refugee camps. The Better Shelter was designed for ease of transport and could be snap fitted together by a team of four refugees in 4-5 hours depending on their skill level.

Throughout time, factory produced prefabrication has been hailed as a catch-all solution to efficient housing; one that provides better quality at a lower cost. However, while the factory provides many benefits, closed system products are often less-than-ideal and are not suited to address the cultural and physical needs of individual users. Additionally, these examples provide those in need with a finished kit or product which still does not provide access to the means of housing production but rather to another commodified product. Currently, 1 billion people reside in informal settlements and more than 1.8 billion people globally lack adequate housing. This problem of unequal access means that people are unable to secure adequate housing simply because they cannot afford to participate in the techno-economic structures of housing. Rather than deploying complete prefabricated housing kits, this contemporary crisis may demand solutions that include access to house-building as a process and methods of production traditionally controlled by construction industries. In an age where DIY culture and Open information are disrupting traditional structures of industrialized production, can the distribution of house-building technologies provide housing solutions to those in need?

A close analysis of product type prefabricated solutions deployed during WWI and WWII as previously discussed offer strategies for effectively using unskilled labor on site to assemble buildings in a short time. We can further this analysis by additionally studying precedents of prefabricated systems that have been further democratized by distributing the *means to produce housing* through the machinery itself or through Open-source communities.

DISCUSSION: DISTRIBUTING THE MEANS OF HOUSING PRODUCTION

The CINVA-Ram, was designed and developed by Roul Ramirez in 1956 at the Inter-American Housing Center (CINVA), in Bogotá, Columbia. This machine was developed with an ethos of "easy to manufacture, easy to maintain and repair" and used common plate steel, and welding in its base construction. This block press exemplifies how earthen block making skills, and earthen building construction methods could be transmitted to people needing housing through a machine. Low-tech / low-skilled block making instructions embedded in the machine's processing informed the would-be block maker via the machine. The machine itself did not utilize a motor and was powered by a lever action press operated by one to two workers. Two experienced workers could produce two blocks per minute, roughly 80 blocks per hour. It was popularly deployed internationally by human development organizations such as the Peace Corp and DIYers.

Today, the Open-Source architectural movement with origins in Open-Source software are using internet-based channels to co-design and distribute new means of production. One of these projects is Open Source Ecology led by Marcin Jakubowski. Open Source Ecology, "seeks to democratize human wellbeing and the industrial tools that help to create it". Their Open-Source Global Village Construction Set is comprised of 50, each one deemed essential in starting a civilization. Related specifically to housing, the Open Source Ecology C.E.B. (Compressed Earth Brick) Press automates and improves on the CINVA-Ram and can be used for on-site production of the Open-Source microhouse. Rather than simply distributing a machine, the goal of OSE is to distribute the instructions for an individual user with internet access to be able to produce their own machine capable of producing housing or performing a task necessary to sustaining life.

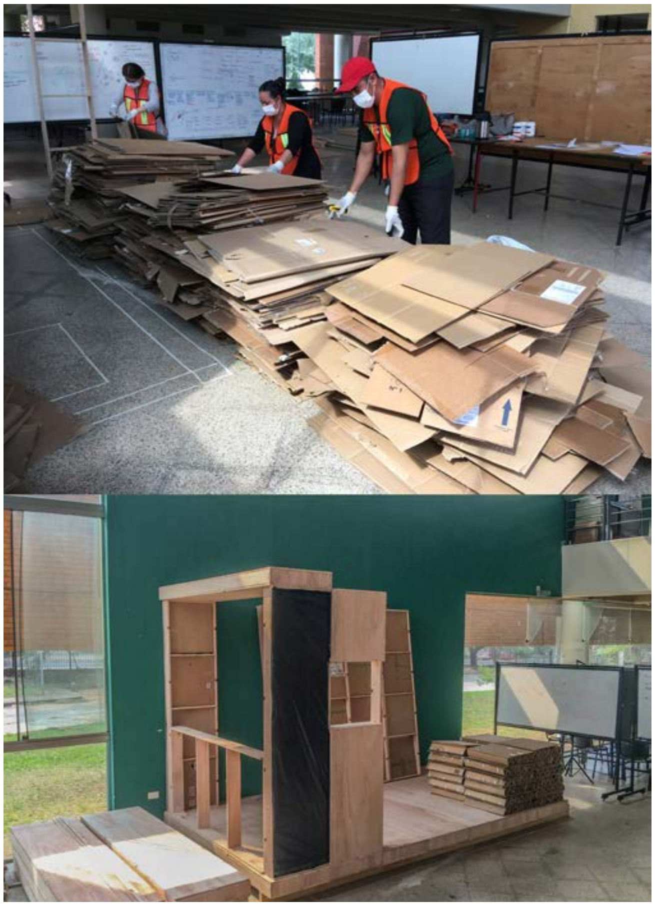

Figure 2. Volunteers construct prototypes of the PU2 out of reclaimed cardboard. Dr. Julio Duarte.

Another example of the distribution of process is found within grass roots housing movements which are gaining traction. In 2019 Dr. Julio Duarte of Penn State University, hosted a workshop in Asuncion, Paraguay to work with local cardboard pickers, figure 2, to explore the second prototype unit or PU2 – a modular unit constructed of panels made by laminating a recycled cardboard core between plywood on site.

In each of these three examples, the CINVA-RAM, Open Source Ecology, and the PU2, the individual in need of housing becomes an active participant in the process. There is an emphasis on distributing the means to produce housing rather than simply deploying a prefabricated housing kit. While these projects are still developing, they represent a way of thinking that can prove successful in making housing more accessible though this emphasis on process and are deployed as a multi-faceted solution to a compounding problem. For example, each of these examples increases accessibility by utilizing locally available or free materials. In the case of the CINVA-RAM and the CEB press, earth available on site is used to produce housing and in the PU2, a large percentage of reclaimed cardboard is utilized in the fabrication of the building components. There is also a social component to these three precedents. For example, one CINVA-RAM may be shared amongst a larger community. With the CEB press, the Open-Source plans are published for free access on the internet. Finally, the PU2, it relies on a network of local cardboard pickers to obtain the material to process into housing.

CONCLUSIONS AND FUTURE WORK

This ongoing research studies the process-based approach to the global housing crisis through the study of historical prefabricated housing systems such as Wachsmann and Gropius's Packaged House System as well as contemporary Open-Source architectural movements which incorporate an additional social component such as the OSE microhouse and the PU2. Currently, the authors are developing a prototypical Universal Building Machine or UBM, to study architectural production methods and machines deliverable to the building site. While industrial-scale housing production is inaccessible to the masses due to cost, the UBM is developed so that it can be assembled from common standardized parts with instructions distributed through online Open-Source frameworks as seen in figure 3.

The UBM is further influenced by case study research of the Location Orientation Manipulator, or L.O.M., developed by architect Konrad Wachsmann and his PhD students, John Bollinger, and Xavier Mendoza to study the kinematics of building assembly at USC in 1971. Through developing the UBM the authors explore the viability and possibilities of technological solutions that 1) process material, 2) handle material, 3) fabricate components, and 4) assemble system components. Wachsmann's work was not specifically intended to bring accessible housing to the masses, but rather provide prefabricated housing that exhibited a high quality achieved through industrial processes, housing that was flexible, adaptable, mobile, and easy to assemble

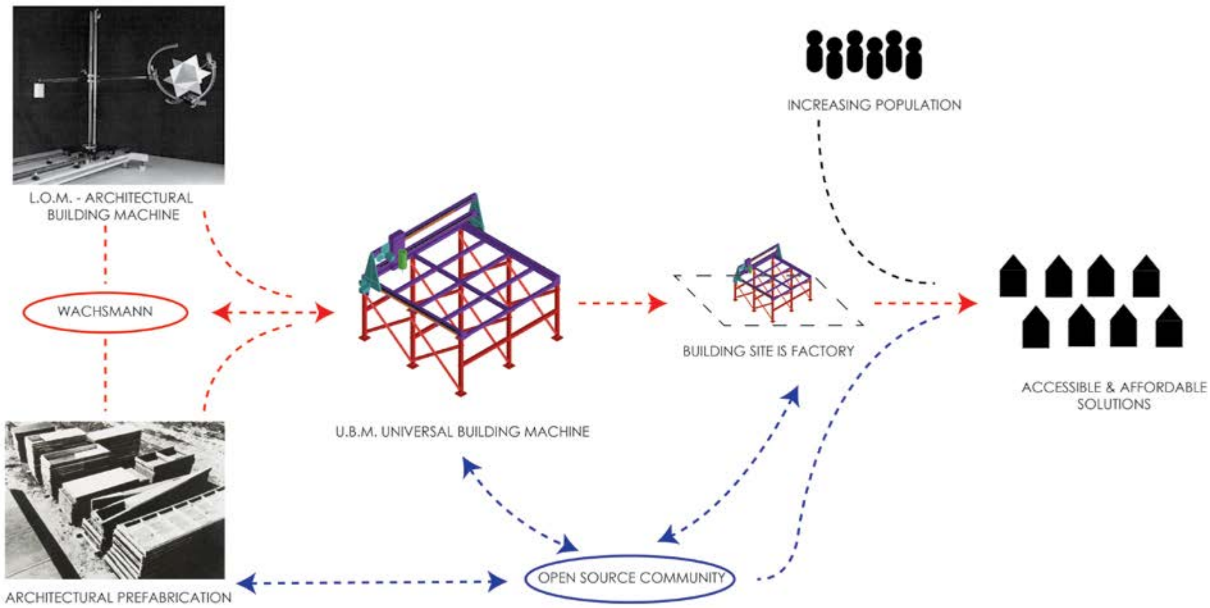

Figure 3. The UBM becomes a place to study theoretical principles of prefabrication and Open-Source accessibility models as adapted to the contemporary global housing crisis. Elizabeth Andrzejewski.

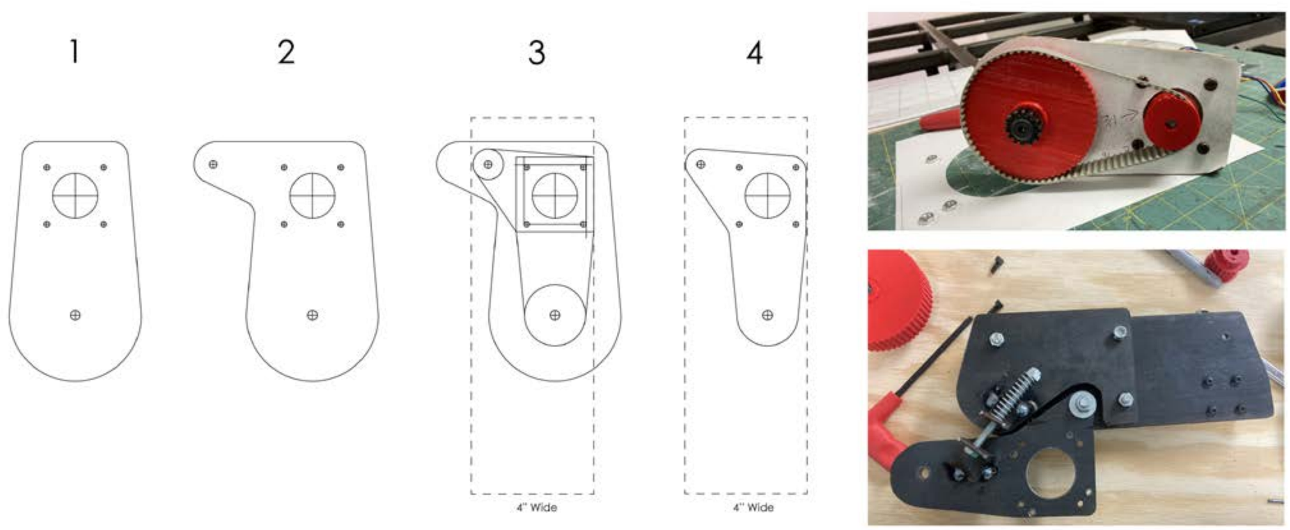

Figure 4. The iteration of the drive component from the perspective of accessibility resulted in a part that could easily fit on a standard 4” wide by .25” thick steel bar. Elizabeth Andrzejewski.

and dissemble. This prototypical UBM derived from architectural building and informed by the efficiency and durability of prefabricated systems, tests the feasibility of a mobile on-site automated building component fabrication and assembly to meet a growing global demand for affordable housing.

The development of the UBM is guided by an ethos of accessibility. Tools, materials, and process/skills to replicate the machine are being minimized. Common materials are used when available, and when they are not, parts are being designed to have more than one use. The construction process of the machine uses a system of patterns and printed templates to aid unskilled people to construct the machine. Ideally the machine can be dissembled, moved, modified, upgraded, and reassembled.

Furthermore, the UBM is designed for the Open-source community and ease of replication to allow for greater accessibility to precise and efficient fabrication methods. One machine becomes accessible, affordable, and deployable. Figure 4 shows part of the development of the UBMs main axis. It is fabricated using standardized motors and fasteners in addition to standard profile steel and a common desktop 3D printer. Through the iterative process of the drive component, material accessibility was considered, and the parts were revised to allow them to be produced out of a standard 4" wide flat stock steel.

In the future, it is hoped that a version of the UBM will be replicated and tested by a community and to create and assemble building components. At this point, the success of this project can be measured by the buy-in of the individual to subvert their current situation living situation and their success using the machine. By promoting accessibility to advanced building technologies developed and designed to be distributed to people in need, the UBM could be part of a larger solution to eventually empower individuals to participate in the construction and maintenance of their own sustainable homes.

ENDNOTES

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